2nd EDITION!

MICHAEL ABRASH'S ZEN OF GRAPHICS PROGRAMMING

Special coverage of optimized 3D polygon rendering and BSP trees

Master the art of creating fast PC graphics and games

THE CORIOLIS GROUP

2nd EDITION!

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Michael Abrash

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ZEN OF GRAPHICS PROGRAMMING

Who Is This Book for?

This book is for intermediate to advanced PC programmers in C, C++, and assembly language who want to learn the techniques of fast graphics programming and animation including 3-D animation.

What Do I Need to Use It?

You need some background in programming in C and assembly. An Intel-based PC is required to run the code. Most of the assembly code is applicable to any Intel-based PC. Some of the listings require a 386, 486, or Pentium, and will not run on earlier processors. A VGA graphics adapter is required to run nearly all of the demo code.

A debugger like CodeView or Turbo Debugger is very helpful in examining the machine code generated by C and C++ compilers.

What Sort of Code Is Present on the Code Disk?

The code disk contains Michael Abrash's well-known X-Sharp library for 3-D animation, as well as numerous programs that demonstrate graphics techniques of various kinds, including VGA setup, optimized graphics primitives, Mode X, 2-D animation, and 3-D animation including texture mapping.

These programs have been tested with the latest Borland compilers and assemblers, and most will work with earlier versions of those compilers and assemblers. The code is quite generic and performs very little I/O, so translation to other C compilers or assemblers like Microsoft C/C++, MASM, Mix C or A86 should not be difficult. Please note that we cannot provide technical assistance with such conversions.

To my parents, Merritt and Barbara, for hanging in there until I finally grew up, for always being there when I needed them, and for teaching me to care.

Dear Reader:

Time and again, I'll bet you've looked at some three-inch-thick software manual and wondered, *How do I make sense of all this?* All the facts may be there, but something important is usually missing: that not-quite-definable right-brain sense of orientation that comes of knowing what the big picture is and how to impose its order on that impenetrable ocean of details.

To help you move in the direction of that necessary big-picture understanding of the software tools you use, The Coriolis Group has created the Zen series of books for software developers. Early books in the series will focus on code optimization, high-performance graphics, component-oriented programming, and arcade game development. Mastering these subjects requires more than just a list of API calls and a haphazard description of how things work.

No. Mastering topics like these requires that you study the experience of the Zen masters in each area, people like Michael Abrash, Peter Aitken, and Diana Gruber—people who have spent years of study, experimentation, and thought becoming what they are. Bringing this experience to you in readable, accessible, *enjoyable* form is what we're doing with our Zen titles.

We don't think there's ever been anything quite like these books, and we invite your comments and suggestions. In what areas have you encountered the sorts of walls that only a Zen master can truly climb? Let us know. We'll do our best to bring the wisdom down the mountain and place it on your bookshelf.

—Jeff Duntemann KG7JF

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Introduction

If you want to write graphics programs—especially games—that look terrific and run like greased lightning, you've come to the right place. Simply put, this is a book about high-performance graphics programming for PCs. This book has every last bit of the Mode X and X-Sharp 2-D and 3-D animation code that started many game authors on their way, and much more: Hardware, software, performance, algorithms, animation, you name it—anything and everything to do with PC graphics, explained thoroughly, implemented in C and assembly language, and finally scraped down to the bare metal so that it runs like nobody's business.

This isn't intended to be the only graphics book you'll ever need; no one book can do that. Neither is it a book about how to do any single sort of graphics—it's not about how to do a flight simulator, for example—nor is it an exhaustive, dry, reference book. What this *is* is a book that will teach you, by example, about the key graphics elements of PC graphics applications such as games, animation, visualization, CAD, graphing, and yes, flight simulators, and will show you how to write top-flight graphics code. What's even more important is that this book will show you how to explore further on your own, how to keep expanding the limits of your graphics knowledge and skills. In short, this book will give you a good start on PC graphics, along with a ton of working code—enough so that you will have the core skills needed for commercial-quality game graphics when you're done—and will then be your springboard to bigger and better things.

Who This Book Is for

This book is for anyone who wants to be a PC graphics programmer, and is not yet an expert. Even intermediate graphics programmers will surely learn many new things from this book, and novices should find this to be a treasure trove. This is the book I wish I could have had ten years ago, when I wrote PC video games for a living; back then, I could have opened this book to almost any page and learned something new and useful. The only prerequisite for this book is that you must already be able to program; it will also help a good deal if you're able to at least read C and assembly language code, although there is no code in here that's so complicated that, say, a Pascal programmer couldn't figure it out given good C and assembly reference books to help.

Basically, if you know how to program and want to write software with screaming fast, great-looking PC graphics, read on!

Where all This Came From

When I had pulled together all the many years' worth of material that make up this book, I started to wonder when the making of this book had started; where exactly had this particular accumulation of knowledge begun? In one sense, it began when Jeff Duntemann's Coriolis Group got into the book publishing business, and Jeff called to ask if I wanted to do a book based on my years of writing about PC graphics. Did I ever! Readers had been asking me for such a book for years, and I had actually tried to get Jeff and a couple of other publishers to do it once or twice before, but all the pieces had never fallen into place—until now. I leaped at the chance.

In another sense, this book began when Jon Erickson at *Dr. Dobb's Journal* gave me the chance back in 1990 to write a graphics column for 100,000 readers. It wasn't until I wrote for *DDJ* that I really understood what a remarkably large and diverse group graphics programmers were, and how much they cared about their work. (One particularly instructive lesson came when I published an early version of Mode X that had a mode set bug. Fixes rolled in from all over the net—and not one person was the slightest bit mean or mean-spirited, bless their souls!)

The key to this book came way back in 1986, though—back when an 8 MHz AT was a high-end system and an EGA was state of the art, at $500 to $1,000 a pop. While living in Pennsylvania back then, I read an article in *Programmer's Journal* (now long gone, but a wonderful home-brewed mishmash of hardcore technical stuff and corny puns in its day) about 8088 optimization—and I knew that the article, though well-intentioned, was just *wrong*. In a fit of passion, I dashed off an article that politely but thoroughly explained why the first article was mistaken, and sent my work off to *PJ*. When I didn't hear from *PJ* for months, I figured they had round-filed my article. By that time, I had other things on my mind anyway; I had decided it was time to see what life was like at the heart of the microcomputer industry, and moved to Silicon Valley.

Right after I got to California, however, I had the pleasant surprise of opening the mailbox one day to find a contract from *PJ* (for a princely $265, lousy money even then, but a sale was and is a sale). Better yet, the West Coast Computer Faire was coming up, and Robert Keller, the editor of *PJ*, wanted to know if we could get together.

We could, and did, and Robert, his wife, and I went out for my first (and so far last, but highly enjoyable) experience with Indonesian cuisine. On the way back, Robert wanted to know if I would write a column for him. The idea intrigued me—there was a lot I wanted to write about in the areas of graphics and performance programming—but although I had written some articles, I wasn't an experienced writer, wasn't sure I could actually deliver good stuff on a regular basis, and was busy as heck with a highly stressful job and a one-year-old child, so I hemmed and hawed. I think Robert thought the problem was money, and that might indeed have been a factor; he had offered $200 per column, probably all the old *PJ* crew (which ran on the shortest shoestring I've ever seen or care to see) could comfortably manage. So as I made noncommittal noises, Robert drove like a maniac (a lost maniac, at that) through San Francisco, bumping the price up in increments detectable only with a magnifying glass.

"Two-twenty-five," Robert said.

"Well," I said.

"Two-fifty."

"Um."

"Two-*sixty*," he ventured.

"Ah."

And so on; by the time we pulled up at my car, Robert had worked his way up to $325, practically a dollar at a time. I was trying hard not to laugh by this point, and though I was tempted to see whether he'd start going by quarters next, I actually did want to do the column, and I was late getting home anyway. So I said okay, and we shook hands, and that was really the beginning of all the pages you hold in your hand. The twenty-two columns I did for *PJ* taught me how to write, how to meet a deadline, how much fun it is to share information—and how much fun it is to get knowledge back in return.

In the years since, I have written several books and innumerable articles and columns, and I've enjoyed it all immensely—and my guess is that none of that would have happened without Robert's persistence in the face of limited resources. So thank you, Robert!

What This Book Is all About

Many, many people have seen one or another of my articles over the years since Robert got me started, and a sizeable number of them have asked where they can find the rest of my work. Until recently, I have had to suggest they refer back to the original articles, but that's a problem because the articles are spread out over about one hundred issues of several magazines, some of which haven't been around for years now. Likewise, *Power Graphics Programming*, which collected the early *PJ* articles, has been out of print for years. Happily, with the help of Jeff Duntemann and the Coriolis Group, that problem is now solved. The best of my performance programming articles were collected together last year in *Zen of Code Optimization*, (also from Coriolis Group Books) and now the best of my graphics programming articles (from my columns in *PJ* and *DDJ*, plus some articles I wrote for *PC TECHNIQUES*) are gathered together in this book.

I say "the best," but what I really mean is "all the material that's still useful"; I have culled those articles that the passing of time has rendered irrelevant, but everything else—nearly 50 articles in all—is in here. Better yet, I've gone over all the material, updating it as needed, and improving it when I see that there's a better way to explain than my original approach. As I reread all this material in preparation for this book, I was astonished at the broad range of topics covered, from VGA internals to 3-D animation, from sprites to blurry-fast lines, circles, and ellipses. My readers and I have explored an amazingly eclectic set of graphics topics, touching on a great many important areas of PC graphics, and always—*always*—with both in-depth explanation and high-performance, high-quality code as part of the package. You can talk all you want about concepts and design and algorithms, and those all matter—but if you're doing graphics and you don't have pedal-to-the-metal code, you don't have anything much to speak of.

This book reflects my personal evolution as a graphics programmer over many years; after all, I wasn't born knowing this stuff! A large part of why I write articles is because I invariably learn something new, and in reading this book you'll be taking much the same journey of exploration that I've taken—but without the annoying and time-wasting mistakes and wrong turns.

Another reason I write is the sheer pleasure of sharing what I've learned. Some of the code and concepts in this book have gotten broad use in the real world, and every time I hear of a nifty program that uses some of the code I've published, or that started with my code (and there are a quite a few such programs), all the late-night hours that went into these articles are justified. Even better, it truly warms my heart when someone comes up to me at a conference or sends me e-mail thanking me for getting them started with graphics. All the good stuff that helped all those people is in here—a complete tour of performance programming for the VGA, the Mode X material that made the unique, undocumented capabilities of that superb VGA game mode available to everyone, the X-Sharp 3-D code that jump-started many a game programmer, a rich set of graphics primitives, and much more. Enjoy!

Or, as Mr. Spock might say, live long and write much fast graphics code.

What You'll Find in This Book

This book covers three broad graphics topics: VGA programming, graphics primitives, and animation. The topics are intertwined; for example, many of the graphics primitive implementations use techniques developed in the discussion of VGA programming, and the animation software builds heavily on the rest of the book. The book isn't as sequential as that might imply, however, because both the VGA and graphics are such large and complex subjects that there is no linear way to discuss them. Instead, this book discusses one particular feature or technique in depth at a time, with plenty of code, and then another, and another, and so on. Over the course of the book, the broad picture comes into focus, especially as new algorithms or features use features discussed earlier, but in different ways. So if you sometimes feel like you need more explanation of a particular topic, look in the index or read on; odds are it'll come up again in another context, one in which it may well make more sense to you.

One important point is that while most of the code in this book is written specifically for the VGA, it is almost entirely applicable to Super VGAs, given some minor changes for banking, although there is only a smattering of Super VGA-specific code. Also, Parts I, II, and VIII are the only truly hardware-specific portions of this book;

much of the rest of the code is easily ported to other environments. For example, it took only a day to port X-Sharp from DOS to Windows. Also, VGA capability, though no longer at the cutting edge, is near-universal nowadays, because almost every graphics accelerator contains full VGA functionality; that means that it's very worthwhile for you to understand the VGA, all the more so because there is no equivalent standard for accelerated graphics. Furthermore, widespread VGA compatibility means that the VGA is the ideal hardware platform for us to use in our explorations, since it will allow the software in this book to run on at least 95 percent of the PCs out there, and surely more than three-quarters of all the computers in existence.

There are nine parts to this book, as follows:

Part I describes the core of the VGA, the internal workings that can be harnessed to double, triple, and even quadruple graphics performance. This is the unglamorous but essential foundation for much of the high-performance code to follow, and although it's not the most exciting part of the book, I suggest you at least skim through it for maximum benefit from the splashy stuff later on. Part I covers only VGA 16-color mode, but the VGA's hardware is the same in 256-color mode, and, in fact, a thorough understanding of the hardware in 16-color mode turns out to be essential for proper understanding of Mode X later on.

Part II discusses the VGA's powerful color capabilities, and lays the groundwork for the Mode X discussion in Part VIII.

Part III kicks off the discussion of graphics primitives with a look at two ways to draw lines *fast*, and Part IV tackles drawing circles and ellipses similarly fast.

Part V covers the intricacies of filled polygons, the fundamental building block of realtime 3-D graphics.

Part VI returns to lines and polygons, but in the context of antialiasing, the process of smoothing graphics images to improve their perceived quality.

Part VII delves into several sorts of animation, both hardware-dependent (page-flipping) and hardware-independent (dirty rectangles), leading into Part VIII, which describes Mode X, and puts it to work in a full-fledged sprite-based animation program.

Part IX pulls together much of what we've covered in the rest of the book into the X-Sharp 3-D package. X-Sharp uses Mode X and the page flipping and polygon-filling code developed earlier to implement realtime 3-D animation, and goes on to add lighting, texture mapping, and more.

And after Part IX... Why, then it's time for you to apply what you've learned, keep exploring and learning, write your own graphics applications, and make some jaws drop!

A Couple of Notes before We Begin

There are two things I need to attend to before we get underway. First, please be aware that some of the listings in this book look rather compressed, in that some additional whitespace would make them more aesthetically pleasing, and arguably more readable. Most of these listings were originally squeezed down to fit in the 300 to 400 lines of listings that I was typically allowed for a magazine article; I tend to be aggressive in getting as much functionality as possible into my published code, so even 400 lines was almost always a tight fit. The good news is that the code has been well tested, by thousands of readers (the bugs that did show up, like the Mode X mode set bug mentioned above, have been fixed in this book), so you can have a high level of confidence that it works as advertised.

Second, I need to define a few basic graphics acronyms that may be unfamiliar to some of you. *VGA* stands for *Video Graphics Array,* originally the graphics chip that IBM put on the motherboards of Micro Channel machines, but now the base standard for graphics for the PC world. Documented standard VGA modes go up to 640×480 resolution in 16 colors, and 320×200 in 256 colors, although in this book we'll see undocumented 256-color modes with resolutions up to 360×480. *SVGA* stands for *Super VGA,* evolutionary descendants of the VGA with higher resolutions and more colors; unfortunately, there is no standard for SVGA, because each manufacturer extended the VGA in a proprietary way. *EGA* is *Enhanced Graphics Adapter,* the direct ancestor of the VGA and the graphics standard in the mid-1980s; the EGA was much like the VGA, but had a maximum resolution of 640×350, and didn't support any 256-color modes. *CGA* is *Color/Graphics Adapter,* the first graphics adapter for the PC, back in 1981, with maximum resolution of 640×200 and a maximum of four simultaneous colors in graphics mode. *MDA* is *Monochrome Display Adapter,* the first black-and-white adapter for the PC. The *MDA* supported only text mode, with no graphics capabilities, leaving the door open for the *Hercules Graphics Card* (*HGC*) to set the standard for graphics capabilities in monochrome mode. Partly because of its low cost, the HGC was very popular for many years, but dirt-cheap VGAs replaced the HGC in the early 1990s.

Acknowledgments

Because this book was written over many years, in many different settings, an unusually large number of people have played a part in making this book possible. First and foremost, thanks (yet again) to Jeff Duntemann for getting this book started, doing the dirty work, and keeping things on track and everyone's spirits up. Thanks to Dan Illowsky for not only contributing ideas and encouragement, but also getting me started writing articles long ago, when I lacked the confidence to do it on my own—and for teaching me how to handle the business end of things. Thanks to Will Fastie for giving me my first crack at writing for a large audience in the long-gone but still-missed *PC Tech Journal,* and for showing me how much fun it could be in his even longer-vanished but genuinely terrific column in *Creative Computing* (the most enjoyable single column I have ever read in a computer magazine; I used to haunt the mailbox around the beginning of the month just to see what Will had to say). Thanks to Robert Keller, Erin O'Connor, Liz Oakley, Steve Baker, and the rest of the cast of thousands that made *PJ* a uniquely fun magazine—especially Erin, who did more than anyone to teach me the proper use of the English language. (To this day, Erin will still patiently explain to me when one should use "that" and when one should use "which," even though eight years of instruction on this and related topics have left no discernible imprint on my brain.) Thanks to Jon Erickson, Tami Zemel, Monica Berg, and the rest of the *DDJ* crew for excellent, professional editing, and for just being great people. Thanks to the Coriolis gang for their tireless hard work: Jeff Duntemann and Keith Weiskamp on the editorial and publishing side, and Brad Grannis, Rob Mauhar, and Michelle Stroup who handled art, design, and layout. Thanks to Jim Mischel who did a terrific job testing code for the book and putting the code disk together. Thanks to Jack Tseng, for teaching me a lot about graphics hardware, and even more about how much difference hard work can make. Thanks to John Cockerham, David Stafford, Terje Mathisen, the BitMan, Chris Hecker, Jim Mackraz, Melvin Lafitte, John Navas, Phil Coleman, Anton Truenfels, John Carmack, John Miles, John Bridges, Jim Kent, Hal Hardenberg, Dave Miller, Steve Levy, Jack Davis, Duane Strong, Daev Rohr, Bill Weber, Dan Gochnauer, Patrick Milligan, Tom Wilson, the people in the ibm.pc/fast.code topic on Bix, and all the rest of you who have been so generous with your ideas and suggestions. I've done my best to acknowledge contributors by name in this book, but if your name is omitted, my apologies, and consider yourself thanked; this book could not have happened without you. And, of course, thanks to Shay and Emily for their generous patience with my passion for writing and computers.

And, finally, thanks to the readers of my articles and to you, the reader of this book. You are, after all, the ultimate reason why I write, and I hope you learn as much and have as much fun reading this book as I did writing it!

Michael Abrash (mabrash@bix.com, mabrash@mcimail.com)
Redmond, Washington, 1994

Chapter 1

Bones and Sinew

At the Very Heart of Standard PC Graphics

The VGA is unparalleled in the history of computer graphics, for it is by far the most widely-used graphics standard ever, the closest we may ever come to a *lingua franca* of computer graphics. No other graphics standard has even come close to the 50,000,000 or so VGAs in use today, and virtually every PC compatible sold today has full VGA compatibility built in. There are, of course, a variety of graphics accelerators that outperform the standard VGA, and indeed, it is becoming hard to find a plain vanilla VGA anymore—but there is no standard for accelerators, and every accelerator contains a true-blue VGA at its core.

What that means is that if you write your programs for the VGA, you'll have the largest possible market for your software. In order for graphics-based software to succeed, however, it must perform well. Wringing the best performance from the VGA is no simple task, and it's *impossible* unless you really understand how the VGA works—unless you have the internals down cold. This book is about PC graphics at many levels, but high performance is the foundation for all that is to come, so it is with the inner workings of the VGA that we will begin our exploration of PC graphics.

The rest of Part I is a guided tour of the heart of the VGA; after you've absorbed what we'll cover in this and the next seven chapters, you'll have the foundation for understanding just about everything the VGA can do, including the fabled Mode X and more. As you read through this part of the book, please keep in mind that the *really* exciting stuff—animation, 3-D, blurry-fast lines and circles and polygons—has to wait until we have the fundamentals out of the way. So hold on and follow along, and before you know it the fireworks will be well underway.

We'll start our exploration with a quick overview of the VGA, and then we'll dive right in and get a taste of what the VGA can do.

The VGA

The VGA is the baseline adapter for modern IBM PC compatibles, present in virtually every PC sold today or in the last several years. (Note that the VGA is often nothing more than a chip on a motherboard, with some memory, a DAC, and maybe a couple of glue chips; nonetheless, I'll refer to it as an adapter from now on for simplicity.) It guarantees that every PC is capable of documented resolutions up to 640×480 (with 16 possible colors per pixel) and 320×200 (with 256 colors per pixel), as well as undocumented—but nonetheless thoroughly standard—resolutions up to 360×480 in 256-color mode, as we'll see in Parts II and VIII. In order for a video adapter to claim VGA compatibility, it must support all the features and code discussed in this book (with a very few minor exceptions that I'll note)—and my experience is that just about 100 percent of the video hardware currently shipping or shipped since 1990 is in fact VGA compatible. Therefore, VGA code will run on nearly all of the 50,000,000 or so PC compatibles out there, with the exceptions being almost entirely obsolete machines from the 1980s. This makes good VGA code and VGA programming expertise valuable commodities indeed.

Right off the bat, I'd like to make one thing perfectly clear: The VGA is hard—sometimes *very* hard—to program for good performance. Hard, but not impossible—and that's why I like this odd board. It's a throwback to an earlier generation of micros, when inventive coding and a solid understanding of the hardware were the best tools for improving performance. Increasingly, faster processors and powerful coprocessors are seen as the solution to the sluggish software produced by high-level languages and layers of interface and driver code, and that's surely a valid approach. However, there are tens of millions of VGAs installed right now, in machines ranging from 6-MHz 286s to 90-MHz Pentiums. What's more, because the VGAs are generally 8- or at best 16-bit devices, and because of display memory wait states, a faster processor isn't as much of a help as you'd expect. The upshot is that only a seasoned performance programmer who understands the VGA through and through can drive the board to its fullest potential.

Throughout this book, I'll explore the VGA by selecting a specific algorithm or feature and implementing code to support it on the VGA, examining aspects of the VGA architecture as they become relevant. You'll get to see VGA features in context, where they are more comprehensible than in IBM's somewhat arcane documentation, and you'll get working code to use or to modify to meet your needs.

The prime directive of VGA programming is that there's rarely just one way to program the VGA for a given purpose. Once you understand the tools the VGA provides, you'll be able to combine them to generate the particular synergy your application needs. My VGA routines are not intended to be taken as gospel, or to show "best" implementations, but rather to start you down the road to understanding the VGA.

Let's begin.

An Introduction to VGA Programming

Most discussions of the VGA start out with a traditional "Here's a block diagram of the VGA" approach, with lists of registers and statistics. I'll get to that eventually, but you can find it in IBM's VGA documentation and several other books. Besides, it's numbing to read specifications and explanations, and the VGA is an exciting adapter, the kind that makes you want to get your hands dirty probing under the hood, to write some nifty code just to see what the board can do. What's more, the best way to understand the VGA is to see it work, so let's jump right into a sample of the VGA in action, getting a feel for the VGA's architecture in the process.

Listing 1.1 is a sample VGA program that pans around an animated 16-color medium-resolution (640×350) playfield. There's a lot packed into this code; I'm going to focus on the VGA-specific aspects so we don't get sidetracked. I'm not going to explain how the ball is animated, for example; we'll get to animation in Parts VII, VIII, and IX of this book. What I will do is cover each of the VGA features used in this program—the virtual screen, vertical and horizontal panning, color plane manipulation, multiplane block copying, and page flipping—at a conceptual level, letting the code itself demonstrate the implementation details. We'll return to many of these concepts in more depth later in this book.

At the Core

A little background is necessary before we're ready to examine Listing 1.1. The VGA is built around four functional blocks, named the CRT Controller (CRTC), the Sequence Controller (SC), the Attribute Controller (AC), and the Graphics Controller (GC). The single-chip VGA could have been designed to treat the registers for all the blocks as one large set, addressed at one pair of I/O ports, but in the EGA, each of these blocks was a separate chip, and the legacy of EGA compatibility is why each of these blocks has a separate set of registers and is addressed at different I/O ports in the VGA.

Each of these blocks has a sizable complement of registers. It is not particularly important that you understand why a given block has a given register; all the registers together make up the programming interface, and it is the entire interface that is of interest to the VGA programmer. However, the means by which most VGA registers are addressed makes it necessary for you to remember which registers are in which blocks.

Most VGA registers are addressed as *internally indexed* registers. The internal address of the register is written to a given block's Index register, and then the data for that register is written to the block's Data register. For example, GC register 8, the Bit Mask register, is set to 0FFH by writing 8 to port 3CEH, the GC Index register, and then writing 0FFH to port 3CFH, the GC Data register. Internal indexing makes it possible to address the 9 GC registers through only two ports, and allows the entire

VGA programming interface to be squeezed into fewer than a dozen ports. The downside is that two I/O operations are required to access most VGA registers.

The ports used to control the VGA are shown in Table 1.1 The CRTC, SC, and GC Data registers are located at the addresses of their respective Index registers plus one. However, the AC Index and Data registers are located at the same address, 3C0H. The function of this port toggles on every **OUT** to 3C0H, and resets to Index mode (in which the Index register is programmed by the next **OUT** to 3C0H) on every read from the Input Status 1 register (3DAH when the VGA is in a color mode, 3BAH in monochrome modes). Note that all CRTC registers are addressed at either 3DXH or 3BXH, the former in color modes and the latter in monochrome modes. This provides compatibility with the register addressing of the now-vanished Color/Graphics Adapter and Monochrome Display Adapter.

The method used in the VGA BIOS to set registers is to point DX to the desired Index register, load AL with the index, perform a byte **OUT**, increment DX to point to the Data register (except in the case of the AC, where DX remains the same), load AL with the desired data, and perform a byte **OUT**. A handy shortcut is to point DX to the desired Index register, load AL with the index, load AH with the data, and perform a word **OUT**. Since the high byte of the **OUT** value goes to port DX+1, this is equivalent to the first method but is faster. However, this technique does not work for programming the AC Index and Data registers; both AC registers are addressed at 3C0H, so two separate byte **OUT**s must be used to program the AC. (Actually, word **OUT**s to the AC

Table 1.1 The Ports Through which the VGA Is Controlled.

Register	Address
AC Index/Data register	3C0H (write with toggle)
AC Index register	3C0H (read)
AC Data register	3C1H (read)
Miscellaneous Output register	3C2H (write) 3CCH (read)
Input Status 0 register	3C2H (read)
SC Index register	3C4H (read/write)
SC Data register	3C5H (read/write)
GC Index register	3CEH (read/write)
GC Data register	3CFH (read/write)
CRTC Index register	3B4H/3D4H (read/write)
CRTC Data register	3B5H/3D5H (read/write)
Input Status 1 register/ AC Index/Data reset	3 BAH/3DAH (read)
Feature Control	3BAH/3DAH (write) 3CAH (read)

do work in the EGA, but not in the VGA, so they shouldn't be used.) As mentioned above, you must be sure which mode—Index or Data—the AC is in before you do an **OUT** to 3C0H; you can read the Input Status 1 register at any time to force the AC to Index mode.

How safe is the word-**OUT** method of addressing VGA registers? I have, in the past, run into adapter/computer combinations that had trouble with word **OUT**s; however, all such problems I am aware of have been fixed. Moreover, a great deal of graphics software now uses word **OUT**s, so any computer or VGA that doesn't properly support word **OUT**s could scarcely be considered a clone at all.

A speed tip: The setting of each chip's Index register remains the same until it is reprogrammed. This means that in cases where you are setting the same internal register repeatedly, you can set the Index register to point to that internal register once, then write to the Data register multiple times. For example, the Bit Mask register (GC register 8) is often set repeatedly inside a loop when drawing lines. The standard code for this is:

```
MOV   DX,03CEH    ;point to GC Index register
MOV   AL,8        ;internal index of Bit Mask register
OUT   DX,AX       ;AH contains Bit Mask register setting
```

Alternatively, the GC Index register could initially be set to point to the Bit Mask register with:

```
MOV   DX,03CEH  ;point to GC Index register
MOV   AL,8      ;internal index of Bit Mask register
OUT   DX,AL     ;set GC Index register
INC   DX        ;point to GC Data register
```

and then the Bit Mask register could be set repeatedly with the byte-size ***OUT*** *instruction:*

```
OUT    DX,AL    ;AL contains Bit Mask register setting
```

which is generally faster (and never slower) than a word-sized ***OUT****, and which does not require AH to be set, freeing up a register. Of course, this method only works if the GC Index register remains unchanged throughout the loop.*

Linear Planes and True VGA Modes

The VGA's memory is organized as four 64K planes. Each of these planes is a linear bitmap; that is, each byte from a given plane controls eight adjacent pixels on the screen, the next byte controls the next eight pixels, and so on to the end of the scan line. The next byte then controls the first eight pixels of the next scan line, and so on to the end of the screen.

The VGA adds a powerful twist to linear addressing; the logical width of the screen in VGA memory need not be the same as the physical width of the display. The programmer is free to define all or part of the VGA's large memory map as a logical screen of up to 4,080 pixels in width, and then use the physical screen as a window onto any part of the logical screen. What's more, a virtual screen can have any logical height up to the capacity of VGA memory. Such a virtual screen could be used to store a spreadsheet or a CAD/CAM drawing, for instance. As we will see shortly, the VGA provides excellent hardware for moving around the virtual screen; taken together, the virtual screen and the VGA's smooth panning capabilities can generate very impressive effects.

All four linear planes are addressed in the same 64K memory space starting at A000:0000. Consequently, there are four bytes at any given address in VGA memory. The VGA provides special hardware to assist the CPU in manipulating all four planes, in parallel, with a single memory access, so that the programmer doesn't have to spend a great deal of time switching between planes. Astute use of this VGA hardware allows VGA software to as much as quadruple performance by processing the data for all the planes in parallel.

Each memory plane provides one bit of data for each pixel. The bits for a given pixel from each of the four planes are combined into a nibble that serves as an address into the VGA's palette RAM, which maps the one of sixteen colors selected by display memory into any one of sixty-four colors, as shown in Figure 1.1. All sixty-four mappings for all sixteen colors are independently programmable. (We'll discuss the VGA's color capabilities in detail starting in Chapter 11.)

The VGA BIOS supports several graphics modes (modes 4, 5, and 6) in which VGA memory appears not to be organized as four linear planes. These modes exist for CGA compatibility only, and are not true VGA graphics modes; use them when you need CGA-type operation and ignore them the rest of the time. The VGA's special features are most powerful in true VGA modes, and it is on the 16-color true-VGA modes (modes 0DH (320×200), 0EH (640×200), 10H (640×350), and 12H (640×480)) that I will concentrate in this part of the book. There is also a 256-color mode, mode 13H, that appears to be a single linear plane, but, as we will see in Parts II and VIII of this book, that's a polite fiction—and discarding that fiction gives us an opportunity to unleash the power of the VGA's hardware for vastly better performance. VGA text modes, which feature soft fonts, are another matter entirely, upon which we'll touch from time to time.

With that background out of the way, we can get on to the sample VGA program shown in Listing 1.1. I suggest you run the program before continuing, since the explanations will mean far more to you if you've seen the features in action.

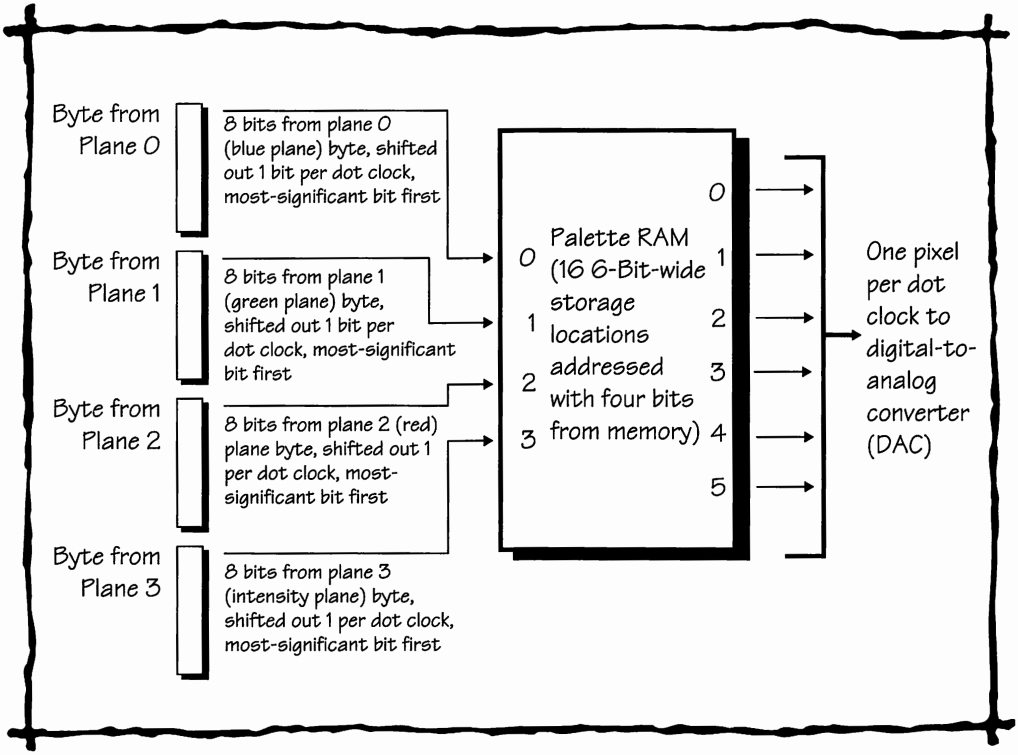

Byte from Plane 0
8 bits from plane 0 (blue plane) byte, shifted out 1 bit per dot clock, most-significant bit first
Byte from Plane 1
8 bits from plane 1 (green plane) byte, shifted out 1 bit per dot clock, most-significant bit first
Byte from Plane 2
8 bits from plane 2 (red) plane byte, shifted out 1 per dot clock, most-significant bit first
Byte from Plane 3
8 bits from plane 3 (intensity plane) byte, shifted out 1 per dot clock, most-significant bit first
0
1
2
3
Palette RAM (16 6-Bit-wide storage locations addressed with four bits from memory)
0
1
2
3
4
5
One pixel per dot clock to digital-to-analog converter (DAC)

Figure 1.1 Video Data from Memory to Pixel

LISTING 1.1 L1-1.ASM

```
; Sample VGA program.
; Animates four balls bouncing around a playfield by using
; page flipping. Playfield is panned smoothly both horizontally
; and vertically.
; By Michael Abrash.
;
stack   segment para stack 'STACK'
        db      512 dup(?)
stack   ends
;
MEDRES_VIDEO_MODE       equ     0       ;define for 640x350 video mode
                                        ; comment out for 640x200 mode
VIDEO_SEGMENT   equu     0a000h          ;display memory segment for
                                        ; true VGA graphics modes
LOGICAL_SCREEN_WIDTH    equ     672/8   ;width in bytes and height in scan
LOGICAL_SCREEN_HEIGHT   equ     384     ; lines of the virtual screen
                                        ; we'll work with
PAGE0           equ     0       ;flag for page 0 when page flipping
PAGE1           equ     1       ;flag for page 1 when page flipping
PAGE0_OFFSET    equ     0       ;start offset of page 0 in VGA memory
PAGE1_OFFSET    equ     LOGICAL_SCREEN_WIDTH * LOGICAL_SCREEN_HEIGHT
                        ;start offset of page 1 (both pages
                        ; are 672x384 virtual screens)
```

```
BALL_WIDTH      equ     24/8    ;width of ball in display memory bytes
BALL_HEIGHT     equ     24      ;height of ball in scan lines
BLANK_OFFSET    equ     PAGE1_OFFSET * 2        ;start of blank image
                                                ; in VGA memory
BALL_OFFSET     equ     BLANK_OFFSET + (BALL_WIDTH * BALL_HEIGHT)
                                ;start offset of ball image in VGA memory
NUM_BALLS       equ     4       ;number of balls to animate
;
; VGA register equates.
;
SC_INDEX        equ     3c4h    ;SC index register
MAP_MASK        equ     2       ;SC map mask register
GC_INDEX        equ     3ceh    ;GC index register
GC_MODE         equ     5       ;GC mode register
CRTC_INDEX      equ     03d4h   ;CRTC index register
START_ADDRESS_HIGH equ  0ch     ;CRTC start address high byte
START_ADDRESS_LOW equ   0dh     ;CRTC start address low byte
CRTC_OFFSET     equ     13h     ;CRTC offset register
INPUT_STATUS_1  equ     03dah   ;VGA status register
VSYNC_MASK      equ     08h     ;vertical sync bit in status register 1
DE_MASK         equ     01h     ;display enable bit in status register 1
AC_INDEX        equ     03c0h   ;AC index register
HPELPAN         equ     20h OR 13h   ;AC horizontal pel panning register
                                     ; (bit 7 is high to keep palette RAM
                                     ; addressing on)
dseg    segment para common 'DATA'
CurrentPage             db      PAGE1           ;page to draw to
CurrentPageOffset       dw      PAGE1_OFFSET
;
; Four plane's worth of multicolored ball image.
;
BallPlane0Image label   byte            ;blue plane image
        db      000h, 03ch, 000h, 001h, 0ffh, 080h
        db      007h, 0ffh, 0e0h, 00fh, 0ffh, 0f0h
        db      4 * 3 dup(000h)
        db      07fh, 0ffh, 0feh, 0ffh, 0ffh, 0ffh
        db      0ffh, 0ffh, 0ffh, 0ffh, 0ffh, 0ffh
        db      4 * 3 dup(000h)
        db      07fh, 0ffh, 0feh, 03fh, 0ffh, 0fch
        db      03fh, 0ffh, 0fch, 01fh, 0ffh, 0f8h
        db      4 * 3 dup(000h)
BallPlane1Image label   byte            ;green plane image
        db      4 * 3 dup(000h)
        db      01fh, 0ffh, 0f8h, 03fh, 0ffh, 0fch
        db      03fh, 0ffh, 0fch, 07fh, 0ffh, 0feh
        db      07fh, 0ffh, 0feh, 0ffh, 0ffh, 0ffh
        db      0ffh, 0ffh, 0ffh, 0ffh, 0ffh, 0ffh
        db      8 * 3 dup(000h)
        db      00fh, 0ffh, 0f0h, 007h, 0ffh, 0e0h
        db      001h, 0ffh, 080h, 000h, 03ch, 000h
BallPlane2Image label   byte            ;red plane image
        db      12 * 3 dup(000h)
        db      0ffh, 0ffh, 0ffh, 0ffh, 0ffh, 0ffh
        db      0ffh, 0ffh, 0ffh, 07fh, 0ffh, 0feh
        db      07fh, 0ffh, 0feh, 03fh, 0ffh, 0fch
        db      03fh, 0ffh, 0fch, 01fh, 0ffh, 0f8h
        db      00fh, 0ffh, 0f0h, 007h, 0ffh, 0e0h
        db      001h, 0ffh, 080h, 000h, 03ch, 000h
BallPlane3Image label   byte            ;intensity on for all planes,
                                        ; to produce high-intensity colors
        db      000h, 03ch, 000h, 001h, 0ffh, 080h
        db      007h, 0ffh, 0e0h, 00fh, 0ffh, 0f0h
        db      01fh, 0ffh, 0f8h, 03fh, 0ffh, 0fch
        db      03fh, 0ffh, 0fch, 07fh, 0ffh, 0feh
        db      07fh, 0ffh, 0feh, 0ffh, 0ffh, 0ffh
        db      0ffh, 0ffh, 0ffh, 0ffh, 0ffh, 0ffh
        db      0ffh, 0ffh, 0ffh, 0ffh, 0ffh, 0ffh
        db      0ffh, 0ffh, 0ffh, 07fh, 0ffh, 0feh
        db      07fh, 0ffh, 0feh, 03fh, 0ffh, 0fch
        db      03fh, 0ffh, 0fch, 01fh, 0ffh, 0f8h
        db      00fh, 0ffh, 0f0h, 007h, 0ffh, 0e0h
        db      001h, 0ffh, 080h, 000h, 03ch, 000h
;
BallX           dw      15, 50, 40, 70          ;array of ball x coords
BallY           dw      40, 200, 110, 300       ;array of ball y coords
LastBallX       dw      15, 50, 40, 70          ;previous ball x coords
LastBallY       dw      40, 100, 160, 30        ;previous ball y coords
BallXInc        dw      1, 1, 1, 1              ;x move factors for ball
BallYInc        dw      8, 8, 8, 8              ;y move factors for ball
BallRep         dw      1, 1, 1, 1              ;# times to keep moving
                                                ; ball according to current
                                                ; increments
BallControl     dw      Ball0Control, Ball1Control     ;pointers to current
                dw      Ball2Control, Ball3Control     ; locations in ball
                                                       ; control strings
BallControlString     dw    Ball0Control, Ball1Control ;pointers to
                      dw    Ball2Control, Ball3Control ; start of ball
                                                       ; control strings
;
; Ball control strings.
;
Ball0Control    label   word
        dw      10, 1, 4, 10, -1, 4, 10, -1, -4, 10, 1, -4, 0
Ball1Control    label   word
        dw      12, -1, 1, 28, -1, -1, 12, 1, -1, 28, 1, 1, 0
Ball2Control    label   word
        dw      20, 0, -1, 40, 0, 1, 20, 0, -1, 0
Ball3Control    label   word
        dw      8, 1, 0, 52, -1, 0, 44, 1, 0, 0
;
; Panning control string.
;
ifdef MEDRES_VIDEO_MODE
PanningControlString    dw      32, 1, 0, 34, 0, 1, 32, -1, 0, 34, 0, -1, 0
else
PanningControlString    dw      32, 1, 0, 184, 0, 1, 32, -1, 0, 184, 0, -1, 0
endif
PanningControl  dw      PanningControlString   ;pointer to current location
                                               ; in panning control string
PanningRep      dw      1      ;# times to pan according to current
                               ; panning increments
PanningXInc     dw      1      ;x panning factor
PanningYInc     dw      0      ;y panning factor
HPan            db      0      ;horizontal pel panning setting
PanningStartOffset dw   0      ;start offset adjustment to produce vertical
                               ; panning & coarse horizontal panning
dseg    ends
;
; Macro to set indexed register P2 of chip with index register
; at P1 to AL.
;
SETREG  macro   P1, P2
```

```
        mov     dx,P1
        mov     ah,al
        mov     al,P2
        out     dx,ax
        endm
;
cseg    segment para public 'CODE'
        assume  cs:cseg, ds:dseg
start   proc    near
        mov     ax,dseg
        mov     ds,ax
;
; Select graphics mode.
;
ifdef MEDRES_VIDEO_MODE
        mov     ax,010h
else
        mov     ax,0eh
endif
        int     10h
;
; ES always points to VGA memory.
;
        mov     ax,VIDEO_SEGMENT
        mov     es,ax
;
; Draw border around playfield in both pages.
;
        mov     di,PAGE0_OFFSET
        call    DrawBorder      ;page 0 border
        mov     di,PAGE1_OFFSET
        call    DrawBorder      ;page 1 border
;
; Draw all four plane's worth of the ball to undisplayed VGA memory.
;
        mov     al,01h          ;enable plane 0
        SETREG  SC_INDEX, MAP_MASK
        mov     si,offset BallPlane0Image
        mov     di,BALL_OFFSET
        mov     cx,BALL_WIDTH * BALL_HEIGHT
        rep movsb
        mov     al,02h          ;enable plane 1
        SETREG  SC_INDEX, MAP_MASK
        mov     si,offset BallPlane1Image
        mov     di,BALL_OFFSET
        mov     cx,BALL_WIDTH * BALL_HEIGHT
        rep movsb
        mov     al,04h          ;enable plane 2
        SETREG  SC_INDEX, MAP_MASK
        mov     si,offset BallPlane2Image
        mov     di,BALL_OFFSET
        mov     cx,BALL_WIDTH * BALL_HEIGHT
        rep movsb
        mov     al,08h          ;enable plane 3
        SETREG  SC_INDEX, MAP_MASK
        mov     si,offset BallPlane3Image
        mov     di,BALL_OFFSET
        mov     cx,BALL_WIDTH * BALL_HEIGHT
        rep movsb
;
```

```
; Draw a blank image the size of the ball to undisplayed VGA memory.
;
        mov     al,0fh                  ;enable all memory planes, since the
        SETREG  SC_INDEX, MAP_MASK      ; blank has to erase all planes
        mov     di,BLANK_OFFSET
        mov     cx,BALL_WIDTH * BALL_HEIGHT
        sub     al,al
        rep stosb
;
; Set VGA to write mode 1, for block copying ball and blank images.
;
        mov     dx,GC_INDEX
        mov     al,GC_MODE
        out     dx,al           ;point GC Index to GC Mode register
        inc     dx              ;point to GC Data register
        jmp     $+2             ;delay to let bus settle
        in      al,dx           ;get current state of GC Mode
        and     al,not 3        ;clear the write mode bits
        or      al,1            ;set the write mode field to 1
        jmp     $+2             ;delay to let bus settle
        out     dx,al
;
; Set VGA offset register in words to define logical screen width.
;
        mov     al,LOGICAL_SCREEN_WIDTH / 2
        SETREG  CRTC_INDEX, CRTC_OFFSET
;
; Move the balls by erasing each ball, moving it, and
; redrawing it, then switching pages when they're all moved.
;
BallAnimationLoop:
        mov     bx,( NUM_BALLS * 2 ) - 2
EachBallLoop:
;
; Erase old image of ball in this page (at location from one more earlier).
;
        mov     si,BLANK_OFFSET ;point to blank image
        mov     cx,[LastBallX+bx]
        mov     dx,[LastBallY+bx]
        call    DrawBall
;
; Set new last ball location.
;
        mov     ax,[BallX+bx]
        mov     [LastballX+bx],ax
        mov     ax,[BallY+bx]
        mov     [LastballY+bx],ax
;
; Change the ball movement values if it's time to do so.
;
        dec     [BallRep+bx]            ;has current repeat factor run out?
        jnz     MoveBall
        mov     si,[BallControl+bx]     ;it's time to change movement values
        lodsw                           ;get new repeat factor from
                                        ; control string
        and     ax,ax                   ;at end of control string?
        jnz     SetNewMove
        mov     si,[BallControlString+bx]        ;reset control string
        lodsw                            ;get new repeat factor
SetNewMove:
        mov     [BallRep+bx],ax         ;set new movement repeat factor
        lodsw                           ;set new x movement increment
        mov     [BallXInc+bx],ax
        lodsw                           ;set new y movement increment
        mov     [BallYInc+bx],ax
        mov     [BallControl+bx],si     ;save new control string pointer
;
; Move the ball.
;
MoveBall:
        mov     ax,[BallXInc+bx]
        add     [BallX+bx],ax           ;move in x direction
        mov     ax,[BallYInc+bx]
        add     [BallY+bx],ax           ;move in y direction
;
; Draw ball at new location.
;
        mov     si,BALL_OFFSET  ;point to ball's image
        mov     cx,[BallX+bx]
        mov     dx,[BallY+bx]
        call    DrawBall
;
        dec     bx
        dec     bx
        jns     EachBallLoop


;
; Set up the next panning state (but don't program it into the
; VGA yet).
;
        call    AdjustPanning


;
; Wait for display enable (pixel data being displayed) so we know
; we're nowhere near vertical sync, where the start address gets
; latched and used.
;
        call    WaitDisplayEnable
;
; Flip to the new page by changing the start address.
;
        mov     ax,[CurrentPageOffset]
        add     ax,[PanningStartOffset]
        push    ax
        SETREG  CRTC_INDEX, START_ADDRESS_LOW
        mov     al,byte ptr [CurrentPageOffset+1]
        pop     ax
        mov     al,ah
        SETREG  CRTC_INDEX, START_ADDRESS_HIGH
;
; Wait for vertical sync so the new start address has a chance
; to take effect.
;
        call    WaitVSync
;
; Set horizontal panning now, just as new start address takes effect.
;
        mov     al,[HPan]
        mov     dx,INPUT_STATUS_1
        in      al,dx                   ;reset AC addressing to index reg
        mov     dx,AC_INDEX
        mov     al,HPELPAN
        out     dx,al                   ;set AC index to pel pan reg
        mov     al,[HPan]
        out     dx,al                   ;set new pel panning
;
; Flip the page to draw to to the undisplayed page.
;
        xor     [CurrentPage],1
        jnz     IsPage1
        mov     [CurrentPageOffset],PAGE0_OFFSET
        jmp     short EndFlipPage
IsPage1:
        mov     [CurrentPageOffset],PAGE1_OFFSET
EndFlipPage:
;
; Exit if a key's been hit.
;
        mov     ah,1
        int     16h
        jnz     Done
        jmp     BallAnimationLoop
;
; Finished, clear key, reset screen mode and exit.
;
Done:
        mov     ah,0    ;clear key
        int     16h
;
        mov     ax,3    ;reset to text mode
        int     10h
;
        mov     ah,4ch  ;exit to DOS
        int     21h
;
start   endp
;
; Routine to draw a ball-sized image to all planes, copying from
; offset SI in VGA memory to offset CX,DX (x,y) in VGA memory in
; the current page.
;
DrawBall        proc    near
        mov     ax,LOGICAL_SCREEN_WIDTH
        mul     dx      ;offset of start of top image scan line
        add     ax,cx   ;offset of upper left of image
        add     ax,[CurrentPageOffset]  ;offset of start of page
        mov     di,ax
        mov     bp,BALL_HEIGHT
        push    ds
        push    es
        pop     ds      ;move from VGA memory to VGA memory
DrawBallLoop:
        push    di
        mov     cx,BALL_WIDTH
        rep movsb       ;draw a scan line of image
        pop     di
        add     di,LOGICAL_SCREEN_WIDTH ;point to next destination scan line
        dec     bp
        jnz     DrawBallLoop
        pop     ds
        ret
DrawBall        endp
```

```
;
; Wait for the leading edge of vertical sync pulse.
;
WaitVSync       proc    near
        mov     dx,INPUT_STATUS_1
WaitNotVSyncLoop:
        in      al,dx
        and     al,VSYNC_MASK
        jnz     WaitNotVSyncLoop
WaitVSyncLoop:
        in      al,dx
        and     al,VSYNC_MASK
        jz      WaitVSyncLoop
        ret
WaitVSync       endp

;
; Wait for display enable to happen (pixels to be scanned to
; the screen, indicating we're in the middle of displaying a frame).
;
WaitDisplayEnable       proc    near
        mov     dx,INPUT_STATUS_1
WaitDELoop:
        in      al,dx
        and     al,DE_MASK
        jnz     WaitDELoop
        ret
WaitDisplayEnable       endp

;
; Perform horizontal/vertical panning.
;
AdjustPanning   proc    near
        dec     [PanningRep]    ;time to get new panning values?
        jnz     DoPan
        mov     si,[PanningControl]     ;point to current location in
                                        ; panning control string
        lodsw                           ;get panning repeat factor
        and     ax,ax                   ;at end of panning control string?
        jnz     SetnewPanValues
        mov     si,offset PanningControlString  ;reset to start of string
        lodsw                           ;get panning repeat factor
SetNewPanValues:
        mov     [PanningRep],ax         ;set new panning repeat value
        lodsw
        mov     [PanningXInc],ax        ;horizontal panning value
        lodsw
        mov     [PanningYInc],ax        ;vertical panning value
        mov     [PanningControl],si     ;save current location in panning
                                        ; control string
;
; Pan according to panning values.
;
DoPan:
        mov     ax,[PanningXInc]        ;horizontal panning
        and     ax,ax
        js      PanLeft                 ;negative means pan left
        jz      CheckVerticalPan
        mov     al,[HPan]
        inc     al                      ;pan right; if pel pan reaches
        cmp     al,8                    ; 8, it's time to move to the
        jb      SetHPan                 ; next byte with a pel pan of 0
        sub     al,al                   ; and a start offset that's one
        inc     [PanningStartOffset]    ; higher
        jmp     short SetHPan
PanLeft:
        mov     al,[HPan]
        dec     al                      ;pan left; if pel pan reaches -1,
        jns     SetHPan                 ; it's time to move to the next
        mov     al,7                    ; byte with a pel pan of 7 and a
        dec     [PanningStartOffset]    ; start offset that's one lower
SetHPan:
        mov     [HPan],al               ;save new pel pan value
CheckVerticalPan:
        mov     ax,[PanningYInc]        ;vertical panning
        and     ax,ax
        js      PanUp                   ;negative means pan up
        jz      EndPan
        add     [PanningStartOffset],LOGICAL_SCREEN_WIDTH
                                        ;pan down by advancing the start
                                        ; address by a scan line
        jmp     short EndPan
PanUp:
        sub     [PanningStartOffset],LOGICAL_SCREEN_WIDTH
                                        ;pan up by retarding the start
                                        ; address by a scan line
EndPan:
        ret
;
; Draw textured border around playfield that starts at DI.
;
DrawBorder      proc    near
;
; Draw the left border.
;
        push    di
        mov     cx,LOGICAL_SCREEN_HEIGHT / 16
DrawLeftBorderLoop:
        mov     al,0ch          ;select red color for block
        call    DrawBorderBlock
        add     di,LOGICAL_SCREEN_WIDTH * 8
        mov     al,0eh          ;select yellow color for block
        call    DrawBorderBlock
        add     di,LOGICAL_SCREEN_WIDTH * 8
        loop    DrawLeftBorderLoop
        pop     di
;
; Draw the right border.
;
        push    di
        add     di,LOGICAL_SCREEN_WIDTH - 1
        mov     cx,LOGICAL_SCREEN_HEIGHT / 16
DrawRightBorderLoop:
        mov     al,0eh          ;select yellow color for block
        call    DrawBorderBlock
        add     di,LOGICAL_SCREEN_WIDTH * 8
        mov     al,0ch          ;select red color for block
        call    DrawBorderBlock
        add     di,LOGICAL_SCREEN_WIDTH * 8
        loop    DrawRightBorderLoop
        pop     di
;
```

```
; Draw the top border.
;
        push    di
        mov     cx,(LOGICAL_SCREEN_WIDTH - 2) / 2
DrawTopBorderLoop:
        inc     di
        mov     al,0eh          ;select yellow color for block
        call    DrawBorderBlock
        inc     di
        mov     al,0ch          ;select red color for block
        call    DrawBorderBlock
        loop    DrawTopBorderLoop
        pop     di
;
; Draw the bottom border.
;
        add     di,(LOGICAL_SCREEN_HEIGHT - 8) * LOGICAL_SCREEN_WIDTH
        mov     cx,(LOGICAL_SCREEN_WIDTH - 2) / 2
DrawBottomBorderLoop:
        inc     di
        mov     al,0ch          ;select red color for block
        call    DrawBorderBlock
        inc     di
        mov     al,0eh          ;select yellow color for block
        call    DrawBorderBlock
        loop    DrawBottomBorderLoop
        ret
DrawBorder      endp
;
; Draws an 8x8 border block in color in AL at location DI.
; DI preserved.
;
DrawBorderBlock proc    near
        push    di
        SETREG  SC_INDEX, MAP_MASK
        mov     al,0ffh
        rept 8
        stosb
        add     di,LOGICAL_SCREEN_WIDTH - 1
        endm
        pop     di
        ret
DrawBorderBlock endp
AdjustPanning   endp
cseg    ends
        end     start
```

Smooth Panning

The first thing you'll notice upon running the sample program is the remarkable smoothness with which the display pans from side-to-side and up-and-down. That the display can pan at all is made possible by two VGA features: 256K of display memory and the virtual screen capability. Even the most memory-hungry of the VGA modes, mode 12H (640×480), uses only 37.5K per plane, for a total of 150K out of the total 256K of VGA memory. The medium-resolution mode, mode 10H (640×350), requires only 28K per plane, for a total of 112K. Consequently, there is room in VGA memory to store more than two full screens of video data in mode 10H (which the sample program uses), and there is room in all modes to store a larger virtual screen than is actually displayed. In the sample program, memory is organized as two virtual screens, each with a resolution of 672×384, as shown in Figure 1.2. The area of the virtual screen actually displayed at any given time is selected by setting the display memory address at which to begin fetching video data; this is set by way of the start address registers (Start Address High, CRTC register 0CH, and Start Address Low, CRTC register 0DH). Together these registers make up a 16-bit display memory address at which the CRTC begins fetching data at the beginning of each video frame. Increasing the start address causes higher-memory areas of the virtual screen to be displayed. For example, the Start Address High register could be set to 80H and the Start Address Low register could be set to 00H in order to cause the display screen to reflect memory starting at offset 8000H in each plane, rather than at the default offset of 0.

The logical height of the virtual screen is defined by the amount of VGA memory available. As the VGA scans display memory for video data, it progresses from the start address toward higher memory one scan line at a time, until the frame is completed. Consequently, if the start address is increased, lines farther toward the bottom of the virtual screen are displayed; in effect, the virtual screen appears to scroll up on the physical screen.

The logical width of the virtual screen is defined by the Offset register (CRTC register 13H), which allows redefinition of the number of words of display memory considered to make up one scan line. Normally, 40 words of display memory constitute a

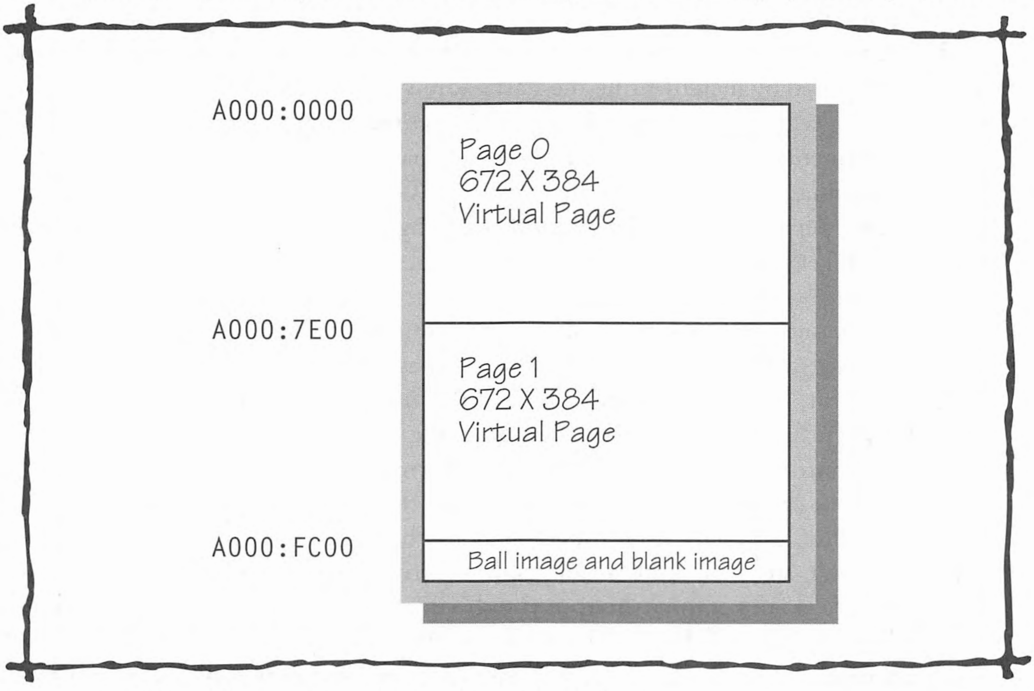


Figure 1.2 Video Memory Organization for Listing 1.1

scan line; after the CRTC scans these 40 words for 640 pixels worth of data, it advances 40 words from the start of that scan line to find the start of the next scan line in memory. This means that displayed scan lines are contiguous in memory. However, the Offset register can be set so that scan lines are logically wider (or narrower, for that matter) than their displayed width. The sample program sets the Offset register to 2AH, making the logical width of the virtual screen 42 words, or 42 * 2 * 8 = 672 pixels, as contrasted with the actual width of the mode 10h screen, 40 words or 640 pixels. The logical height of the virtual screen in the sample program is 384; this is accomplished simply by reserving 84 * 384 contiguous bytes of VGA memory for the virtual screen, where 84 is the virtual screen width in bytes and 384 is the virtual screen height in scan lines.

The start address is the key to panning around the virtual screen. The start address registers select the row of the virtual screen that maps to the top of the display; panning down a scan line requires only that the start address be increased by the logical scan line width in bytes, which is equal to the Offset register times two. The start address registers select the column that maps to the left edge of the display as well, allowing horizontal panning, although in this case only relatively coarse byte-sized adjustments—panning by eight pixels at a time—are supported.

Smooth horizontal panning is provided by the Horizontal Pel Panning register, AC register 13H, working in conjunction with the start address. Up to 7 pixels worth of single pixel panning of the displayed image to the left is performed by increasing the Horizontal Pel Panning register from 0 to 7. This exhausts the range of motion possible via the Horizontal Pel Panning register; the next pixel's worth of smooth panning is accomplished by incrementing the start address by one and resetting the Horizontal Pel Panning register to 0. Smooth horizontal panning should be viewed as a series of fine adjustments in the 8-pixel range between coarse byte-sized adjustments.

A horizontal panning oddity: Alone among VGA modes, text mode (in most cases) has 9 dots per character clock. Smooth panning in this mode requires cycling the Horizontal Pel Panning register through the values 8, 0, 1, 2, 3, 4, 5, 6, and 7. 8 is the "no panning" setting.

There is one annoying quirk about programming the AC. When the AC Index register is set, only the lower five bits are used as the internal index. The next most significant bit, bit 5, controls the source of the video data sent to the monitor by the VGA. When bit 5 is set to 1, the output of the palette RAM, derived from display memory, controls the displayed pixels; this is normal operation. When bit 5 is 0, video data does not come from the palette RAM, and the screen becomes a solid color. The only time bit 5 of the AC Index register should be 0 is during the setting of a palette RAM register, since the CPU is only able to write to palette RAM when bit 5 is 0. (Some VGAs do not enforce this, but you should always set bit 5 to 0 before writing to the palette RAM just to be safe.) Immediately after setting palette RAM, however, 20h (or any other value with bit 5 set to 1) should be written to the AC Index register to restore normal video, and at all other times bit 5 should be set to 1.

By the way, palette RAM can be set via the BIOS video interrupt (interrupt 10H), function 10H. Whenever an VGA function can be performed reasonably well through a BIOS function, as it can in the case of setting palette RAM, it should be, both because there is no point in reinventing the wheel and because the BIOS may well mask incompatibilities between the IBM VGA and VGA clones.

Color Plane Manipulation

The VGA provides a considerable amount of hardware assistance for manipulating the four display memory planes. Two features illustrated by the sample program are the ability to control which planes are written to by a CPU write and the ability to copy four bytes—one from each plane—with a single CPU read and a single CPU write.

The Map Mask register (SC register 2) selects which planes are written to by CPU writes. If bit 0 of the Map Mask register is 1, then each byte written by the CPU will be written to VGA memory plane 0, the plane that provides the video data for the least significant bit of the palette RAM address. If bit 0 of the Map Mask register is 0, then CPU writes will not affect plane 0. Bits 1, 2, and 3 of the Map Mask register similarly control CPU access to planes 1, 2, and 3, respectively. Any of the sixteen possible combinations of enabled and disabled planes can be selected. Beware, however, of writing to an area of memory that is not zeroed. Planes that are disabled by the Map Mask register are not altered by CPU writes, so old and new images can mix on the screen, producing unwanted color effects as, say, three planes from the old image mix with one plane from the new image. The sample program solves this by ensuring that the memory written to is zeroed. A better way to set all planes at once is provided by the set/reset capabilities of the VGA, which I'll cover in Chapter 3.

The sample program writes the image of the colored ball to VGA memory by enabling one plane at a time and writing the image of the ball for that plane. Each image is written to the same VGA addresses; only the destination plane, selected by the Map Mask register, is different. You might think of the ball's image as consisting of four colored overlays, which together make up a multicolored image. The sample program writes a blank image to VGA memory by enabling all planes and writing a block of zero bytes; the zero bytes are written to all four VGA planes simultaneously.

The images are written to a nondisplayed portion of VGA memory in order to take advantage of a useful VGA hardware feature, the ability to copy all four planes at once. As shown by the image-loading code discussed above, four different sets of reads and writes—and several OUTs as well—are required to copy a multicolored image into VGA memory as would be needed to draw the same image into a non-planar pixel buffer. This causes unacceptably slow performance, all the more so because the wait states that occur on accesses to VGA memory make it very desirable to minimize display memory accesses, and because OUTs tend to be very slow.

The solution is to take advantage of the VGA's write mode 1, which is selected via bits 0 and 1 of the GC Mode register (GC register 5). (Be careful to preserve bits 2-7 when setting bits 0 and 1, as is done in Listing 1.1.) In write mode 1, a single CPU read loads the addressed byte from all four planes into the VGA's four internal latches, and a single CPU write writes the contents of the latches to the four planes. During the write, the byte written by the CPU is irrelevant.

The sample program uses write mode 1 to copy the images that were previously drawn to the high end of VGA memory into a desired area of display memory, all in a single block copy operation. This is an excellent way to keep the number of reads, writes, and OUTs required to manipulate the VGA's display memory low enough to allow real-time drawing.

The Map Mask register can still mask out planes in write mode 1. All four planes are copied in the sample program because the Map Mask register is still 0Fh from when the blank image was created.

The animated images appear to move a bit jerkily because they are byte-aligned and so must move a minimum of 8 pixels horizontally. This is easily solved by storing rotated versions of all images in VGA memory, and then in each instance drawing the correct rotation for the pixel alignment at which the image is to be drawn; we'll see this technique in action in Chapter 34.

Don't worry if you're not catching everything in this chapter on the first pass; the VGA is a complicated beast, and learning about it is an iterative process. We'll be going over these features again, in different contexts, over the course of the rest of this book.

Page Flipping

When animated graphics are drawn directly on the screen, with no intermediate frame-composition stage, the image typically flickers and/or ripples, an unavoidable result of modifying display memory at the same time that it is being scanned for video data. The display memory of the VGA makes it possible to perform page flipping, which eliminates such problems. The basic premise of page flipping is that one area of display memory is displayed while another is being modified. The modifications never affect an area of memory as it is providing video data, so no undesirable side effects occur. Once the modification is complete, the modified buffer is selected for display, causing the screen to change to the new image in a single frame's time, typically 1/60th or 1/70th of a second. The other buffer is then available for modification.

As described above, the VGA has 64K per plane, enough to hold two pages and more in 640×350 mode 10H, but not enough for two pages in 640×480 mode 12H. For page flipping, two non-overlapping areas of display memory are needed. The sample program uses two 672×384 virtual pages, each 32,256 bytes long, one starting at A000:0000 and the other starting at A000:7E00. Flipping between the pages is as simple as setting the start address registers to point to one display area or the other—but, as it turns out, that's not as simple as it sounds.

The timing of the switch between pages is critical to achieving flicker-free animation. It is essential that the program never be modifying an area of display memory as that memory is providing video data. Achieving this is surprisingly complicated on the VGA, however.

The problem is as follows. The start address is latched by the VGA's internal circuitry exactly once per frame, typically (but not always on all clones) at the start of the vertical sync pulse. The vertical sync status is, in fact, available as bit 3 of the Input Status 0 register, addressable at 3BAH (in monochrome modes) or 3DAH (color). Unfortunately, by the time the vertical sync status is observed by a program, the start address for the next frame has already been latched, having happened the instant the vertical sync pulse began. That means that it's no good to wait for vertical sync to begin, then set the new start address; if we did that, we'd have to wait until the *next* vertical sync pulse to start drawing, because the page wouldn't flip until then.

Clearly, what we want is to set the new start address, then wait for the start of the vertical sync pulse, at which point we can be sure the page has flipped. However, we can't just set the start address and wait, because we might have the extreme misfortune to set one of the start address registers before the start of vertical sync and the other after, resulting in mismatched halves of the start address and a nasty jump of the displayed image for one frame.

One possible solution to this problem is to pick a second page start address that has a 0 value for the lower byte, so only the Start Address High register ever needs to be set, but in the sample program in Listing 1.1 I've gone for generality and always set both bytes. To avoid mismatched start address bytes, the sample program waits for pixel data to be displayed, as indicated by the Display Enable status; this tells us we're somewhere in the displayed portion of the frame, far enough away from vertical sync so we can be sure the new start address will get used at the next vertical sync. Once the Display Enable status is observed, the program sets the new start address, waits for vertical sync to happen, sets the new pel panning state, and then continues drawing. Don't worry about the details right now; page flipping will come up again, at considerably greater length, in later chapters.

As an interesting side note, be aware that if you run DOS software under a multitasking environment such as Windows NT, timeslicing delays can make mismatched start address bytes or mismatched start address and pel panning settings much more likely, for the graphics code can be interrupted at any time. This is also possible, although much less likely, under non-multitasking environments such as DOS, because strategically placed interrupts can cause the same sorts of problems there. For maximum safety, you should disable interrupts around the key portions of your page-flipping code, although here we run into the problem that if interrupts are disabled from the time we start looking for Display Enable until we set the Pel

> *Panning register, they will be off for far too long, and keyboard, mouse, and network events will potentially be lost. Also, disabling interrupts won't help in true multitasking environments, which never let a program hog the entire CPU. This is one reason that pel panning, although indubitably flashy, isn't widely used and should be reserved for only those cases where it's absolutely necessary.*

Waiting for the sync pulse has the side effect of causing program execution to synchronize to the VGA's frame rate of 60 or 70 frames per second, depending on the display mode. This synchronization has the useful consequence of causing the program to execute at the same speed on any CPU that can draw fast enough to complete the drawing in a single frame; the program just idles for the rest of each frame that it finishes before the VGA is finished displaying the previous frame.

An important point illustrated by the sample program is that while the VGA's display memory is far larger and more versatile than is the case with earlier adapters, it is nonetheless a limited resource and must be used judiciously. The sample program uses VGA memory to store two 672×384 virtual pages, leaving only 1024 bytes free to store images. In this case, the only images needed are a colored ball and a blank block with which to erase it, so there is no problem, but many applications require dozens or hundreds of images. The tradeoffs between virtual page size, page flipping, and image storage must always be kept in mind when designing programs for the VGA.

To see the program run in 640x200 16-color mode, comment out the **EQU** line for **MEDRES_VIDEO_MODE**.

The Hazards of VGA Clones

Earlier, I said that any VGA that doesn't support the features and functionality covered in this book can't properly be called VGA compatible. I also noted that there are some exceptions, however, and we've just come to the most prominent one. You see, all VGAs really *are* compatible with the IBM VGA's functionality when it comes to drawing pixels into display memory; all the write modes and read modes and set/reset capabilities and everything else involved with manipulating display memory really does work in the same way on all VGAs and VGA clones. That compatibility isn't as airtight when it comes to scanning pixels out of display memory and onto the screen in certain infrequently-used ways, however.

The areas of incompatibility of which I'm aware are illustrated by the sample program, and may in fact have caused you to see some glitches when you ran Listing 1.1. The problem, which arises only on certain VGAs, is that some settings of the Row Offset register cause some pixels to be dropped or displaced to the wrong place on the screen; often, this happens only in conjunction with certain start address settings. (In my experience, only VRAM (Video RAM)-based VGAs exhibit this problem, no doubt due to the way that pixel data is fetched from VRAM in large blocks.) Panning and large virtual bitmaps can be made to work reliably, by careful selection of virtual bitmap sizes and start addresses, but it's difficult; that's one of the reasons that most commercial software does not use these features, although a number of games do. The upshot is that if you're going to use oversized virtual bitmaps and pan around them, you should take great care to test your software on a wide variety of VRAM- and DRAM-based VGAs.

Just the Beginning

That pretty well covers the important points of the sample VGA program in Listing 1.1. There are many VGA features we didn't even touch on, but the object was to give you a feel for the variety of features available on the VGA, to convey the flexibility and complexity of the VGA's resources, and in general to give you an initial sense of what VGA programming is like. Starting with the next chapter, we'll begin to explore the VGA systematically, on a more detailed basis.

The Macro Assembler

The code in this book is written in both C and assembly. I think C is a good development environment, but I believe that often the best code (although not necessarily the easiest to write or the most reliable) is written in assembly. This is especially true of graphics code for the x86 family, given segments, the string instructions, and the asymmetric and limited register set, and for real-time programming of a complex board like the VGA, there's really no other choice for the lowest-level code.

Before I'm deluged with protests from C devotees, let me add that the majority of my productive work is done in C; no programmer is immune to the laws of time, and C is simply a more time-efficient environment in which to develop, particularly when working in a programming team. In this book, however, we're after the *sine qua non* of PC graphics—performance—and we can't get there from here without a fair amount of assembly language.

Now that we know what the VGA looks like in broad strokes and have a sense of what VGA programming is like, we can start looking at specific areas in depth. In the next chapter, we'll take a look at the hardware assistance the VGA provides the CPU during display memory access. There are four latches and four ALUs in those chips, along with some useful masks and comparators, and it's that hardware that's the difference between sluggish performance and making the VGA get up and dance.

Parallel Processing with the VGA

Chapter 2

Taking on Graphics Memory Four Bytes at a Time

This heading refers to the ability of the VGA chip to manipulate up to four bytes of display memory at once. In particular, the VGA provides four ALUs (Arithmetic Logic Units) to assist the CPU during display memory writes, and this hardware is a tremendous resource in the task of manipulating the VGA's sizable frame buffer. The ALUs are actually only one part of the surprisingly complex data flow architecture of the VGA, but since they're involved in almost all memory access operations, they're a good place to begin.

VGA Programming: ALUs and Latches

I'm going to begin our detailed tour of the VGA at the heart of the flow of data through the VGA: the four ALUs built into the VGA's Graphics Controller (GC) circuitry. The ALUs (one for each display memory plane) are capable of ORing, ANDing, and XORing CPU data and display memory data together, as well as masking off some or all of the bits in the data from affecting the final result. All the ALUs perform the same logical operation at any given time, but each ALU operates on a different display memory byte.

Recall that the VGA has four display memory planes, with one byte in each plane at any given display memory address. All four display memory bytes operated on are read from and written to the same address, but each ALU operates on a byte that was read from a different plane and writes the result to that plane. This arrangement allows four display memory bytes to be modified by a single CPU write (which must often be preceded by a single CPU read, as we will see). The benefit is vastly improved performance; if the CPU had to select each of the four planes in turn via **OUT**s and perform the four logical operations itself, VGA performance would slow to a crawl.

Figure 2.1 is a simplified depiction of data flow around the ALUs. Each ALU has a matching latch, which holds the byte read from the corresponding plane during the last CPU read from display memory, even if that particular plane wasn't the plane that the CPU actually read on the last read access. (Only one byte can be read by the CPU with a single display memory read; the plane supplying the byte is selected by the Read Map register. However, the bytes at the specified address in all four planes are always read when the CPU reads display memory, and those four bytes are stored in their respective latches.)

Each ALU logically combines the byte written by the CPU and the byte stored in the matching latch, according to the settings of bits 3 and 4 of the Data Rotate register (and the Bit Mask register as well, which I'll cover next time), and then writes the result to display memory. It is most important to understand that neither ALU operand comes directly from display memory. The temptation is to think of the ALUs as combining CPU data and the contents of the display memory address being written to, but they actually combine CPU data and the contents of the last display memory location read, which need not be the location being modified. The most common application of the ALUs is indeed to modify a given display memory location, but doing so requires a read from that location to load the latches before the write that modifies it. Omission of the read results in a write operation that logically combines CPU data with whatever data happens to be in the latches from the last read, which is normally undesirable.

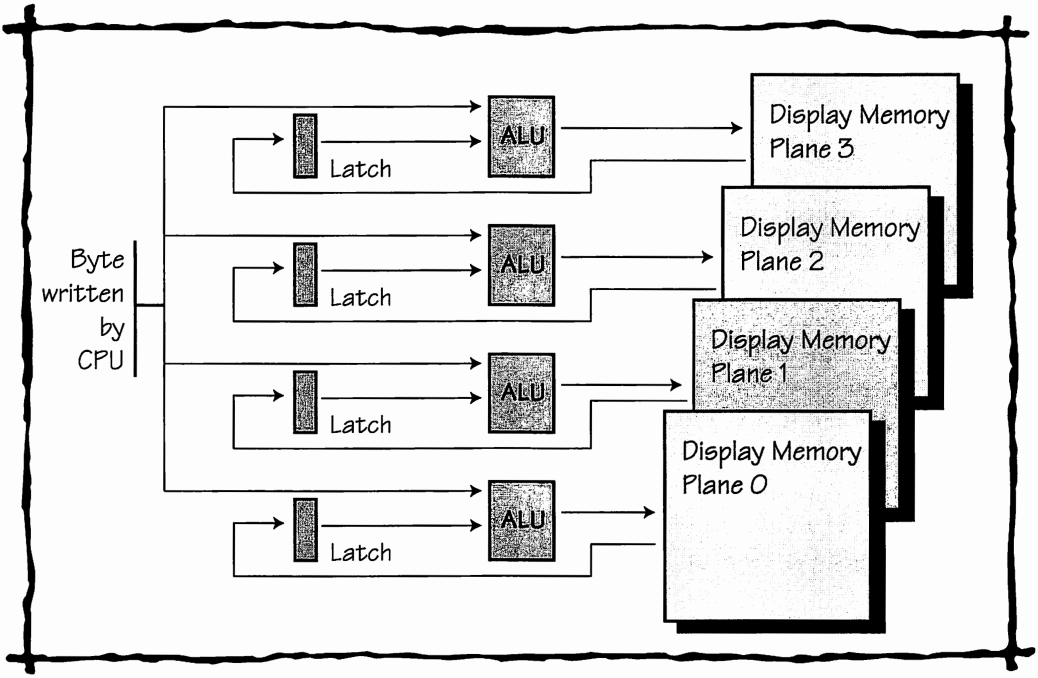


Figure 2.1 VGA ALU Data Flow

Occasionally, however, the independence of the latches from the display memory location being written to can be used to great advantage. The latches can be used to perform 4-byte-at-a-time (one byte from each plane) block copying; in this application, the latches are loaded with a read from the source area and written unmodified to the destination area. The latches can be written unmodified in one of two ways: By selecting write mode 1 (for an example of this, see the last chapter), or by setting the Bit Mask register to 0 so only the latched bits are written.

The latches can also be used to draw a fairly complex area fill pattern, with a different bit pattern used to fill each plane. The mechanism for this is as follows: First, generate the desired pattern across all planes at any display memory address. Generating the pattern requires a separate write operation for each plane, so that each plane's byte will be unique. Next, read that memory address to store the pattern in the latches. The contents of the latches can now be written to memory any number of times by using either write mode 1 or the bit mask, since they will not change until a read is performed. If the fill pattern does not require a different bit pattern for each plane—that is, if the pattern is black and white—filling can be performed more easily by simply fanning the CPU byte out to all four planes with write mode 0. The set/reset registers can be used in conjunction with fanning out the data to support a variety of two-color patterns. More on this in Chapter 3.

The sample program in Listing 2.1 fills the screen with horizontal bars, then illustrates the operation of each of the four ALU logical functions by writing a vertical 80-pixel-wide box filled with solid, empty, and vertical and horizontal bar patterns over that background using each of the functions in turn. When observing the output of the sample program, it is important to remember that all four vertical boxes are drawn with *exactly* the same code—only the logical function that is in effect differs from box to box.

All graphics in the sample program are done in black-and-white by writing to all planes, in order to show the operation of the ALUs most clearly. Selective enabling of planes via the Map Mask register and/or set/reset would produce color effects; in that case, the operation of the logical functions must be evaluated on a plane-by-plane basis, since only the enabled planes would be affected by each operation.

LISTING 2.1 L2-1.ASM

```
; Program to illustrate operation of ALUs and latches of the VGA's
;  Graphics Controller.  Draws a variety of patterns against
;  a horizontally striped background, using each of the 4 available
;  logical functions (data unmodified, AND, OR, XOR) in turn to combine
;  the images with the background.
; By Michael Abrash.
;
stack   segment para stack 'STACK'
        db      512 dup(?)
stack   ends
;
VGA_VIDEO_SEGMENT       equ     0a000h  ;VGA display memory segment
SCREEN_HEIGHT           equ     350
```

```
SCREEN_WIDTH_IN_BYTES   equ     80
DEMO_AREA_HEIGHT        equ     336     ;# of scan lines in area
                                        ; logical function operation
                                        ; is demonstrated in
DEMO_AREA_WIDTH_IN_BYTES equ    40      ;width in bytes of area
                                        ; logical function operation
                                        ; is demonstrated in
VERTICAL_BOX_WIDTH_IN_BYTES equ 10      ;width in bytes of the box used to
                                        ; demonstrate each logical function
;
; VGA register equates.
;
GC_INDEX        equ     3ceh    ;GC index register
GC_ROTATE       equ     3       ;GC data rotate/logical function
                                ; register index
GC_MODE         equ     5       ;GC mode register index
;
dseg    segment para common 'DATA'
;
; String used to label logical functions.
;
LabelString     label   byte
        db      'UNMODIFIED    AND       OR        XOR   '
LABEL_STRING_LENGTH     equ     $-LabelString
;
; Strings used to label fill patterns.
;
FillPatternFF   db      'Fill Pattern: 0FFh'
FILL_PATTERN_FF_LENGTH  equ     $ - FillPatternFF
FillPattern00   db      'Fill Pattern: 000h'
FILL_PATTERN_00_LENGTH  equ     $ - FillPattern00
FillPatternVert db      'Fill Pattern: Vertical Bar'
FILL_PATTERN_VERT_LENGTH        equ     $ - FillPatternVert
FillPatternHorz db      'Fill Pattern: Horizontal Bar'
FILL_PATTERN_HORZ_LENGTH equ    $ - FillPatternHorz
;
dseg    ends
;
; Macro to set indexed register INDEX of GC chip to SETTING.
;
SETGC   macro   INDEX, SETTING
        mov     dx,GC_INDEX
        mov     ax,(SETTING SHL 8) OR INDEX
        out     dx,ax
        endm
;
;
; Macro to call BIOS write string function to display text string
;  TEXT_STRING, of length TEXT_LENGTH, at location ROW,COLUMN.
;
TEXT_UP macro   TEXT_STRING, TEXT_LENGTH, ROW, COLUMN
        mov     ah,13h                  ;BIOS write string function
        mov     bp,offset TEXT_STRING   ;ES:BP points to string
        mov     cx,TEXT_LENGTH
        mov     dx,(ROW SHL 8) OR COLUMN        ;position
        sub     al,al           ;string is chars only, cursor not moved
        mov     bl,7            ;text attribute is white (light gray)
        int     10h
        endm
;
cseg    segment para public 'CODE'
```

```
        assume  cs:cseg, ds:dseg
start   proc    near
        mov     ax,dseg
        mov     ds,ax
;
; Select 640x350 graphics mode.
;
        mov     ax,010h
        int     10h
;
; ES points to VGA memory.
;
        mov     ax,VGA_VIDEO_SEGMENT
        mov     es,ax
;
; Draw background of horizontal bars.
;
        mov     dx,SCREEN_HEIGHT/4
                                ;# of bars to draw (each 4 pixels high)
        sub     di,di           ;start at offset 0 in display memory
        mov     ax,0ffffh       ;fill pattern for light areas of bars
        mov     bx,DEMO_AREA_WIDTH_IN_BYTES / 2 ;length of each bar
        mov     si,SCREEN_WIDTH_IN_BYTES - DEMO_AREA_WIDTH_IN_BYTES
        mov     bp,(SCREEN_WIDTH_IN_BYTES * 3) - DEMO_AREA_WIDTH_IN_BYTES
BackgroundLoop:
        mov     cx,bx           ;length of bar
    rep stosw                   ;draw top half of bar
        add     di,si           ;point to start of bottom half of bar
        mov     cx,bx           ;length of bar
    rep stosw                   ;draw bottom half of bar
        add     di,bp           ;point to start of top of next bar
        dec     dx
        jnz     BackgroundLoop
;
; Draw vertical boxes filled with a variety of fill patterns
;  using each of the 4 logical functions in turn.
;
        SETGC   GC_ROTATE, 0            ;select data unmodified
                                        ; logical function...
        mov     di,0
        call    DrawVerticalBox         ;...and draw box
;
        SETGC   GC_ROTATE, 08h          ;select AND logical function...
        mov     di,10
        call    DrawVerticalBox         ;...and draw box
;
        SETGC   GC_ROTATE, 10h          ;select OR logical function...
        mov     di,20
        call    DrawVerticalBox         ;...and draw box
;
        SETGC   GC_ROTATE, 18h          ;select XOR logical function...
        mov     di,30
        call    DrawVerticalBox         ;...and draw box
;
; Reset the logical function to data unmodified, the default state.
;
        SETGC   GC_ROTATE, 0
;
; Label the screen.
;
        push    ds
        pop     es      ;strings we'll display are passed to BIOS
                        ; by pointing ES:BP to them
;
; Label the logical functions, using the VGA BIOS's
;  write string function.
;
        TEXT_UP LabelString, LABEL_STRING_LENGTH, 24, 0
;
; Label the fill patterns, using the VGA BIOS's
;  write string function.
;
        TEXT_UP FillPatternFF, FILL_PATTERN_FF_LENGTH, 3, 42
        TEXT_UP FillPattern00, FILL_PATTERN_00_LENGTH, 9, 42
        TEXT_UP FillPatternVert, FILL_PATTERN_VERT_LENGTH, 15, 42
        TEXT_UP FillPatternHorz, FILL_PATTERN_HORZ_LENGTH, 21, 42
;
; Wait until a key's been hit to reset screen mode & exit.
;
WaitForKey:
        mov     ah,1
        int     16h
        jz      WaitForKey
;
; Finished.  Clear key, reset screen mode and exit.
;
Done:
        mov     ah,0    ;clear key that we just detected
        int     16h
;
        mov     ax,3    ;reset to text mode
        int     10h
;
        mov     ah,4ch  ;exit to DOS
        int     21h
;
start   endp
;
; Subroutine to draw a box 80x336 in size, using currently selected
;  logical function, with upper left corner at the display memory offset
;  in DI.  Box is filled with four patterns.  Top quarter of area is
;  filled with 0FFh (solid) pattern, next quarter is filled with 00h
;  (empty) pattern, next quarter is filled with 33h (double pixel wide
;  vertical bar) pattern, and bottom quarter is filled with double pixel
;  high horizontal bar pattern.
;
; Macro to draw a column of the specified width in bytes, one-quarter
;  of the height of the box, with the specified fill pattern.
;
DRAW_BOX_QUARTER        macro   FILL, WIDTH
        local   RowLoop, ColumnLoop
        mov     al,FILL                 ;fill pattern
        mov     dx,DEMO_AREA_HEIGHT / 4 ;1/4 of the full box height
RowLoop:
        mov     cx,WIDTH
ColumnLoop:
        mov     ah,es:[di]      ;load display memory contents into
                                ; GC latches (we don't actually care
                                ; about value read into AH)
        stosb                   ;write pattern, which is logically
                                ; combined with latch contents for each
                                ; plane and then written to display
                                ; memory
        loop    ColumnLoop
        add     di,SCREEN_WIDTH_IN_BYTES - WIDTH
                                ;point to start of next line down in box
        dec     dx
        jnz     RowLoop
        endm
;
DrawVerticalBox proc    near
        DRAW_BOX_QUARTER        0ffh, VERTICAL_BOX_WIDTH_IN_BYTES
                                        ;first fill pattern: solid fill
        DRAW_BOX_QUARTER        0, VERTICAL_BOX_WIDTH_IN_BYTES
                                        ;second fill pattern: empty fill
        DRAW_BOX_QUARTER        033h, VERTICAL_BOX_WIDTH_IN_BYTES
                                        ;third fill pattern: double-pixel
                                        ; wide vertical bars
        mov     dx,DEMO_AREA_HEIGHT / 4 / 4
                                ;fourth fill pattern: horizontal bars in
                                ; sets of 4 scan lines
        sub     ax,ax
        mov     si,VERTICAL_BOX_WIDTH_IN_BYTES  ;width of fill area
HorzBarLoop:
        dec     ax              ;0ffh fill (smaller to do word than byte DEC)
        mov     cx,si           ;width to fill
HBLoop1:
        mov     bl,es:[di]      ;load latches (don't care about value)
        stosb                   ;write solid pattern, through ALUs
        loop    HBLoop1
        add     di,SCREEN_WIDTH_IN_BYTES - VERTICAL_BOX_WIDTH_IN_BYTES
        mov     cx,si           ;width to fill
HBLoop2:
        mov     bl,es:[di]      ;load latches
        stosb                   ;write solid pattern, through ALUs
        loop    HBLoop2
        add     di,SCREEN_WIDTH_IN_BYTES - VERTICAL_BOX_WIDTH_IN_BYTES
        inc     ax              ;0 fill (smaller to do word than byte DEC)
        mov     cx,si           ;width to fill
HBLoop3:
        mov     bl,es:[di]      ;load latches
        stosb                   ;write empty pattern, through ALUs
        loop    HBLoop3
        add     di,SCREEN_WIDTH_IN_BYTES - VERTICAL_BOX_WIDTH_IN_BYTES
        mov     cx,si           ;width to fill
HBLoop4:
        mov     bl,es:[di]      ;load latches
        stosb                   ;write empty pattern, through ALUs
        loop    HBLoop4
        add     di,SCREEN_WIDTH_IN_BYTES - VERTICAL_BOX_WIDTH_IN_BYTES
        dec     dx
        jnz     HorzBarLoop
;
        ret
DrawVerticalBox endp
cseg    ends
        end     start
```

Logical function 0, which writes the CPU data unmodified, is the standard mode of operation of the ALUs. In this mode, the CPU data is combined with the latched data by ignoring the latched data entirely. Expressed as a logical function, this could be considered CPU data ANDed with 1 (or ORed with 0). This is the mode to use whenever you want to place CPU data into display memory, replacing the previous contents entirely. It may occur to you that there is no need to latch display memory at all when the data unmodified function is selected. In the sample program, that is true, but if the bit mask is being used, the latches must be loaded even for the data unmodified function, as I'll discuss in the next chapter.

Logical functions 1 through 3 cause the CPU data to be ANDed, ORed, and XORed with the latched data, respectively. Of these, XOR is the most useful, since exclusive-ORing is a traditional way to perform animation. The uses of the AND and OR logical functions are less obvious. AND can be used to mask a blank area into display memory, or to mask off those portions of a drawing operation that don't overlap an existing display memory image. OR could conceivably be used to force an image into display memory over an existing image. To be honest, I haven't encountered any particularly valuable applications for AND and OR, but they're the sort of building-block features that could come in handy in just the right context, so keep them in mind.

Notes on the ALU/Latch Demo Program

VGA settings such as the logical function select should be restored to their default condition before the BIOS is called to output text or draw pixels. The VGA BIOS does not guarantee that it will set most VGA registers except on mode sets, and there are so many compatible BIOSes around that the code of the IBM BIOS is not a reliable guide. For instance, when the BIOS is called to draw text, it's likely that the result will be illegible if the Bit Mask register is not in its default state. Similarly, a mode set should generally be performed before exiting a program that tinkers with VGA settings.

Along the same lines, the sample program does not explicitly set the Map Mask register to ensure that all planes are enabled for writing. The mode set for mode 10H leaves all planes enabled, so I did not bother to program the Map Mask register, or any other register besides the Data Rotate register, for that matter. However, the profusion of compatible BIOSes means there is some small risk in relying on the BIOS to leave registers set properly. For the highly safety-conscious, the best course would be to program data control registers such as the Map Mask and Read Mask explicitly before relying on their contents.

On the other hand, any function the BIOS provides explicitly—as part of the interface specification—such as setting the palette RAM, should be used in preference to programming the hardware directly whenever possible, because the BIOS may mask hardware differences between VGA implementations.

The code that draws each vertical box in the sample program reads from display memory immediately before writing to display memory. The read operation loads the VGA latches. The value that is read is irrelevant as far as the sample program is concerned. The read operation is present only because it is necessary to perform a read to load the latches, and there is no way to read without placing a value in a register. This is a bit of a nuisance, since it means that the value of some 8-bit register must be destroyed. Under certain circumstances, a single logical instruction such as **XOR** or **AND** can be used to perform both the read to load the latches and then write to modify display memory without affecting any CPU registers, as we'll see later on.

All text in the sample program is drawn by VGA BIOS function 13H, the write string function. This function is also present in the AT's BIOS, but not in the XT's or PC's, and as a result is rarely used; the function is always available if a VGA is installed, however. Text drawn with this function is relatively slow. If speed is important, a program can draw text directly into display memory much faster in any given display mode. The great virtue of the BIOS write string function in the case of the VGA is that it provides an uncomplicated way to get text on the screen reliably in any mode and color, over any background.

The expression used to load DX in the **TEXT_UP** macro in the sample program may seem strange, but it's a convenient way to save a byte of program code and a few cycles of execution time. DX is being loaded with a word value that's composed of two independent immediate byte values. The obvious way to implement this would be with:

```
MOV  DL,VALUE1
MOV  DH,VALUE2
```

which requires four instruction bytes. By shifting the value destined for the high byte into the high byte with MASM's shift- left operator, **SHL** (*100H would work also), and then logically combining the values with MASM's **OR** operator (or the **ADD** operator), both halves of DX can be loaded with a single instruction, as in:

```
MOV  DX,(VALUE2 SHL 8) OR VALUE1
```

which takes only three bytes and is faster, being a single instruction. (Note, though, that in 32-bit protected mode, there's a size and performance penalty for 16-bit instructions such as the **MOV** above; see my book *Zen of Code Optimization* for details.) As shown, a macro is an ideal place to use this technique; the macro invocation can refer to two separate byte values, making matters easier for the programmer, while the macro itself can combine the values into a single word-sized constant.

*A minor optimization tip illustrated in the listing is the use of **INC AX** and **DEC AX** in the **DrawVerticalBox** subroutine when only AL actually needs to be modified. Word-sized register increment and decrement instructions (or dword-sized instructions in 32-bit protected mode) are only one byte long, while byte-sized register increment and decrement instructions are two bytes long. Consequently, when size counts, it is worth using a whole 16-bit (or 32-bit) register instead of the low 8 bits of that register for **INC** and **DEC**—if you don't need the upper portion of the register for any other purpose, or if you can be sure that the **INC** or **DEC** won't affect the upper part of the register.*

The latches and ALUs are central to high-performance VGA code, since they allow programs to process across all four memory planes without a series of **OUT**s and read/write operations. It is not always easy to arrange a program to exploit this power, however, because the ALUs are far more limited than a CPU. In many instances, however, additional hardware in the VGA, including the bit mask, the set/reset features, and the barrel shifter, can assist the ALUs in controlling data, as we'll see in the next few chapters.

VGA Data Machinery

Chapter 3

The Barrel Shifter, Bit Mask, and Set/Reset Mechanisms

In the last chapter, we examined a simplified model of data flow within the GC portion of the VGA, featuring the latches and ALUs. Now we're ready to expand that model to include the barrel shifter, bit mask, and the set/reset capabilities, leaving only the write modes to be explored over the next few chapters.

VGA Data Rotation

Figure 3.1 shows an expanded model of GC data flow, featuring the barrel shifter and bit mask circuitry. Let's look at the barrel shifter first. A barrel shifter is circuitry capable of shifting—or rotating, in the VGA's case—data an arbitrary number of bits in a single operation, as opposed to being able to shift only one bit position at a time. The barrel shifter in the VGA can rotate incoming CPU data up to seven bits to the right (toward the least significant bit), with bit 0 wrapping back to bit 7, after which the VGA continues processing the rotated byte just as it normally processes unrotated CPU data. Thanks to the nature of barrel shifters, this rotation requires no extra processing time over unrotated VGA operations. The number of bits by which CPU data is shifted is controlled by bits 2-0 of GC register 3, the Data Rotate register, which also contains the ALU function select bits (data unmodified, AND, OR, and XOR) that we looked at in the last chapter.

The barrel shifter is powerful, but (as sometimes happens in this business) it sounds more useful than it really is. This is because the GC can only rotate CPU data, a task that the CPU itself is perfectly capable of performing. Two **OUT**s are needed to select a given rotation: One to set the GC Index register, and one to set the Data Rotate

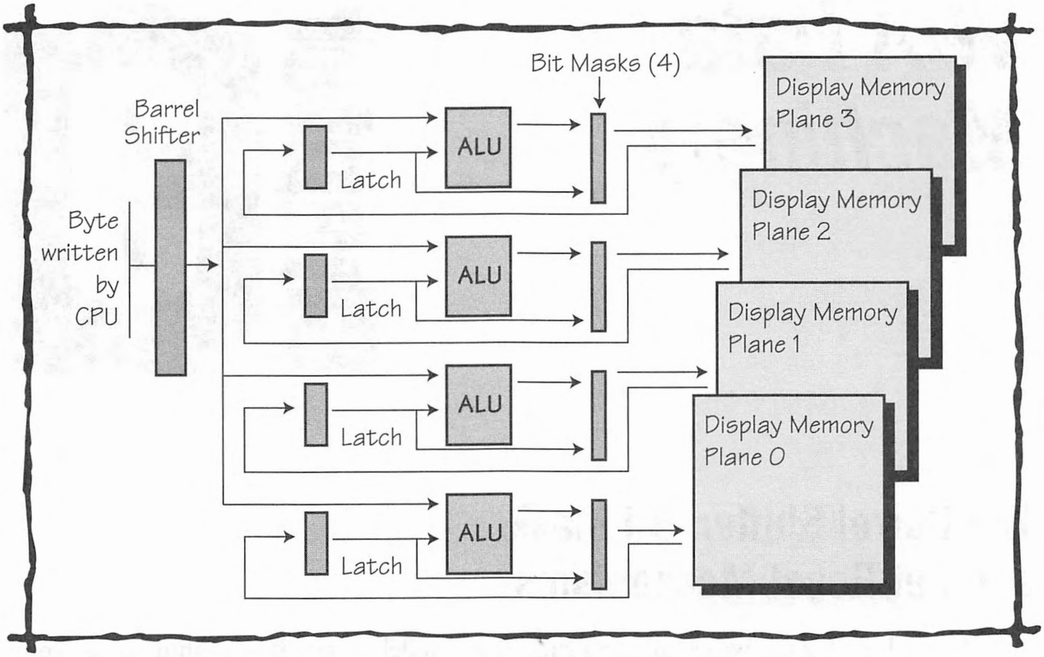


Figure 3.1 Data Flow through the Graphics Controller

register. However, with careful programming it's sometimes possible to leave the GC Index always pointing to the Data Rotate register, so only one **OUT** is needed. Even so, it's often easier and/or faster to simply have the CPU rotate the data of interest CL times than to set the Data Rotate register. (Bear in mind that a single **OUT** takes from 11 to 31 cycles on a 486—and longer if the VGA is sluggish at responding to **OUT**s, as many VGAs are.) If only the VGA could rotate *latched* data, then there would be all sorts of useful applications for rotation, but, sadly, only CPU data can be rotated.

The drawing of bit-mapped text is one use for the barrel shifter, and I'll demonstrate that application below. In general, though, don't knock yourself out trying to figure out how to work data rotation into your programs—it just isn't all that useful in most cases.

The Bit Mask

The VGA has bit mask circuitry for each of the four memory planes. The four bit masks operate in parallel and are all driven by the same mask data for each operation, so they're generally referred to in the singular, as "the bit mask." Figure 3.2 illustrates the operation of one bit of the bit mask for one plane. This circuitry occurs eight times in the bit mask for a given plane, once for each bit of the byte written to display memory. Briefly, the bit mask determines on a bit-by-bit basis whether the source for each byte written to display memory is the ALU for that plane or the latch for that plane.

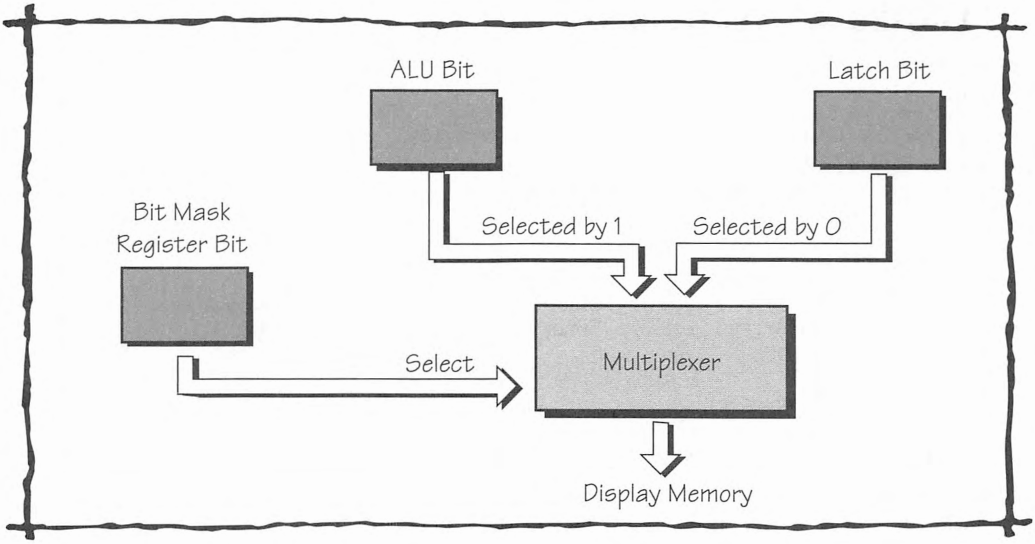


Figure 3.2 Bit Mask Operation

The bit mask is controlled by GC register 8, the Bit Mask register. If a given bit of the Bit Mask register is 1, then the corresponding bit of data from the ALUs is written to display memory for all four planes, while if that bit is 0, then the corresponding bit of data from the latches for the four planes is written to display memory unchanged. (In write mode 3, the actual bit mask that's applied to data written to display memory is the logical AND of the contents of the Bit Mask register and the data written by the CPU, as we'll see in Chapter 4.)

The most common use of the bit mask is to allow updating of selected bits within a display memory byte. This works as follows: The display memory byte of interest is latched; the bit mask is set to preserve all but the bit or bits to be changed; the CPU writes to display memory, with the bit mask preserving the indicated latched bits and allowing ALU data through to change the other bits. Remember, though, that it is not possible to alter selected bits in a display memory byte *directly;* the byte must first be latched by a CPU read, and then the bit mask can keep selected bits of the latched byte unchanged.

Listing 3.1 shows a program that uses the bit mask data rotation capabilities of the GC to draw bitmapped text at any screen location. The BIOS only draws characters on character boundaries; in 640×480 graphics mode the default font is drawn on byte boundaries horizontally and every 16 scan lines vertically. However, with direct bitmapped text drawing of the sort used in Listing 3.1, it's possible to draw any font of any size anywhere on the screen (and a lot faster than via DOS or the BIOS, as well).

LISTING 3.1 L3-1.ASM

```
; Program to illustrate operation of data rotate and bit mask
;  features of Graphics Controller.  Draws 8x8 character at
;  specified location, using VGA's 8x8 ROM font.  Designed
;  for use with modes 0Dh, 0Eh, 0Fh, 10h, and 12h.
; By Michael Abrash.
;
stack   segment para stack 'STACK'
        db      512 dup(?)
stack   ends
;
VGA_VIDEO_SEGMENT       equ     0a000h  ;VGA display memory segment
SCREEN_WIDTH_IN_BYTES   equ     044ah   ;offset of BIOS variable
FONT_CHARACTER_SIZE     equ     8       ;# bytes in each font char
;
; VGA register equates.
;
GC_INDEX        equ     3ceh    ;GC index register
GC_ROTATE       equ     3       ;GC data rotate/logical function
                                ; register index
GC_BIT_MASK     equ     8       ;GC bit mask register index
;
dseg    segment para common 'DATA'
TEST_TEXT_ROW   equ     69      ;row to display test text at
TEST_TEXT_COL   equ     17      ;column to display test text at
TEST_TEXT_WIDTH equ     8       ;width of a character in pixels

TestString      label   byte
        db      'Hello, world!',0       ;test string to print.
FontPointer     dd      ?               ;font offset
dseg    ends
;
; Macro to set indexed register INDEX of GC chip to SETTING.
;
SETGC   macro   INDEX, SETTING
        mov     dx,GC_INDEX
        mov     ax,(SETTING SHL 8) OR INDEX
        out     dx,ax
        endm
;
cseg    segment para public 'CODE'
        assume  cs:cseg, ds:dseg
start   proc    near
        mov     ax,dseg
        mov     ds,ax
;
; Select 640x480 graphics mode.
;
        mov     ax,012h
        int     10h
;
; Set driver to use the 8x8 font.
;
         mov     ah,11h      ;VGA BIOS character generator function,
         mov     al,30h      ; return info subfunction
         mov     bh,3        ;get 8x8 font pointer
         int     10h
         call    SelectFont
;
```

```
; Print the test string.
;
        mov     si,offset TestString
        mov     bx,TEST_TEXT_ROW
        mov     cx,TEST_TEXT_COL
StringOutLoop:
        lodsb
        and     al,al
        jz      StringOutDone
        call    DrawChar
        add     cx,TEST_TEXT_WIDTH
        jmp     StringOutLoop
StringOutDone:
;
; Reset the data rotate and bit mask registers.
;
        SETGC   GC_ROTATE, 0
        SETGC   GC_BIT_MASK, 0ffh
;
; Wait for a keystroke.
;
        mov     ah,1
        int     21h
;
; Return to text mode.
;
        mov     ax,03h
        int     10h
;
; Exit to DOS.
;
        mov     ah,4ch
        int     21h
Start   endp
;
; Subroutine to draw a text character in a linear graphics mode
;  (0Dh, 0Eh, 0Fh, 010h, 012h).
; Font used should be pointed to by FontPointer.
;
; Input:
;  AL = character to draw
;  BX = row to draw text character at
;  CX = column to draw text character at
;
;  Forces ALU function to "move".
;
DrawChar        proc    near
        push    ax
        push    bx
        push    cx
        push    dx
        push    si
        push    di
        push    bp
        push    ds
;
; Set DS:SI to point to font and ES to point to display memory.
;
        lds     si,[FontPointer]        ;point to font
        mov     dx,VGA_VIDEO_SEGMENT
        mov     es,dx                   ;point to display memory
;
; Calculate screen address of byte character starts in.
;
        push    ds     ;point to BIOS data segment
        sub     dx,dx
        mov     ds,dx
        xchg    ax,bx
        mov     di,ds:[SCREEN_WIDTH_IN_BYTES]   ;retrieve BIOS
                                                ; screen width
        pop     ds
        mul     di     ;calculate offset of start of row
        push    di     ;set aside screen width
        mov     di,cx    ;set aside the column
        and     cl,0111b ;keep only the column in-byte address
        shr     di,1
        shr     di,1
        shr     di,1     ;divide column by 8 to make a byte address
        add     di,ax    ;and point to byte
;
; Calculate font address of character.
;
        sub     bh,bh
        shl     bx,1     ;assumes 8 bytes per character; use
        shl     bx,1     ; a multiply otherwise
        shl     bx,1     ;offset in font of character
        add     si,bx    ;offset in font segment of character
;
; Set up the GC rotation.
;
        mov     dx,GC_INDEX
        mov     al,GC_ROTATE
        mov     ah,cl
        out     dx,ax
;
; Set up BH as bit mask for left half,
; BL as rotation for right half.
;
        mov     bx,0ffffh
        shr     bh,cl
        neg     cl
        add     cl,8
        shl     bl,cl
;
; Draw the character, left half first, then right half in the
; succeeding byte, using the data rotation to position the character
; across the byte boundary and then using the bit mask to get the
; proper portion of the character into each byte.
; Does not check for case where character is byte-aligned and
; no rotation and only one write is required.
;
        mov     bp,FONT_CHARACTER_SIZE
        mov     dx,GC_INDEX
        pop     cx     ;get back screen width
        dec     cx
        dec     cx     ; -2 because do two bytes for each char
CharacterLoop:
;
; Set the bit mask for the left half of the character.
;
```

```
        mov     al,GC_BIT_MASK
        mov     ah,bh
        out     dx,ax
;
; Get the next character byte & write it to display memory.
; (Left half of character.)
;
        mov     al,[si]         ;get character byte
        mov     ah,es:[di]      ;load latches
        stosb                   ;write character byte
;
; Set the bit mask for the right half of the character.
;
        mov     al,GC_BIT_MASK
        mov     ah,bl
        out     dx,ax
;
; Get the character byte again & write it to display memory.
; (Right half of character.)
;
        lodsb                   ;get character byte
        mov     ah,es:[di]      ;load latches
        stosb                   ;write character byte
;
; Point to next line of character in display memory.
;
        add     di,cx
;
        dec     bp
        jnz     CharacterLoop
;
        pop     ds
        pop     bp
        pop     di
        pop     si
        pop     dx
        pop     cx
        pop     bx
        pop     ax
        ret
DrawChar        endp
;
; Set the pointer to the font to draw from to ES:BP.
;
SelectFont      proc    near
        mov     word ptr [FontPointer],bp       ;save pointer
        mov     word ptr [FontPointer+2],es
        ret
SelectFont      endp
;
cseg    ends
        end     start
```

The bit mask can be used for much more than bit-aligned fonts. For example, the bit mask is useful for fast pixel drawing, such as that performed when drawing lines, as we'll see in Chapter 14. It's also useful for drawing the edges of primitives, such as filled polygons, that potentially involve modifying some but not all of the pixels controlled by a single byte of display memory.

display memory need to be changed, because it allows full use of the VGA's four-way parallel processing capabilities for the pixels that are to be drawn, without interfering with the pixels that are to be left unchanged. The alternative would be plane-by-plane processing, which from a performance perspective would be undesirable indeed.

It's worth pointing out again that the bit mask operates on the data in the latches, not on the data in display memory. This makes the bit mask a flexible resource that with a little imagination can be used for some interesting purposes. For example, you could fill the latches with a solid background color (by writing the color somewhere in display memory, then reading that location to load the latches), and then use the Bit Mask register (or write mode 3, as we'll see later) as a mask through which to draw a foreground color stencilled into the background color *without* reading display memory first. This only works for writing whole bytes at a time (clipped bytes require the use of the bit mask; unfortunately, we're already using it for stencilling in this case), but it completely eliminates reading display memory and does foreground-plus-background drawing in one blurry-fast pass.

This last-described example is a good illustration of how I'd suggest you approach the VGA: As a rich collection of hardware resources that can profitably be combined in some non-obvious ways. Don't let yourself be limited by the obvious applications for the latches, bit mask, write modes, read modes, map mask, ALUs, and set/reset circuitry. Instead, try to imagine how they could work together to perform whatever task you happen to need done at any given time. I've made my code as much as four times faster by doing this, as the discussion of Mode X in Part VIII demonstrates.

The example code in Listing 3.1 is designed to illustrate the use of the Data Rotate and Bit Mask registers, and is not as fast or as complete as it might be. The case where text *is* byte-aligned could be detected and performed much faster, without the use of the Bit Mask or Data Rotate registers and with only one display memory access per font byte (to write the font byte), rather than four (to read display memory and write the font byte to each of the two bytes the character spans). Likewise, non-aligned text drawing could be streamlined to one display memory access per byte by having the CPU rotate and combine the font data directly, rather than setting up the VGA's hardware to do it. (Listing 3.1 was designed to illustrate VGA data rotation and bit masking rather than the fastest way to draw text. We'll see faster text-drawing code soon.) One excellent rule of thumb is to minimize display memory accesses of all types, especially reads, which tend to be considerably slower than writes. Also, in Listing 3.1 it would be faster to use a table lookup to calculate the bit masks for the two halves of each character rather than the shifts used in the example.

For another (and more complex) example of drawing bit-mapped text on the VGA, see John Cockerham's article, "Pixel Alignment of EGA Fonts," *PC Tech Journal*, January, 1987. Parenthetically, I'd like to pass along John's comment about the VGA: "When programming the VGA, *everything* is complex."

He's got a point there.

The VGA's Set/Reset Circuitry

At last we come to the final aspect of data flow through the GC on write mode 0 writes: the set/reset circuitry. Figure 3.3 shows data flow on a write mode 0 write. The only difference between this figure and Figure 3.1 is that on its way to each plane potentially the rotated CPU data passes through the set/reset circuitry, which may or may not replace the CPU data with set/reset data. Briefly put, the set/reset circuitry enables the programmer to elect to independently replace the CPU data for each plane with either 00 or 0FFH.

What is the use of such a feature? Well, the standard way to control color is to set the Map Mask register to enable writes to only those planes that need to be set to produce the desired color. For example, the Map Mask register would be set to 09H to draw in high-intensity blue; here, bits 0 and 3 are set to 1, so only the blue plane (plane 0) and the intensity plane (plane 3) are written to.

Remember, though, that planes that are disabled by the Map Mask register are not written to or modified in any way. This means that the above approach works only if

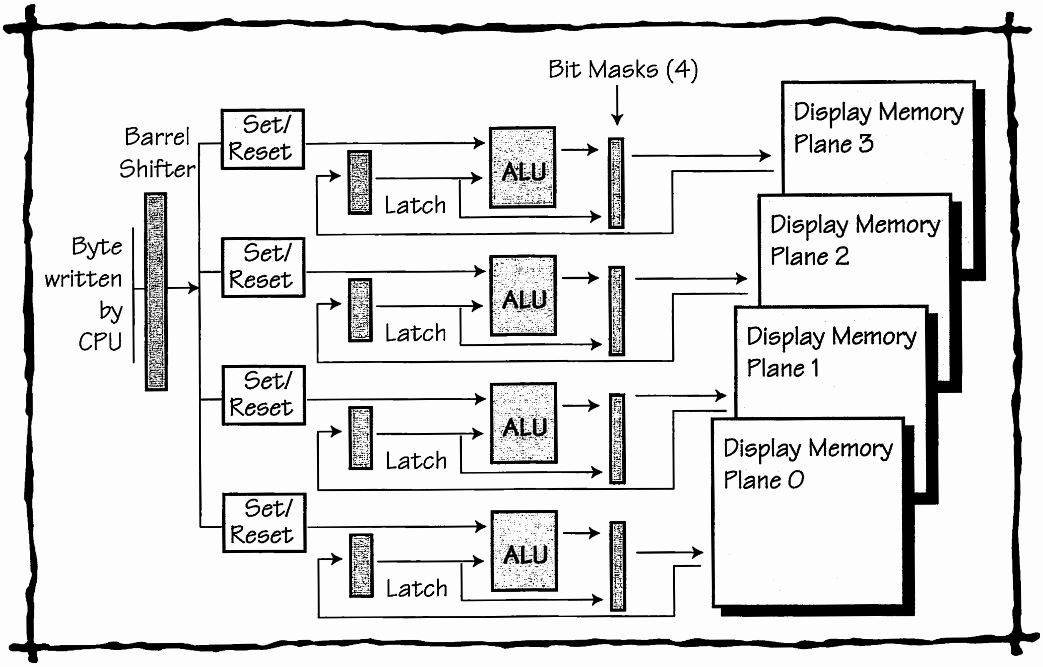


Figure 3.3 Data Flow During a Write Mode 0 Write Operation

Remember, though, that planes that are disabled by the Map Mask register are not written to or modified in any way. This means that the above approach works only if the memory being written to is zeroed; if, however, the memory already contains nonzero data, that data will remain in the planes disabled by the Map Mask, and the end result will be that some planes contain the data just written and other planes contain old data. In short, color control using the Map Mask does not force all planes to contain the desired color. In particular, it is not possible to force some planes to zero and other planes to one in a single write with the Map Mask register.

The program in Listing 3.2 illustrates this problem. A green pattern (plane 1 set to 1, planes 0, 2, and 3 set to 0) is first written to display memory. Display memory is then filled with blue (only plane 0 set to 1), with a Map Mask setting of 01H. Where the blue crosses the green, cyan is produced, rather than blue, because the Map Mask register setting of 01H that produces blue leaves the green plane (plane 1) unchanged. In order to generate blue unconditionally, it would be necessary to set the Map Mask register to 0FH, clear memory, and then set the Map Mask register to 01H and fill with blue.

LISTING 3.2 L3-2.ASM

```
; Program to illustrate operation of Map Mask register when drawing
;  to memory that already contains data.
; By Michael Abrash.
;
stack   segment para stack 'STACK'
        db      512 dup(?)
stack   ends
;
EGA_VIDEO_SEGMENT       equ     0a000h  ;EGA display memory segment
;
; EGA register equates.
;
SC_INDEX        equ     3c4h    ;SC index register
SC_MAP_MASK     equ     2       ;SC map mask register
;
; Macro to set indexed register INDEX of SC chip to SETTING.
;
SETSC   macro   INDEX, SETTING
        mov     dx,SC_INDEX
        mov     al,INDEX
        out     dx,al
        inc     dx
        mov     al,SETTING
        out     dx,al
        dec     dx
        endm
;
cseg    segment para public 'CODE'
        assume  cs:cseg
start   proc    near
;
; Select 640x480 graphics mode.
;
```

```
        mov     ax,012h
        int     10h
;
        mov     ax,EGA_VIDEO_SEGMENT
        mov     es,ax                   ;point to video memory
;
; Draw 24 10-scan-line high horizontal bars in green, 10 scan lines apart.
;
        SETSC   SC_MAP_MASK,02h         ;map mask setting enables only
                                        ; plane 1, the green plane
        sub     di,di           ;start at beginning of video memory
        mov     al,0ffh
        mov     bp,24           ;# bars to draw
HorzBarLoop:
        mov     cx,80*10        ;# bytes per horizontal bar
        rep stosb               ;draw bar
        add     di,80*10        ;point to start of next bar
        dec     bp
        jnz     HorzBarLoop
;
; Fill screen with blue, using Map Mask register to enable writes
; to blue plane only.
;
        SETSC   SC_MAP_MASK,01h         ;map mask setting enables only
                                        ; plane 0, the blue plane
        sub     di,di
        mov     cx,80*480               ;# bytes per screen
        mov     al,0ffh
        rep stosb                       ;perform fill (affects only
                                        ; plane 0, the blue plane)

;
; Wait for a keystroke.
;
        mov     ah,1
        int     21h
;
; Restore text mode.
;
        mov     ax,03h
        int     10h
;
; Exit to DOS.
;
        mov     ah,4ch
        int     21h
start   endp
cseg    ends
        end     start
```

Setting all Planes to a Single Color

The set/reset circuitry can be used to force some planes to 0-bits and others to 1-bits during a single write, while letting CPU data go to still other planes, and so provides an efficient way to set all planes to a desired color. The set/reset circuitry works as follows:

For each of the bits 0-3 in the Enable Set/Reset register (Graphics Controller register 1) that is 1, the corresponding bit in the Set/Reset register (GC register 0) is extended to a byte (0 or 0FFH) and replaces the CPU data for the corresponding plane.

For each of the bits in the Enable Set/Reset register that is 0, the CPU data is used unchanged for that plane (normal operation). For example, if the Enable Set/Reset register is set to 01H and the Set/Reset register is set to 05H, then the CPU data is replaced for plane 0 only (the blue plane), and the value it is replaced with is 0FFH (bit 0 of the Set/Reset register extended to a byte). Note that in this case, bits 1-3 of the Set/Reset register have no effect.

It is important to understand that the set/reset circuitry directly replaces CPU data in Graphics Controller data flow. Refer back to Figure 3.3 to see that the output of the set/reset circuitry passes through (and may be transformed by) the ALU and the bit mask before being written to memory, and even then the Map Mask register must enable the write. When using set/reset, it is generally desirable to set the Map Mask register to enable all planes the set/reset circuitry is controlling, since those memory planes which are disabled by the Map Mask register cannot be modified, and the purpose of enabling set/reset for a plane is to force that plane to be set by the set/reset circuitry.

Listing 3.3 illustrates the use of set/reset to force a specific color to be written. This program is the same as that of Listing 3.2, except that set/reset rather than the Map Mask register is used to control color. The preexisting pattern is completely overwritten this time, because the set/reset circuitry writes 0-bytes to planes that must be off as well as 0FFH-bytes to planes that must be on.

LISTING 3.3 L3-3.ASM

```
; Program to illustrate operation of set/reset circuitry to force
;  setting of memory that already contains data.
; By Michael Abrash.
;
stack   segment para stack 'STACK'
        db      512 dup(?)
stack   ends
;
EGA_VIDEO_SEGMENT       equ     0a000h  ;EGA display memory segment
;
; EGA register equates.
;
SC_INDEX        equ     3c4h    ;SC index register
SC_MAP_MASK     equ     2       ;SC map mask register
GC_INDEX        equ     3ceh    ;GC index register
GC_SET_RESET    equ     0       ;GC set/reset register
GC_ENABLE_SET_RESET equ 1       ;GC enable set/reset register
;
; Macro to set indexed register INDEX of SC chip to SETTING.
;
SETSC   macro   INDEX, SETTING
        mov     dx,SC_INDEX
        mov     al,INDEX
        out     dx,al
        inc     dx
        mov     al,SETTING
        out     dx,al
        dec     dx
        endm
```

```
;
; Macro to set indexed register INDEX of GC chip to SETTING.
;
SETGC   macro   INDEX, SETTING
        mov     dx,GC_INDEX
        mov     al,INDEX
        out     dx,al
        inc     dx
        mov     al,SETTING
        out     dx,al
        dec     dx
        endm
;
cseg    segment para public 'CODE'
        assume  cs:cseg
start   proc    near
;
; Select 640x480 graphics mode.
;
        mov     ax,012h
        int     10h
;
        mov     ax,EGA_VIDEO_SEGMENT
        mov     es,ax                   ;point to video memory
;
; Draw 24 10-scan-line high horizontal bars in green, 10 scan lines apart.
;
        SETSC   SC_MAP_MASK,02h         ;map mask setting enables only
                                        ; plane 1, the green plane
        sub     di,di           ;start at beginning of video memory
        mov     al,0ffh
        mov     bp,24           ;# bars to draw
HorzBarLoop:
        mov     cx,80*10        ;# bytes per horizontal bar
        rep stosb               ;draw bar
        add     di,80*10        ;point to start of next bar
        dec     bp
        jnz     HorzBarLoop
;
; Fill screen with blue, using set/reset to force plane 0 to 1's and all
; other plane to 0's.
;
        SETSC   SC_MAP_MASK,0fh         ;must set map mask to enable all
                                        ; planes, so set/reset values can
                                        ; be written to memory
        SETGC   GC_ENABLE_SET_RESET,0fh ;CPU data to all planes will be
                                        ; replaced by set/reset value
        SETGC   GC_SET_RESET,01h        ;set/reset value is 0ffh for plane 0
                                        ; (the blue plane) and 0 for other
                                        ; planes
        sub     di,di
        mov     cx,80*480               ;# bytes per screen
        mov     al,0ffh                 ;since set/reset is enabled for all
                                        ; planes, the CPU data is ignored-
                                        ; only the act of writing is
                                        ; important
        rep stosb                       ;perform fill (affects all planes)
;
; Turn off set/reset.
;
        SETGC   GC_ENABLE_SET_RESET,0
```

```
;
; Wait for a keystroke.
;
        mov     ah,1
        int     21h
;
; Restore text mode.
;
        mov     ax,03h
        int     10h
;
; Exit to DOS.
;
        mov     ah,4ch
        int     21h
start   endp
cseg    ends
        end     start
```

Manipulating Planes Individually

Listing 3.4 illustrates the use of set/reset to control only some, rather than all, planes. Here, the set/reset circuitry forces plane 2 to 1 and planes 0 and 3 to 0. Because bit 1 of the Enable Set/Reset register is 0, however, set/reset does not affect plane 1; the CPU data goes unchanged to the plane 1 ALU. Consequently, the CPU data can be used to control the value written to plane 1. Given the settings of the other three planes, this means that each bit of CPU data that is 1 generates a brown pixel, and each bit that is 0 generates a red pixel. Writing alternating bytes of 07H and 0E0H, then, creates a vertically striped pattern of brown and red.

In Listing 3.4, note that the vertical bars are 10 and 6 bytes wide, and do not start on byte boundaries. Although set/reset replaces an entire byte of CPU data for a plane, the combination of set/reset for some planes and CPU data for other planes, as in the example above, can be used to control individual pixels.

LISTING 3.4 L3-4.ASM

```
; Program to illustrate operation of set/reset circuitry in conjunction
;  with CPU data to modify setting of memory that already contains data.
; By Michael Abrash.
;
stack   segment para stack 'STACK'
        db      512 dup(?)
stack   ends
;
EGA_VIDEO_SEGMENT       equ     0a000h  ;EGA display memory segment
;
; EGA register equates.
;
SC_INDEX        equ     3c4h    ;SC index register
SC_MAP_MASK     equ     2       ;SC map mask register
GC_INDEX        equ     3ceh    ;GC index register
GC_SET_RESET    equ     0       ;GC set/reset register
GC_ENABLE_SET_RESET equ 1       ;GC enable set/reset register
```

```
;
; Macro to set indexed register INDEX of SC chip to SETTING.
;
SETSC   macro   INDEX, SETTING
        mov     dx,SC_INDEX
        mov     al,INDEX
        out     dx,al
        inc     dx
        mov     al,SETTING
        out     dx,al
        dec     dx
        endm
;
; Macro to set indexed register INDEX of GC chip to SETTING.
;
SETGC   macro   INDEX, SETTING
        mov     dx,GC_INDEX
        mov     al,INDEX
        out     dx,al
        inc     dx
        mov     al,SETTING
        out     dx,al
        dec     dx
        endm
;
cseg    segment para public 'CODE'
        assume  cs:cseg
start   proc    near
;
; Select 640x350 graphics mode.
;
        mov     ax,010h
        int     10h
;
        mov     ax,EGA_VIDEO_SEGMENT
        mov     es,ax  ;point to video memory
;
; Draw 18 10-scan-line high horizontal bars in green, 10 scan lines apart.
;
        SETSC   SC_MAP_MASK,02h      ;map mask setting enables only
                                     ; plane 1, the green plane
        sub     di,di             ;start at beginning of video memory
        mov     al,0ffh
        mov     bp,18             ;# bars to draw
HorzBarLoop:
        mov     cx,80*10          ;# bytes per horizontal bar
        rep stosb                    ;draw bar
        add     di,80*10          ;point to start of next bar
        dec     bp
        jnz     HorzBarLoop
;
; Fill screen with alternating bars of red and brown, using CPU data
; to set plane 1 and set/reset to set planes 0, 2 & 3.
;
        SETSC   SC_MAP_MASK,0fh   ;must set map mask to enable all
                                  ; planes, so set/reset values can
                                  ; be written to planes 0, 2 & 3
                                  ; and CPU data can be written to
                                  ; plane 1 (the green plane)
        SETGC   GC_ENABLE_SET_RESET,0dh   ;CPU data to planes 0, 2 & 3 will be
```

```
                                             ; replaced by set/reset value
        SETGC   GC_SET_RESET,04h    ;set/reset value is 0ffh for plane 2
                                       ; (the red plane) and 0 for other
                                       ; planes
        sub     di,di
        mov     cx,80*350/2         ;# words per screen
        mov     ax,07e0h             ;CPU data controls only plane 1;
                                     ; set/reset controls other planes
        rep stosw   ;perform fill (affects all planes)
;
; Turn off set/reset.
;
        SETGC   GC_ENABLE_SET_RESET,0
;
; Wait for a keystroke.
;
        mov     ah,1
        int     21h
;
; Restore text mode.
;
        mov     ax,03h
        int     10h
;
; Exit to DOS.
;
        mov     ah,4ch
        int     21h
start   endp
cseg    ends
        end     start
```

There is no clearly defined role for the set/reset circuitry, as there is for, say, the bit mask. In many cases, set/reset is largely interchangeable with CPU data, particularly with CPU data written in write mode 2 (write mode 2 operates similarly to the set/reset circuitry, as we'll see in Chapter 5). The most powerful use of set/reset, in my experience, is in applications such as the example of Listing 3.4, where it is used to force the value written to certain planes while the CPU data is written to other planes. In general, though, think of set/reset as one more tool you have at your disposal in getting the VGA to do what you need done, in this case a tool that lets you force all bits in each plane to either zero or one, or pass CPU data through unchanged, on each write to display memory. As tools go, set/reset is a handy one, and it'll pop up often in this book.

Notes on Set/Reset

The set/reset circuitry is not active in write modes 1 or 2. The Enable Set/Reset register is inactive in write mode 3, but the Set/Reset register provides the primary drawing color in write mode 3, as discussed in the next chapter.

Be aware that because set/reset directly replaces CPU data, it does not necessarily have to force an entire display memory byte to 0 or 0FFH, even when set/reset is replacing CPU data for all planes. For example, if the Bit Mask register is set to 80H, the set/reset circuitry can only modify bit 7 of the destination byte in each plane, since the other seven bits will come from the latches for each plane. Similarly, the set/reset value for each plane can be modified by that plane's ALU. Once again, this illustrates that set/reset merely replaces the CPU data for selected planes; the set/reset value is then processed in exactly the same way that CPU data normally is.

A Brief Note on Word OUTs

In the early days of the EGA and VGA, there was considerable debate about whether it was safe to do word **OUT**s (**OUT DX,AX**) to set Index/Data register pairs in a single instruction. Long ago, there were a few computers with buses that weren't quite PC-compatible, in that the two bytes in each word **OUT** went to the VGA in the wrong order: Data register first, then Index register, with predictably disastrous results. Consequently, I generally wrote my code in those days to use two 8-bit **OUT**s to set indexed registers. Later on, I made it a habit to use macros that could do either one 16-bit **OUT** or two 8-bit **OUT**s, depending on how I chose to assemble the code, and in fact you'll find both ways of dealing with **OUT**s sprinkled through the code in this part of the book. Using macros for word **OUT**s is still not a bad idea in that it does no harm, but in my opinion it's no longer necessary. Word **OUT**s are standard now, and it's been a long time since I've heard of them causing any problems.

VGA Write Mode 3

Chapter 4

The Write Mode that Grows on You

Over the last three chapters, we've covered the VGA's write path from stem to stern—with one exception. Thus far, we've only looked at how writes work in write mode 0, the straightforward, workhorse mode in which each byte that the CPU writes to display memory fans out across the four planes. (Actually, we also took a quick look at write mode 1, in which the latches are always copied unmodified, but since exactly the same result can be achieved by setting the Bit Mask register to 0 in write mode 0, write mode 1 is of little real significance.)

Write mode 0 is a very useful mode, but some of VGA's most interesting capabilities involve the two write modes that we have yet to examine: write mode 1, and, especially, write mode 3. We'll get to write mode 1 in the next chapter, but right now I want to focus on write mode 3, which can be confusing at first, but turns out to be quite a bit more powerful than one might initially think.

A Mode Born in Strangeness

Write mode 3 is strange indeed, and its use is not immediately obvious. The first time I encountered write mode 3, I understood immediately how it functioned, but could think of very few useful applications for it. As time passed, and as I came to understand the atrocious performance characteristics of **OUT** instructions, and the importance of text and pattern drawing as well, write mode 3 grew considerably in my estimation. In fact, my esteem for this mode ultimately reached the point where in the last major chunk of 16-color graphics code I wrote, write mode 3 was used more than write mode 0 overall, excluding simple pixel copying. So write mode 3 is well worth using, but to use it you must first understand it. Here's how it works.

In write mode 3, set/reset is automatically enabled for all four planes (the Enable Set/Reset register is ignored). The CPU data byte is rotated and then ANDed with the contents of the Bit Mask register, and the result of this operation is used as the contents of the Bit Mask register alone would normally be used. (If this is Greek to you, have a look back at Chapters 1 through 3. There's no way to understand write mode 3 without understanding the rest of the VGA's write data path first.)

That's what write mode 3 does—but what is it *for?* It turns out that write mode 3 is excellent for a surprisingly large number of purposes, because it makes it possible to avoid the bane of VGA performance, OUTs. Some uses for write mode 3 include lines, circles, and solid and two-color pattern fills. Most importantly, write mode 3 is ideal for transparent text; that is, it makes it possible to draw text in 16-color graphics mode quickly without wiping out the background in the process. (As we'll see at the end of this chapter, write mode 3 is potentially terrific for opaque text—text drawn with the character box filled in with a solid color—as well.)

Listing 4.1 is a modification of code I presented in Chapter 3. That code used the data rotate and bit mask features of the VGA to draw bit-mapped text in write mode 0. Listing 4.1 uses write mode 3 in place of the bit mask to draw bit-mapped text, and in the process gains the useful ability to preserve the background into which the text is being drawn. Where the original text-drawing code drew the entire character box for each character, with 0 bits in the font pattern causing a black box to appear around each character, the code in Listing 4.1 affects display memory only when 1 bits in the font pattern are drawn. As a result, the characters appear to be painted into the background, rather than over it. Another advantage of the code in Listing 4.1 is that the characters can be drawn in any of the 16 available colors.

LISTING 4.1 L4-1.ASM

```
; Program to illustrate operation of write mode 3 of the VGA.
;  Draws 8x8 characters at arbitrary locations without disturbing
;  the background, using VGA's 8x8 ROM font.  Designed
;  for use with modes 0Dh, 0Eh, 0Fh, 10h, and 12h.
; Runs only on VGAs (in Models 50 & up and IBM Display Adapter
;  and 100% compatibles).
; Assembled with MASM
; By Michael Abrash
;
stack   segment para stack 'STACK'
        db      512 dup(?)
stack   ends
;
VGA_VIDEO_SEGMENT       equ     0a000h  ;VGA display memory segment
SCREEN_WIDTH_IN_BYTES   equ     044ah   ;offset of BIOS variable
FONT_CHARACTER_SIZE     equ     8       ;# bytes in each font char
;
; VGA register equates.
;
SC_INDEX        equ     3c4h    ;SC index register
SC_MAP_MASK     equ     2       ;SC map mask register index
GC_INDEX        equ     3ceh    ;GC index register
```

```
GC_SET_RESET   equ     0       ;GC set/reset register index
GC_ENABLE_SET_RESET equ 1      ;GC enable set/reset register index
GC_ROTATE      equ     3       ;GC data rotate/logical function
                               ; register index
GC_MODE        equ     5       ;GC Mode register
GC_BIT_MASK    equ     8       ;GC bit mask register index
;
dseg    segment para common 'DATA'
TEST_TEXT_ROW  equ     69      ;row to display test text at
TEST_TEXT_COL  equ     17      ;column to display test text at
TEST_TEXT_WIDTH equ    8       ;width of a character in pixels
TestString      label   byte
        db      'Hello, world!',0       ;test string to print.
FontPointer     dd      ?               ;font offset
dseg    ends
;
cseg    segment para public 'CODE'
        assume  cs:cseg, ds:dseg
start   proc    near
        mov     ax,dseg
        mov     ds,ax
;
; Select 640x480 graphics mode.
;
        mov     ax,012h
        int     10h
;
; Set the screen to all blue, using the readability of VGA registers
; to preserve reserved bits.
;
        mov     dx,GC_INDEX
        mov     al,GC_SET_RESET
        out     dx,al
        inc     dx
        in      al,dx
        and     al,0f0h
        or      al,1                ;blue plane only set, others reset
        out     dx,al
        dec     dx
        mov     al,GC_ENABLE_SET_RESET
        out     dx,al
        inc     dx
        in      al,dx
        and     al,0f0h
        or      al,0fh              ;enable set/reset for all planes
        out     dx,al
        mov     dx,VGA_VIDEO_SEGMENT
        mov     es,dx               ;point to display memory
        mov     di,0
        mov     cx,8000h            ;fill all 32k words
        mov     ax,0ffffh           ;because of set/reset, the value
                                    ; written actually doesn't matter
        rep stosw                   ;fill with blue
;
; Set driver to use the 8x8 font.
;
        mov     ah,11h          ;VGA BIOS character generator function,
        mov     al,30h          ; return info subfunction
        mov     bh,3            ;get 8x8 font pointer
        int     10h
        call    SelectFont
```

```
;
; Print the test string, cycling through colors.
;
        mov     si,offset TestString
        mov     bx,TEST_TEXT_ROW
        mov     cx,TEST_TEXT_COL
        mov     ah,0                ;start with color 0
StringOutLoop:
        lodsb
        and     al,al
        jz      StringOutDone
        push    ax                  ;preserve color
        call    DrawChar
        pop     ax                  ;restore color
        inc     ah                  ;next color
        and     ah,0fh              ;colors range from 0 to 15
        add     cx,TEST_TEXT_WIDTH
        jmp     StringOutLoop
StringOutDone:
;
; Wait for a key, then set to text mode & end.
;
        mov     ah,1
        int     21h             ;wait for a key
        mov     ax,3
        int     10h             ;restore text mode
;
; Exit to DOS.
;
        mov     ah,4ch
        int     21h
Start   endp
;
; Subroutine to draw a text character in a linear graphics mode
;  (0Dh, 0Eh, 0Fh, 010h, 012h). Background around the pixels that
;  make up the character is preserved.
; Font used should be pointed to by FontPointer.
;
; Input:
;  AL = character to draw
;  AH = color to draw character in (0-15)
;  BX = row to draw text character at
;  CX = column to draw text character at
;
;  Forces ALU function to "move".
;  Forces write mode 3.
;
DrawChar        proc    near
        push    ax
        push    bx
        push    cx
        push    dx
        push    si
        push    di
        push    bp
        push    ds

        push    ax      ;preserve character to draw in AL
;
; Set up set/reset to produce character color, using the readability
; of VGA register to preserve the setting of reserved bits 7-4.
;
```

```
        mov     dx,GC_INDEX
        mov     al,GC_SET_RESET
        out     dx,al
        inc     dx
        in      al,dx
        and     al,0f0h
        and     ah,0fh
        or      al,ah
        out     dx,al
;
; Select write mode 3, using the readability of VGA registers
; to leave bits other than the write mode bits unchanged.
;
        mov     dx,GC_INDEX
        mov     al,GC_MODE
        out     dx,al
        inc     dx
        in      al,dx
        or      al,3
        out     dx,al
;
; Set DS:SI to point to font and ES to point to display memory.
;
        lds     si,[FontPointer]        ;point to font
        mov     dx,VGA_VIDEO_SEGMENT
        mov     es,dx                   ;point to display memory
;
; Calculate screen address of byte character starts in.
;
        pop     ax              ;get back character to draw in AL

        push    ds              ;point to BIOS data segment
        sub     dx,dx
        mov     ds,dx
        xchg    ax,bx
        mov     di,ds:[SCREEN_WIDTH_IN_BYTES]   ;retrieve BIOS
                                                ; screen width
        pop     ds
        mul     di              ;calculate offset of start of row
        push    di              ;set aside screen width
        mov     di,cx           ;set aside the column
        and     cl,0111b        ;keep only the column in-byte address
        shr     di,1
        shr     di,1
        shr     di,1            ;divide column by 8 to make a byte address
        add     di,ax           ;and point to byte
;
; Calculate font address of character.
;
        sub     bh,bh
        shl     bx,1            ;assumes 8 bytes per character; use
        shl     bx,1            ; a multiply otherwise
        shl     bx,1            ;offset in font of character
        add     si,bx           ;offset in font segment of character
;
; Set up the GC rotation. In write mode 3, this is the rotation
; of CPU data before it is ANDed with the Bit Mask register to
; form the bit mask. Force the ALU function to "move". Uses the
; readability of VGA registers to leave reserved bits unchanged.
;
        mov     dx,GC_INDEX
        mov     al,GC_ROTATE
        out     dx,al
        inc     dx
        in      al,dx
        and     al,0e0h
        or      al,cl
        out     dx,al
;
; Set up BH as bit mask for left half, BL as rotation for right half.
;
        mov     bx,0ffffh
        shr     bh,cl
        neg     cl
        add     cl,8
        shl     bl,cl
;
; Draw the character, left half first, then right half in the
; succeeding byte, using the data rotation to position the character
; across the byte boundary and then using write mode 3 to combine the
; character data with the bit mask to allow the set/reset value (the
; character color) through only for the proper portion (where the
; font bits for the character are 1) of the character for each byte.
; Wherever the font bits for the character are 0, the background
; color is preserved.
; Does not check for case where character is byte-aligned and
; no rotation and only one write is required.
;
        mov     bp,FONT_CHARACTER_SIZE
        mov     dx,GC_INDEX
        pop     cx                ;get back screen width
        dec     cx
        dec     cx                ; -2 because do two bytes for each char
CharacterLoop:
;
; Set the bit mask for the left half of the character.
;
        mov     al,GC_BIT_MASK
        mov     ah,bh
        out     dx,ax
;
; Get the next character byte & write it to display memory.
; (Left half of character.)
;
        mov     al,[si]           ;get character byte
        mov     ah,es:[di]        ;load latches
        stosb                     ;write character byte
;
; Set the bit mask for the right half of the character.
;
        mov     al,GC_BIT_MASK
        mov     ah,bl
        out     dx,ax
;
; Get the character byte again & write it to display memory.
; (Right half of character.)
;
        lodsb                     ;get character byte
        mov     ah,es:[di]        ;load latches
        stosb                     ;write character byte
;
; Point to next line of character in display memory.
;
```

```
        add     di,cx
;
        dec     bp
        jnz     CharacterLoop
;
        pop     ds
        pop     bp
        pop     di
        pop     si
        pop     dx
        pop     cx
        pop     bx
        pop     ax
        ret
DrawChar        endp
;
; Set the pointer to the font to draw from to ES:BP.
;
SelectFont      proc    near
        mov     word ptr [FontPointer],bp       ;save pointer
        mov     word ptr [FontPointer+2],es
        ret
SelectFont      endp
;
cseg    ends
        end     start
```

The key to understanding Listing 4.1 is understanding the effect of ANDing the rotated CPU data with the contents of the Bit Mask register. The CPU data is the pattern for the character to be drawn, with bits equal to 1 indicating where character pixels are to appear. The Data Rotate register is set to rotate the CPU data to pixel-align it, since without rotation characters could only be drawn on byte boundaries.

*As I pointed out in Chapter 3, the CPU is perfectly capable of rotating the data itself, and it's often the case that that's more efficient. The problem with using the Data Rotate register is that the **OUT** that sets that register is time-consuming, especially for proportional text, which requires a different rotation for each character. Also, if the code performs full-byte accesses to display memory—that is, if it combines pieces of two adjacent characters into one byte—whenever possible for efficiency, the CPU generally has to do extra work to prepare the data so the VGA's rotator can handle it.*

At the same time that the Data Rotate register is set, the Bit Mask register is set to allow the CPU to modify only that portion of the display memory byte accessed that the pixel-aligned character falls in, so that other characters and/or graphics data won't be wiped out. The result of ANDing the rotated CPU data byte with the contents of the Bit Mask register is a bit mask that allows only the bits equal to 1 in the original character pattern (rotated and masked to provide pixel alignment) to be modified by the CPU; all other bits come straight from the latches. The latches should have previously been loaded from the target address, so the effect of the ultimate synthesized bit mask value is to allow the CPU to modify only those pixels in display memory that correspond to the 1 bits in that part of the pixel-aligned character that falls in the currently addressed byte. The color of the pixels set by the CPU is determined by the contents of the Set/Reset register.

Whew. It sounds complex, but given an understanding of what the data rotator, set/reset, and the bit mask do, it's not that bad. One good way to make sense of it is to refer to the original text-drawing program in Listing 3.1 back in Chapter 3, and then see how Listing 4.1. differs from that program.

It's worth noting that the results generated by Listing 4.1 could have been accomplished without write mode 3. Write mode 0 could have been used instead, but at a significant performance cost. Instead of letting write mode 3 rotate the CPU data and AND it with the contents of the Bit Mask register, the CPU could simply have rotated the CPU data directly and ANDed it with the value destined for the Bit Mask register and then set the Bit Mask register to the resulting value. Additionally, enable set/reset could have been forced on for all planes, emulating what write mode 3 does to provide pixel colors.

The write mode 3 approach used in Listing 4.1 can be efficiently extended to drawing large blocks of text. For example, suppose that we were to draw a line of 8-pixel-wide bit-mapped text 40 characters long. We could then set up the bit mask and data rotation as appropriate for the left portion of each bit-aligned character (the portion of each character to the left of the byte boundary) and then draw the left portions only of all 40 characters in write mode 3. Then the bit mask could be set up for the right portion of each character, and the right portions of all 40 characters could be drawn. The VGA's fast rotator would be used to do all rotation, and the only **OUT**s required would be those required to set the bit mask and data rotation. This technique could well outperform single-character bit-mapped text drivers such as the one in Listing 4.1 by a significant margin. Listing 4.2 illustrates one implementation of such an approach. Incidentally, note the use of the 8x14 ROM font in Listing 4.2, rather than the 8x8 ROM font used in Listing 4.1. There is also an 8x16 font stored in ROM, along with the tables used to alter the 8x14 and 8x16 ROM fonts into 9x14 and 9x16 fonts.

LISTING 4.2 L4-2.ASM

```
; Program to illustrate high-speed text-drawing operation of
;  write mode 3 of the VGA.
;  Draws a string of 8x14 characters at arbitrary locations
;  without disturbing the background, using VGA's 8x14 ROM font.
;  Designed for use with modes 0Dh, 0Eh, 0Fh, 10h, and 12h.
; Runs only on VGAs (in Models 50 & up and IBM Display Adapter
;  and 100% compatibles).
; Assembled with MASM
; By Michael Abrash
;
stack   segment para stack 'STACK'
```

```
        db      512 dup(?)
stack   ends
;
VGA_VIDEO_SEGMENT       equ     0a000h      ;VGA display memory segment
SCREEN_WIDTH_IN_BYTES   equ     044ah       ;offset of BIOS variable
FONT_CHARACTER_SIZE     equ     14          ;# bytes in each font char
;
; VGA register equates.
;
SC_INDEX                equ     3c4h        ;SC index register
SC_MAP_MASK             equ     2           ;SC map mask register index
GC_INDEX                equ     3ceh        ;GC index register
GC_SET_RESET            equ     0           ;GC set/reset register index
GC_ENABLE_SET_RESET     equ     1           ;GC enable set/reset register index
GC_ROTATE               equ     3           ;GC data rotate/logical function
                                            ; register index
GC_MODE                 equ     5           ;GC Mode register
GC_BIT_MASK             equ     8           ;GC bit mask register index
;
dseg    segment para common 'DATA'
TEST_TEXT_ROW           equ     69          ;row to display test text at
TEST_TEXT_COL           equ     17          ;column to display test text at
TEST_TEXT_COLOR         equ     0fh         ;high intensity white
TestString      label   byte
        db      'Hello, world!',0           ;test string to print.
FontPointer     dd      ?                   ;font offset
dseg    ends
;
cseg    segment para public 'CODE'
        assume  cs:cseg, ds:dseg
start   proc    near
        mov     ax,dseg
        mov     ds,ax
;
; Select 640x480 graphics mode.
;
        mov     ax,012h
        int     10h
;
; Set the screen to all blue, using the readability of VGA registers
; to preserve reserved bits.
;
        mov     dx,GC_INDEX
        mov     al,GC_SET_RESET
        out     dx,al
        inc     dx
        in      al,dx
        and     al,0f0h
        or      al,1                ;blue plane only set, others reset
        out     dx,al
        dec     dx
        mov     al,GC_ENABLE_SET_RESET
        out     dx,al
        inc     dx
        in      al,dx
        and     al,0f0h
        or      al,0fh              ;enable set/reset for all planes
        out     dx,al
        mov     dx,VGA_VIDEO_SEGMENT
        mov     es,dx               ;point to display memory
        mov     di,0
        mov     cx,8000h            ;fill all 32k words
        mov     ax,0ffffh           ;because of set/reset, the value
                                    ; written actually doesn't matter
        rep stosw                   ;fill with blue
;
; Set driver to use the 8x14 font.
;
        mov     ah,11h          ;VGA BIOS character generator function,
        mov     al,30h          ; return info subfunction
        mov     bh,2            ;get 8x14 font pointer
        int     10h
        call    SelectFont
;
; Print the test string.
;
        mov     si,offset TestString
        mov     bx,TEST_TEXT_ROW
        mov     cx,TEST_TEXT_COL
        mov     ah,TEST_TEXT_COLOR
        call    DrawString
;
; Wait for a key, then set to text mode & end.
;
        mov     ah,1
        int     21h             ;wait for a key
        mov     ax,3
        int     10h             ;restore text mode
;
; Exit to DOS.
;
        mov     ah,4ch
        int     21h
Start   endp
;
; Subroutine to draw a text string left-to-right in a linear
;  graphics mode (0Dh, 0Eh, 0Fh, 010h, 012h) with 8-dot-wide
;  characters. Background around the pixels that make up the
;  characters is preserved.
; Font used should be pointed to by FontPointer.
;
; Input:
;  AH = color to draw string in
;  BX = row to draw string on
;  CX = column to start string at
;  DS:SI = string to draw
;
;  Forces ALU function to "move".
;  Forces write mode 3.
;
DrawString      proc    near
        push    ax
        push    bx
        push    cx
        push    dx
        push    si
        push    di
        push    bp
        push    ds
;
; Set up set/reset to produce character color, using the readability
; of VGA register to preserve the setting of reserved bits 7-4.
;
```

```
        mov     dx,GC_INDEX
        mov     al,GC_SET_RESET
        out     dx,al
        inc     dx
        in      al,dx
        and     al,0f0h
        and     ah,0fh
        or      al,ah
        out     dx,al
;
; Select write mode 3, using the readability of VGA registers
; to leave bits other than the write mode bits unchanged.
;
        mov     dx,GC_INDEX
        mov     al,GC_MODE
        out     dx,al
        inc     dx
        in      al,dx
        or      al,3
        out     dx,al
        mov     dx,VGA_VIDEO_SEGMENT
        mov     es,dx                   ;point to display memory
;
; Calculate screen address of byte character starts in.
;
        push    ds              ;point to BIOS data segment
        sub     dx,dx
        mov     ds,dx
        mov     di,ds:[SCREEN_WIDTH_IN_BYTES]   ;retrieve BIOS
                                                ; screen width
        pop     ds
        mov     ax,bx           ;row
        mul     di              ;calculate offset of start of row
        push    di              ;set aside screen width
        mov     di,cx           ;set aside the column
        and     cl,0111b        ;keep only the column in-byte address
        shr     di,1
        shr     di,1
        shr     di,1            ;divide column by 8 to make a byte address
        add     di,ax           ;and point to byte
;
; Set up the GC rotation. In write mode 3, this is the rotation
; of CPU data before it is ANDed with the Bit Mask register to
; form the bit mask. Force the ALU function to "move". Uses the
; readability of VGA registers to leave reserved bits unchanged.
;
        mov     dx,GC_INDEX
        mov     al,GC_ROTATE
        out     dx,al
        inc     dx
        in      al,dx
        and     al,0e0h
        or      al,cl
        out     dx,al
;
; Set up BH as bit mask for left half, BL as rotation for right half.
;
        mov     bx,0ffffh
        shr     bh,cl
        neg     cl
        add     cl,8
        shl     bl,cl
```

```
;
; Draw all characters, left portion first, then right portion in the
; succeeding byte, using the data rotation to position the character
; across the byte boundary and then using write mode 3 to combine the
; character data with the bit mask to allow the set/reset value (the
; character color) through only for the proper portion (where the
; font bits for the character are 1) of the character for each byte.
; Wherever the font bits for the character are 0, the background
; color is preserved.
; Does not check for case where character is byte-aligned and
; no rotation and only one write is required.
;
; Draw the left portion of each character in the string.
;
        pop     cx              ;get back screen width
        push    si
        push    di
        push    bx
;
; Set the bit mask for the left half of the character.
;
        mov     dx,GC_INDEX
        mov     al,GC_BIT_MASK
        mov     ah,bh
        out     dx,ax
LeftHalfLoop:
        lodsb
        and     al,al
        jz      LeftHalfLoopDone
        call    CharacterUp
        inc     di              ;point to next character location
        jmp     LeftHalfLoop
LeftHalfLoopDone:
        pop     bx
        pop     di
        pop     si
;
; Draw the right portion of each character in the string.
;
        inc     di              ;right portion of each character is across
                                ; byte boundary
;
; Set the bit mask for the right half of the character.
;
        mov     dx,GC_INDEX
        mov     al,GC_BIT_MASK
        mov     ah,bl
        out     dx,ax
RightHalfLoop:
        lodsb
        and     al,al
        jz      RightHalfLoopDone
        call    CharacterUp
        inc     di              ;point to next character location
        jmp     RightHalfLoop
RightHalfLoopDone:
;
        pop     ds
        pop     bp
        pop     di
        pop     si
        pop     dx
        pop     cx
        pop     bx
        pop     ax
        ret
DrawString      endp
;
; Draw a character.
;
; Input:
;  AL = character
;  CX = screen width
;  ES:DI = address to draw character at
;
CharacterUp     proc    near
        push    cx
        push    si
        push    di
        push    ds
;
; Set DS:SI to point to font and ES to point to display memory.
;
        lds     si,[FontPointer]        ;point to font
;
; Calculate font address of character.
;
        mov     bl,14           ;14 bytes per character
        mul     bl
        add     si,ax           ;offset in font segment of character

        mov     bp,FONT_CHARACTER_SIZE
        dec     cx              ; -1 because one byte per char
CharacterLoop:
        lodsb                   ;get character byte
        mov     ah,es:[di]      ;load latches
        stosb                   ;write character byte
;
; Point to next line of character in display memory.
;
        add     di,cx
;
        dec     bp
        jnz     CharacterLoop
;
        pop     ds
        pop     di
        pop     si
        pop     cx
        ret
CharacterUp     endp
;
; Set the pointer to the font to draw from to ES:BP.
;
SelectFont      proc    near
        mov     word ptr [FontPointer],bp       ;save pointer
        mov     word ptr [FontPointer+2],es
        ret
SelectFont      endp
;
cseg    ends
        end     start
```

In this chapter I've tried to give you a feel for how write mode 3 works and what it might be used for, rather than providing polished, optimized, plug-it-in-and-go code. Like the rest of the VGA's write path, write mode 3 is a resource that can be used in a remarkable variety of ways, and I don't want to lock you into thinking of it as useful in just one context. Instead, you should take the time to thoroughly understand what write mode 3 does, and then, when you do VGA programming, think about how write mode 3 can best be applied to the task at hand. Because I focused on illustrating the operation of write mode 3, neither listing in this chapter is the fastest way to accomplish the desired result. For example, Listing 4.2 could be made nearly twice as fast by simply having the CPU rotate, mask, and join the bytes from adjacent characters, then draw the combined bytes to display memory in a single operation.

Similarly, Listing 4.1 is designed to illustrate write mode 3 and its interaction with the rest of the VGA as a contrast to Listing 3.1 in Chapter 3, rather than for maximum speed, and it could be made considerably more efficient. If we were going for performance, we'd have the CPU not only rotate the bytes into position, but also do the masking by ANDing in software. Even more significantly, we would have the CPU combine adjacent characters into complete, rotated bytes whenever possible, so that only one drawing operation would be required per byte of display memory modified. By doing this, we would eliminate all per-character **OUT**s, and would minimize display memory accesses, approximately doubling text-drawing speed.

As a final note, consider that non-transparent text could also be accelerated with write mode 3. The latches could be filled with the background (text box) color, set/reset could be set to the foreground (text) color, and write mode 3 could then be used to turn monochrome text bytes written by the CPU into characters on the screen with just one write per byte. There are complications, such as drawing partial bytes, and rotating the bytes to align the characters, which we'll revisit later on in Chapter 40, while we're working through the details of the X-Sharp library. Nonetheless, the performance benefit of this approach can be a speedup of as much as four times—all thanks to the decidedly quirky but surprisingly powerful and flexible write mode 3.

A Note on Preserving Register Bits

If you take a quick look, you'll see that the code in Listing 4.1 uses the readable register feature of the VGA to preserve reserved bits and bits other than those being modified. Older adapters such as the CGA and EGA had few readable registers, so it was necessary to set all bits in a register whenever that register was modified. Happily, all VGA registers are readable, which makes it possible to change only those bits of immediate interest, and, in general, I highly recommend doing exactly that, since IBM (or clone manufacturers) may well someday use some of those reserved bits or change the meanings of some of the bits that are currently in use.

Chapter 5

Yet Another VGA Write Mode

Write Mode 2, Chunky Bitmaps, and Text-Graphics Coexistence

In the last chapter, we learned about the markedly peculiar write mode 3 of the VGA, after having spent three chapters learning the ins and outs of the VGA's data path in write mode 0, touching on write mode 1 as well in the first chapter. In all, the VGA supports four write modes—write modes 0, 1, 2, and 3—and read modes 0 and 1 as well. Which leaves two burning questions: What is write mode 2, and how the heck do you *read* VGA memory?

Write mode 2 is a bit unusual but not really hard to understand, particularly if you followed the description of set/reset in Chapter 3. Reading VGA memory, on the other hand, can be stranger than you could ever imagine.

Let's start with the easy stuff, write mode 2, and save the read modes for the next chapter.

Write Mode 2 and Set/Reset

Remember how set/reset works? Good, because that's pretty much how write mode 2 works. (You *don't* remember? Well, I'll provide a brief refresher, but I suggest that you go back through Chapters 1 through 3 and come up to speed on the VGA.)

Recall that the set/reset circuitry for each of the four planes affects the byte written by the CPU in one of three ways: By replacing the CPU byte with 0, by replacing it with 0FFH, or by leaving it unchanged. The nature of the transformation for each plane is controlled by two bits. The enable set/reset bit for a given plane selects whether the CPU byte is replaced or not, and the set/reset bit for that plane selects the value with which the CPU byte is replaced if the enable set/reset bit is 1. The net effect of set/reset is to independently force any, none, or all planes to either of all ones or all zeros on CPU writes. As we discussed in Chapter 3, this is a convenient way to force a specific color to appear no matter what color the pixels being overwritten are. Set/reset also allows the CPU to control the contents of some planes while the set/reset circuitry controls the contents of other planes.

Write mode 2 is basically a set/reset-type mode with enable set/reset always on for all planes and the set/reset data coming directly from the byte written by the CPU. Put another way, the lower four bits written by the CPU are written across the four planes, thereby becoming a color value. Put yet another way, bit 0 of the CPU byte is expanded to a byte and sent to the plane 0 ALU (if bit 0 is 0, a 0 byte is the CPU-side input to the plane 0 ALU, while if bit 0 is 1, a 0FFH byte is the CPU-side input); likewise, bit 1 of the CPU byte is expanded to a byte for plane 1, bit 2 is expanded for plane 2, and bit 3 is expanded for plane 3.

It's possible that you understand write mode 2 thoroughly at this point; nonetheless, I suspect that some additional explanation of an admittedly non-obvious mode wouldn't hurt. Let's follow the CPU byte through the VGA in write mode 2, step by step.

A Byte's Progress in Write Mode 2

Figure 5.1 shows the write mode 2 data path. The CPU byte comes into the VGA and is split into four separate bits, one for each plane. Bits 7-4 of the CPU byte vanish into the bit bucket, never to be heard from again. Speculation long held that those 4 unused bits indicated that IBM would someday come out with an 8-plane adapter that supported 256 colors. When IBM did finally come out with a 256-color mode (mode 13H of the VGA), it turned out not to be planar at all, and the upper nibble of the CPU byte remains unused in write mode 2 to this day.

The bit of the CPU byte sent to each plane is expanded to a 0 or 0FFH byte, depending on whether the bit is 0 or 1, respectively. The byte for each plane then becomes the CPU-side input to the respective plane's ALU. From this point on, the write mode 2 data path is identical to the write mode 0 data path. As discussed in earlier articles, the latch byte for each plane is the other ALU input, and the ALU either ANDs, ORs, or XORs the two bytes together or simply passes the CPU-side byte through. The byte generated by each plane's ALU then goes through the bit mask circuitry, which selects on a bit-by-bit basis between the ALU byte and the latch byte. Finally, the byte from the bit mask circuitry for each plane is written to that plane if the corresponding bit in the Map Mask register is set to 1.

It's worth noting two differences between write mode 2 and write mode 0, the standard write mode of the VGA. First, rotation of the CPU data byte does not take place in write mode 2. Second, the Set/Reset and Enable Set/Reset registers have no effect in write mode 2.

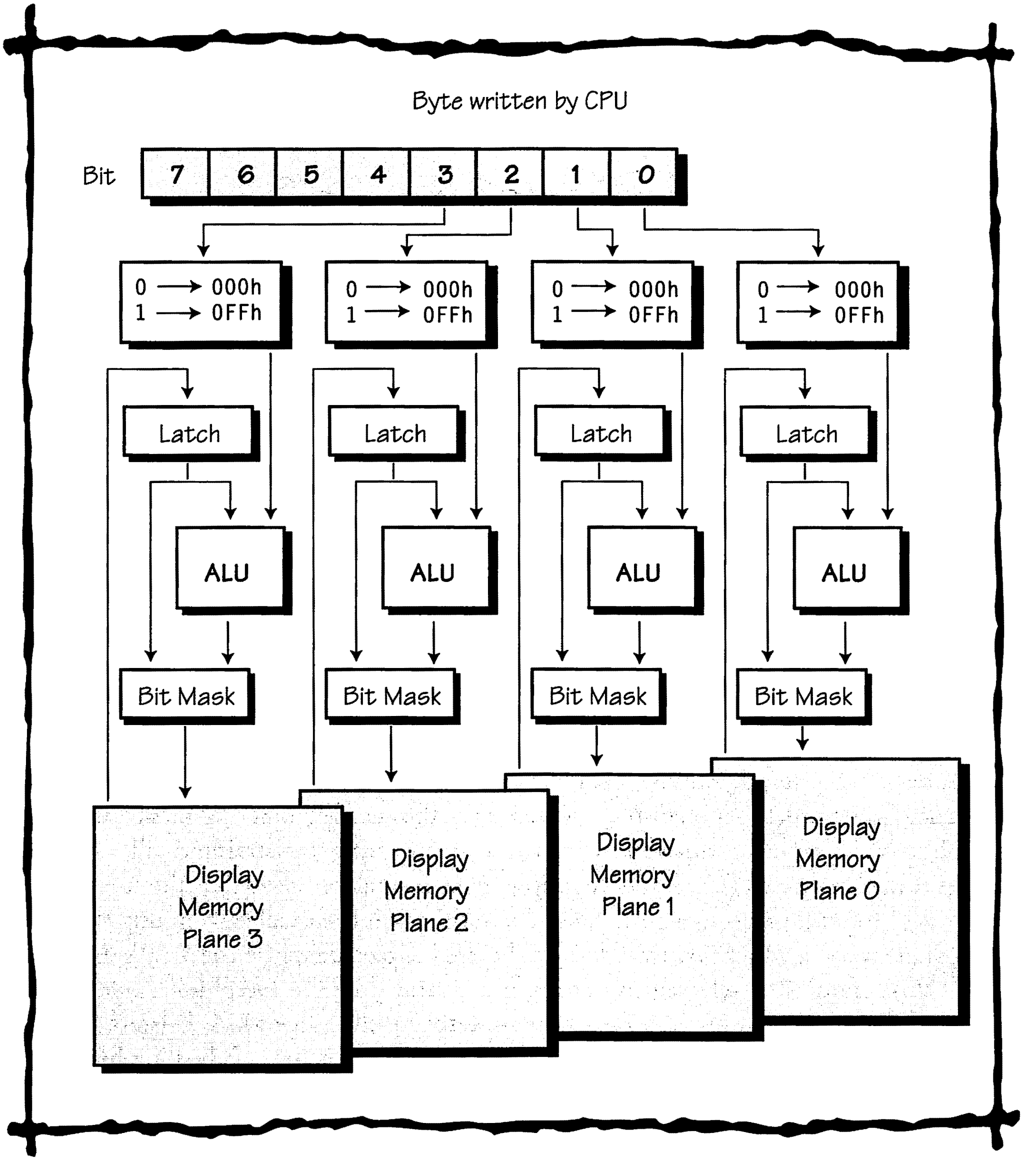


Figure 5.1 VGA Data Flow in Write Mode 2

Now that we understand the mechanics of write mode 2, we can step back and get a feel for what it might be useful for. View bits 3-0 of the CPU byte as a single pixel in one of sixteen colors. Next imagine that nibble turned sideways and written across the four planes, one bit to a plane. Finally, expand each of the bits to a byte, as shown in Figure 5.2, so that 8 pixels are drawn in the color selected by bits 3-0 of the CPU byte. Within the constraints of the VGA's data paths, that's exactly what write mode 2 does.

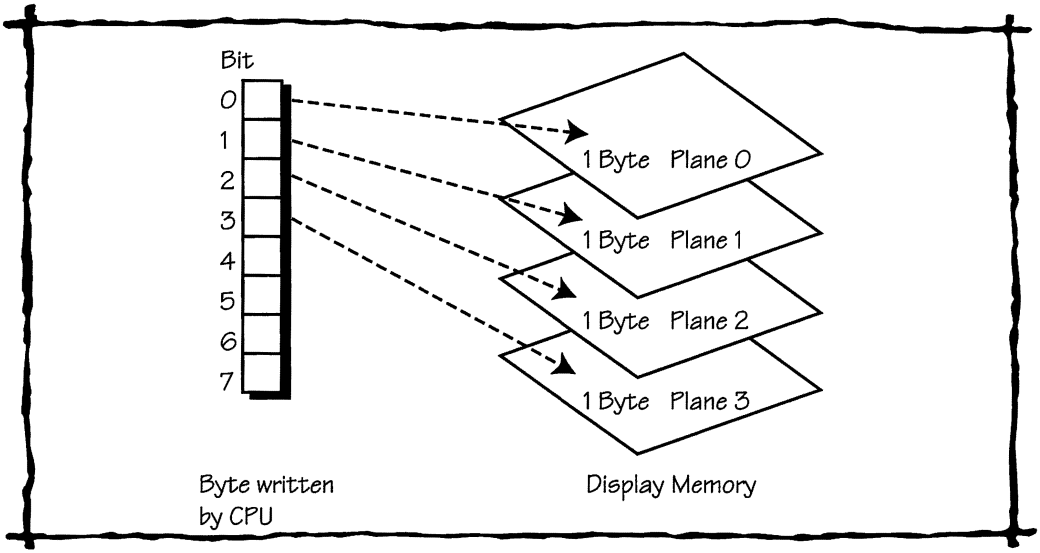


Figure 5.2 Bit-To-Byte Expansion in Write Mode 2

By "the constraints of the VGA's data paths," I mean the ALUs, the bit mask, and the map mask. As Figure 5.1 indicates, the ALUs can modify the color written by the CPU, the map mask can prevent the CPU from altering selected planes, and the bit mask can prevent the CPU from altering selected bits of the byte written to. (Actually, the bit mask simply substitutes latch bits for ALU bits, but since the latches are normally loaded from the destination display memory byte, the net effect of the bit mask is usually to preserve bits of the destination byte.) These are not really constraints at all, of course, but rather features of the VGA; I simply want to make it clear that the use of write mode 2 to set 8 pixels to a given color is a rather simple special case among the many possible ways in which write mode 2 can be used to feed data into the VGA's data path.

Write mode 2 is selected by setting bits 1 and 0 of the Graphics Mode register (Graphics Controller register 5) to 1 and 0, respectively. Since VGA registers are readable, the correct way to select write mode 2 on the VGA is to read the Graphics Mode register, mask off bits 1 and 0, OR in 00000010b (02H), and write the result back to the Graphics Mode register, thereby leaving the other bits in the register undisturbed.

Copying Chunky Bitmaps to VGA Memory Using Write Mode 2

Let's take a look at two examples of write mode 2 in action. Listing 5.1 presents a program that uses write mode 2 to copy a graphics image in chunky format to the VGA. In chunky format adjacent bits in a single byte make up each pixel: mode 4 of the CGA, EGA, and VGA is a 2-bit-per-pixel chunky mode, and mode 13H of the VGA is an 8-bit-per-pixel chunky mode. Chunky format is convenient, since all the information about each pixel is contained in a single byte; consequently chunky format is often used to store bitmaps in system memory.

Unfortunately, VGA memory is organized as a planar rather than chunky bitmap in modes 0DH through 12H, with the bits that make up each pixel spread across four planes. The conversion from chunky to planar format in write mode 0 is quite a nuisance, requiring a good deal of bit manipulation. In write mode 2, however, the conversion becomes a snap, as shown in Listing 5.1. Once the VGA is placed in write mode 2, the lower four bits (the lower nibble) of the CPU byte (a single 4-bit chunky pixel) become eight planar pixels, all the same color. As discussed in Chapter 3, the bit mask makes it possible to narrow the effect of the CPU write down to a single pixel.

Given the above, conversion of a chunky 4-bit-per-pixel bitmap to the VGA's planar format in write mode 2 is trivial. First, the Bit Mask register is set to allow only the VGA display memory bits corresponding to the leftmost chunky pixel of the two stored in the first chunky bitmap byte to be modified. Next, the destination byte in display memory is read in order to load the latches. Then a byte containing two chunky pixels is read from the chunky bitmap in system memory, and the byte is rotated four bits to the right to get the leftmost chunky pixel in position. This rotated byte is written to the destination byte; since write mode 2 is active, each bit of the chunky pixel goes to its respective plane, and since the Bit Mask register is set up to allow only one bit in each plane to be modified, a single pixel in the color of the chunky pixel is written to VGA memory.

The above process is then repeated for the rightmost chunky pixel, if necessary, and repeated again for as many pixels as there are in the image.

LISTING 5.1 L5-1.ASM

```
; Program to illustrate one use of write mode 2 of the VGA and EGA by
; animating the image of an "A" drawn by copying it from a chunky
; bit-map in system memory to a planar bit-map in VGA or EGA memory.
;
; Assemble with MASM or TASM
;
; By Michael Abrash
;
Stack   segment para stack 'STACK'
        db      512 dup(0)
Stack   ends

SCREEN_WIDTH_IN_BYTES    equ     80
DISPLAY_MEMORY_SEGMENT   equ     0a000h
SC_INDEX                 equ     3c4h    ;Sequence Controller Index register
MAP_MASK                 equ     2       ;index of Map Mask register
GC_INDEX                 equ     03ceh   ;Graphics Controller Index reg
GRAPHICS_MODE               equ     5       ;index of Graphics Mode reg
BIT_MASK                 equ     8       ;index of Bit Mask reg

Data    segment para common 'DATA'
;
; Current location of "A" as it is animated across the screen.
;
CurrentX        dw      ?
CurrentY        dw      ?
```

```
RemainingLength dw      ?
;
; Chunky bit-map image of a yellow "A" on a bright blue background
;
AImage          label   byte
                dw      13, 13          ;width, height in pixels
                db      000h, 000h, 000h, 000h, 000h, 000h, 000h
                db      009h, 099h, 099h, 099h, 099h, 099h, 000h
                db      009h, 099h, 099h, 099h, 099h, 099h, 000h
                db      009h, 099h, 099h, 0e9h, 099h, 099h, 000h
                db      009h, 099h, 09eh, 0eeh, 099h, 099h, 000h
                db      009h, 099h, 0eeh, 09eh, 0e9h, 099h, 000h
                db      009h, 09eh, 0e9h, 099h, 0eeh, 099h, 000h
                db      009h, 09eh, 0eeh, 0eeh, 0eeh, 099h, 000h
                db      009h, 09eh, 0e9h, 099h, 0eeh, 099h, 000h
                db      009h, 09eh, 0e9h, 099h, 0eeh, 099h, 000h
                db      009h, 099h, 099h, 099h, 099h, 099h, 000h
                db      009h, 099h, 099h, 099h, 099h, 099h, 000h
                db      000h, 000h, 000h, 000h, 000h, 000h, 000h
Data    ends

Code    segment para public 'CODE'
        assume  cs:Code, ds:Data
Start   proc    near
        mov     ax,Data
        mov     ds,ax
        mov     ax,10h
        int     10h    ;select video mode 10h (640x350)
;
; Prepare for animation.
;
        mov     [CurrentX],0
        mov     [CurrentY],200
        mov     [RemainingLength],600  ;move 600 times
;
; Animate, repeating RemainingLength times. It's unnecessary to erase
; the old image, since the one pixel of blank fringe around the image
; erases the part of the old image not overlapped by the new image.
;
AnimationLoop:
        mov     bx,[CurrentX]
        mov     cx,[CurrentY]
        mov     si,offset AImage
        call    DrawFromChunkyBitmap ;draw the "A" image
        inc     [CurrentX]              ;move one pixel to the right

        mov     cx,0                    ;delay so we don't move the
DelayLoop:                              ; image too fast; adjust as
                                        ; needed
        loop    DelayLoop

        dec     [RemainingLength]
        jnz     AnimationLoop
;
; Wait for a key before returning to text mode and ending.
;
        mov     ah,01h
        int     21h
        mov     ax,03h
        int     10h
        mov     ah,4ch
        int     21h
Start   endp
;
; Draw an image stored in a chunky-bit map into planar VGA/EGA memory
; at the specified location.
;
; Input:
;       BX = X screen location at which to draw the upper left corner
;               of the image
;       CX = Y screen location at which to draw the upper left corner
;               of the image
;       DS:SI = pointer to chunky image to draw, as follows:
;               word at 0: width of image, in pixels
;               word at 2: height of image, in pixels
;               byte at 4: msb/lsb = first & second chunky pixels,
;                       repeating for the remainder of the scan line
;                       of the image, then for all scan lines. Images
;                       with odd widths have an unused null nibble
;                       padding each scan line out to a byte width
;
; AX, BX, CX, DX, SI, DI, ES destroyed.
;
DrawFromChunkyBitmap    proc    near
        cld
;
; Select write mode 2.
;
        mov     dx,GC_INDEX
        mov     al,GRAPHICS_MODE
        out     dx,al
        inc     dx
        mov     al,02h
        out     dx,al
;
; Enable writes to all 4 planes.
;
        mov     dx,SC_INDEX
        mov     al,MAP_MASK
        out     dx,al
        inc     dx
        mov     al,0fh
        out     dx,al
;
; Point ES:DI to the display memory byte in which the first pixel
; of the image goes, with AH set up as the bit mask to access that
; pixel within the addressed byte.
;
        mov     ax,SCREEN_WIDTH_IN_BYTES
        mul     cx          ;offset of start of top scan line
        mov     di,ax
        mov     cl,bl
        and     cl,111b
        mov     ah,80h   ;set AH to the bit mask for the
        shr     ah,cl    ; initial pixel
        shr     bx,1
        shr     bx,1
        shr     bx,1        ;X in bytes
        add     di,bx    ;offset of upper left byte of image
        mov     bx,DISPLAY_MEMORY_SEGMENT
        mov     es,bx    ;ES:DI points to the byte at which the
                            ; upper left of the image goes
```

```
;
; Get the width and height of the image.
;
        mov     cx,[si]     ;get the width
        inc     si
        inc     si
        mov     bx,[si]     ;get the height
        inc     si
        inc     si
        mov     dx,GC_INDEX
        mov     al,BIT_MASK
        out     dx,al       ;leave the GC Index register pointing
        inc     dx             ; to the Bit Mask register
RowLoop:

        push    ax  ;preserve the left column's bit mask
        push    cx  ;preserve the width
        push    di  ;preserve the destination offset

ColumnLoop:
        mov     al,ah
        out     dx,al       ;set the bit mask to draw this pixel
        mov     al,es:[di]     ;load the latches
        mov     al,[si]        ;get the next two chunky pixels
        shr     al,1
        shr     al,1
        shr     al,1
        shr     al,1              ;move the first pixel into the lsb
        stosb                     ;draw the first pixel
        ror     ah,1              ;move mask to next pixel position
        jc      CheckMorePixels   ;is next pixel in the adjacent byte?
        dec     di                ;no

CheckMorePixels:
        dec     cx                        ;see if there are any more pixels
        jz      AdvanceToNextScanLine   ; across in image
        mov     al,ah
        out     dx,al                   ;set the bit mask to draw this pixel
        mov     al,es:[di]                ;load the latches
        lodsb                             ;get the same two chunky pixels again
                                          ; and advance pointer to the next
                                          ; two pixels
        stosb                             ;draw the second of the two pixels
        ror     ah,1                      ;move mask to next pixel position
        jc      CheckMorePixels2        ;is next pixel in the adjacent byte?
        dec     di                        ;no

CheckMorePixels2:
        loop    ColumnLoop              ;see if there are any more pixels
                                        ; across in the image
        jmp     short CheckMoreScanLines

AdvanceToNextScanLine:
        inc     si              ;advance to the start of the next
                                ; scan line in the image

CheckMoreScanLines:
        pop     di              ;get back the destination offset
        pop     cx              ;get back the width
        pop     ax              ;get back the left column's bit mask
        add     di,SCREEN_WIDTH_IN_BYTES
                                ;point to the start of the next scan
                                ; line of the image
        dec     bx              ;see if there are any more scan lines
        jnz     RowLoop         ; in the image
        ret
DrawFromChunkyBitmap    endp
Code    ends
        end     Start
```

“That’s an interesting application of write mode 2,” you may well say, “but is it really useful?” While the ability to convert chunky bitmaps into VGA bitmaps does have its uses, Listing 5.1 is primarily intended to illustrate the mechanics of write mode 2.

For performance, it’s best to store 16-color bitmaps in pre-separated four-plane format in system memory, and copy one plane at a time to the screen. Ideally, such bitmaps should be copied one scan line at a time, with all four planes completed for one scan line before moving on to the next. I say this because when entire images are copied one plane at a time, nasty transient color effects can occur as one plane becomes visibly changed before other planes have been modified.

Drawing Color-Patterned Lines Using Write Mode 2

A more serviceable use of write mode 2 is shown in the program presented in Listing 5.2. The program draws multicolored horizontal, vertical, and diagonal lines, basing the color patterns on passed color tables. Write mode 2 is ideal because in this application color can vary from one pixel to the next, and in write mode 2 all that’s required to set pixel color is a change of the lower nibble of the byte written by the CPU. Set/reset could be used to achieve the same result, but an index/data pair of OUTs would be required to set the Set/Reset register to each new color. Similarly, the Map Mask register could be used in write mode 0 to set pixel color, but in this case not only would an index/data pair of OUTs be required but there would also be no guarantee that data already in display memory wouldn’t interfere with the color of the pixel being drawn, since the Map Mask register allows only selected planes to be drawn to.

Listing 5.2 is hardly a comprehensive line drawing program. It draws only a few special line cases, and although it is reasonably fast, it is far from the fastest possible code to handle those cases, because it goes through a dot-plot routine and because it draws horizontal lines a pixel rather than a byte at a time. Write mode 2 would, however, serve just as well in a full-blown line drawing routine. For any type of patterned line drawing on the VGA, the basic approach remains the same: Use the bit mask to select the pixel (or pixels) to be altered and use the CPU byte in write mode 2 to select the color in which to draw.

LISTING 5.2 L5-2.ASM

```
; Program to illustrate one use of write mode 2 of the VGA and EGA by
; drawing lines in color patterns.
;
; Assemble with MASM or TASM
;
; By Michael Abrash
;
Stack   segment para stack 'STACK'
        db      512 dup(0)
Stack   ends

SCREEN_WIDTH_IN_BYTES    equ     80
GRAPHICS_SEGMENT         equ    0a000h   ;mode 10 bit-map segment
SC_INDEX                 equ     3c4h    ;Sequence Controller Index register
MAP_MASK                 equ     2       ;index of Map Mask register
GC_INDEX                 equ     03ceh   ;Graphics Controller Index reg
GRAPHICS_MODE               equ     5       ;index of Graphics Mode reg
BIT_MASK                 equ     8       ;index of Bit Mask reg

Data    segment para common 'DATA'
Pattern0        db      16
                db      0, 1, 2, 3, 4, 5, 6, 7, 8
                db      9, 10, 11, 12, 13, 14, 15
Pattern1        db      6
                db      2, 2, 2, 10, 10, 10
Pattern2        db      8
                db      15, 15, 15, 0, 0, 15, 0, 0
Pattern3        db      9
                db      1, 1, 1, 2, 2, 2, 4, 4, 4
Data    ends

Code    segment para public 'CODE'
        assume  cs:Code, ds:Data
Start   proc    near
        mov     ax,Data
        mov     ds,ax
        mov     ax,10h
        int     10h             ;select video mode 10h (640x350)
;
; Draw 8 radial lines in upper left quadrant in pattern 0.
;
        mov     bx,0
        mov     cx,0
        mov     si,offset Pattern0
        call    QuadrantUp
;
; Draw 8 radial lines in upper right quadrant in pattern 1.
;
        mov     bx,320
        mov     cx,0
        mov     si,offset Pattern1
        call    QuadrantUp
;
; Draw 8 radial lines in lower left quadrant in pattern 2.
;
        mov     bx,0
        mov     cx,175
        mov     si,offset Pattern2
        call    QuadrantUp
```

```
;
; Draw 8 radial lines in lower right quadrant in pattern 3.
;
        mov     bx,320
        mov     cx,175
        mov     si,offset Pattern3
        call    QuadrantUp
;
; Wait for a key before returning to text mode and ending.
;
        mov     ah,01h
        int     21h
        mov     ax,03h
        int     10h
        mov     ah,4ch
        int     21h
;
; Draws 8 radial lines with specified pattern in specified mode 10h
; quadrant.
;
; Input:
;       BX = X coordinate of upper left corner of quadrant
;       CX = Y coordinate of upper left corner of quadrant
;       SI = pointer to pattern, in following form:
;               Byte 0: Length of pattern
;               Byte 1: Start of pattern, one color per byte
;
; AX, BX, CX, DX destroyed
;
QuadrantUp      proc    near
        add     bx,160
        add     cx,87           ;point to the center of the quadrant
        mov     ax,0
        mov     dx,160
        call    LineUp          ;draw horizontal line to right edge
        mov     ax,1
        mov     dx,88
        call    LineUp          ;draw diagonal line to upper right
        mov     ax,2
        mov     dx,88
        call    LineUp          ;draw vertical line to top edge
        mov     ax,3
        mov     dx,88
        call    LineUp          ;draw diagonal line to upper left
        mov     ax,4
        mov     dx,161
        call    LineUp          ;draw horizontal line to left edge
        mov     ax,5
        mov     dx,88
        call    LineUp          ;draw diagonal line to lower left
        mov     ax,6
        mov     dx,88
        call    LineUp          ;draw vertical line to bottom edge
        mov     ax,7
        mov     dx,88
        call    LineUp          ;draw diagonal line to bottom right
        ret
QuadrantUp      endp
;
; Draws a horizontal, vertical, or diagonal line (one of the eight
; possible radial lines) of the specified length from the specified
; starting point.
```

```
;
; Input:
;       AX = line direction, as follows:
;               3  2  1
;               4  *  0
;               5  6  7
;       BX = X coordinate of starting point
;       CX = Y coordinate of starting point
;       DX = length of line (number of pixels drawn)
;
; All registers preserved.
;
; Table of vectors to routines for each of the 8 possible lines.
;
LineUpVectors   label   word
        dw      LineUp0, LineUp1, LineUp2, LineUp3
        dw      LineUp4, LineUp5, LineUp6, LineUp7


;
; Macro to draw horizontal, vertical, or diagonal line.
;
; Input:
;       XParm = 1 to draw right, -1 to draw left, 0 to not move horz.
;       YParm = 1 to draw up, -1 to draw down, 0 to not move vert.
;       BX = X start location
;       CX = Y start location
;       DX = number of pixels to draw
;       DS:SI = line pattern
;
MLineUp macro   XParm, YParm
        local   LineUpLoop, CheckMoreLine
        mov     di,si           ;set aside start offset of pattern
        lodsb                   ;get length of pattern
        mov     ah,al

LineUpLoop:
        lodsb                   ;get color of this pixel...
        call    DotUpInColor    ;...and draw it
if XParm EQ 1
        inc     bx
endif
if XParm EQ -1
        dec     bx
endif
if YParm EQ 1
        inc     cx
endif
if YParm EQ -1
        dec     cx
endif
        dec     ah              ;at end of pattern?
        jnz     CheckMoreLine
        mov     si,di           ;get back start of pattern
        lodsb
        mov     ah,al           ;reset pattern count

CheckMoreLine:
        dec     dx
        jnz     LineUpLoop
        jmp     LineUpEnd
        endm
```

```
LineUp  proc    near
        push    ax
        push    bx
        push    cx
        push    dx
        push    si
        push    di
        push    es

        mov     di,ax

        mov     ax,GRAPHICS_SEGMENT
        mov     es,ax

        push    dx              ;save line length
;
; Enable writes to all planes.
;
        mov     dx,SC_INDEX
        mov     al,MAP_MASK
        out     dx,al
        inc     dx
        mov     al,0fh
        out     dx,al
;
; Select write mode 2.
;
        mov     dx,GC_INDEX
        mov     al,GRAPHICS_MODE
        out     dx,al
        inc     dx
        mov     al,02h
        out     dx,al
;
; Vector to proper routine.
;
        pop     dx              ;get back line length

        shl     di,1
        jmp     cs:[LineUpVectors+di]
;
; Horizontal line to right.
;
LineUp0:
        MLineUp 1, 0
;
; Diagonal line to upper right.
;
LineUp1:
        MLineUp 1, -1
;
; Vertical line to top.
;
LineUp2:
        MLineUp 0, -1
;
; Diagonal line to upper left.
;
LineUp3:
        MLineUp -1, -1
```

```
;
; Horizontal line to left.
;
LineUp4:
        MLineUp -1, 0
;
; Diagonal line to bottom left.
;
LineUp5:
        MLineUp -1, 1
;
; Vertical line to bottom.
;
LineUp6:
        MLineUp 0, 1
;
; Diagonal line to bottom right.
;
LineUp7:
        MLineUp 1, 1

LineUpEnd:
        pop     es
        pop     di
        pop     si
        pop     dx
        pop     cx
        pop     bx
        pop     ax
        ret
LineUp  endp
;
; Draws a dot in the specified color at the specified location.
; Assumes that the VGA is in write mode 2 with writes to all planes
; enabled and that ES points to display memory.
;
; Input:
;       AL = dot color
;       BX = X coordinate of dot
;       CX = Y coordinate of dot
;       ES = display memory segment
;
; All registers preserved.
;
DotUpInColor    proc    near
        push    bx
        push    cx
        push    dx
        push    di
;
; Point ES:DI to the display memory byte in which the pixel goes, with
; the bit mask set up to access that pixel within the addressed byte.
;
        push    ax              ;preserve dot color
        mov     ax,SCREEN_WIDTH_IN_BYTES
        mul     cx              ;offset of start of top scan line
        mov     di,ax
        mov     cl,bl
        and     cl,111b
        mov     dx,GC_INDEX
        mov     al,BIT_MASK
        out     dx,al
        inc     dx
        mov     al,80h
        shr     al,cl
        out     dx,al           ;set the bit mask for the pixel
        shr     bx,1
        shr     bx,1
        shr     bx,1            ;X in bytes
        add     di,bx           ;offset of byte pixel is in
        mov     al,es:[di]      ;load latches
        pop     ax              ;get back dot color
        stosb                   ;write dot in desired color

        pop     di
        pop     dx
        pop     cx
        pop     bx
        ret
DotUpInColor    endp
Start   endp
Code    ends
        end     Start
```

When to Use Write Mode 2 and when to Use Set/Reset

As indicated above, write mode 2 and set/reset are functionally interchangeable. Write mode 2 lends itself to more efficient implementations when the drawing color changes frequently, as in Listing 5.2.

Set/reset tends to be superior when many pixels in succession are drawn in the same color, since with set/reset enabled for all planes the Set/Reset register provides the color data and as a result the CPU is free to draw whatever byte value it wishes. For example, the CPU can execute an **OR** instruction to display memory when set/reset is enabled for all planes, thus both loading the latches and writing the color value with a single instruction, secure in the knowledge that the value it writes is ignored in favor of the set/reset color.

Set/reset is also the mode of choice whenever it is necessary to force the value written to some planes to a fixed value while allowing the CPU byte to modify other planes. This is the mode of operation when set/reset is enabled for some but not all planes.

Mode 13H—320×200 with 256 Colors

I'm going to take a minute—and I do mean a minute—to discuss the programming model for mode 13H, the VGA's 320×200 256-color mode. Frankly, there's just not much to it, especially compared to the convoluted 16-color model that we've explored over the last five chapters. Mode 13H offers the simplest programming model in the history of PC graphics: A linear bitmap starting at A000:0000, consisting of 64,000 bytes, each controlling one pixel. The byte at offset 0 controls the upper left pixel on the screen, the byte at offset 319 controls the upper right pixel on the screen, the byte at offset 320 controls the second pixel down at the left of the screen, and the byte at offset 63,999 controls the lower right pixel on the screen. That's all there is to it; it's so simple that I'm not going to spend any time on a demo program, especially given that some of the listings later in this book, such as the antialiasing code in Chapter 25, use mode 13H.

Flipping Pages from Text to Graphics and Back

A while back, I got an interesting letter from Phil Coleman, of La Jolla, who wrote:

"Suppose I have the EGA in mode 10H (640×350 16-color graphics). I would like to preserve some or all of the image while I temporarily switch to text mode 3 to give my user a 'Help' screen. Naturally memory is scarce so I'd rather not make a copy of the video buffer at A000H to 'remember' the image while I digress to the Help text. The EGA BIOS says that the screen memory will not be cleared on a mode set if bit 7 of AL is set. Yet if I try that, it is clear that writing text into the B800H buffer trashes much more than the 4K bytes of a text page; when I switch back to mode 10H, "ghosts" appear in the form of bands of colored dots. (When in text mode, I do make a copy of the 4K buffer at B800H before showing the help; and I restore the 4K before switching back to mode 10H.) Is there a way to preserve the graphics image while I switch to text mode?"

"A corollary to this question is: Where does the 64/128/256K of EGA memory "hide" when the EGA is in text mode? Some I guess is used to store character sets, but what happens to the rest? Or rather, how can I protect it?"

Those are good questions. Alas, answering them in full would require extensive explanation that would have little general application, so I'm not going to do that. However, the issue of how to go to text mode and back without losing the graphics image certainly rates a short discussion, complete with some working code. That's especially true given that both the discussion and the code apply just as well to the VGA as to the EGA (with a few differences in mode 12H, the VGA's high-resolution mode, as noted below).

Phil is indeed correct in his observation that setting bit 7 of AL instructs the BIOS not to clear display memory on mode sets, and he is also correct in surmising that a font is loaded when going to text mode. The normal mode 10H bitmap occupies the first 28,000 bytes of each of the VGA's four planes. (The mode 12H bitmap takes up the first 38,400 bytes of each plane.) The normal mode 3 character/attribute memory map resides in the first 4000 bytes of planes 0 and 1 (the blue and green planes in mode 10H). The standard font in mode 3 is stored in the first 8K of plane 2 (the red plane in mode 10H). Neither mode 3 nor any other text mode makes use of plane 3 (the intensity plane in mode 10H); if necessary, plane 3 could be used as scratch memory in text mode.

Consequently, you can get away with saving a total of just under 16K bytes—the first 4000 bytes of planes 0 and 1 and the first 8K bytes of plane 2—when going from mode 10H or mode 12H to mode 3, to be restored on returning to graphics mode.

That's hardly all there is to the matter of going from text to graphics and back without bitmap corruption, though. One interesting point is that the mode 10H bitmap can be relocated to A000:8000 simply by doing a mode set to mode 10H and setting the start address (programmed at CRT Controller registers 0CH and 0DH) to 8000H. You can then access display memory starting at A800:8000 instead of the normal A000:0000, with the resultant display exactly like that of normal mode 10H. There are BIOS issues, since the BIOS doesn't automatically access display memory at the new start address, but if your program does all its drawing directly without the help of the BIOS, that's no problem.

The mode 12H bitmap can't start at A000:8000, because it's so long that it would run off the end of display memory. However, the mode 12H bitmap can be relocated to, say, A000:6000, where it would fit without conflicting with the default font or the normal text mode memory map, although it would overlap two of the upper pages available for use (but rarely used) by text-mode programs.

At any rate, once the graphics mode bitmap is relocated, flipping to text mode and back becomes painless. The memory used by mode 3 doesn't overlap the relocated mode 10H bitmap at all (unless additional portions of font memory are loaded), so all you need do is set bit 7 of AL on mode sets in order to flip back and forth between the two modes.

Another interesting point about flipping from graphics to text and back is that the standard mode 3 character/attribute map doesn't actually take up every byte of the first 4000 bytes of planes 0 and 1. The standard mode 3 character/attribute map actually only takes up every even byte of the first 4000 in each plane; the odd bytes are left untouched. This means that only about 12K bytes actually have to be saved when going to text mode. The code in Listing 5.3 flips from graphics mode to text mode and back, saving only those 12K bytes that actually have to be saved. This code saves and restores the first 8K of plane 2 (the font area) while in graphics mode, but performs the save and restore of the 4000 bytes used for the character/attribute map while in text mode, because the characters and attributes, which are actually stored in the even bytes of planes 0 and 1, respectively, appear to be contiguous bytes in memory in text mode and so are easily saved as a single block.

Explaining why only every other byte of planes 0 and 1 is used in text mode and why characters and attributes appear to be contiguous bytes when they are actually in different planes is a large part of the explanation I'm not going to go into now. One bit of fallout from this, however, is that if you flip to text mode and preserve the graphics bitmap using the mechanism illustrated in Listing 5.3, you shouldn't write to any text page other than page 0 (that is, don't write to any offset in display memory above 3999 in text mode) or alter the Page Select bit in the Miscellaneous Output register (3C2H) while in text mode. In order to allow completely unfettered access to text pages, it would be necessary to save every byte in the first 32K of each of planes 0 and 1. (On the other hand, this *would* allow up to 16 text screens to be stored simultaneously, with any one displayable instantly.) Moreover, if any fonts other than the default font are loaded, the portions of plane 2 that those particular fonts are loaded into would have to be saved, up to a maximum of all 64K of plane 2. In the worst case, a full 128K would have to be saved in order to preserve all the memory potentially used by text mode.

As I said, Phil Coleman's question is an interesting one, and I've only touched on the intriguing possibilities arising from the various configurations of display memory in VGA graphics and text modes. Right now, though, we've still got the basics of the remarkably complex (but rewarding!) VGA to cover.

LISTING 5.3 L5-3.ASM

```
; Program to illustrate flipping from bit-mapped graphics mode to
; text mode and back without losing any of the graphics bit-map.
;
; Assemble with MASM or TASM
;
; By Michael Abrash
;
Stack   segment para stack 'STACK'
        db      512 dup(0)
Stack   ends

GRAPHICS_SEGMENT    equ     0a000h  ;mode 10 bit-map segment
TEXT_SEGMENT        equ     0b800h  ;mode 3 bit-map segment
SC_INDEX            equ     3c4h    ;Sequence Controller Index register
MAP_MASK            equ     2       ;index of Map Mask register
GC_INDEX            equ     3ceh    ;Graphics Controller Index register
READ_MAP            equ     4       ;index of Read Map register

Data    segment para common 'DATA'

GStrikeAnyKeyMsg0       label   byte
        db      0dh, 0ah, 'Graphics mode', 0dh, 0ah
        db      'Strike any key to continue...', 0dh, 0ah, '$'

GStrikeAnyKeyMsg1       label   byte
        db      0dh, 0ah, 'Graphics mode again', 0dh, 0ah
        db      'Strike any key to continue...', 0dh, 0ah, '$'

TStrikeAnyKeyMsg        label   byte
        db      0dh, 0ah, 'Text mode', 0dh, 0ah
        db      'Strike any key to continue...', 0dh, 0ah, '$'

Plane2Save      db      2000h dup (?)   ;save area for plane 2 data
                                        ; where font gets loaded
CharAttSave     db      4000 dup (?)    ;save area for memory wiped
                                        ; out by character/attribute
                                        ; data in text mode
Data    ends

Code    segment para public 'CODE'
        assume  cs:Code, ds:Data
```

```
Start   proc    near
        mov     ax,10h
        int     10h             ;select video mode 10h (640x350)
;
; Fill the graphics bit-map with a colored pattern.
;
        cld
        mov     ax,GRAPHICS_SEGMENT
        mov     es,ax
        mov     ah,3            ;initial fill pattern
        mov     cx,4            ;four planes to fill
        mov     dx,SC_INDEX
        mov     al,MAP_MASK
        out     dx,al           ;leave the SC Index pointing to the
        inc     dx              ; Map Mask register

FillBitMap:
        mov     al,10h
        shr     al,cl           ;generate map mask for this plane
        out     dx,al           ;set map mask for this plane
        sub     di,di           ;start at offset 0
        mov     al,ah           ;get the fill pattern
        push    cx              ;preserve plane count
        mov     cx,8000h        ;fill 32K words
        rep stosw               ;do fill for this plane
        pop     cx              ;get back plane count
        shl     ah,1
        shl     ah,1
        loop    FillBitMap
;
; Put up "strike any key" message.
;
        mov     ax,Data
        mov     ds,ax
        mov     dx,offset GStrikeAnyKeyMsg0
        mov     ah,9
        int     21h
;
; Wait for a key.
;
        mov     ah,01h
        int     21h
;
; Save the 8K of plane 2 that will be used by the font.
;
        mov     dx,GC_INDEX
        mov     al,READ_MAP
        out     dx,al
        inc     dx
        mov     al,2
        out     dx,al           ;set up to read from plane 2
        mov     ax,Data
        mov     es,ax
        mov     ax,GRAPHICS_SEGMENT
        mov     ds,ax
        sub     si,si
        mov     di,offset Plane2Save
        mov     cx,2000h/2      ;save 8K (length of default font)
        rep movsw
;
; Go to text mode without clearing display memory.
;
```

```
        mov     ax,083h
        int     10h
;
; Save the text mode bit-map.
;
        mov     ax,Data
        mov     es,ax
        mov     ax,TEXT_SEGMENT
        mov     ds,ax
        sub     si,si
        mov     di,offset CharAttSave
        mov     cx,4000/2       ;length of one text screen in words
        rep movsw
;
; Fill the text mode screen with dots and put up "strike any key"
; message.
;
        mov     ax,TEXT_SEGMENT
        mov     es,ax
        sub     di,di
        mov     al,'.'          ;fill character
        mov     ah,7            ;fill attribute
        mov     cx,4000/2       ;length of one text screen in words
        rep stosw
        mov     ax,Data
        mov     ds,ax
        mov     dx,offset TStrikeAnyKeyMsg
        mov     ah,9
        int     21h
;
; Wait for a key.
;
        mov     ah,01h
        int     21h
;
; Restore the text mode screen to the state it was in on entering
; text mode.
;
        mov     ax,Data
        mov     ds,ax
        mov     ax,TEXT_SEGMENT
        mov     es,ax
        mov     si,offset CharAttSave
        sub     di,di
        mov     cx,4000/2       ;length of one text screen in words
        rep movsw
;
; Return to mode 10h without clearing display memory.
;
        mov     ax,90h
        int     10h
;
; Restore the portion of plane 2 that was wiped out by the font.
;
        mov     dx,SC_INDEX
        mov     al,MAP_MASK
        out     dx,al
        inc     dx
        mov     al,4
        out     dx,al           ;set up to write to plane 2
        mov     ax,Data
        mov     ds,ax
        mov     ax,GRAPHICS_SEGMENT
        mov     es,ax
        mov     si,offset Plane2Save
        sub     di,di
        mov     cx,2000h/2      ;restore 8K (length of default font)
        rep movsw
;
; Put up "strike any key" message.
;
        mov     ax,Data
        mov     ds,ax
        mov     dx,offset GStrikeAnyKeyMsg1
        mov     ah,9
        int     21h
;
; Wait for a key before returning to text mode and ending.
;
        mov     ah,01h
        int     21h
        mov     ax,03h
        int     10h
        mov     ah,4ch
        int     21h
Start   endp
Code    ends
        end     Start
```

Reading VGA Memory

Chapter 6

Read Modes 0 and 1, and the Color Don't Care Register

Well, it's taken five chapters, but we've finally covered the data write path and all four write modes of the VGA. Now it's time to tackle the VGA's two read modes. While the read modes aren't as complex as the write modes, they're nothing to sneeze at. In particular, read mode 1 (also known as color compare mode) is rather unusual and not at all intuitive.

You may well ask, isn't *anything* about programming the VGA straightforward? Well...no. But then, clearing up the mysteries of VGA programming is what this part of the book is all about, so let's get started.

Read Mode 0

Read mode 0 is actually relatively uncomplicated, given that you understand the four-plane nature of the VGA. (If you don't understand the four-plane nature of the VGA, I strongly urge you to read Chapters 1-5 before continuing with this chapter.) Read mode 0, the read mode counterpart of write mode 0, lets you read from one (and only one) plane of VGA memory at any one time.

Read mode 0 is selected by setting bit 3 of the Graphics Mode register (Graphics Controller register 5) to 0. When read mode 0 is active, the plane that supplies the data when the CPU reads VGA memory is the plane selected by bits 1 and 0 of the Read Map register (Graphics Controller register 4). When the Read Map register is set to 0, CPU reads come from plane 0 (the plane that normally contains blue pixel data). When the Read Map register is set to 1, CPU reads come from plane 1; when the Read Map register is 2, CPU reads come from plane 2; and when the Read Map register is 3, CPU reads come from plane 3.

That all seems simple enough; in read mode 0, the Read Map register acts as a selector among the four planes, determining which one of the planes will supply the value returned to the CPU. There is a slight complication, however, in that the value written to the Read Map register in order to read from a given plane is not the same as the value written to the Map Mask register (Sequence Controller register 2) in order to write to that plane.

Why is that? Well, in read mode 0, one and only one plane can be read at a time, so there are only four possible settings of the Read Map register: 0, 1, 2, or 3, to select reads from plane 0, 1, 2, or 3. In write mode 0, by contrast (in fact, in any write mode), any or all planes may be written to at once, since the byte written by the CPU can "fan out" to multiple planes. Consequently, there are not four but sixteen possible settings of the Map Mask register. The setting of the Map Mask register to write only to plane 0 is 1; to write only to plane 1 is 2; to write only to plane 2 is 4; and to write only to plane 3 is 8.

As you can see, the settings of the Read Map and Map Mask registers for accessing a given plane don't match. The code in Listing 6.1 illustrates this. Listing 6.1 simply copies a sixteen-color image from system memory to VGA memory, one plane at a time, then animates by repeatedly copying the image back to system memory, again one plane at a time, clearing the old image, and copying the image to a new location in VGA memory. Note the differing settings of the Read Map and Map Mask registers.

LISTING 6.1 L6-1.ASM

```
; Program to illustrate the use of the Read Map register in read mode 0.
; Animates by copying a 16-color image from VGA memory to system memory,
; one plane at a time, then copying the image back to a new location
; in VGA memory.
;
; By Michael Abrash
;
stack   segment word stack 'STACK'
        db      512 dup (?)
stack   ends
;
data    segment word 'DATA'
IMAGE_WIDTH     EQU     4               ;in bytes
IMAGE_HEIGHT    EQU     32              ;in pixels
LEFT_BOUND      EQU     10              ;in bytes
RIGHT_BOUND     EQU     66              ;in bytes
VGA_SEGMENT     EQU     0a000h
SCREEN_WIDTH    EQU     80              ;in bytes
SC_INDEX        EQU     3c4h            ;Sequence Controller Index register
GC_INDEX        EQU     3ceh            ;Graphics Controller Index register
MAP_MASK        EQU     2               ;Map Mask register index in SC
READ_MAP        EQU     4               ;Read Map register index in GC
;
; Base pattern for 16-color image.
;
PatternPlane0   label   byte
        db      32 dup (0ffh,0ffh,0,0)
```

```
PatternPlane1   label   byte
        db      32 dup (0ffh,0,0ffh,0)
PatternPlane2   label   byte
        db      32 dup (0f0h,0f0h,0f0h,0f0h)
PatternPlane3   label   byte
        db      32 dup (0cch,0cch,0cch,0cch)
;
; Temporary storage for 16-color image during animation.
;
ImagePlane0     db      32*4 dup (?)
ImagePlane1     db      32*4 dup (?)
ImagePlane2     db      32*4 dup (?)
ImagePlane3     db      32*4 dup (?)
;
; Current image location & direction.
;
ImageX          dw      40      ;in bytes
ImageY          dw      100     ;in pixels
ImageXDirection dw      1       ;in bytes
data    ends
;
code    segment word 'CODE'
        assume  cs:code,ds:data
Start   proc    near
        cld
        mov     ax,data
        mov     ds,ax
;
; Select graphics mode 10h.
;
        mov     ax,10h
        int     10h
;
; Draw the initial image.
;
        mov     si,offset PatternPlane0
        call    DrawImage
;
; Loop to animate by copying the image from VGA memory to system memory,
; erasing the image, and copying the image from system memory to a new
; location in VGA memory. Ends when a key is hit.
;
AnimateLoop:
;
; Copy the image from VGA memory to system memory.
;
        mov     di,offset ImagePlane0
        call    GetImage
;
; Clear the image from VGA memory.
;
        call    EraseImage
;
; Advance the image X coordinate, reversing direction if either edge
; of the screen has been reached.
;
        mov     ax,[ImageX]
        cmp     ax,LEFT_BOUND
        jz      ReverseDirection
        cmp     ax,RIGHT_BOUND
        jnz     SetNewX
```

```
ReverseDirection:
        neg     [ImageXDirection]
SetNewX:
        add     ax,[ImageXDirection]
        mov     [ImageX],ax
;
; Draw the image by copying it from system memory to VGA memory.
;
        mov     si,offset ImagePlane0
        call    DrawImage
;
; Slow things down a bit for visibility (adjust as needed).
;
        mov     cx,0
DelayLoop:
        loop    DelayLoop
;
; See if a key has been hit, ending the program.
;
        mov     ah,1
        int     16h
        jz              AnimateLoop
;
; Clear the key, return to text mode, and return to DOS.
;
        sub     ah,ah
        int     16h
        mov     ax,3
        int     10h
        mov     ah,4ch
        int     21h
Start   endp
;
; Draws the image at offset DS:SI to the current image location in
; VGA memory.
;
DrawImage       proc    near
        mov     ax,VGA_SEGMENT
        mov     es,ax
        call    GetImageOffset  ;ES:DI is the destination address for the
                                ; image in VGA memory
        mov     dx,SC_INDEX
        mov     al,1            ;do plane 0 first
DrawImagePlaneLoop:
        push    di              ;image is drawn at the same offset in
                                ; each plane
        push    ax              ;preserve plane select
        mov     al,MAP_MASK     ;Map Mask index
        out     dx,al           ;point SC Index to the Map Mask register
        pop     ax              ;get back plane select
        inc     dx              ;point to SC index register
        out     dx,al           ;set up the Map Mask to allow writes to
                                ; the plane of interest
        dec     dx              ;point back to SC Data register
        mov     bx,IMAGE_HEIGHT ;# of scan lines in image
DrawImageLoop:
        mov     cx,IMAGE_WIDTH  ;# of bytes across image
        rep     movsb
        add     di,SCREEN_WIDTH-IMAGE_WIDTH
                                ;point to next scan line of image
        dec     bx              ;any more scan lines?
        jnz     DrawImageLoop
        pop     di              ;get back image start offset in VGA memory
        shl     al,1            ;Map Mask setting for next plane
        cmp     al,10h          ;have we done all four planes?
        jnz     DrawImagePlaneLoop
        ret
DrawImage       endp
;
; Copies the image from its current location in VGA memory into the
; buffer at DS:DI.
;
GetImage        proc    near
        mov     si,di           ;move destination offset into SI
        call    GetImageOffset  ;DI is offset of image in VGA memory
        xchg    si,di   ;SI is offset of image, DI is destination offset
        push    ds
        pop     es              ;ES:DI is destination
        mov     ax,VGA_SEGMENT
        mov     ds,ax           ;DS:SI is source
;
        mov     dx,GC_INDEX
        sub     al,al           ;do plane 0 first
GetImagePlaneLoop:
        push    si              ;image comes from same offset in each plane
        push    ax              ;preserve plane select
        mov     al,READ_MAP     ;Read Map index
        out     dx,al           ;point GC Index to Read Map register
        pop     ax              ;get back plane select
        inc     dx              ;point to GC Index register
        out     dx,al           ;set up the Read Map to select reads from
                                ; the plane of interest
        dec     dx              ;point back to GC data register
        mov     bx,IMAGE_HEIGHT ;# of scan lines in image
GetImageLoop:
        mov     cx,IMAGE_WIDTH  ;# of bytes across image
        rep     movsb
        add     si,SCREEN_WIDTH-IMAGE_WIDTH
                                ;point to next scan line of image
        dec     bx              ;any more scan lines?
        jnz     GetImageLoop
        pop     si              ;get back image start offset
        inc     al              ;Read Map setting for next plane
        cmp     al,4            ;have we done all four planes?
        jnz     GetImagePlaneLoop
        push    es
        pop     ds              ;restore original DS
        ret
GetImage        endp
;
; Erases the image at its current location.
;
EraseImage      proc    near
        mov     dx,SC_INDEX
        mov     al,MAP_MASK
        out     dx,al           ;point SC Index to the Map Mask register
        inc     dx              ;point to SC Data register
        mov     al,0fh
        out     dx,al           ;set up the Map Mask to allow writes to go to
                                ; all 4 planes
        mov     ax,VGA_SEGMENT
        mov     es,ax
        call    GetImageOffset  ;ES:DI points to the start address
                                ; of the image
        sub     al,al           ;erase with zeros
        mov     bx,IMAGE_HEIGHT ;# of scan lines in image
EraseImageLoop:
        mov     cx,IMAGE_WIDTH  ;# of bytes across image
        rep     stosb
        add     di,SCREEN_WIDTH-IMAGE_WIDTH
                                ;point to next scan line of image
        dec     bx              ;any more scan lines?
        jnz     EraseImageLoop
        ret
EraseImage      endp
;
; Returns the current offset of the image in the VGA segment in DI.
;
GetImageOffset  proc    near
        mov     ax,SCREEN_WIDTH
        mul     [ImageY]
        add     ax,[ImageX]
        mov     di,ax
        ret
GetImageOffset  endp
code    ends
        end     Start
```

By the way, the code in Listing 6.1 is intended only to illustrate read mode 0, and is, in general, a poor way to perform animation, since it's slow and tends to flicker. Later in this book, we'll take a look at some far better VGA animation techniques.

As you'd expect, neither the read mode nor the setting of the Read Map register affects CPU *writes* to VGA memory in any way.

An important point regarding reading VGA memory involves the VGA's latches. (Remember that each of the four latches stores a byte for one plane; on CPU writes, the latches can provide some or all of the data written to display memory, allowing fast copying and efficient pixel masking.) Whenever the CPU reads a given address in VGA memory, each of the four latches is loaded with the contents of the byte at that address in its respective plane. Even though the CPU only receives data from one plane in read mode 0, all four planes are always read, and the values read are stored in the latches. This is true in read mode 1 as well. In short, whenever the CPU reads VGA memory in any read mode, all four planes are read and all four latches are always loaded.

Read Mode 1

Read mode 0 is the workhorse read mode, but it's got an annoying limitation: Whenever you want to determine the color of a given pixel in read mode 0, you have to perform four VGA memory reads, one for each plane, and then interpret the four bytes you've read as eight 16-color pixels. That's a lot of programming. The code is also likely to run slowly, all the more so because a standard IBM VGA takes an average of 1.1 microseconds to complete each memory read, and read mode 0 requires four reads in order to read the four planes, not to mention the even greater amount of time taken by the OUTs required to switch between the planes. (1.1 microseconds may not sound like much, but on a 66-MHz 486, it's 73 clock cycles! Local-bus VGAs can be a good deal faster, but a read from the fastest local-bus adapter I've yet seen would still cost in the neighborhood of 10 486/66 cycles.)

Read mode 1, also known as *color compare mode*, provides special hardware assistance for determining whether a pixel is a given color. With a single read mode 1 read, you can determine whether each of up to eight pixels is a specific color, and you can even specify any or all planes as "don't care" planes in the pixel color comparison.

Read mode 1 is selected by setting bit 3 of the Graphics Mode register (Graphics Controller register 5) to 1. In its simplest form, read mode 1 compares the cross-plane value of each of the eight pixels at a given address to the color value in bits 3-0 of the Color Compare register (Graphics Controller register 2), and returns a 1 to the CPU in the bit position of each pixel that matches the color in the Color Compare register and a 0 for each pixel that does not match.

That's certainly interesting, but what's read mode 1 good for? One obvious application is in implementing flood-fill algorithms, since read mode 1 makes it easy to tell when a given byte contains a pixel of a boundary color. Another application is in detecting on-screen object collisions, as illustrated by the code in Listing 6.2.

LISTING 6.2 L6-2.ASM

```
; Program to illustrate use of read mode 1 (color compare mode)
; to detect collisions in display memory. Draws a yellow line on a
; blue background, then draws a perpendicular green line until the
; yellow line is reached.
;
; By Michael Abrash
;
stack   segment word stack 'STACK'
        db      512 dup (?)
stack   ends
;
VGA_SEGMENT             EQU     0a000h
SCREEN_WIDTH            EQU     80      ;in bytes
GC_INDEX                EQU     3ceh    ;Graphics Controller Index register
SET_RESET               EQU     0       ;Set/Reset register index in GC
ENABLE_SET_RESET        EQU     1       ;Enable Set/Reset register index in GC
COLOR_COMPARE           EQU     2       ;Color Compare register index in GC
GRAPHICS_MODE           EQU     5       ;Graphics Mode register index in GC
BIT_MASK                EQU     8       ;Bit Mask register index in GC
;
code            segment         word 'CODE'
                assume          cs:code
Start           proc            near
                cld
```

```
;
; Select graphics mode 10h.
;
        mov     ax,10h
        int     10h
;
; Fill the screen with blue.
;
        mov     al,1                    ;blue is color 1
        call    SelectSetResetColor     ;set to draw in blue
        mov     ax,VGA_SEGMENT
        mov     es,ax
        sub     di,di
        mov     cx,7000h
        rep     stosb           ;the value written actually doesn't
                                ; matter, since set/reset is providing
                                ; the data written to display memory
;
; Draw a vertical yellow line.
;
        mov     al,14                   ;yellow is color 14
        call    SelectSetResetColor     ;set to draw in yellow
        mov     dx,GC_INDEX
        mov     al,BIT_MASK
        out     dx,al                   ;point GC Index to Bit Mask
        inc     dx                      ;point to GC Data
        mov     al,10h
        out     dx,al                   ;set Bit Mask to 10h
        mov     di,40                   ;start in the middle of the top line
        mov     cx,350                  ;do full height of screen
VLineLoop:
        mov     al,es:[di]              ;load the latches
        stosb                   ;write next pixel of yellow line (set/reset
                                ; provides the data written to display
                                ; memory, and AL is actually ignored)
        add     di,SCREEN_WIDTH-1       ;point to the next scan line
        loop    VLineLoop
;
; Select write mode 0 and read mode 1.
;
        mov     dx,GC_INDEX
        mov     al,GRAPHICS_MODE
        out     dx,al           ;point GC Index to Graphics Mode register
        inc     dx              ;point to GC Data
        mov     al,00001000b    ;bit 3=1 is read mode 1, bits 1 & 0=00
                                ; is write mode 0
        out     dx,al           ;set Graphics Mode to read mode 1,
                                ; write mode 0
;
; Draw a horizontal green line, one pixel at a time, from left
; to right until color compare reports a yellow pixel is encountered.
;
; Draw in green.
;
        mov     al,2                    ;green is color 2
        call    SelectSetResetColor     ;set to draw in green
;
; Set color compare to look for yellow.
;
        mov     dx,GC_INDEX
        mov     al,COLOR_COMPARE
        out     dx,al           ;point GC Index to Color Compare register
        inc     dx              ;point to GC Data
        mov     al,14           ;we're looking for yellow, color 14
        out     dx,al           ;set color compare to look for yellow
        dec     dx              ;point to GC Index
;
; Set up for quick access to Bit Mask register.
;
        mov     al,BIT_MASK
        out     dx,al           ;point GC Index to Bit Mask register
        inc     dx              ;point to GC Data
;
; Set initial pixel mask and display memory offset.
;
        mov     al,80h                  ;initial pixel mask
        mov     di,100*SCREEN_WIDTH
                                        ;start at left edge of scan line 100
HLineLoop:
        mov     ah,es:[di]      ;do a read mode 1 (color compare) read.
                                ; This also loads the latches.
        and     ah,al           ;is the pixel of current interest yellow?
        jnz     WaitKeyAndDone  ;yes-we've reached the yellow line, so we're
                                ; done
        out     dx,al           ;set the Bit Mask register so that we
                                ; modify only the pixel of interest
        mov     es:[di],al      ;draw the pixel. The value written is
                                ; irrelevant, since set/reset is providing
                                ; the data written to display memory
        ror     al,1            ;shift pixel mask to the next pixel
        adc     di,0            ;advance the display memory offset if
                                ; the pixel mask wrapped
;
; Slow things down a bit for visibility (adjust as needed).
;
        mov     cx,0
DelayLoop:
        loop    DelayLoop

        jmp     HLineLoop
;
; Wait for a key to be pressed to end, then return to text mode and
; return to DOS.
;
WaitKeyAndDone:
WaitKeyLoop:
        mov     ah,1
        int     16h
        jz      WaitKeyLoop
        sub     ah,ah
        int     16h             ;clear the key
        mov     ax,3
        int     10h             ;return to text mode
        mov     ah,4ch
        int     21h             ;done
Start   endp
;
; Enables set/reset for all planes, and sets the set/reset color
; to AL.
;
SelectSetResetColor     proc    near
        mov     dx,GC_INDEX
        push    ax              ;preserve color
        mov     al,SET_RESET
        out     dx,al           ;point GC Index to Set/Reset register
        inc     dx              ;point to GC Data
        pop     ax              ;get back color
        out     dx,al           ;set Set/Reset register to selected color
        dec     dx              ;point to GC Index
        mov     al,ENABLE_SET_RESET
        out     dx,al           ;point GC Index to Enable Set/Reset register
        inc     dx              ;point to GC Data
        mov     al,0fh
        out     dx,al           ;enable set/reset for all planes
        ret
SelectSetResetColor     endp
code    ends
        end     Start
```

When all Planes "Don't Care"

Still and all, there aren't all that many uses for basic color compare operations. There is, however, a genuinely odd application of read mode 1 that's worth knowing about; but in order to understand that, we must first look at the "don't care" aspect of color compare operation.

As described above, during read mode 1 reads the color stored in the Color Compare register is compared to each of the 8 pixels at a given address in VGA memory. But—and it's a big but—any plane for which the corresponding bit in the Color Don't Care register is a 0 is always considered a color compare match, regardless of the values of that plane's bits in the pixels and in the Color Compare register.

Let's look at this another way. A given pixel is controlled by four bits, one in each plane. Normally (when the Color Don't Care register is 0FH), the color in the Color Compare register is compared to the four bits of each pixel; bit 0 of the Color Compare register is compared to the plane 0 bit of each pixel, bit 1 of the Color Compare register is compared to the plane 1 bit of each pixel, and so on. That is, when the lower four bits of the Color Don't Care register are all set to 1, then all four bits of a given pixel must match the Color Compare register in order for a read mode 1 read to return a 1 for that pixel to the CPU.

However, if any bit of the Color Don't Care register is 0, then the corresponding bit of each pixel is unconditionally considered to match the corresponding bit of the Color Compare register. You might think of the Color Don't Care register as selecting exactly which planes should matter in a given read mode 1 read. At the extreme, if all bits of the Color Don't Care register are 0, then read mode 1 reads will always return 0FFH, since all planes are considered to match all bits of all pixels.

Now, we're all prone to using tools the "right" way—that is, in the way in which they were intended to be used. By that token, the Color Don't Care register is clearly intended to mask one or more planes out of a color comparison, and as such, has limited use. However, the Color Don't Care register becomes far more interesting in exactly the "extreme" case described above, where all planes become "don't care" planes.

Why? Well, as I've said, when all planes are "don't care" planes, read mode 1 reads always return 0FFH. Now, when you AND any value with 0FFH, the value remains unchanged, and that can be awfully handy when you're using the bit mask to modify selected pixels in VGA memory. Recall that you must always read VGA memory to load the latches before writing to VGA memory when you're using the bit mask. Traditionally, two separate instructions—a read followed by a write—are used to perform this task. The code in Listing 6.2 uses this approach. Suppose, however, that you've set the VGA to read mode 1, with the Color Don't Care register set to 0 (meaning all reads of VGA memory will return 0FFH). Under these circumstances, you can use a single **AND** instruction to both read and write VGA memory, since ANDing any value with 0FFH leaves that value unchanged.

Listing 6.3 illustrates an efficient use of write mode 3 in conjunction with read mode 1 and a Color Don't Care register setting of 0. The mask in AL is passed directly to the VGA's bit mask (that's how write mode 3 works—see Chapter 4 for details). Because the VGA always returns 0FFH, the single **AND** instruction loads the latches, and writes the value in AL, unmodified, to the VGA, where it is used to generate the bit mask. This is more compact and register-efficient than using separate instructions to read and write, although it is not necessarily faster by cycle count, because on a 486 or a Pentium **MOV** is a 1-cycle instruction, but **AND** with memory is a 3-cycle instruction. However, given display memory wait states, it is often the case that the two approaches run at the same speed, and the register that the above approach frees up can frequently be used to save one or more cycles in any case.

By the way, Listing 6.3 illustrates how write mode 3 can make for excellent pixel- and line-drawing code.

LISTING 6.3 L6-3.ASM

```
; Program that draws a diagonal line to illustrate the use of a
; Color Don't Care register setting of 0FFH to support fast
; read-modify-write operations to VGA memory in write mode 3 by
; drawing a diagonal line.
;
; Note: Works on VGAs only.
;
; By Michael Abrash
;
stack   segment word stack 'STACK'
        db      512 dup (?)
stack   ends
;
VGA_SEGMENT             EQU     0a000h
SCREEN_WIDTH            EQU     80      ;in bytes
GC_INDEX                EQU     3ceh    ;Graphics Controller Index register
SET_RESET               EQU     0       ;Set/Reset register index in GC
ENABLE_SET_RESET        EQU     1       ;Enable Set/Reset register index in GC
GRAPHICS_MODE           EQU     5       ;Graphics Mode register index in GC
COLOR_DONT_CARE         EQU     7       ;Color Don't Care register index in GC
;
```

```
code    segment word 'CODE'
        assume  cs:code
Start   proc    near
;
; Select graphics mode 12h.
;
        mov     ax,12h
        int     10h
;
; Select write mode 3 and read mode 1.
;
        mov     dx,GC_INDEX
        mov     al,GRAPHICS_MODE
        out     dx,al
        inc     dx
        in      al,dx           ;VGA registers are readable, bless them!
        or      al,00001011b    ;bit 3=1 selects read mode 1, and
                                ; bits 1 & 0=11 selects write mode 3
        jmp     $+2             ;delay between IN and OUT to same port
        out     dx,al
        dec     dx
;
; Set up set/reset to always draw in white.
;
        mov     al,SET_RESET
        out     dx,al
        inc     dx
        mov     al,0fh
        out     dx,al
        dec     dx
        mov     al,ENABLE_SET_RESET
        out     dx,al
        inc     dx
        mov     al,0fh
        out     dx,al
        dec     dx
;
; Set Color Don't Care to 0, so reads of VGA memory always return OFFH.
;
        mov     al,COLOR_DONT_CARE
        out     dx,al
        inc     dx
        sub     al,al
        out     dx,al
;
; Set up the initial memory pointer and pixel mask.
;
        mov     ax,VGA_SEGMENT
        mov     ds,ax
        sub     bx,bx
        mov     al,80h
;
; Draw 400 points on a diagonal line sloping down and to the right.
;
        mov     cx,400
DrawDiagonalLoop:
        and     [bx],al         ;reads display memory, loading the latches,
                                ; then writes AL to the VGA. AL becomes the
                                ; bit mask, and set/reset provides the
                                ; actual data written
        add     bx,SCREEN_WIDTH
                                ; point to the next scan line
        ror     al,1            ;move the pixel mask one pixel to the right
        adc     bx,0    ;advance to the next byte if the pixel mask wrapped
        loop    DrawDiagonalLoop
;
; Wait for a key to be pressed to end, then return to text mode and
; return to DOS.
;
WaitKeyLoop:
        mov     ah,1
        int     16h
        jz      WaitKeyLoop
        sub     ah,ah
        int     16h             ;clear the key
        mov     ax,3
        int     10h             ;return to text mode
        mov     ah,4ch
        int     21h             ;done
Start   endp
code    ends
        end     Start
```

I hope I've given you a good feel for what color compare mode is and what it might be used for. Color compare mode isn't particularly easy to understand, but it's not that complicated in actual operation, and it's certainly useful at times; take some time to study the sample code and perform a few experiments of your own, and you may well find useful applications for color compare mode in your graphics code.

A final note: The Read Map register has no effect in read mode 1, and the Color Compare and Color Don't Care registers have no effect either in read mode 0 or when writing to VGA memory. And with that, by gosh, we're actually done with the basics of accessing VGA memory!

Not to worry—that still leaves us a slew of interesting VGA topics, including smooth panning and scrolling, the split screen, color selection, page flipping, and Mode X. And that's not to mention actual uses to which the VGA's hardware can be put, including lines, circles, polygons, and my personal favorite, animation. We've covered a lot of challenging and rewarding ground—and we've only just begun.

Saving Screens and Other VGA Mysteries

Chapter 7

Useful Nuggets from the VGA Zen File

There are a number of VGA graphics topics that aren't quite involved enough to warrant their own chapters, yet still cause a fair amount of programmer headscratching—and thus deserve treatment somewhere in this book. This is the place, and during the course of this chapter we'll touch on saving and restoring 16-color EGA and VGA screens, the 16-out-of-64 colors issue, and techniques involved in reading and writing VGA control registers.

That's a lot of ground to cover, so let's get started!

Saving and Restoring EGA and VGA Screens

The memory architectures of EGAs and VGAs are similar enough to treat both together in this regard. The basic principle for saving EGA and VGA 16-color graphics screens is astonishingly simple: Write each plane to disk separately. Let's take a look at how this works in the EGA's hi-res mode 10H, which provides 16 colors at 640×350.

All we need do is enable reads from plane 0 and write the 28,000 bytes of plane 0 that are displayed in mode 10H to disk, then enable reads from plane 1 and write the displayed portion of that plane to disk, and so on for planes 2 and 3. The result is a file that's 112,000 (28,000 * 4) bytes long, with the planes stored as four distinct 28,000-byte blocks, as shown in Figure 7.1.

The program shown later on in Listing 7.1 does just what I've described above, putting the screen into mode 10H, putting up some bit- mapped text so there's something to save, and creating the 112K file SNAPSHOT.SCR, which contains the visible portion of the mode 10H frame buffer.

The only part of Listing 7.1 that's even remotely tricky is the use of the Read Map register (Graphics Controller register 4) to make each of the four planes of display

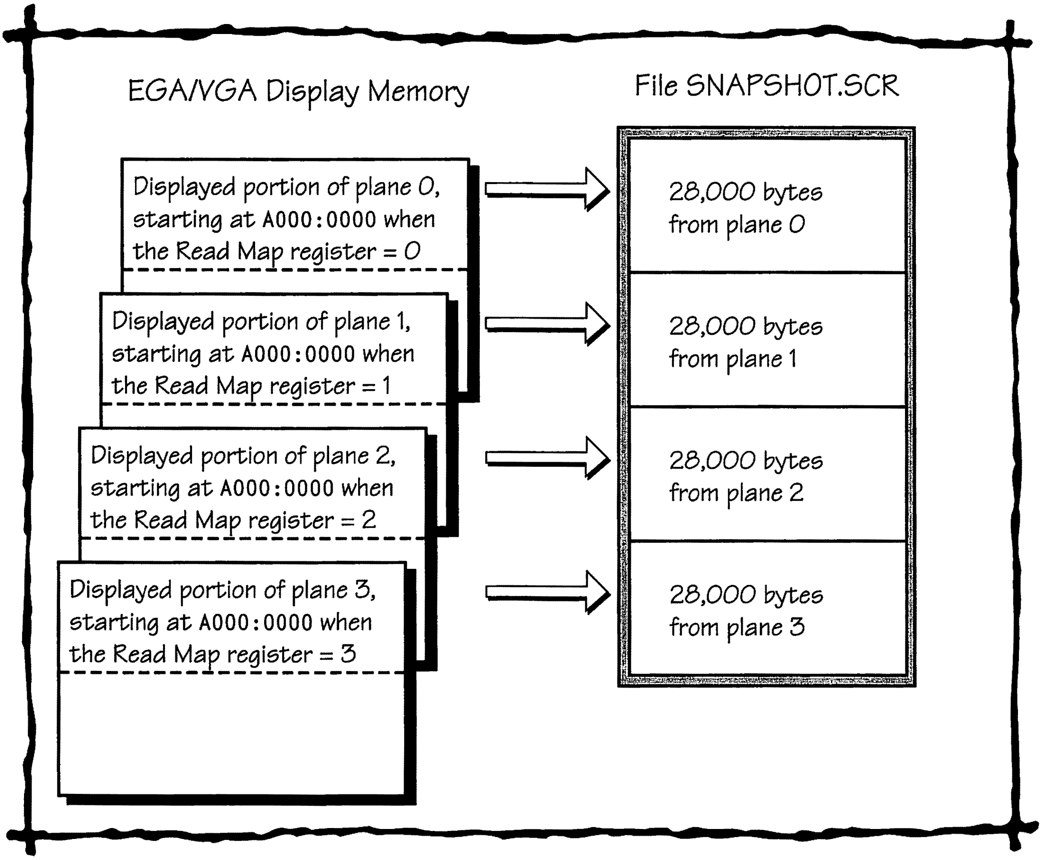

EGA/VGA Display Memory
File SNAPSHOT.SCR
Displayed portion of plane 0, starting at A000:0000 when the Read Map register = 0
Displayed portion of plane 1, starting at A000:0000 when the Read Map register = 1
Displayed portion of plane 2, starting at A000:0000 when the Read Map register = 2
Displayed portion of plane 3, starting at A000:0000 when the Read Map register = 3
28,000 bytes from plane 0
28,000 bytes from plane 1
28,000 bytes from plane 2
28,000 bytes from plane 3

Figure 7.1 Saving EGA/VGA Display Memory

memory readable in turn. The same code is used to write 28,000 bytes of display memory to disk four times, and 28,000 bytes of memory starting at A000:0000 are written to disk each time; however, a different plane is read each time, thanks to the changing setting of the Read Map register. (If this is unclear, refer back to Figure 7.1; you may also want to reread Chapter 6 to brush up on the operation of the Read Map register in particular and reading EGA and VGA memory in general.)

Of course, we'll want the ability to restore what we've saved, and Listing 7.2 does this. Listing 7.2 reverses the action of Listing 7.1, selecting mode 10H and then loading 28,000 bytes from SNAPSHOT.SCR into each plane of display memory. The Map Mask register (Sequence Controller register 2) is used to select the plane to be written to. If your computer is slow enough, you can see the colors of the text change as each plane is loaded when Listing 7.2 runs. Note that Listing 7.2 does not itself draw any text, but rather simply loads the bit map saved by Listing 7.1 back into the mode 10H frame buffer.

LISTING 7.1 L7-1.ASM

```
; Program to put up a mode 10h EGA graphics screen, then save it
; to the file SNAPSHOT.SCR.
;
VGA_SEGMENT             equ  0a000h
GC_INDEX                equ  3ceh       ;Graphics Controller Index register
READ_MAP                equ  4          ;Read Map register index in GC
DISPLAYED_SCREEN_SIZE   equ  (640/8)*350 ;# of displayed bytes per plane in a
                                        ; hi-res graphics screen
;
stack   segment para stack 'STACK'
        db      512 dup (?)
stack   ends
;
Data    segment word 'DATA'
SampleText    db   'This is bit-mapped text, drawn in hi-res '
              db   'EGA graphics mode 10h.', 0dh, 0ah, 0ah
              db   'Saving the screen (including this text)...'
              db   0dh, 0ah, '$'
Filename      db   'SNAPSHOT.SCR',0     ;name of file we're saving to
ErrMsg1       db   '*** Couldn''t open SNAPSHOT.SCR ***',0dh,0ah,'$'
ErrMsg2       db   '*** Error writing to SNAPSHOT.SCR ***',0dh,0ah,'$'
WaitKeyMsg    db   0dh, 0ah, 'Done. Press any key to end...',0dh,0ah,'$'
Handle        dw   ?                    ;handle of file we're saving to
Plane         db   ?                    ;plane being read
Data ends
;
Code    segment
        assume  cs:Code, ds:Data
Start   proc    near
        mov     ax,Data
        mov     ds,ax
;
; Go to hi-res graphics mode.
;
        mov     ax,10h          ;AH = 0 means mode set, AL = 10h selects
                                ; hi-res graphics mode
        int     10h             ;BIOS video interrupt
;
; Put up some text, so the screen isn't empty.
;
        mov     ah,9            ;DOS print string function
        mov     dx,offset SampleText
        int     21h
;
; Delete SNAPSHOT.SCR if it exists.
;
        mov     ah,41h          ;DOS unlink file function
        mov     dx,offset Filename
        int     21h
;
; Create the file SNAPSHOT.SCR.
;
        mov     ah,3ch          ;DOS create file function
        mov     dx,offset Filename
        sub     cx,cx           ;make it a normal file
        int     21h
        mov     [Handle],ax  ;save the handle
        jnc     SaveTheScreen;we're ready to save if no error
        mov     ah,9            ;DOS print string function
        mov     dx,offset ErrMsg1
        int     21h             ;notify of the error
        jmp     short Done      ;and done
;
; Loop through the 4 planes, making each readable in turn and
; writing it to disk. Note that all 4 planes are readable at
; A000:0000; the Read Map register selects which plane is readable
; at any one time.
;
SaveTheScreen:
        mov     [Plane],0       ;start with plane 0
SaveLoop:
        mov     dx,GC_INDEX
        mov     al,READ_MAP     ;set GC Index to Read Map register
        out     dx,al
        inc     dx
        mov     al,[Plane]      ;get the # of the plane we want
                                ; to save
        out     dx,al           ;set to read from the desired plane
        mov     ah,40h          ;DOS write to file function
        mov     bx,[Handle]
        mov     cx,DISPLAYED_SCREEN_SIZE ;# of bytes to save
        sub     dx,dx           ;write all displayed bytes at A000:0000
        push    ds
        mov     si,VGA_SEGMENT
        mov     ds,si
        int     21h             ;write the displayed portion of this plane
        pop     ds
        cmp     ax,DISPLAYED_SCREEN_SIZE ;did all bytes get written?
        jz        SaveLoopBottom
        mov     ah,9            ;DOS print string function
        mov     dx,offset ErrMsg2
        int     21h             ;notify about the error
        jmp     short DoClose;and done
SaveLoopBottom:
        mov     al,[Plane]
        inc     ax              ;point to the next plane
        mov     [Plane],al
        cmp     al,3            ;have we done all planes?
        jbe     SaveLoop        ;no, so do the next plane
;
; Close SNAPSHOT.SCR.
;
DoClose:
        mov     ah,3eh          ;DOS close file function
        mov     bx,[Handle]
        int     21h
;
; Wait for a keypress.
;
        mov     ah,9            ;DOS print string function
        mov     dx,offset WaitKeyMsg
        int     21h             ;prompt
        mov     ah,8            ;DOS input without echo function
        int     21h
;
; Restore text mode.
;
        mov     ax,3
        int     10h
```

```
;
; Done.
;
Done:
        mov     ah,4ch     ;DOS terminate function
        int     21h
Start   endp
Code    ends
        end     Start
```

LISTING 7.2 L7-2.ASM

```
; Program to restore a mode 10h EGA graphics screen from
; the file SNAPSHOT.SCR.
;
VGA_SEGMENT             equ  0a000h
SC_INDEX                equ  3c4h       ;Sequence Controller Index register
MAP_MASK                equ  2          ;Map Mask register index in SC
DISPLAYED_SCREEN_SIZE   equ (640/8)*350 ;# of displayed bytes per plane in a
                                        ; hi-res graphics screen
;
stack   segment para stack 'STACK'
        db      512 dup (?)
stack   ends
;
Data    segment word 'DATA'
Filename     db   'SNAPSHOT.SCR',0       ;name of file we're restoring from
ErrMsg1      db   '*** Couldn''t open SNAPSHOT.SCR ***',0dh,0ah,'$'
ErrMsg2      db   '*** Error reading from SNAPSHOT.SCR ***',0dh,0ah,'$'
WaitKeyMsg   db   0dh, 0ah, 'Done. Press any key to end...',0dh,0ah,'$'
Handle       dw   ?                      ;handle of file we're restoring from
Plane        db   ?                      ;plane being written
Data    ends
;
Code    segment
        assume  cs:Code, ds:Data
Start   proc    near
        mov     ax,Data
        mov     ds,ax
;
; Go to hi-res graphics mode.
;
        mov     ax,10h                ;AH = 0 means mode set, AL = 10h selects
                                      ; hi-res graphics mode
        int     10h                   ;BIOS video interrupt
;
; Open SNAPSHOT.SCR.
;
        mov     ah,3dh                ;DOS open file function
        mov     dx,offset Filename
        sub     al,al                 ;open for reading
        int     21h
        mov     [Handle],ax           ;save the handle
        jnc     RestoreTheScreen      ;we're ready to restore if no error
        mov     ah,9                  ;DOS print string function
        mov     dx,offset ErrMsg1
        int     21h                   ;notify of the error
        jmp     short Done ;and done
;
```

```
; Loop through the 4 planes, making each writable in turn and
; reading it from disk. Note that all 4 planes are writable at
; A000:0000; the Map Mask register selects which planes are readable
; at any one time. We only make one plane readable at a time.
;
RestoreTheScreen:
        mov     [Plane],0                    ;start with plane 0
RestoreLoop:
        mov     dx,SC_INDEX
        mov     al,MAP_MASK                  ;set SC Index to Map Mask register
        out     dx,al
        inc     dx
        mov     cl,[Plane]                   ;get the # of the plane we want
                                             ; to restore
        mov     al,1
        shl     al,cl                        ;set the bit enabling writes to
                                             ; only the one desired plane
        out     dx,al                        ;set to read from desired plane
        mov     ah,3fh                       ;DOS read from file function
        mov     bx,[Handle]
        mov     cx,DISPLAYED_SCREEN_SIZE     ;# of bytes to read
        sub     dx,dx                        ;start loading bytes at A000:0000
        push    ds
        mov     si,VGA_SEGMENT
        mov     ds,si
        int     21h                  ;read the displayed portion of this plane
        pop     ds
        jc      ReadError
        cmp     ax,DISPLAYED_SCREEN_SIZE     ;did all bytes get read?
        jz      RestoreLoopBottom
ReadError:
        mov     ah,9                         ;DOS print string function
        mov     dx,offset ErrMsg2
        int     21h                          ;notify about the error
        jmp     short DoClose                ;and done
RestoreLoopBottom:
        mov     al,[Plane]
        inc     ax                           ;point to the next plane
        mov     [Plane],al
        cmp     al,3                         ;have we done all planes?
        jbe     RestoreLoop                  ;no, so do the next plane
;
; Close SNAPSHOT.SCR.
;
DoClose:
        mov     ah,3eh                       ;DOS close file function
        mov     bx,[Handle]
        int     21h
;
; Wait for a keypress.
;
        mov     ah,8                         ;DOS input without echo function
        int     21h
;
; Restore text mode.
;
        mov     ax,3
        int     10h
;
; Done.
;
```

```
Done:
        mov     ah,4ch                          ;DOS terminate function
        int     21h
Start   endp
Code    ends
        end     Start
```

If you compare Listings 7.1 and 7.2, you will see that the Map Mask register setting used to load a given plane does not match the Read Map register setting used to read that plane. This is so because while only one plane can ever be read at a time, anywhere from zero to four planes can be written to at once; consequently, Read Map register settings are plane selections from 0 to 3, while Map Mask register settings are plane *masks* from 0 to 15, where a bit 0 setting of 1 enables writes to plane 0, a bit 1 setting of 1 enables writes to plane 1, and so on. Again, Chapter 6 provides a detailed explanation of the differences between the Read Map and Map Mask registers.

Screen saving and restoring is pretty simple, eh? There are a few caveats, of course, but nothing serious. First, the adapter's registers must be programmed properly in order for screen saving and restoring to work. For screen saving, you must be in read mode 0; if you're in color compare mode, there's no telling what bit pattern you'll save, but it certainly won't be the desired screen image. For screen restoring, you must be in write mode 0, with the Bit Mask register set to 0FFH and Data Rotate register set to 0 (no data rotation and the logical function set to pass the data through unchanged).

While these requirements are no problem if you're simply calling a subroutine in order to save an image from your program, they pose a considerable problem if you're designing a hot-key operated TSR that can capture a screen image at any time. With the EGA specifically, there's never any way to tell what state the registers are currently in, since the registers aren't readable. (More on this issue later in this chapter.) As a result, any TSR that sets the Bit Mask to 0FFH, the Data Rotate register to 0, and so on runs the risk of interfering with the drawing code of the program that's already running.

What's the solution? Frankly, the solution is to get VGA-specific. A TSR designed for the VGA can simply read out and save the state of the registers of interest, program those registers as needed, save the screen image, and restore the original settings. From a programmer's perspective, readable registers are certainly near the top of the list of things to like about the VGA! The remaining installed base of EGAs is steadily dwindling, and you may be able to ignore it as a market today, as you couldn't even a year or two ago.

If you are going to write a hi-res VGA version of the screen capture program, be sure to account for the increased size of the VGA's mode 12H bit map. The mode 12H

(640×480) screen uses 37.5K per plane of display memory, so for mode 12H the displayed screen size equate in Listings 7.1 and 7.2 should be changed to:

```
DISPLAYED_SCREEN_SIZE   equu   (640/8)*480
```

Similarly, if you're capturing a graphics screen that starts at an offset other than 0 in the segment at A000H, you must change the memory offset used by the disk functions to match. You can, if you so desire, read the start offset of the display memory providing the information shown on the screen from the Start Address registers (CRT Controller registers 0CH and 0DH); these registers are readable even on an EGA.

Finally, be aware that the screen capture and restore programs in Listings 7.1 and 7.2 are only appropriate for EGA/VGA modes 0DH, 0EH, 0FH, 010H, and 012H, since they assume a four- plane configuration of EGA/VGA memory. In all text modes and in CGA graphics modes, and in VGA modes 11H and 13H as well, display memory can simply be written to disk and read back as a linear block of memory, just like a normal array.

While Listings 7.1 and 7.2 are written in assembly, the principles they illustrate apply equally well to high-level languages. In fact, there's no need for any assembly at all when saving an EGA/VGA screen, as long as the high-level language you're using can perform direct port I/O to set up the adapter and can read and write display memory directly.

One tip if you're saving and restoring the screen from a high-level language on an EGA, though: After you've completed the save or restore operation, be sure to put any registers that you've changed back to their default settings. Some high-level languages (and the BIOS as well) assume that various registers are left in a certain state, so on the EGA it's safest to leave the registers in their most likely state. On the VGA, of course, you can just read the registers out before you change them, then put them back the way you found them when you're done.

16 Colors out of 64

How does one produce the 64 colors from which the 16 colors displayed by the EGA can be chosen? The answer is simple enough: There's a BIOS function that lets you select the mapping of the 16 possible pixel values to the 64 possible colors. Let's lay out a bit of background before proceeding, however.

The EGA sends pixel information to the monitor on 6 pins. This means that there are 2 to the 6th, or 64 possible colors that an EGA can generate. However, for compatibility with pre-EGA monitors, in 200-scan-line modes Enhanced Color Display-compatible monitors ignore two of the signals. As a result, in CGA-compatible modes (modes 4, 5, 6, and the 200-scan-line versions of modes 0, 1, 2, and 3) you can select from only 16 colors (although the colors can still be remapped, as described below). If you're not hooked up to a monitor capable of displaying 350 scan lines (such as the old IBM Color Display), you can never select from more than 16 colors, since those monitors only accept four input signals. For now, we'll assume we're in one of the 350-scan line color modes, a group which includes mode 10H and the 350-scan-line versions of modes 0, 1, 2, and 3.

Each pixel comes out of memory (or, in text mode, out of the attribute-handling portion of the EGA) as a 4-bit value, denoting 1 of 16 possible colors. In graphics modes, the 4-bit pixel value is made up of one bit from each plane, with 8 pixels' worth of data stored at any given byte address in display memory. Normally, we think of the 4-bit value of a pixel as being that pixel's color, so a pixel value of 0 is black, a pixel value of 1 is blue, and so on, as if that's a built-in feature of the EGA.

Actually, though, the correspondence of pixel values to color is absolutely arbitrary, depending solely on how the color-mapping portion of the EGA containing the palette registers is programmed. If you cared to have color 0 be bright red and color 1 be black, that could easily be arranged, as could a mapping in which all 16 colors were yellow. What's more, these mappings affect text-mode characters as readily as they do graphics-mode pixels, so you could map text attribute 0 to white and text attribute 15 to black to produce a black on white display, if you wished.

Each of the 16 palette registers stores the mapping of one of the 16 possible 4-bit pixel values from memory to one of 64 possible 6-bit pixel values to be sent to the monitor as video data, as shown in Figure 7.2. A 4-bit pixel value of 0 causes the 6-bit value stored in palette register 0 to be sent to the display as the color of that pixel, a pixel value of 1 causes the contents of palette register 1 to be sent to the display, and so on. Since there are only four input bits, it stands to reason that only 16 colors are available at any one time; since there are six output bits, however, those 16 colors can be mapped to any of 64 colors. The mapping for each of the 16 pixel values is controlled by the lower six bits of the corresponding palette register, as shown in Figure 7.3. Secondary red, green, and blue are less-intense versions of red, green, and blue, although their exact effects vary from monitor to monitor. The best way to figure out what the 64 colors look like on your monitor is to see them, and that's just what the program in Listing 7.3, which we'll discuss shortly, lets you do.

How does one go about setting the palette registers? Well, it's certainly possible to set the palette registers directly by addressing them at registers 0 through 0FH of the Attribute Controller. However, setting the palette registers is a bit tricky—bit 5 of the Attribute Controller Index register must be 0 while the palette registers are written to, and glitches can occur if the updating doesn't take place during the blanking interval—and besides, it turns out that there's no need at all to go straight to the hardware on this one. Conveniently, the EGA BIOS provides us with video function 10H, which supports setting either any one palette register or all 16 palette registers (and the overscan register as well) with a single video interrupt.

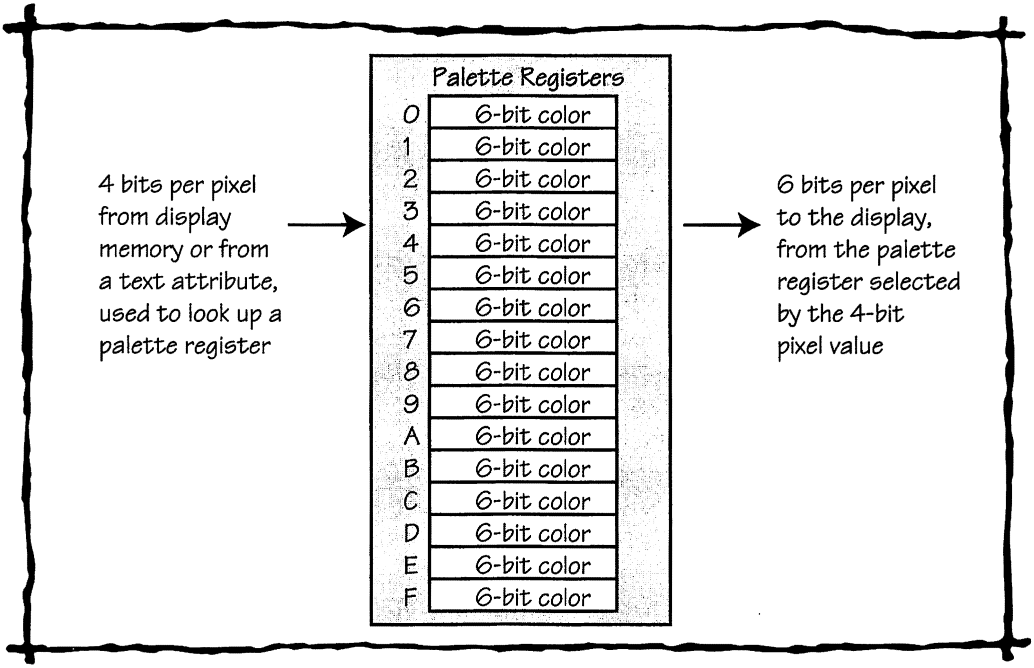


Figure 7.2 Color Translation via the Palette Registers

Video function 10H is invoked by performing an INT 10H with AH set to 10H. If AL is 0 (subfunction 0), then BL contains the number of the palette register to set, and BH contains the value to set that register to. If AL is 1 (subfunction 1), then BH contains the value to set the overscan (border) color to. Finally, if AL is 2 (subfunction 2), then ES:DX points to a 17-byte array containing the values to set palette registers 0-15 and the overscan register to. (For completeness, although it's unrelated to the palette registers, there is one more subfunction of video function 10H. If AL = 3

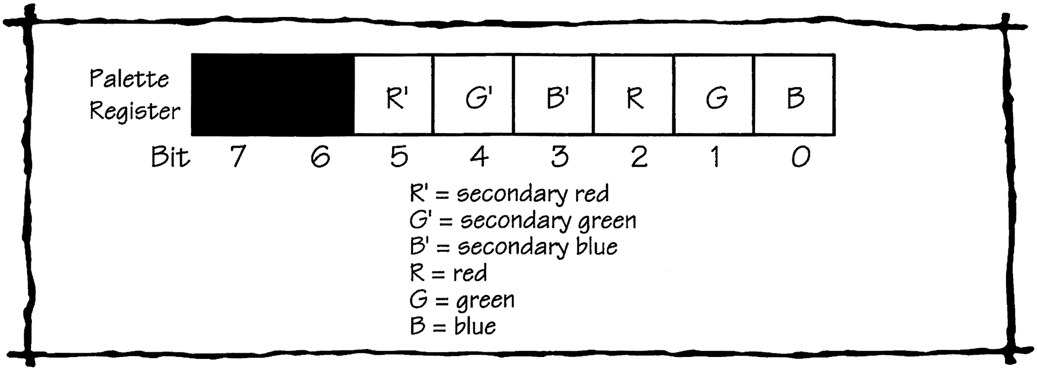


Figure 7.3 Bit Organization within a Palette Register

(subfunction 3), bit 0 of BL is set to 1 to cause bit 7 of text attributes to select blinking, or set to 0 to cause bit 7 of text attributes to select high-intensity reverse video).

Listing 7.3 uses video function 10H, subfunction 2 to step through all 64 possible colors. This is accomplished by putting up 16 color bars, one for each of the 16 possible 4-bit pixel values, then changing the mapping provided by the palette registers to select a different group of 16 colors from the set of 64 each time a key is pressed. Initially, colors 0-15 are displayed, then 1-16, then 2-17, and so on up to color 3FH wrapping around to colors 0-14, and finally back to colors 0-15. (By the way, at mode set time the 16 palette registers are not set to colors 0-15, but rather to 0H, 1H, 2H, 3H, 4H, 5H, 14H, 7H, 38H, 39H, 3AH, 3BH, 3CH, 3DH, 3EH, and 3FH, respectively. Bits 6, 5, and 4—secondary red, green, and blue—are all set to 1 in palette registers 8-15 in order to produce high-intensity colors. Palette register 6 is set to 14H to produce brown, rather than the yellow that the expected value of 6H would produce.)

When you run Listing 7.3, you'll see that the whole screen changes color as each new color set is selected. This occurs because most of the pixels on the screen have a value of 0, selecting the background color stored in palette register 0, and we're reprogramming palette register 0 right along with the other 15 palette registers.

It's important to understand that in Listing 7.3 the contents of display memory are never changed after initialization. The only change is the mapping from the 4-bit pixel data coming out of display memory to the 6-bit data going to the monitor. For this reason, it's technically inaccurate to speak of bits in display memory as representing colors; more accurately, they represent attributes in the range 0-15, which are mapped to colors 0-3FH by the palette registers.

LISTING 7.3 L7-3.ASM

```
; Program to illustrate the color mapping capabilities of the
; EGA's palette registers.
;
VGA_SEGMENT     equ  0a000h
SC_INDEX        equ  3c4h          ;Sequence Controller Index register
MAP_MASK        equ  2             ;Map Mask register index in SC
BAR_HEIGHT      equ  14            ;height of each bar
TOP_BAR         equ  BAR_HEIGHT*6  ;start the bars down a bit to
                                   ; leave room for text
;
stack   segment para stack 'STACK'
        db      512 dup (?)
stack   ends
;
Data    segment word 'DATA'
KeyMsg  db   'Press any key to see the next color set. '
        db   'There are 64 color sets in all.'
        db   0dh, 0ah, 0ah, 0ah, 0ah
        db   13 dup (' '), 'Attribute'
        db   38 dup (' '), 'Color$'
;
; Used to label the attributes of the color bars.
;
```

```
AttributeNumbers        label   byte
x=      0
        rept            16
if x lt 10
        db              '0', x+'0', 'h', 0ah, 8, 8, 8
else
        db              '0', x+'A'-10, 'h', 0ah, 8, 8, 8
endif
x=      x+1
        endm
        db              '$'
;
; Used to label the colors of the color bars. (Color values are
; filled in on the fly.)
;
ColorNumbers            label   byte
        rept            16
        db              '000h', 0ah, 8, 8, 8, 8
        endm
COLOR_ENTRY_LENGTH      equ     ($-ColorNumbers)/16
        db              '$'
;
CurrentColor    db      ?
;
; Space for the array of 16 colors we'll pass to the BIOS, plus
; an overscan setting of black.
;
ColorTable      db      16 dup (?), 0
Data    ends
;
Code    segment
        assume  cs:Code, ds:Data
Start   proc    near
        cld
        mov     ax,Data
        mov     ds,ax
;
; Go to hi-res graphics mode.
;
        mov     ax,10h          ;AH = 0 means mode set, AL = 10h selects
                                ; hi-res graphics mode
        int     10h             ;BIOS video interrupt
;
; Put up relevant text.
;
        mov     ah,9                    ;DOS print string function
        mov     dx,offset KeyMsg
        int     21h
;
; Put up the color bars, one in each of the 16 possible pixel values
; (which we'll call attributes).
;
        mov     cx,16                   ;we'll put up 16 color bars
        sub     al,al                   ;start with attribute 0
BarLoop:
        push    ax
        push    cx
        call    BarUp
        pop     cx
        pop     ax
        inc     ax                  ;select the next attribute
        loop    BarLoop
;
; Put up the attribute labels.
;
        mov     ah,2                ;video interrupt set cursor position function
        sub     bh,bh               ;page 0
        mov     dh,TOP_BAR/14       ;counting in character rows, match to
                                    ; top of first bar, counting in
                                    ; scan lines
        mov     dl,16               ;just to left of bars
        int     10h
        mov     ah,9                ;DOS print string function
        mov     dx,offset AttributeNumbers
        int     21h
;
; Loop through the color set, one new setting per keypress.
;
        mov     [CurrentColor],0    ;start with color zero
ColorLoop:
;
; Set the palette registers to the current color set, consisting
; of the current color mapped to attribute 0, current color + 1
; mapped to attribute 1, and so on.
;
        mov     al,[CurrentColor]
        mov     bx,offset ColorTable
        mov     cx,16             ;we have 16 colors to set
PaletteSetLoop:
        and     al,3fh            ;limit to 6-bit color values
        mov     [bx],al           ;build the 16-color table used for setting
        inc     bx                ; the palette registers
        inc     ax
        loop    PaletteSetLoop
        mov     ah,10h            ;video interrupt palette function
        mov     al,2              ;subfunction to set all 16 palette registers
                                  ; and overscan at once
        mov     dx,offset ColorTable
        push    ds
        pop     es                ;ES:DX points to the color table
        int     10h               ;invoke the video interrupt to set the palette
;
; Put up the color numbers, so we can see how attributes map
; to color values, and so we can see how each color # looks
; (at least on this particular screen).
;
        call    ColorNumbersUp
;
; Wait for a keypress, so they can see this color set.
;
WaitKey:
        mov     ah,8              ;DOS input without echo function
        int     21h
;
; Advance to the next color set.
;
        mov     al,[CurrentColor]
        inc     ax
        mov     [CurrentColor],al
        cmp     al,64
        jbe     ColorLoop
;
; Restore text mode.
;
        mov     ax,3
        int     10h
;
; Done.
;
Done:
        mov     ah,4ch          ;DOS terminate function
        int     21h
;
; Puts up a bar consisting of the specified attribute (pixel value),
; at a vertical position corresponding to the attribute.
;
; Input: AL = attribute
;
BarUp   proc    near
        mov     dx,SC_INDEX
        mov     ah,al
        mov     al,MAP_MASK
        out     dx,al
        inc     dx
        mov     al,ah
        out     dx,al           ;set the Map Mask register to produce
                                ; the desired color
        mov     ah,BAR_HEIGHT
        mul     ah              ;row of top of bar
        add     ax,TOP_BAR      ;start a few lines down to leave room for
                                ; text
        mov     dx,80           ;rows are 80 bytes long
        mul     dx              ;offset in bytes of start of scan line bar
                                ; starts on
        add     ax,20           ;offset in bytes of upper left corner of bar
        mov     di,ax
        mov     ax,VGA_SEGMENT
        mov     es,ax           ;ES:DI points to offset of upper left
                                ; corner of bar
        mov     dx,BAR_HEIGHT
        mov     al,0ffh
BarLineLoop:
        mov     cx,40           ;make the bars 40 wide
        rep     stosb           ;do one scan line of the bar
        add     di,40           ;point to the start of the next scan line
                                ; of the bar
        dec     dx
        jnz     BarLineLoop
        ret
BarUp   endp
;
; Converts AL to a hex digit in the range 0-F.
;
BinToHexDigit   proc    near
        cmp     al,9
        ja              IsHex
        add     al,'0'
        ret
IsHex:
        add     al,'A'-10
        ret
BinToHexDigit   endp
;
; Displays the color values generated by the color bars given the
; current palette register settings off to the right of the color
; bars.
;
ColorNumbersUp  proc    near
        mov     ah,2            ;video interrupt set cursor position function
        sub     bh,bh           ;page 0
        mov     dh,TOP_BAR/14   ;counting in character rows, match to
                                ; top of first bar, counting in
                                ; scan lines
        mov     dl,20+40+1      ;just to right of bars
        int     10h
        mov     al,[CurrentColor] ;start with the current color
        mov     bx,offset ColorNumbers+1
                                ;build color number text string on the fly
        mov     cx,16           ;we've got 16 colors to do
ColorNumberLoop:
        push    ax              ;save the color #
        and     al,3fh          ;limit to 6-bit color values
        shr     al,1
        shr     al,1
        shr     al,1
        shr     al,1            ;isolate the high nibble of the color #
        call    BinToHexDigit   ;convert the high color # nibble
        mov     [bx],al         ; and put it into the text
        pop     ax              ;get back the color #
        push    ax              ;save the color #
        and     al,0fh          ;isolate the low color # nibble
        call    BinToHexDigit   ;convert the low nibble of the
                                ; color # to ASCII
        mov     [bx+1],al       ; and put it into the text
        add     bx,COLOR_ENTRY_LENGTH       ;point to the next entry
        pop     ax              ;get back the color #
        inc     ax              ;next color #
        loop    ColorNumberLoop
        mov     ah,9            ;DOS print string function
        mov     dx,offset ColorNumbers
        int     21h             ;put up the attribute numbers
        ret
ColorNumbersUp  endp
;
Start   endp
Code    ends
        end     Start
```

Overscan

While we're at it, I'm going to touch on overscan. Overscan is the color of the border of the display, the rectangular area around the edge of the monitor that's outside the region displaying active video data but inside the blanking area. The overscan (or border) color can be programmed to any of the 64 possible colors by either setting Attribute Controller register 11H directly or calling video function 10H, subfunction 1.

On ECD-compatible monitors, however, there's too little scan time to display a proper border when the EGA is in 350-scan-line mode, so overscan should always be 0 (black) unless you're in 200-scan-line mode. Note, though, that a VGA can easily display a border on a VGA-compatible monitor, and VGAs are in fact programmed at mode set for an 8-pixel-wide border in all modes; all you need do is set the overscan color on any VGA to see the border.

A Bonus Blanker

An interesting bonus: The Attribute Controller provides a very convenient way to blank the screen, in the form of the aforementioned bit 5 of the Attribute Controller Index register (at address 3C0H after the Input Status 1 register—3DAH in color, 3BAH in monochrome—has been read and on every other write to 3C0H thereafter). Whenever bit 5 of the AC Index register is 0, video data is cut off, effectively blanking the screen. Setting bit 5 of the AC Index back to 1 restores video data immediately. Listing 7.4 illustrates this simple but effective form of screen blanking.

LISTING 7.4 L7-4.ASM

```
; Program to demonstrate screen blanking via bit 5 of the
; Attribute Controller Index register.
;
AC_INDEX          equ  3c0h       ;Attribute Controller Index register
INPUT_STATUS_1    equ  3dah       ;color-mode address of the Input
                                  ; Status 1 register
;
; Macro to wait for and clear the next keypress.
;
WAIT_KEY  macro
        mov     ah,8              ;DOS input without echo function
        int     21h
        endm
;
stack   segment para stack 'STACK'
        db      512 dup (?)
stack   ends
;
Data segment word 'DATA'
SampleText   db   'This is bit-mapped text, drawn in hi-res '
             db   'EGA graphics mode 10h.', 0dh, 0ah, 0ah
             db   'Press any key to blank the screen, then '
             db   'any key to unblank it,', 0dh, 0ah
             db   'then any key to end.$'
Data    ends
;
Code    segment
        assume  cs:Code, ds:Data
Start   proc    near
        mov     ax,Data
        mov     ds,ax
```

```
;
; Go to hi-res graphics mode.
;
        mov     ax,10h                  ;AH = 0 means mode set, AL = 10h selects
                                        ; hi-res graphics mode
        int     10h                     ;BIOS video interrupt
;
; Put up some text, so the screen isn't empty.
;
        mov     ah,9                    ;DOS print string function
        mov     dx,offset SampleText
        int     21h
;
        WAIT_KEY
;
; Blank the screen.
;
        mov     dx,INPUT_STATUS_1
        in       al,dx                ;reset port 3c0h to index (rather than data)
                                      ; mode
        mov     dx,AC_INDEX
        sub     al,al                 ;make bit 5 zero...
        out     dx,al                 ;...which blanks the screen
;
        WAIT_KEY
;
; Unblank the screen.
;
        mov     dx,INPUT_STATUS_1
        in       al,dx                ;reset port 3c0h to Index (rather than data)
                                      ; mode
        mov     dx,AC_INDEX
        mov     al,20h                ;make bit 5 one...
        out     dx,al                 ;...which unblanks the screen
;
        WAIT_KEY
;
; Restore text mode.
;
        mov     ax,2
        int     10h
;
; Done.
;
Done:
        mov     ah,4ch                ;DOS terminate function
        int     21h
Start           endp
Code            ends
        end     Start
```

Does that do it for color selection? Yes and no. For the EGA, we've covered the whole of color selection—but not so for the VGA. The VGA can emulate everything we've discussed, but actually performs one 4-bit to 8-bit translation (except in 256-color modes, where all 256 colors are simultaneously available), followed by yet another translation, this one 8-bit to 18-bit. What's more, the VGA has the ability to flip instantly through as many as sixteen 16-color sets. The VGA's color selection capabilities, which are supported by another set of BIOS functions, can be used to produce stunning color effects, as we'll see when we cover them starting in Chapter 11.

Modifying VGA Registers

EGA registers are not readable. VGA registers are readable. This revelation will not come as news to most of you, but many programmers still insist on setting entire VGA registers even when they're modifying only selected bits, as if they were programming the EGA. This comes to mind because I recently received a query inquiring why write mode 1 (in which the contents of the latches are copied directly to display memory) didn't work in Mode X. (I'll go into Mode X in detail later in this book.) Actually, write mode 1 does work in Mode X; it didn't work when this particular correspondent enabled it because he did so by writing the value 01H to the Graphics Mode register. As it happens, the write mode field is only one of several fields in that register, as shown in Figure 7.4. In 256-color modes, one of the other fields—bit 6, which enables 256-color pixel formatting—is not 0, and setting it to 0 messes up the screen quite thoroughly.

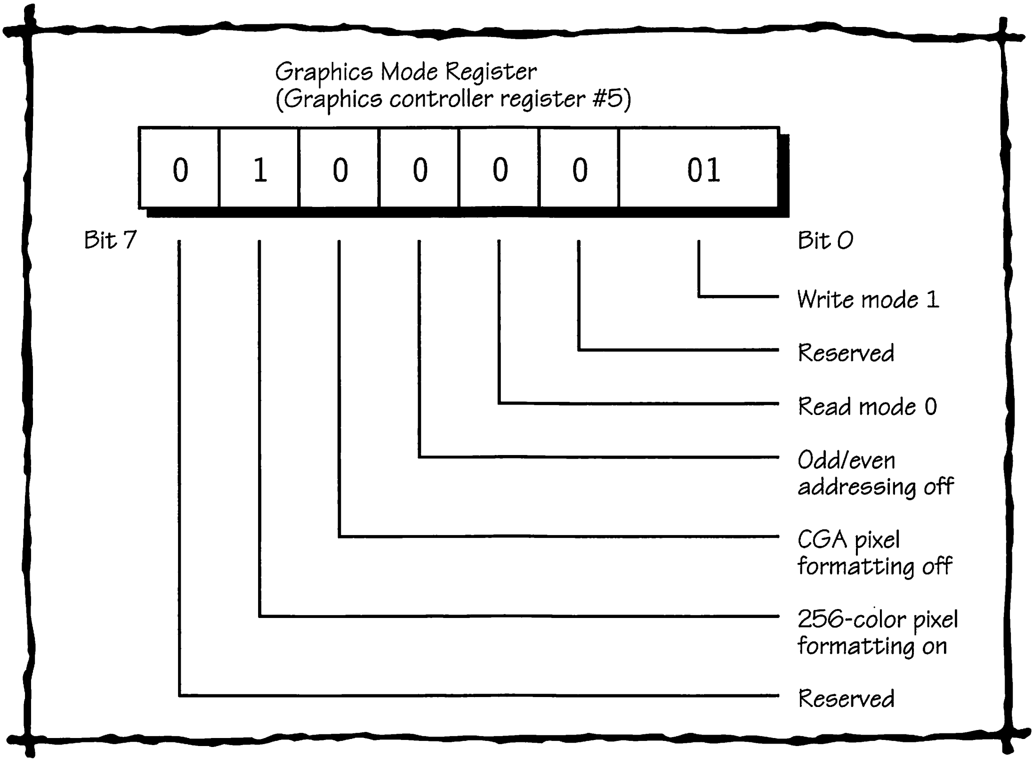


Figure 7.4 Graphics Mode Register Fields

The correct way to set a field within a VGA register is, of course, to read the register, mask off the desired field, insert the desired setting, and write the result back to the register. In the case of setting the VGA to write mode 1, do this:

```
mov  dx,3ceh          ;Graphics controller index
mov  al,5             ;Graphics mode reg index
out  dx,al            ;point GC index to G_MODE
inc  dx               ;Graphics controller data
in   al,dx            ;get current mode setting
and  al,not 3            ;mask off write mode field
or   al,1             ;set write mode field to 1
out  dx,al            ;set write mode 1
```

This approach is more of a nuisance than simply setting the whole register, but it's safer. It's also slower; for cases where you must set a field repeatedly, it might be worthwhile to read and mask the register once at the start, and save it in a variable, so that the value is readily available in memory and need not be repeatedly read from the port. This approach is especially attractive because **IN**s are much slower than memory accesses on 386 and 486 machines.

Astute readers may wonder why I didn't put a delay sequence, such as **JMP $+2**, between the **IN** and **OUT** involving the same register. There are, after all, guidelines from IBM, specifying that a certain period should be allowed to elapse before a second access to an I/O port is attempted, because not all devices can respond as rapidly as a 286 or faster CPU can access a port. My answer is that while I can't guarantee that a delay isn't needed, I've never found a VGA that required one; I suspect that the delay specification has more to do with motherboard chips such as the timer, the interrupt controller, and the like, and I sure hate to waste the delay time if it's not necessary. However, I've never been able to find anyone with the definitive word on whether delays might ever be needed when accessing VGAs, so if you know the gospel truth, or if you know of a VGA/processor combo that does require delays, please let me know by contacting me through the publisher. You'd be doing a favor for a whole generation of graphics programmers who aren't sure whether they're skating on thin ice without those legendary delays.

Video Est Omnis Divisa

Chapter 8

The Joys and Galling Problems of Using Split Screens on the EGA and VGA

The ability to split the screen into two largely independent portions—one displayed above the other on the screen—is one of the more intriguing capabilities of the VGA and EGA. The split screen feature can be used for popups (including popups that slide smoothly onto the screen), or simply to display two separate portions of display memory on a single screen. While it's possible to accomplish the same effects purely in software without using the split screen, software solutions tend to be slow and hard to implement.

By contrast, the basic operation of the split screen is fairly simple, once you grasp the various coding tricks required to pull it off, and understand the limitations and pitfalls—like the fact that the EGA's split screen implementation is a little buggy. Furthermore, panning with the split screen enabled is not as simple as it might seem. All in all, we do have some ground to cover.

Let's start with the basic operation of the split screen.

How the Split Screen Works

The *operation* of the split screen is simplicity itself. A split screen start scan line value is programmed into two EGA registers or three VGA registers. (More on exactly which registers in a moment.) At the beginning of each frame, the video circuitry begins to scan display memory for video data starting at the address specified by the start address registers, just as it normally would. When the video circuitry encounters the specified split screen start scan line in the course of scanning video data onto the screen, it completes that scan line normally, then resets the internal pointer which addresses the next byte of display memory to be read for video data to zero. Display memory from address zero onward is then scanned for video data in the usual way, progressing toward the high end of memory. At the end of the frame, the pointer to the next byte of display memory to scan is reloaded from the start address registers, and the whole process starts over.

The net effect: The contents of display memory starting at offset zero are displayed starting at the scan line following the specified split screen start scan line, as shown in Figure 8.1. It's important to understand that the scan line that matches the split screen scan line is *not* part of the split screen; the split screen starts on the *following* scan line. So, for example, if the split screen scan line is set to zero, the split screen actually starts at scan line 1, the second scan line from the top of the screen.

If both the start address and the split screen start scan line are set to 0, the data at offset zero in display memory is displayed as both the first scan line on the screen *and* the second scan line. There is no way to make the split screen cover the entire screen—it always comes up at least one scan line short.

So, where is the split screen start scan line stored? The answer varies a bit, depending on whether you're talking about the EGA or the VGA. On the EGA, the split screen start scan line is a 9-bit value, with bits 7-0 stored in the Line Compare register (CRTC register 18H) and bit 8 stored in bit 4 of the Overflow register (CRTC register 7). Other bits in the Overflow register serve as the high bits of other values, such as the vertical total and the vertical blanking start. Since EGA registers are—alas!—not readable,

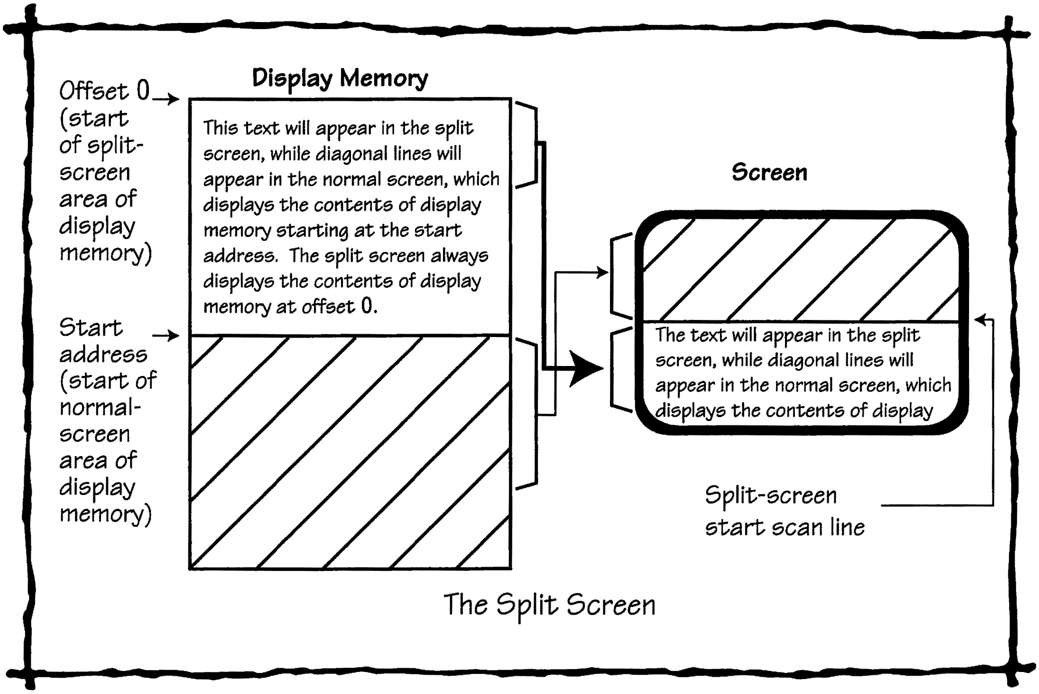

Offset 0 (start of split-screen area of display memory)
Display Memory
This text will appear in the split screen, while diagonal lines will appear in the normal screen, which displays the contents of display memory starting at the start address. The split screen always displays the contents of display memory at offset 0.
Start address (start of normal-screen area of display memory)
Screen
The text will appear in the split screen, while diagonal lines will appear in the normal screen, which displays the contents of display
Split-screen start scan line
The Split Screen

Figure 8.1 Display Memory and the Split Screen

you must know the correct settings for the other bits in the Overflow registers to use the split screen on an EGA. Fortunately, there are only two standard Overflow register settings on the EGA: 11H for 200-scan-line modes and 1FH for 350-scan-line modes.

The VGA, of course, presents no such problem in setting the split screen start scan line, for it has readable registers. However, the VGA supports a 10-bit split screen start scan line value, with bits 8-0 stored just as with the EGA, and bit 9 stored in bit 6 of the Maximum Scan Line register (CRTC register 9).

Turning the split screen on involves nothing more than setting all bits of the split screen start scan line to the scan line after which you want the split screen to start appearing. (Of course, you'll probably want to change the start address before using the split screen; otherwise, you'll just end up displaying the memory at offset zero *twice:* once in the normal screen and once in the split screen.) Turning off the split screen is a simple matter of setting the split screen start scan line to a value equal to or greater than the last scan line displayed; the safest such approach is to set all bits of the split screen start scan line to 1. (That is, in fact, the split screen start scan line value programmed by the BIOS during a mode set.)

The Split Screen in Action

All of the above points are illustrated by Listing 8.1. Listing 8.1 fills display memory starting at offset zero (the split screen area of memory) with text identifying the split screen, fills display memory starting at offset 8000H with a graphics pattern, and sets the start address to 8000H. At this point, the normal screen is being displayed (the split screen start scan line is still set to the BIOS default setting, with all bits equal to 1, so the split screen is off), with the pixels based on the contents of display memory at offset 8000H. The contents of display memory between offset 0 and offset 7FFFH are not visible at all.

Listing 8.1 then slides the split screen up from the bottom of the screen, one scan line at a time. The split screen slides halfway up the screen, bounces down a quarter of the screen, advances another half-screen, drops another quarter-screen, and finally slides all the way up to the top. If you've never seen the split screen in action, you should run Listing 8.1; the smooth overlapping of the split screen on top of the normal display is a striking effect.

Listing 8.1 isn't done just yet, however. After a keypress, Listing 8.1 demonstrates how to turn the split screen off (by setting all bits of the split screen start scan line to 1). After another keypress, Listing 8.1 shows that the split screen can never cover the whole screen, by setting the start address to 0 and then flipping back and forth between the normal screen and the split screen with a split screen start scan line setting of zero. Both the normal screen and the split screen display the same text, but the split screen displays it one scan line lower, because the split screen doesn't start until *after* the first scan line, and that produces a jittering effect as the program switches the split screen on and off. (On the EGA, the split screen may display *two* scan lines lower, for reasons I'll discuss shortly.)

Finally, after another keypress, Listing 8.1 halts.

LISTING 8.1 L8-1.ASM

```
; Demonstrates the VGA/EGA split screen in action.
;
;******************************************************************
IS_VGA              equ  1    ;set to 0 to assemble for EGA
;
VGA_SEGMENT         equ  0a000h
SCREEN_WIDTH        equ  640
SCREEN_HEIGHT       equ  350
CRTC_INDEX          equ  3d4h ;CRT Controller Index register
OVERFLOW            equ  7    ;index of Overflow reg in CRTC
MAXIMUM_SCAN_LINE   equ  9    ;index of Maximum Scan Line register
                              ; in CRTC
START_ADDRESS_HIGH  equ  0ch  ;index of Start Address High register
                              ; in CRTC
START_ADDRESS_LOW   equ  0dh  ;index of Start Address Low register
                              ; in CRTC
LINE_COMPARE        equ  18h  ;index of Line Compare reg (bits 7-0
                              ; of split screen start scan line)
                              ; in CRTC
INPUT_STATUS_0      equ  3dah ;Input Status 0 register
WORD_OUTS_OK        equ  1    ;set to 0 to assemble for
                              ; computers that can't handle
                              ; word outs to indexed VGA registers
;******************************************************************
; Macro to output a word value to a port.
;
OUT_WORD       macro
if WORD_OUTS_OK
        out    dx,ax
else
        out         dx,al
        inc         dx
        xchg        ah,al
        out         dx,al
        dec         dx
        xchg        ah,al
endif
        endm
;******************************************************************
MyStack segment para stack 'STACK'
        db     512 dup (0)
MyStack ends
;******************************************************************
Data    segment
SplitScreenLine dw   ?        ;line the split screen currently
                              ; starts after
StartAddress    dw   ?        ;display memory offset at which
                              ; scanning for video data starts
; Message displayed in split screen.
SplitScreenMsg db   'Split screen text row #'
DigitInsert         dw   ?
                    db   '...$'
Data    ends
;******************************************************************
Code    segment
        assume cs:Code, ds:Data
;******************************************************************
Start   proc   near
```

```
        mov     ax,Data
        mov     ds,ax
;
; Select mode 10h, 640x350 16-color graphics mode.
;
        mov     ax,0010h                ;AH=0 is select mode function
                                        ;AL=10h is mode to select,
                                        ; 640x350 16-color graphics mode
        int     10h
;
; Put text into display memory starting at offset 0, with each row
; labelled as to number. This is the part of memory that will be
; displayed in the split screen portion of the display.
;
        mov     cx,25                   ;# of lines of text we'll draw into
                                        ; the split screen part of memory
FillSplitScreenLoop:
        mov     ah,2                    ;set cursor location function #
        sub     bh,bh                   ;set cursor in page 0
        mov     dh,25
        sub     dh,cl                   ;calculate row to draw in
        sub     dl,dl                   ;start in column 0
        int     10h                     ;set the cursor location
        mov     al,25
        sub     al,cl                   ;calculate row to draw in again
        sub     ah,ah                   ;make the value a word for division
        mov     dh,10
        div     dh                      ;split the row # into two digits
        add     ax,'00'                 ;convert the digits to ASCII
        mov     [DigitInsert],ax        ;put the digits into the text
                                        ; to be displayed
        mov     ah,9
        mov     dx,offset SplitScreenMsg
        int     21h                     ;print the text
        loop    FillSplitScreenLoop
;
; Fill display memory starting at 8000h with a diagonally striped
; pattern.
;
        mov     ax,VGA_SEGMENT
        mov     es,ax
        mov     di,8000h
        mov     dx,SCREEN_HEIGHT        ;fill all lines
        mov     ax,8888h                ;starting fill pattern
        cld
RowLoop:
        mov     cx,SCREEN_WIDTH/8/2     ;fill 1 scan line a word at a time
        rep     stosw                   ;fill the scan line
        ror     ax,1                    ;shift pattern word
        dec     dx
        jnz     RowLoop
;
; Set the start address to 8000h and display that part of memory.
;
        mov     [StartAddress],8000h
        call    SetStartAddress
;
; Slide the split screen half way up the screen and then back down
; a quarter of the screen.
;
        mov     [SplitScreenLine],SCREEN_HEIGHT-1
```

```
                                          ;set the initial line just off
                                          ; the bottom of the screen
        mov     cx,SCREEN_HEIGHT/2
        call    SplitScreenUp
        mov     cx,SCREEN_HEIGHT/4
        call    SplitScreenDown
;
; Now move up another half a screen and then back down a quarter.
;
        mov     cx,SCREEN_HEIGHT/2
        call    SplitScreenUp
        mov     cx,SCREEN_HEIGHT/4
        call    SplitScreenDown
;
; Finally move up to the top of the screen.
;
        mov     cx,SCREEN_HEIGHT/2-2
        call    SplitScreenUp
;
; Wait for a key press (don't echo character).
;
        mov     ah,8                     ;DOS console input without echo function
        int     21h
;
; Turn the split screen off.
;
        mov     [SplitScreenLine],0ffffh
        call    SetSplitScreenScanLine
;
; Wait for a key press (don't echo character).
;
        mov     ah,8                     ;DOS console input without echo function
        int     21h
;
; Display the memory at 0 (the same memory the split screen displays).
;
        mov     [StartAddress],0
        call    SetStartAddress
;
; Flip between the split screen and the normal screen every 10th
; frame until a key is pressed.
;
FlipLoop:
        xor     [SplitScreenLine],0ffffh
        call    SetSplitScreenScanLine
        mov     cx,10
CountVerticalSyncsLoop:
        call    WaitForVerticalSyncEnd
        loop    CountVerticalSyncsLoop
        mov     ah,0bh                    ;DOS character available status
        int     21h
        and     al,al;character available?
        jz      FlipLoop                 ;no, toggle split screen on/off status
        mov     ah,1
        int     21h                       ;clear the character
;
; Return to text mode and DOS.
;
        mov     ax,0003h                  ;AH=0 is select mode function
                                          ;AL=3 is mode to select, text mode
        int     10h                        ;return to text mode
        mov     ah,4ch
        int     21h                        ;return to DOS
Start   endp
;***********************************************************************
; Waits for the leading edge of the vertical sync pulse.
;
; Input: none
;
; Output: none
;
; Registers altered: AL, DX
;
WaitForVerticalSyncStart  proc near
        mov     dx,INPUT_STATUS_0
WaitNotVerticalSync:
        in      al,dx
        test    al,08h
        jnz     WaitNotVerticalSync
WaitVerticalSync:
        in      al,dx
        test    al,08h
        jz      WaitVerticalSync
        ret
WaitForVerticalSyncStart  endp
;***********************************************************************
; Waits for the trailing edge of the vertical sync pulse.
;
; Input: none
;
; Output: none
;
; Registers altered: AL, DX
;
WaitForVerticalSyncEnd    proc near
        mov     dx,INPUT_STATUS_0
WaitVerticalSync2:
        in      al,dx
        test    al,08h
        jz      WaitVerticalSync2
WaitNotVerticalSync2:
        in      al,dx
        test    al,08h
        jnz     WaitNotVerticalSync2
        ret
WaitForVerticalSyncEnd    endp
;***********************************************************************
; Sets the start address to the value specifed by StartAddress.
; Wait for the trailing edge of vertical sync before setting so that
; one half of the address isn't loaded before the start of the frame
; and the other half after, resulting in flicker as one frame is
; displayed with mismatched halves. The new start address won't be
; loaded until the start of the next frame; that is, one full frame
; will be displayed before the new start address takes effect.
;
; Input: none
;
; Output: none
;
; Registers altered: AX, DX
;
```

```
SetStartAddress proc near
        call    WaitForVerticalSyncEnd
        mov     dx,CRTC_INDEX
        mov     al,START_ADDRESS_HIGH
        mov     ah,byte ptr [StartAddress+1]
        cli                     ;make sure both registers get set at once
        OUT_WORD
        mov     al,START_ADDRESS_LOW
        mov     ah,byte ptr [StartAddress]
        OUT_WORD
        sti
        ret
SetStartAddress endp
;*********************************************************************
; Sets the scan line the split screen starts after to the scan line
; specified by SplitScreenLine.
;
; Input: none
;
; Output: none
;
; All registers preserved
;
SetSplitScreenScanLine    proc near
        push    ax
        push    cx
        push    dx
;
; Wait for the leading edge of the vertical sync pulse. This ensures
; that we don't get mismatched portions of the split screen setting
; while setting the two or three split screen registers (register 18h
; set but register 7 not yet set when a match occurs, for example),
; which could produce brief flickering.
;
        call    WaitForVerticalSyncStart
;
; Set the split screen scan line.
;
        mov     dx,CRTC_INDEX
        mov     ah,byte ptr [SplitScreenLine]
        mov     al,LINE_COMPARE
        cli                     ;make sure all the registers get set at once
        OUT_WORD                ;set bits 7-0 of the split screen scan line
        mov     ah,byte ptr [SplitScreenLine+1]
        and     ah,1
        mov     cl,4
        shl     ah,cl           ;move bit 8 of the split split screen scan
                                ; line into position for the Overflow reg
        mov     al,OVERFLOW
if IS_VGA
;
; The Split Screen, Overflow, and Line Compare registers all contain
; part of the split screen start scan line on the VGA. We'll take
; advantage of the readable registers of the VGA to leave other bits
; in the registers we access undisturbed.
;
        out     dx,al           ;set CRTC Index reg to point to Overflow
        inc     dx              ;point to CRTC Data reg
        in      al,dx           ;get the current Overflow reg setting
        and     al,not 10h      ;turn off split screen bit 8
        or      al,ah           ;insert the new split screen bit 8
                                ; (works in any mode)
        out     dx,al           ;set the new split screen bit 8
        dec     dx              ;point to CRTC Index reg
        mov     ah,byte ptr [SplitScreenLine+1]
        and     ah,2
        mov     cl,3
        ror     ah,cl           ;move bit 9 of the split split screen scan
                                ; line into position for the Maximum Scan
                                ; Line register
        mov     al,MAXIMUM_SCAN_LINE
        out     dx,al           ;set CRTC Index reg to point to Maximum
                                ; Scan Line
        inc     dx              ;point to CRTC Data reg
        in      al,dx           ;get the current Maximum Scan Line setting
        and     al,not 40h      ;turn off split screen bit 9
        or      al,ah           ;insert the new split screen bit 9
                                ; (works in any mode)
        out     dx,al           ;set the new split screen bit 9
else
;
; Only the Split Screen and Overflow registers contain part of the
; Split Screen start scan line and need to be set on the EGA.
; EGA registers are not readable, so we have to set the non-split
; screen bits of the Overflow register to a preset value, in this
; case the value for 350-scan-line modes.
;
        or      ah,0fh          ;insert the new split screen bit 8
                                ; (only works in 350-scan-line EGA modes)
        OUT_WORD                ;set the new split screen bit 8
endif
        sti
        pop     dx
        pop     cx
        pop     ax
        ret
SetSplitScreenScanLine    endp
;*********************************************************************
; Moves the split screen up the specified number of scan lines.
;
; Input: CX = # of scan lines to move the split screen up by
;
; Output: none
;
; Registers altered: CX
;
SplitScreenUp   proc near
SplitScreenUpLoop:
        dec     [SplitScreenLine]
        call    SetSplitScreenScanLine
        loop    SplitScreenUpLoop
        ret
SplitScreenUp   endp
;*********************************************************************
; Moves the split screen down the specified number of scan lines.
;
; Input: CX = # of scan lines to move the split screen down by
;
; Output: none
;
```

```
; Registers altered: CX
;
SplitScreenDown proc near
SplitScreenDownLoop:
        inc     [SplitScreenLine]
        call    SetSplitScreenScanLine
        loop    SplitScreenDownLoop
        ret
SplitScreenDown endp
;*****************************************************************
Code    ends
        end     Start
```

VGA and EGA Split-Screen Operation Don't Mix

You must set the **IS_VGA** equate at the start of Listing 8.1 correctly for the adapter the code will run on in order for the program to perform properly. This equate determines how the upper bits of the split screen start scan line are set by **SetSplitScreenRow**. If **IS_VGA** is 0 (specifying an EGA target), then bit 8 of the split screen start scan line is set by programming the entire Overflow register to 1FH; this is hard-wired for the 350-scan-line modes of the EGA. If **IS_VGA** is 1 (specifying a VGA target), then bits 8 and 9 of the split screen start scan line are set by reading the registers they reside in, changing only the split-screen-related bits, and writing the modified settings back to their respective registers.

The VGA version of Listing 8.1 won't work on an EGA, because EGA registers aren't readable. The EGA version of Listing 8.1 won't work on a VGA, both because VGA monitors require different vertical settings than EGA monitors and because the EGA version doesn't set bit 9 of the split screen start scan line. In short, there is no way that I know of to support both VGA and EGA split screens with common code; separate drivers are required. This is one of the reasons that split screens are so rarely used in PC programming.

By the way, Listing 8.1 operates in mode 10H because that's the highest-resolution mode the VGA and EGA share. That's not the only mode the split screen works in, however. In fact, it works in *all* modes, as we'll see later.

Setting the Split-Screen-Related Registers

Setting the split-screen-related registers is not as simple a matter as merely outputting the right values to the right registers; timing is also important. The split screen start scan line value is checked against the number of each scan line as that scan line is displayed, which means that the split screen start scan line potentially takes effect the moment it is set. In other words, if the screen is displaying scan line 15 and you set the split screen start to 16, that change will be picked up immediately and the split screen will start after the next scan line. This is markedly different from changes to the start address, which take effect only at the start of the next frame.

The instantly-effective nature of the split screen is a bit of a problem, not because the changed screen appears as soon as the new split screen start scan line is set—that seems to me to be an advantage—but because the changed screen can appear *before* the new split screen start scan line is set.

Remember, the split screen start scan line is spread out over two or three registers. What if the incompletely-changed value matches the current scan line after you've set one register but before you've set the rest? For one frame, you'll see the split screen in a wrong place—possibly a very wrong place—resulting in jumping and flicker.

The solution is simple: Set the split screen start scan line at a time when it can't possibly match the currently displayed scan line. The easy way to do that is to set it when there isn't any currently displayed scan line—during vertical non-display time. One safe time that's easy to find is the start of the vertical sync pulse, which is typically pretty near the middle of vertical non-display time, and that's the approach I've followed in Listing 8.1. I've also disabled interrupts during the period when the split screen registers are being set. This isn't absolutely necessary, but if it's not done, there's the possibility that an interrupt will occur between register sets and delay the later register sets until display time, again causing flicker.

One interesting effect of setting the split screen registers at the start of vertical sync is that it has the effect of synchronizing the program to the display adapter's frame rate. No matter how fast the computer running Listing 8.1 may be, the split screen will move at a maximum rate of once per frame. This is handy for regulating execution speed over a wide variety of hardware performance ranges; however, be aware that the VGA supports 70 Hz frame rates in all non-480-scan-line modes, while the VGA in 480-scan-line-modes and the EGA in all color modes support 60 Hz frame rates.

The Problem with the EGA Split Screen

I mentioned earlier that the EGA's split screen is a little buggy. How? you may well ask, particularly given that Listing 8.1 illustrates that the EGA split screen seems pretty functional.

The bug is this: The first scan line of the EGA split screen—the scan line starting at offset zero in display memory—is displayed not once but twice. In other words, the first line of split screen display memory, and only the first line, is replicated one unnecessary time, pushing all the other lines down by one.

That's not a fatal bug, of course. In fact, if the first few scan lines are identical, it's not even noticeable. The EGA's split-screen bug can produce visible distortion given certain patterns, however, so you should try to make the top few lines identical (if possible) when designing split-screen images that might be displayed on EGAs, and you should in any case check how your split-screens look on both VGAs and EGAs.

I have an important caution here: Don't count on the EGA's split-screen bug; that is, don't rely on the first scan line being doubled when you design your split screens. IBM designed and made the original EGA, but a lot of companies cloned it, and there's no guarantee that all EGA clones copy the bug. It is a certainty, at least, that the VGA didn't copy it.

There's another respect in which the EGA is inferior to the VGA when it comes to the split screen, and that's in the area of panning when the split screen is on. This isn't a bug—it's just one of the many areas in which the VGA's designers learned from the shortcomings of the EGA and went the EGA one better.

Split Screen and Panning

Back in Chapter 1, I presented a program that performed smooth horizontal panning. Smooth horizontal panning consists of two parts: Byte-by-byte (8-pixel) panning by changing the start address, and pixel-by-pixel intrabyte panning by setting the Pel Panning register (AC register 13H) to adjust alignment by 0 to 7 pixels. (IBM prefers its own jargon and uses the word "pel" instead of "pixel" in much of their documentation, hence "pel panning." Then there's DASD, a.k.a. Direct Access Storage Device—IBM-speak for hard disk.)

Horizontal smooth panning works just fine, although I've always harbored some doubts that any one horizontal-smooth-panning approach works properly on all display board clones. (More on this later.) There's a catch when using horizontal smooth panning with the split screen up, though, and it's a serious catch: You can't byte-pan the split screen (which always starts at offset zero, no matter what the setting of the start address registers)—but you *can* pel-pan the split screen.

Put another way, when the normal portion of the screen is horizontally smooth-panned, the split screen portion moves a pixel at a time until it's time to move to the next byte, then jumps back to the start of the current byte. As the top part of the screen moves smoothly about, the split screen will move and jump, move and jump, over and over.

Believe me, it's not a pretty sight.

What's to be done? On the EGA, nothing. Unless you're willing to have your users' eyes doing the jitterbug, don't use horizontal smooth scrolling while the split screen is up. Byte panning is fine—just don't change the Pel Panning register from its default setting.

On the VGA, there is recourse. A VGA-only bit, bit 5 of the AC Mode Control register (AC register 10H), turns off pel panning in the split screen. In other words, when this bit is set to 1, pel panning is reset to zero before the first line of the split screen, and remains zero until the end of the frame. This doesn't allow you to pan the split screen horizontally, mind you—there's no way to do that—but it does let you pan the normal screen while the split screen stays rock-solid. This can be used to produce an attractive "streaming tape" effect in the normal screen while the split screen is used to display non-moving information.

The Split Screen and Horizontal Panning: An Example

Listing 8.2 illustrates the interaction of horizontal smooth panning with the split screen, as well as the suppression of pel panning in the split screen. Listing 8.2 creates a virtual screen 1024 pixels across by setting the Offset register (CRTC register 13H) to 64, sets the normal screen to scan video data beginning far enough up in display memory to leave room for the split screen starting at offset zero, turns on the split screen, and fills in the normal screen and split screen with distinctive patterns. Next, Listing 8.2 pans the normal screen horizontally without setting bit 5 of the AC Mode Control register to 1. As you'd expect, the split screen jerks about quite horribly. After a key press, Listing 8.2 sets bit 5 of the Mode Control register and pans the normal screen again. This time, the split screen doesn't budge an inch—*if* the code is running on a VGA.

By the way, if **IS_VGA** is set to 0 in Listing 8.2, the program will assemble in a form that will run on the EGA and *only* the EGA. Pel panning suppression in the split screen won't work in this version, however, because the EGA lacks the capability to support that feature. When the EGA version runs, the split screen simply jerks back and forth during both panning sessions.

LISTING 8.2 L8-2.ASM

```
; Demonstrates the interaction of the split screen and
; horizontal pel panning. On a VGA, first pans right in the top
; half while the split screen jerks around, because split screen
; pel panning suppression is disabled, then enables split screen
; pel panning suppression and pans right in the top half while the
; split screen remains stable. On an EGA, the split screen jerks
; around in both cases, because the EGA doesn't support split
; screen pel panning suppression.
;
; The jerking in the split screen occurs because the split screen
; is being pel panned (panned by single pixels--intrabyte panning),
; but is not and cannot be byte panned (panned by single bytes--
; "extrabyte" panning) because the start address of the split screen
; is forever fixed at 0.
;*********************************************************************
IS_VGA              equ  1          ;set to 0 to assemble for EGA
;
VGA_SEGMENT         equ  0a000h
LOGICAL_SCREEN_WIDTH equ 1024       ;# of pixels across virtual
                                    ; screen that we'll pan across
SCREEN_HEIGHT       equ  350
SPLIT_SCREEN_START  equ  200        ;start scan line for split screen
```

```
SPLIT_SCREEN_HEIGHT     equ     SCREEN_HEIGHT-SPLIT_SCREEN_START-1
CRTC_INDEX              equ     3d4h      ;CRT Controller Index register
AC_INDEX                equ     3c0h      ;Attribute Controller Index reg
OVERFLOW                equ     7         ;index of Overflow reg in CRTC
MAXIMUM_SCAN_LINE       equ     9         ;index of Maximum Scan Line register
                                          ; in CRTC
START_ADDRESS_HIGH      equ     0ch       ;index of Start Address High register
                                          ; in CRTC
START_ADDRESS_LOW       equ     0dh       ;index of Start Address Low register
                                          ; in CRTC
HOFFSET                 equ     13h       ;index of Horizontal Offset register
                                          ; in CRTC
LINE_COMPARE            equ     18h       ;index of Line Compare reg (bits 7-0
                                          ; of split screen start scan line)
                                          ; in CRTC
AC_MODE_CONTROL         equ     10h       ;index of Mode Control reg in AC
PEL_PANNING             equ     13h       ;index of Pel Panning reg in AC
INPUT_STATUS_0          equ     3dah      ;Input Status 0 register
WORD_OUTS_OK            equ     1         ;set to 0 to assemble for
                                          ; computers that can't handle
                                          ; word outs to indexed VGA registers
;**********************************************************************
; Macro to output a word value to a port.
;
OUT_WORD             macro
if WORD_OUTS_OK
        out          dx,ax
else
        out          dx,al
        inc          dx
        xchg         ah,al
        out          dx,al
        dec          dx
        xchg         ah,al
endif
        endm
;**********************************************************************
MyStack segment para stack 'STACK'
        db      512 dup (0)
MyStack ends
;**********************************************************************
Data    segment
SplitScreenLine      dw   ?         ;line the split screen currently
                                    ; starts after
StartAddress         dw   ?         ;display memory offset at which
                                    ; scanning for video data starts
PelPan               db   ?         ;current intrabyte horizontal pel
                                    ; panning setting
Data    ends
;**********************************************************************
Code    segment
        assume  cs:Code, ds:Data
;**********************************************************************
Start   proc    near
        mov     ax,Data
        mov     ds,ax
;
; Select mode 10h, 640x350 16-color graphics mode.
;
        mov     ax,0010h                  ;AH=0 is select mode function
                                          ;AL=10h is mode to select,
                                          ; 640x350 16-color graphics mode
        int     10h
;
; Set the Offset register to make the offset from the start of one
; scan line to the start of the next the desired number of pixels.
; This gives us a virtual screen wider than the actual screen to
; pan across.
; Note that the Offset register is programmed with the logical
; screen width in words, not bytes, hence the final division by 2.
;
        mov     dx,CRTC_INDEX
        mov     ax,(LOGICAL_SCREEN_WIDTH/8/2 shl 8) or HOFFSET
        OUT_WORD
;
; Set the start address to display the memory just past the split
; screen memory.
;
        mov     [StartAddress],SPLIT_SCREEN_HEIGHT*(LOGICAL_SCREEN_WIDTH/8)
        call    SetStartAddress
;
; Set the split screen start scan line.
;
        mov     [SplitScreenLine],SPLIT_SCREEN_START
        call    SetSplitScreenScanLine
;
; Fill the split screen portion of display memory (starting at
; offset 0) with a choppy diagonal pattern sloping left.
;
        mov     ax,VGA_SEGMENT
        mov     es,ax
        sub     di,di
        mov     dx,SPLIT_SCREEN_HEIGHT
                                    ;fill all lines in the split screen
        mov     ax,0FF0h            ;starting fill pattern
        cld
RowLoop:
        mov     cx,LOGICAL_SCREEN_WIDTH/8/4
                                    ;fill 1 scan line
ColumnLoop:
        stosw                       ;draw part of a diagonal line
        mov     word ptr es:[di],0  ;make vertical blank spaces so
                                    ; panning effects can be seen easily
        inc     di
        inc     di
        loop    ColumnLoop
        rol     ax,1                ;shift pattern word
        dec     dx
        jnz     RowLoop
;
; Fill the portion of display memory that will be displayed in the
; normal screen (the non-split screen part of the display) with a
; choppy diagonal pattern sloping right.
;
        mov     di,SPLIT_SCREEN_HEIGHT*(LOGICAL_SCREEN_WIDTH/8)
        mov     dx,SCREEN_HEIGHT    ;fill all lines
        mov     ax,0c510h           ;starting fill pattern
        cld
RowLoop2:
        mov     cx,LOGICAL_SCREEN_WIDTH/8/4
                                    ;fill 1 scan line
ColumnLoop2:
        stosw                       ;draw part of a diagonal line
        mov     word ptr es:[di],0        ;make vertical blank spaces so
                                          ; panning effects can be seen easily
        inc     di
        inc     di
        loop    ColumnLoop2
        ror     ax,1                      ;shift pattern word
        dec     dx
        jnz     RowLoop2
;
; Pel pan the non-split screen portion of the display; because
; split screen pel panning suppression is not turned on, the split
; screen jerks back and forth as the pel panning setting cycles.
;
        mov     cx,200                    ;pan 200 pixels to the left
        call    PanRight
;
; Wait for a key press (don't echo character).
;
        mov     ah,8                 ;DOS console input without echo function
        int     21h
;
; Return to the original screen location, with pel panning turned off.
;
        mov     [StartAddress],SPLIT_SCREEN_HEIGHT*(LOGICAL_SCREEN_WIDTH/8)
        call    SetStartAddress
        mov     [PelPan],0
        call    SetPelPan
;
; Turn on split screen pel panning suppression, so the split screen
; won't be affected by pel panning. Not done on EGA because both
; readable registers and the split screen pel panning suppression bit
; aren't supported by EGAs.
;
if IS_VGA
        mov     dx,INPUT_STATUS_0
        in      al,dx                     ;reset the AC Index/Data toggle to
                                          ; Index state
        mov     al,20h+AC_MODE_CONTROL
                                          ;bit 5 set to 1 to keep video on
        mov     dx,AC_INDEX               ;point to AC Index/Data register
        out     dx,al
        inc     dx                   ;point to AC Data reg (for reads only)
        in      al,dx                     ;get the current AC Mode Control reg
        or      al,20h                    ;enable split screen pel panning
                                          ; suppression
        dec     dx                        ;point to AC Index/Data reg (Data for
                                          ; writes only)
        out     dx,al                ;write the new AC Mode Control setting
                                          ; with split screen pel panning
                                          ; suppression turned on
endif
;
; Pel pan the non-split screen portion of the display; because
; split screen pel panning suppression is turned on, the split
; screen will not move as the pel panning setting cycles.
;
        mov     cx,200                    ;pan 200 pixels to the left
        call    PanRight
;
; Wait for a key press (don't echo character).
;
```

```
        mov     ah,8                   ;DOS console input without echo function
        int     21h
;
; Return to text mode and DOS.
;
        mov     ax,0003h                    ;AH=0 is select mode function
                                            ;AL=3 is mode to select, text mode
        int     10h                         ;return to text mode
        mov     ah,4ch
        int     21h                         ;return to DOS
Start   endp
;*******************************************************************
; Waits for the leading edge of the vertical sync pulse.
;
; Input: none
;
; Output: none
;
; Registers altered: AL, DX
;
WaitForVerticalSyncStart  proc near
        mov     dx,INPUT_STATUS_0
WaitNotVerticalSync:
        in      al,dx
        test    al,08h
        jnz     WaitNotVerticalSync
WaitVerticalSync:
        in      al,dx
        test    al,08h
        jz      WaitVerticalSync
        ret
WaitForVerticalSyncStart  endp
;*******************************************************************
; Waits for the trailing edge of the vertical sync pulse.
;
; Input: none
;
; Output: none
;
; Registers altered: AL, DX
;
WaitForVerticalSyncEnd    proc near
        mov     dx,INPUT_STATUS_0
WaitVerticalSync2:
        in      al,dx
        test    al,08h
        jz      WaitVerticalSync2
WaitNotVerticalSync2:
        in      al,dx
        test    al,08h
        jnz     WaitNotVerticalSync2
        ret
WaitForVerticalSyncEnd    endp
;*******************************************************************
; Sets the start address to the value specifed by StartAddress.
; Wait for the trailing edge of vertical sync before setting so that
; one half of the address isn't loaded before the start of the frame
; and the other half after, resulting in flicker as one frame is
; displayed with mismatched halves. The new start address won't be
; loaded until the start of the next frame; that is, one full frame
; will be displayed before the new start address takes effect.
```

```
;
; Input: none
;
; Output: none
;
; Registers altered: AX, DX
;
SetStartAddress proc near
        call    WaitForVerticalSyncEnd
        mov     dx,CRTC_INDEX
        mov     al,START_ADDRESS_HIGH
        mov     ah,byte ptr [StartAddress+1]
        cli                             ;make sure both registers get set at once
        OUT_WORD
        mov     al,START_ADDRESS_LOW
        mov     ah,byte ptr [StartAddress]
        OUT_WORD
        sti
        ret
SetStartAddress endp
;*********************************************************************
; Sets the horizontal pel panning setting to the value specified
; by PelPan. Waits until the start of vertical sync to do so, so
; the new pel pan setting can be loaded during non-display time
; and can be ready by the start of the next frame.
;
; Input: none
;
; Output: none
;
; Registers altered: AL, DX
;
SetPelPan       proc near
        call    WaitForVerticalSyncStart  ;also resets the AC
                                          ; Index/Data toggle
                                          ; to Index state
        mov     dx,AC_INDEX
        mov     al,PEL_PANNING+20h        ;bit 5 set to 1 to keep video on
        out     dx,al                     ;point the AC Index to Pel Pan reg
        mov     al,[PelPan]
        out     dx,al                     ;load the new Pel Pan setting
        ret
SetPelPan       endp
;*********************************************************************
; Sets the scan line the split screen starts after to the scan line
; specified by SplitScreenLine.
;
; Input: none
;
; Output: none
;
; All registers preserved
;
SetSplitScreenScanLine    proc near
        push    ax
        push    cx
        push    dx
;
; Wait for the leading edge of the vertical sync pulse. This ensures
; that we don't get mismatched portions of the split screen setting
; while setting the two or three split screen registers (register 18h
; set but register 7 not yet set when a match occurs, for example),
; which could produce brief flickering.
;
        call    WaitForVerticalSyncStart
;
; Set the split screen scan line.
;
        mov     dx,CRTC_INDEX
        mov     ah,byte ptr [SplitScreenLine]
        mov     al,LINE_COMPARE
        cli                     ;make sure all the registers get set at once
        OUT_WORD                ;set bits 7-0 of the split screen scan line
        mov     ah,byte ptr [SplitScreenLine+1]
        and     ah,1
        mov     cl,4
        shl     ah,cl                ;move bit 8 of the split split screen scan
                                     ; line into position for the Overflow reg
        mov     al,OVERFLOW
if IS_VGA
;
; The Split Screen, Overflow, and Line Compare registers all contain
; part of the split screen start scan line on the VGA. We'll take
; advantage of the readable registers of the VGA to leave other bits
; in the registers we access undisturbed.
;
        out     dx,al                ;set CRTC Index reg to point to Overflow
        inc     dx                   ;point to CRTC Data reg
        in      al,dx                ;get the current Overflow reg setting
        and     al,not 10h           ;turn off split screen bit 8
        or      al,ah                ;insert the new split screen bit 8
                                     ; (works in any mode)
        out     dx,al                ;set the new split screen bit 8
        dec     dx                   ;point to CRTC Index reg
        mov     ah,byte ptr [SplitScreenLine+1]
        and     ah,2
        mov     cl,3
        ror     ah,cl                ;move bit 9 of the split split screen scan
                                     ; line into position for the Maximum Scan
                                     ; Line register
        mov     al,MAXIMUM_SCAN_LINE
        out     dx,al                ;set CRTC Index reg to point to Maximum
                                     ; Scan Line
        inc     dx                   ;point to CRTC Data reg
        in      al,dx                ;get the current Maximum Scan Line setting
        and     al,not 40h           ;turn off split screen bit 9
        or      al,ah                ;insert the new split screen bit 9
                                     ; (works in any mode)
        out     dx,al                ;set the new split screen bit 9
else
;
; Only the Split Screen and Overflow registers contain part of the
; Split Screen start scan line and need to be set on the EGA.
; EGA registers are not readable, so we have to set the non-split
; screen bits of the Overflow register to a preset value, in this
; case the value for 350-scan-line modes.
;
        or      ah,0fh               ;insert the new split screen bit 8
                                     ; (only works in 350-scan-line EGA modes)
        OUT_WORD                     ;set the new split screen bit 8
endif
        sti
        pop     dx
        pop     cx
        pop     ax
        ret
SetSplitScreenScanLine    endp
;**********************************************************************
; Pan horizontally to the right the number of pixels specified by CX.
;
; Input: CX = # of pixels by which to pan horizontally
;
; Output: none
;
; Registers altered: AX, CX, DX
;
PanRight        proc near
PanLoop:
        inc     [PelPan]
        and     [PelPan],07h
        jnz     DoSetStartAddress
        inc     [StartAddress]
DoSetStartAddress:
        call    SetStartAddress
        call    SetPelPan
        loop    PanLoop
        ret
PanRight        endp
;**********************************************************************
Code    ends
        end     Start
```

Notes on Setting and Reading Registers

There are a few interesting points regarding setting and reading registers to be made about Listing 8.2. First, bit 5 of the AC Index register should be set to 1 whenever palette RAM is not being set (which is to say, all the time in your code, because palette RAM should normally be set via the BIOS). When bit 5 is 0, video data from display memory is no longer sent to palette RAM, and the screen becomes a solid color—not normally a desirable state of affairs.

Recall also that the AC Index and Data registers are both written to at I/O address 3C0H, with the toggle that determines which one is written to at any time switching state on every write to 3C0H; this toggle is reset to index mode by each read from the Input Status 0 register (3DAH in color modes, 3BAH in monochrome modes). The AC Index and Data registers can also be written to at 3C1H on the EGA, but not on the VGA, so steer clear of that practice.

On the VGA, reading AC registers is a bit different from writing to them. The AC Data register can be read from 3C0H, and the AC register currently addressed by the AC Index register can be read from 3C1H; reading does not affect the state of the AC index/data toggle. Listing 8.2 illustrates reading from and writing to the AC registers. Finally, setting the start address registers (CRTC registers 0CH and 0DH) has its complications. As with the split screen registers, the start address registers must be set together and without interruption at a time when there's no chance of a partial setting being used for a frame. However, it's a little more difficult to know when that might be the case with the start address registers than it was with the split screen registers, because it's not clear when the start address is used.

You see, the start address is loaded into the EGA's or VGA's internal display memory pointer once per frame. The internal pointer is then advanced, byte-by-byte and line-by-line, until the end of the frame (with a possible resetting to zero if the split screen line is reached), and is then reloaded for the next frame. That's straightforward enough; the real question is, *Exactly when is the start address loaded?*

In his excellent book *Programmer's Guide to PC Video Systems* (Microsoft Press) Richard Wilton says that the start address is loaded at the start of the vertical sync pulse. (Wilton calls it vertical retrace, which can also be taken to mean vertical non-display time, but given that he's testing the vertical sync status bit in the Input Status 0 register, I assume he means that the start address is loaded at the start of vertical sync.) Consequently, he waits until the *end* of the vertical sync pulse to set the start address registers, confident that the start address won't take effect until the next frame.

I'm sure Richard is right when it comes to the real McCoy IBM VGA and EGA, but I'm less confident that every clone out there loads the start address at the start of vertical sync.

> *For that very reason, I generally advise people not to use horizontal smooth panning unless they can test their software on all the makes of display adapter it might run on. I've used Richard's approach in Listings 8.1 and 8.2, and so far as I've seen it works fine, but be aware that there are potential, albeit unproven, hazards to relying on the setting of the start address registers to occur at a specific time in the frame.*

The interaction of the start address registers and the Pel Panning register is worthy of note. After waiting for the end of vertical sync to set the start address in Listing 8.2, I wait for the start of the *next* vertical sync to set the Pel Panning register. That's because the start address doesn't take effect until the start of the next frame, but the pel panning setting takes effect at the start of the next line; if we set the pel panning at the same time we set the start address, we'd get a whole frame with the old start address and the new pel panning settings mixed together, causing the screen to jump. As with the split screen registers, it's safest to set the Pel Panning register during non-display time. For maximum reliability, we'd have interrupts off from the time we set the start address registers to the time we change the pel planning setting, to make sure an interrupt doesn't come in and cause us to miss the start of a vertical sync and thus get a mismatched pel panning/start address pair for a frame, although for modularity I haven't done this in Listing 8.2. (Also, doing so would require disabling interrupts for much too long a time.)

What if you wanted to pan faster? Well, you could of course just move two pixels at a time rather than one; I assure you no one will ever notice when you're panning at a rate of 10 or more times per second.

Split Screens in Other Modes

So far we've only discussed the split screen in mode 10H. What about other modes? Generally, the split screen works in any mode; the basic rule is that when a scan line on the screen matches the split screen scan line, the internal display memory pointer is reset to zero. I've found this to be true even in oddball modes, such as line-doubled CGA modes and the 320x200 256-color mode (which is really a 320x400 mode with each line repeated. For split-screen purposes, the VGA and EGA seem to count purely in scan lines, not in rows or doubled scan lines or the like. However, I have run into small anomalies in those modes on clones, and I haven't tested all modes (nor, lord knows, all clones!) so be careful when using the split screen in modes other than modes 0DH-12H, and test your code on a variety of hardware.

Come to think of it, I warn you about the hazards of running fancy VGA code on clones pretty often, don't I? Ah, well—just one of the hazards of the diversity and competition of the PC market! It is a fact of life, though—if you're a commercial developer and don't test your video code on at least half a dozen VGAs, you're living dangerously.

What of the split screen in text mode? It works fine; in fact, it not only resets the internal memory pointer to zero, but also resets the text scan line counter—which marks which line within the font you're on—to zero, so the split screen starts out with a full row of text. There's only one trick with text mode: When split screen pel panning suppression is on, the pel panning setting is forced to 0 for the rest of the frame. Unfortunately, 0 is *not* the "no-panning" setting for 9-dot-wide text; 8 is. The result is that when you turn on split screen pel panning suppression, the text in the split screen won't pan with the normal screen, as intended, but will also display the undesirable characteristic of moving one pixel to the left. Whether this causes any noticeable on-screen effects depends on the text displayed by a particular application; for example, there should be no problem if the split screen has a border of blanks on the left side.

How Safe?

So, how safe *is* it to use the split screen? My opinion is that it's perfectly safe, although I'd welcome input from people with extensive split screen experience—and the effects are striking enough that the split screen is well worth using in certain applications.

I'm a little more leery of horizontal smooth scrolling, with or without the split screen. Still, the Wilton book doesn't advise any particular caution, and I haven't heard any horror stories from the field lately, so the clone manufacturers must finally have gotten it right. (I vividly remember some early clones years back that *didn't* quite get it right.) So, on balance, I'd say to use horizontal smooth scrolling if you really need it; on the other hand, in fast animation you can often get away with byte scrolling, which is easier, faster, and safer. (I recently saw a game that scrolled as smoothly as you could ever want. It was only by stopping it with Ctrl-NumLock that I was able to be sure that it was, in fact, byte-panning, not pel panning)

In short, use the fancy stuff—but only when you have to.

Higher 256-Color Resolution on the VGA

Chapter 9

When Is 320x200 Really 320x400?

One of the more appealing features of the VGA is its ability to display 256 simultaneous colors. Unfortunately, one of the *less* appealing features of the VGA is the limited resolution (320×200) of the one 256-color mode the IBM-standard BIOS supports. (There are, of course, higher resolution 256-color modes in the legion of SuperVGAs, but they are by no means a standard, and differences between seemingly identical modes from different manufacturers can be vexing.) More colors can often compensate for less resolution, but the resolution difference between the 640×480 16-color mode and the 320×200 256-color mode is so great that many programmers must regretfully decide that they simply can't afford to use the 256-color mode.

If there's one thing we've learned about the VGA, however, it's that there's *never* just one way to do things. With the VGA, alternatives always exist for the clever programmer, and that's more true than you might imagine with 256-color mode. Not only is there a high 256-color resolution, there are *lots* of higher 256-color resolutions, going all the way up to 360×480—and that's with the vanilla IBM VGA!

In this chapter, I'm going to focus on one of my favorite 256-color modes, which provides 320×400 resolution and two graphics pages and can be set up with very little reprogramming of the VGA. In the next chapter, I'll discuss higher-resolution 256-color modes, and starting in Chapter 32, I'll cover the high-performance "Mode X" 256-color programming that many games use.

So. Let's get started.

Why 320x200? Only IBM Knows for Sure

The first question, of course, is, "How can it be possible to get higher 256-color resolutions out of the VGA?" After all, there were no unused higher resolutions to be found in the CGA, Hercules card, or EGA.

The answer is another question. "Why did IBM *not* use the higher-resolution 256-color modes of the VGA?" The VGA is easily capable of twice the 200-scan-line vertical resolution of mode 13H, the 256-color mode, and IBM clearly made a decision not to support a higher-resolution 256-color mode. In fact, mode 13H *does* display 400 scan lines, but each row of pixels is displayed on two successive scan lines, resulting in an effective resolution of 320×200. This is the same scan-doubling approach used by the VGA to convert the CGA's 200-scan-line modes to 400 scan lines; however, the resolution of the CGA has long been fixed at 200 scan lines, so IBM had no choice with the CGA modes but to scan-double the lines. Mode 13H has no such historical limitation—it's the first 256-color mode ever offered by IBM, if you don't count the late and unlamented Professional Graphics Controller (PGC). Why, then, would IBM choose to limit the resolution of mode 13H?

There's no way to know, but one good guess is that IBM wanted a standard 256-color mode across all PS/2 computers (for which the VGA was originally created), and mode 13H is the highest-resolution 256-color mode that could fill the bill. You see, each 256-color pixel requires one byte of display memory, so a 320×200 256-color mode requires 64,000 bytes of display memory. That's no problem for the VGA, which has 256K of display memory, but it's a stretch for the MCGA of the Model 30, since the MCGA comes with only 64K.

On the other hand, the smaller display memory size of the MCGA also limits the number of colors supported in 640×480 mode to 2, rather than the 16 supported by the VGA. In this case, though, IBM simply created two modes and made both available on the VGA: mode 11H for 640×480 2-color graphics and mode 12H for 640×480 16-color graphics. The same could have been done for 256-color graphics—but wasn't. Why? I don't know. Maybe IBM just didn't like the odd aspect ratio of a 320×400 graphics mode. Maybe they didn't want to have to worry about how to map in more than 64K of display memory. Heck, maybe they made a mistake in designing the chip. Whatever the reason, mode 13H is really a 400-scan-line mode masquerading as a 200-scan-line mode, and we can readily end that masquerade.

320x400 256-Color Mode

Okay, what's so great about 320×400 256-color mode? Two things: easy, safe mode sets and page flipping.

As I said above, mode 13H is really a 320×400 mode, albeit with each line doubled to produce an effective resolution of 320×200. That means that we don't need to change any display timings, widths, or heights in order to tweak mode 13H into 320×400 mode—and that makes 320×400 a safe choice. Basically, 320×400 mode differs from mode 13H only in the settings of *mode* bits, which are sure to be consistent from one VGA clone to the next and which work equally well with all monitors. The other hi-res 256-color modes differ from mode 13H not only in the settings of the mode bits but also in the settings of timing and dimension registers, which may not be exactly the same on all VGA clones and particularly not on all multisync monitors. (Because multisyncs sometimes shrink the active area of the screen when used with standard VGA modes, some VGAs use alternate register settings for multisync monitors that adjust the CRT Controller timings to use as much of the screen area as possible for displaying pixels.)

The other good thing about 320×400 256-color mode is that two pages are supported. Each 320×400 256-color mode requires 128,000 bytes of display memory, so we can just barely manage two pages in 320×400 mode, one starting at offset 0 in display memory and the other starting at offset 8000H. Those two pages are the largest pair of pages that can fit in the VGA's 256K, though, and the higher-resolution 256-color modes, which use still larger bitmaps (areas of display memory that control pixels on the screen), can't support two pages at all. As we've seen in earlier chapters and will see again in this book, paging is very useful for off-screen construction of images and fast, smooth animation.

That's why I like 320×400 256-color mode. The next step is to understand how display memory is organized in 320×400 mode, and that's not so simple.

Display Memory Organization in 320x400 Mode

First, let's look at why display memory must be organized differently in 320×400 256-color mode than in mode 13H. The designers of the VGA intentionally limited the maximum size of the bitmap in mode 13H to 64K, thereby limiting resolution to 320×200. This was accomplished *in hardware*, so there is no way to extend the bitmap organization of mode 13H to 320×400 mode.

That's a shame, because mode 13H has the simplest bitmap organization of any mode—one long, linear bitmap, with each byte controlling one pixel. We can't have that organization, though, so we'll have to find an acceptable substitute if we want to use a higher 256-color resolution.

We're talking about the VGA, so of course there are actually *several* bitmap organizations that let us use higher 256-color resolutions than mode 13H. The one I like best is shown in Figure 9.1. Each byte controls one 256-color pixel. Pixel 0 is at address 0 in plane 0, pixel 1 is at address 0 in plane 1, pixel 2 is at address 0 in plane 2, pixel 3 is at address 0 in plane 3, pixel 4 is at address 1 in plane 0, and so on.

Let's look at this another way. Ideally, we'd like one long bitmap, with each pixel at the address that's just after the address of the pixel to the left. Well, that's true in this case too, *if* you consider the number of the plane that the pixel is in to be part of the

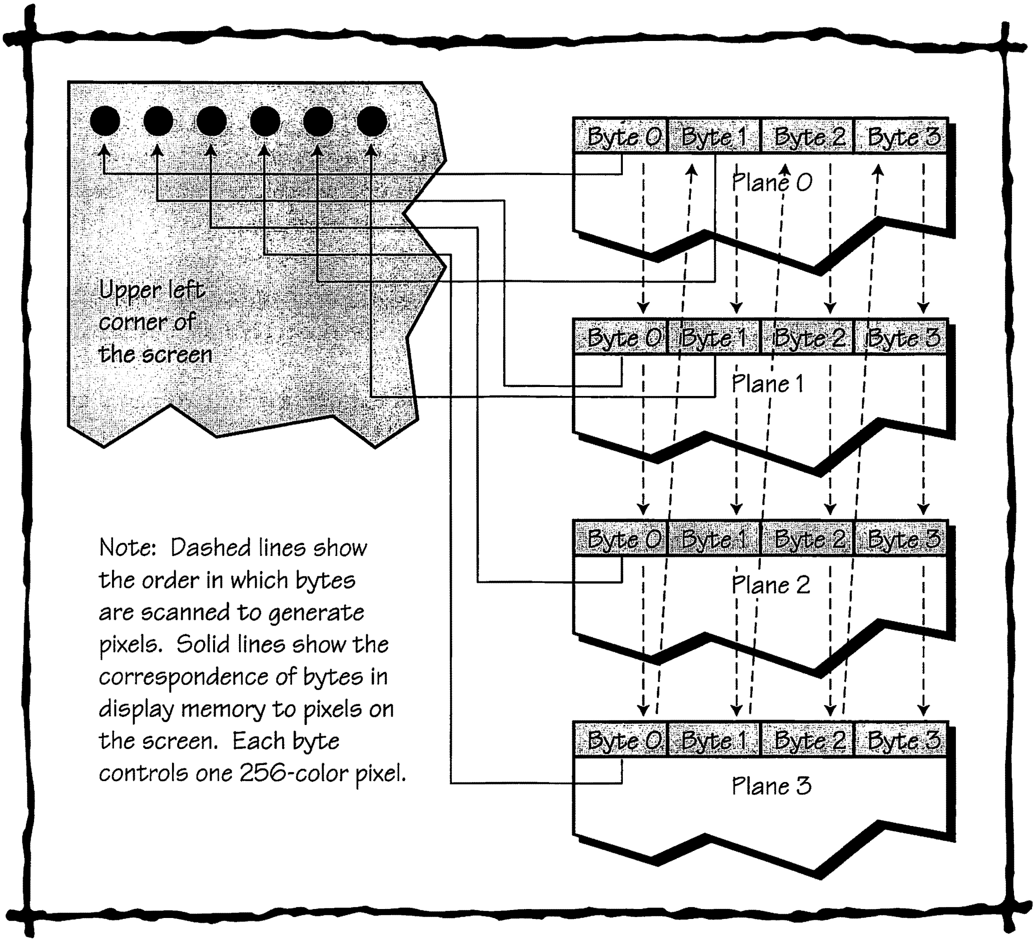

Byte 0
Byte 1
Byte 2
Byte 3
Plane 0
Plane 1
Plane 2
Plane 3
Upper left corner of the screen
Note: Dashed lines show the order in which bytes are scanned to generate pixels. Solid lines show the correspondence of bytes in display memory to pixels on the screen. Each byte controls one 256-color pixel.

Figure 9.1 Bitmap Organization in 320x400 256-Color Mode

pixel's address. View the pixel numbers on the screen as increasing from left to right and from the end of one scan line to the start of the next. Then the pixel number, *n*, of the pixel at display memory address *address* in plane *plane* is:

$n = (address * 4) + plane$

To turn that around, the display memory address of pixel number *n* is given by:

$address = n / 4$

and the plane of pixel *n* is given by:

plane = *n* modulo 4

Basically, the full address of the pixel, its pixel number, is broken into two components: the display memory address and the plane.

By the way, because 320×400 mode has a significantly different memory organization from mode 13H, the BIOS text routines won't work in 320×400 mode. If you want to draw text in 320×400 mode, you'll have to look up a font in the BIOS ROM and draw the text yourself. Likewise, the BIOS read pixel and write pixel routines won't work in 320×400 mode, but that's no problem because I'll provide equivalent routines in the next section.

Our next task is to convert standard mode 13H into 320×400 mode. That's accomplished by undoing some of the mode bits that are set up especially for mode 13H, so that from a programming perspective the VGA reverts to a straightforward planar model of memory. That means taking the VGA out of chain 4 mode and doubleword mode, turning off the double display of each scan line, making sure chain mode, odd/even mode, and word mode are turned off, and selecting byte mode for video data display. All that's done in the **Set320By400Mode** subroutine in Listing 9.1, which we'll discuss next.

Reading and Writing Pixels

The basic graphics functions in any mode are functions to read and write single pixels. Any more complex function can be built on these primitives, although that's rarely the speediest solution. What's more, once you understand the operation of the read and write pixel functions, you've got all the knowledge you need to create functions that perform more complex graphics functions. Consequently, we'll start our exploration of 320×400 mode with pixel-at-a-time line drawing.

Listing 9.1 draws 8 multi-colored octagons in turn, drawing a new one on top of the old one each time a key is pressed. The main-loop code of Listing 9.1 should be easily understood; a series of diagonal, horizontal, and vertical lines are drawn one pixel at a time based on a list of line descriptors, with the draw colors incremented for each successive time through the line list.

LISTING 9.1 L9-1.ASM

```
; Program to demonstrate pixel drawing in 320x400 256-color
; mode on the VGA. Draws 8 lines to form an octagon, a pixel
; at a time. Draws 8 octagons in all, one on top of the other,
; each in a different color set. Although it's not used, a
; pixel read function is also provided.
;
VGA_SEGMENT     equ  0a000h
SC_INDEX        equ  3c4h           ;Sequence Controller Index register
GC_INDEX        equ  3ceh           ;Graphics Controller Index register
CRTC_INDEX      equ  3d4h           ;CRT Controller Index register
MAP_MASK        equ  2              ;Map Mask register index in SC
MEMORY_MODE     equ  4              ;Memory Mode register index in SC
```

```
MAX_SCAN_LINE          equ  9                 ;Maximum Scan Line reg index in CRTC
START_ADDRESS_HIGH     equ  0ch               ;Start Address High reg index in CRTC
UNDERLINE              equ  14h               ;Underline Location reg index in CRTC
MODE_CONTROL           equ  17h               ;Mode Control register index in CRTC
READ_MAP               equ  4                 ;Read Map register index in GC
GRAPHICS_MODE          equ  5                 ;Graphics Mode register index in GC
MISCELLANEOUS          equ  6                 ;Miscellaneous register index in GC
SCREEN_WIDTH           equ  320               ;# of pixels across screen
SCREEN_HEIGHT          equ  400               ;# of scan lines on screen
WORD_OUTS_OK           equ  1                 ;set to 0 to assemble for
                                              ; computers that can't handle
                                              ; word outs to indexed VGA registers
;
stack      segment     para stack 'STACK'
                       db   512 dup (?)
stack      ends
;
Data       segment     word 'DATA'
;
BaseColor        db     0
;
; Structure used to control drawing of a line.
;
LineControl struc
StartX           dw     ?
StartY           dw     ?
LineXInc         dw     ?
LineYInc         dw     ?
BaseLength       dw     ?
LineColor        db     ?
LineControl      ends
;
; List of descriptors for lines to draw.
;
LineList         label  LineControl
        LineControl     <130,110,1,0,60,0>
        LineControl     <190,110,1,1,60,1>
        LineControl     <250,170,0,1,60,2>
        LineControl     <250,230,-1,1,60,3>
        LineControl     <190,290,-1,0,60,4>
        LineControl     <130,290,-1,-1,60,5>
        LineControl     <70,230,0,-1,60,6>
        LineControl     <70,170,1,-1,60,7>
        LineControl     <-1,0,0,0,0,0>
Data    ends
;
; Macro to output a word value to a port.
;
OUT_WORD         macro
if WORD_OUTS_OK
        out      dx,ax
else
        out      dx,al
        inc      dx
        xchg     ah,al
        out      dx,al
        dec      dx
        xchg     ah,al
endif
        endm
```

```
;
; Macro to output a constant value to an indexed VGA register.
;
CONSTANT_TO_INDEXED_REGISTER   macroADDRESS, INDEX, VALUE
        mov     dx,ADDRESS
        mov     ax,(VALUE shl 8) + INDEX
        OUT_WORD
        endm
;
Code    segment
        assume  cs:Code, ds:Data
Start   proc    near
        mov     ax,Data
        mov     ds,ax
;
; Set 320x400 256-color mode.
;
        call    Set320By400Mode
;
; We're in 320x400 256-color mode. Draw each line in turn.
;
ColorLoop:
        mov     si,offset LineList             ;point to the start of the
                                               ; line descriptor list
LineLoop:
        mov     cx,[si+StartX]                 ;set the initial X coordinate
        cmp     cx,-1
        jz      LinesDone                      ;a descriptor with a -1 X
                                               ; coordinate marks the end
                                               ; of the list
        mov     dx,[si+StartY]                 ;set the initial Y coordinate,
        mov     bl,[si+LineColor]              ; line color,
        mov     bp,[si+BaseLength]             ; and pixel count
        add     bl,[BaseColor]                 ;adjust the line color according
                                               ; to BaseColor
PixelLoop:
        push    cx                        ;save the coordinates
        push    dx
        call    WritePixel                ;draw this pixel
        pop     dx                        ;retrieve the coordinates
        pop     cx
        add     cx,[si+LineXInc]          ;set the coordinates of the
        add     dx,[si+LineYInc]          ; next point of the line
        dec     bp                        ;any more points?
        jnz     PixelLoop                 ;yes, draw the next
        add     si,size LineControl       ;point to the next line descriptor
        jmp     LineLoop                  ; and draw the next line
LinesDone:
        call    GetNextKey                     ;wait for a key, then
        inc     [BaseColor]                    ; bump the color selection and
        cmp     [BaseColor],8                  ; see if we're done
        jb      ColorLoop                      ;not done yet
;
; Wait for a key and return to text mode and end when
; one is pressed.
;
        call    GetNextKey
        mov     ax,0003h
        int     10h                            ;text mode
        mov     ah,4ch
        int     21h  ;done
```

```
;
Start   endp
;
; Sets up 320x400 256-color modes.
;
; Input: none
;
; Output: none
;
Set320By400Mode proc near
;
; First, go to normal 320x200 256-color mode, which is really a
; 320x400 256-color mode with each line scanned twice.
;
        mov     ax,0013h             ;AH = 0 means mode set, AL = 13h selects
                                     ; 256-color graphics mode
        int     10h                  ;BIOS video interrupt
;
; Change CPU addressing of video memory to linear (not odd/even,
; chain, or chain 4), to allow us to access all 256K of display
; memory. When this is done, VGA memory will look just like memory
; in modes 10h and 12h, except that each byte of display memory will
; control one 256-color pixel, with 4 adjacent pixels at any given
; address, one pixel per plane.
;
        mov     dx,SC_INDEX
        mov     al,MEMORY_MODE
        out     dx,al
        inc     dx
        in      al,dx
        and     al,not 08h                ;turn off chain 4
        or      al,04h                    ;turn off odd/even
        out     dx,al
        mov     dx,GC_INDEX
        mov     al,GRAPHICS_MODE
        out     dx,al
        inc     dx
        in      al,dx
        and     al,not 10h                ;turn off odd/even
        out     dx,al
        dec     dx
        mov     al,MISCELLANEOUS
        out     dx,al
        inc     dx
        in      al,dx
        and     al,not 02h                ;turn off chain
        out     dx,al
;
; Now clear the whole screen, since the mode 13h mode set only
; cleared 64K out of the 256K of display memory. Do this before
; we switch the CRTC out of mode 13h, so we don't see garbage
; on the screen when we make the switch.
;
        CONSTANT_TO_INDEXED_REGISTER SC_INDEX,MAP_MASK,0fh
                                          ;enable writes to all planes, so
                                          ; we can clear 4 pixels at a time
        mov     ax,VGA_SEGMENT
        mov     es,ax
        sub     di,di
        mov     ax,di
        mov     cx,8000h  ;# of words in 64K
        cld
        rep     stosw                   ;clear all of display memory
;
; Tweak the mode to 320x400 256-color mode by not scanning each
; line twice.
;
        mov     dx,CRTC_INDEX
        mov     al,MAX_SCAN_LINE
        out     dx,al
        inc     dx
        in      al,dx
        and     al,not 1fh              ;set maximum scan line = 0
        out     dx,al
        dec     dx
;
; Change CRTC scanning from doubleword mode to byte mode, allowing
; the CRTC to scan more than 64K of video data.
;
        mov     al,UNDERLINE
        out     dx,al
        inc     dx
        in      al,dx
        and     al,not 40h              ;turn off doubleword
        out     dx,al
        dec     dx
        mov     al,MODE_CONTROL
        out     dx,al
        inc     dx
        in      al,dx
        or      al,40h             ;turn on the byte mode bit, so memory is
                                   ; scanned for video data in a purely
                                   ; linear way, just as in modes 10h and 12h
        out     dx,al
        ret
Set320By400Mode endp
;
; Draws a pixel in the specified color at the specified
; location in 320x400 256-color mode.
;
; Input:
;       CX = X coordinate of pixel
;       DX = Y coordinate of pixel
;       BL = pixel color
;
; Output: none
;
; Registers altered: AX, CX, DX, DI, ES
;
WritePixel      proc near
        mov     ax,VGA_SEGMENT
        mov     es,ax                 ;point to display memory
        mov     ax,SCREEN_WIDTH/4
                                      ;there are 4 pixels at each address, so
                                      ; each 320-pixel row is 80 bytes wide
                                      ; in each plane
        mul     dx                    ;point to start of desired row
        push    cx                    ;set aside the X coordinate
        shr     cx,1                  ;there are 4 pixels at each address
        shr     cx,1                  ; so divide the X coordinate by 4
        add     ax,cx                 ;point to the pixel's address
        mov     di,ax
        pop     cx                     ;get back the X coordinate
        and     cl,3                   ;get the plane # of the pixel
        mov     ah,1
        shl     ah,cl                  ;set the bit corresponding to the plane
                                       ; the pixel is in
        mov     al,MAP_MASK
        mov     dx,SC_INDEX
        OUT_WORD                       ;set to write to the proper plane for
                                       ; the pixel
        mov     es:[di],bl             ;draw the pixel
        ret
WritePixel      endp
;
; Reads the color of the pixel at the specified location in 320x400
; 256-color mode.
;
; Input:
;       CX = X coordinate of pixel to read
;       DX = Y coordinate of pixel to read
;
; Output:
;       AL = pixel color
;
; Registers altered: AX, CX, DX, SI, ES
;
ReadPixel       proc near
        mov     ax,VGA_SEGMENT
        mov     es,ax                   ;point to display memory
        mov     ax,SCREEN_WIDTH/4
                                        ;there are 4 pixels at each address, so
                                        ; each 320-pixel row is 80 bytes wide
                                        ; in each plane
        mul     dx                      ;point to start of desired row
        push    cx                      ;set aside the X coordinate
        shr     cx,1                    ;there are 4 pixels at each address
        shr     cx,1                    ; so divide the X coordinate by 4
        add     ax,cx                   ;point to the pixel's address
        mov     si,ax
        pop     ax                      ;get back the X coordinate
        and     al,3                    ;get the plane # of the pixel
        mov     ah,al
        mov     al,READ_MAP
        mov     dx,GC_INDEX
        OUT_WORD                        ;set to read from the proper plane for
                                        ; the pixel
        lods    byte ptr es:[si]        ;read the pixel
        ret
ReadPixel       endp
;
; Waits for the next key and returns it in AX.
;
; Input: none
;
; Output:
;       AX = full 16-bit code for key pressed
;
GetNextKey      proc near
WaitKey:
        mov     ah,1
        int     16h
        jz      WaitKey                    ;wait for a key to become available
        sub     ah,ah
        int     16h                     ;read the key
        ret
GetNextKey      endp
;
Code    ends
;
        end     Start
```

The interesting aspects of Listing 9.1 are three. First, the **Set320By400Mode** subroutine selects 320×400 256-color mode. This is accomplished by performing a mode 13H mode set and then putting the VGA into standard planar byte mode. **Set320By400Mode** zeros display memory as well. It's necessary to clear display memory even after a mode 13H mode set because the mode 13H mode set clears only the 64K of display memory that can be accessed in that mode, leaving 192K of display memory untouched.

The second interesting aspect of Listing 9.1 is the **WritePixel** subroutine, which draws a colored pixel at any *x,y* addressable location on the screen. Although it may not be obvious because I've optimized the code a little, the process of drawing a pixel is remarkably simple. First, the pixel's display memory address is calculated as:

address = (*y* * (SCREEN_WIDTH / 4)) + (*x* / 4)

which might be more recognizable as:

address = ((*y* * SCREEN_WIDTH) + *x*) / 4

(There are 4 pixels at each display memory address in 320x400 mode, hence the division by 4.) Then the pixel's plane is calculated as:

plane = *x* and 3

which is equivalent to:

plane = *x* modulo 4

The pixel's color is then written to the addressed byte in the addressed plane. That's all there is to it!

The third item of interest in Listing 9.1 is the **ReadPixel** subroutine. **ReadPixel** is virtually identical to **WritePixel**, save that in **ReadPixel** the Read Map register is programmed with a plane number, while **WritePixel** uses a plane *mask* to set the Map Mask register. Of course, that difference merely reflects a fundamental difference in the operation of the two registers. (If that's Greek to you, refer back to Part I of this book for a refresher on VGA programming.) **ReadPixel** isn't used in Listing 9.1, but I've included it because, as I said above, the read and write pixel functions together can support a whole host of more complex graphics functions.

How does 320×400 256-color mode stack up as regards performance? As it turns out, the programming model of 320×400 mode is actually pretty good for pixel drawing, pretty much on a par with the model of mode 13H. When you run Listing 9.1, you'll no doubt notice that the lines are drawn quite rapidly. (In fact, the drawing could be considerably faster still with a dedicated line-drawing subroutine, which would avoid the multiplication associated with each pixel in Listing 9.1.)

In 320×400 mode, the calculation of the memory address is not significantly slower than in mode 13H, and the calculation and selection of the target plane is quickly accomplished. As with mode 13H, 320×400 mode benefits tremendously from the byte-per-pixel organization of 256-color mode, which eliminates the need for the time-consuming pixel-masking of the 16-color modes. Most important, byte-per-pixel modes never require read-modify-write operations (which can be extremely slow due to display memory wait states) in order to clip and draw pixels. To draw a pixel, you just store its color in display memory—what could be simpler?

More sophisticated operations than pixel drawing are less easy to accomplish in 320×400 mode, but with a little ingenuity it is possible to implement a reasonably efficient version of just about any useful graphics function. A fast line draw for 320×400 256-color mode would be simple (although not as fast as would be possible in mode 13H). Fast image copies could be implemented by copying one-quarter of the image to one plane, one-quarter to the next plane, and so on for all four planes, thereby eliminating the **OUT** per pixel that sequential processing requires. If you're really into performance, you could store your images with all the bytes for plane 0 grouped together, followed by all the bytes for plane 1, and so on. That would allow a single **REP MOVS** instruction to copy all the bytes for a given plane, with just four **REP MOVS** instructions copying the whole image. In a number of cases, in fact, 320×400 256-color mode can actually be much faster than mode 13H, because the VGA's hardware can be used to draw four or even eight pixels with a single access; I'll return to the topic of high-performance programming in 256-color modes other than mode 13H ("non-chain 4" modes) in Chapter 32.

It's all a bit complicated, but as I say, you should be able to design an adequately fast—and often *very* fast—version for 320×400 mode of whatever graphics function you need. If you're not all that concerned with speed, **WritePixel** and **ReadPixel** should meet your needs.

Two 256-Color Pages

Listing 9.2 demonstrates the two pages of 320×400 256-color mode by drawing slanting color bars in page 0, then drawing color bars slanting the other way in page 1 and flipping to page 1 on the next key press. (Note that page 1 is accessed starting at offset 8000H in display memory, and is—unsurprisingly—displayed by setting the start address to 8000H.) Finally, Listing 9.2 draws vertical color bars in page 0 and flips back to page 0 when another key is pressed.

The color bar routines don't use the **WritePixel** subroutine from Listing 9.1; they go straight to display memory instead for improved speed. As I mentioned above, better speed yet could be achieved by a color-bar algorithm that draws all the pixels in plane 0, then all the pixels in plane 1, and so on, thereby avoiding the overhead of constantly reprogramming the Map Mask register.

LISTING 9.2 L9-2.ASM

```
; Program to demonstrate the two pages available in 320x400
; 256-color modes on a VGA.  Draws diagonal color bars in all
; 256 colors in page 0, then does the same in page 1 (but with
; the bars tilted the other way), and finally draws vertical
; color bars in page 0.
;
VGA_SEGMENT          equ  0a000h
SC_INDEX             equ  3c4h       ;Sequence Controller Index register
GC_INDEX             equ  3ceh       ;Graphics Controller Index register
CRTC_INDEX           equ  3d4h       ;CRT Controller Index register
MAP_MASK             equ  2          ;Map Mask register index in SC
MEMORY_MODE          equ  4          ;Memory Mode register index in SC
MAX_SCAN_LINE        equ  9          ;Maximum Scan Line reg index in CRTC
START_ADDRESS_HIGH   equ  0ch        ;Start Address High reg index in CRTC
UNDERLINE            equ  14h        ;Underline Location reg index in CRTC
MODE_CONTROL         equ  17h        ;Mode Control register index in CRTC
GRAPHICS_MODE        equ  5          ;Graphics Mode register index in GC
MISCELLANEOUS        equ  6          ;Miscellaneous register index in GC
SCREEN_WIDTH         equ  320        ;# of pixels across screen
SCREEN_HEIGHT        equ  400        ;# of scan lines on screen
WORD_OUTS_OK         equ  1          ;set to 0 to assemble for
                                     ; computers that can't handle
                                     ; word outs to indexed VGA registers
;
stack     segment   para stack 'STACK'
          db        512 dup (?)
stack     ends
;
; Macro to output a word value to a port.
;
OUT_WORD       macro
if WORD_OUTS_OK
       out      dx,ax
else
       out      dx,al
       inc      dx
       xchg     ah,al
       out      dx,al
       dec      dx
       xchg     ah,al
endif
       endm
;
; Macro to output a constant value to an indexed VGA register.
;
CONSTANT_TO_INDEXED_REGISTER   macroADDRESS, INDEX, VALUE
       mov      dx,ADDRESS
       mov      ax,(VALUE shl 8) + INDEX
       OUT_WORD
       endm
```

```
;
Code   segment
       assume   cs:Code
Start  proc     near
;
; Set 320x400 256-color mode.
;
       call     Set320By400Mode
;
; We're in 320x400 256-color mode, with page 0 displayed.
; Let's fill page 0 with color bars slanting down and to the right.
;
       sub      di,di                    ;page 0 starts at address 0
       mov      bl,1                     ;make color bars slant down and
                                         ; to the right
       call     ColorBarsUp              ;draw the color bars
;
; Now do the same for page 1, but with the color bars
; tilting the other way.
;
       mov      di,8000h                 ;page 1 starts at address 8000h
       mov      bl,-1                    ;make color bars slant down and
                                         ; to the left
       call     ColorBarsUp              ;draw the color bars
;
; Wait for a key and flip to page 1 when one is pressed.
;
       call     GetNextKey
       CONSTANT_TO_INDEXED_REGISTER CRTC_INDEX,START_ADDRESS_HIGH,80h
                                     ;set the Start Address High register
                                     ; to 80h, for a start address of 8000h
;
; Draw vertical bars in page 0 while page 1 is displayed.
;
       sub      di,di                    ;page 0 starts at address 0
       sub      bl,bl                    ;make color bars vertical
       call     ColorBarsUp              ;draw the color bars
;
; Wait for another key and flip back to page 0 when one is pressed.
;
       call     GetNextKey
       CONSTANT_TO_INDEXED_REGISTER CRTC_INDEX,START_ADDRESS_HIGH,00h
                                     ;set the Start Address High register
                                     ; to 00h, for a start address of 0000h
;
; Wait for yet another key and return to text mode and end when
; one is pressed.
;
       call     GetNextKey
       mov      ax,0003h
       int      10h                      ;text mode
       mov      ah,4ch
       int      21h                      ;done
;
Start  endp
;
; Sets up 320x400 256-color modes.
;
; Input: none
;
```

```
; Output: none
;
Set320By400Mode proc near
;
; First, go to normal 320x200 256-color mode, which is really a
; 320x400 256-color mode with each line scanned twice.
;
      mov     ax,0013h              ;AH = 0 means mode set, AL = 13h selects
                                    ; 256-color graphics mode
      int     10h                   ;BIOS video interrupt
;
; Change CPU addressing of video memory to linear (not odd/even,
; chain, or chain 4), to allow us to access all 256K of display
; memory. When this is done, VGA memory will look just like memory
; in modes 10h and 12h, except that each byte of display memory will
; control one 256-color pixel, with 4 adjacent pixels at any given
; address, one pixel per plane.
;
      mov     dx,SC_INDEX
      mov     al,MEMORY_MODE
      out     dx,al
      inc     dx
      in      al,dx
      and     al,not 08h                 ;turn off chain 4
      or      al,04h                     ;turn off odd/even
      out     dx,al
      mov     dx,GC_INDEX
      mov     al,GRAPHICS_MODE
      out     dx,al
      inc     dx
      in      al,dx
      and     al,not 10h                 ;turn off odd/even
      out     dx,al
      dec     dx
      mov     al,MISCELLANEOUS
      out     dx,al
      inc     dx
      in      al,dx
      and     al,not 02h                 ;turn off chain
      out     dx,al
;
; Now clear the whole screen, since the mode 13h mode set only
; cleared 64K out of the 256K of display memory. Do this before
; we switch the CRTC out of mode 13h, so we don't see garbage
; on the screen when we make the switch.
;
      CONSTANT_TO_INDEXED_REGISTER SC_INDEX,MAP_MASK,0fh
                                         ;enable writes to all planes, so
                                         ; we can clear 4 pixels at a time
      mov     ax,VGA_SEGMENT
      mov     es,ax
      sub     di,di
      mov     ax,di
      mov     cx,8000h                   ;# of words in 64K
      cld
      rep     stosw                      ;clear all of display memory
;
; Tweak the mode to 320x400 256-color mode by not scanning each
; line twice.
;
```

```
        mov     dx,CRTC_INDEX
        mov     al,MAX_SCAN_LINE
        out     dx,al
        inc     dx
        in      al,dx
        and     al,not 1fh              ;set maximum scan line = 0
        out     dx,al
        dec     dx
;
; Change CRTC scanning from doubleword mode to byte mode, allowing
; the CRTC to scan more than 64K of video data.
;
        mov     al,UNDERLINE
        out     dx,al
        inc     dx
        in      al,dx
        and     al,not 40h              ;turn off doubleword
        out     dx,al
        dec     dx
        mov     al,MODE_CONTROL
        out     dx,al
        inc     dx
        in      al,dx
        or      al,40h              ;turn on the byte mode bit, so memory is
                                    ; scanned for video data in a purely
                                    ; linear way, just as in modes 10h and 12h
        out     dx,al
        ret
Set320By400Mode endp
;
; Draws a full screen of slanting color bars in the specified page.
;
; Input:
;       DI = page start address
;       BL = 1 to make the bars slant down and to the right, -1 to
;               make them slant down and to the left, 0 to make
;               them vertical.
;
ColorBarsUp     proc near
        mov     ax,VGA_SEGMENT
        mov     es,ax                   ;point to display memory
        sub     bh,bh                   ;start with color 0
        mov     si,SCREEN_HEIGHT        ;# of rows to do
        mov     dx,SC_INDEX
        mov     al,MAP_MASK
        out     dx,al           ;point the SC Index reg to the Map Mask reg
        inc     dx              ;point DX to the SC Data register
RowLoop:
        mov     cx,SCREEN_WIDTH/4
                                        ;4 pixels at each address, so
                                        ; each 320-pixel row is 80 bytes wide
                                        ; in each plane
        push    bx                      ;save the row-start color
ColumnLoop:
MAP_SELECT = 1
        rept    4                       ;do all 4 pixels at this address with
                                        ; in-line code
        mov     al,MAP_SELECT
        out     dx,al                   ;select planes 0, 1, 2, and 3 in turn
        mov     es:[di],bh              ;write this plane's pixel
        inc     bh                      ;set the color for the next pixel
```

```
MAP_SELECT = MAP_SELECT shl 1
       endm
       inc      di                      ;point to the address containing the next
                                        ; 4 pixels
       loop     ColumnLoop              ;do any remaining pixels on this line
       pop      bx                      ;get back the row-start color
       add      bh,bl                   ;select next row-start color (controls
                                        ; slanting of color bars)
       dec      si                      ;count down lines on the screen
       jnz      RowLoop
       ret
ColorBarsUp     endp
;
; Waits for the next key and returns it in AX.
;
GetNextKey      proc near
WaitKey:
       mov      ah,1
       int      16h
       jz       WaitKey                       ;wait for a key to become available
       sub      ah,ah
       int      16h                           ;read the key
       ret
GetNextKey      endp
;
Code   ends
;
       end      Start
```

When you run Listing 9.2, note the extremely smooth edges and fine gradations of color, especially in the screens with slanting color bars. The displays produced by Listing 9.2 make it clear that 320×400 256-color mode can produce effects that are simply not possible in any 16-color mode.

Something to Think About

You can, if you wish, use the display memory organization of 320×400 mode in 320×200 mode by modifying **Set320By400Mode** to leave the maximum scan line setting at 1 in the mode set. (The version of **Set320x400Mode** in Listings 9.1 and 9.2 forces the maximum scan line to 0, doubling the effective resolution of the screen.) Why would you want to do that? For one thing, you could then choose from not two but *four* 320×200 256-color display pages, starting at offsets 0, 4000H, 8000H, and 0C000H in display memory. For another, having only half as many pixels per screen can as much as double drawing speeds; that's one reason that many games run at 320×200, and even then often limit the active display drawing area to only a portion of the screen.

Be it Resolved: 360x480

Chapter 10

Taking 256-Color Modes About as Far as the Standard VGA Can Take Them

In the last chapter, we learned how to coax 320×400 256-color resolution out of a standard VGA. At the time, I noted that the VGA was actually capable of supporting 256-color resolutions as high as 360×480, but didn't pursue the topic further, preferring to concentrate on the versatile and easy-to-set 320×400 256-color mode instead.

Some time back I was sent a particularly useful item from John Bridges, a longtime correspondent and an excellent programmer. It was a complete mode set routine for 360×480 256-color mode that he has placed into the public domain. In addition, John wrote, "I also have a couple of freeware (free, but not public domain) utilities out there, including PICEM, which displays .PIC, .PCX, and .GIF images not only in 360×480×256 but also in 640×350×256, 640×400×256, 640×480×256, and 800×600×256 on SuperVGAs."

In this chapter, I'm going to combine John's mode set code with appropriately modified versions of the dot-plot code from Chapter 9 and the line-drawing code that we'll develop in Chapter 14. Together, those routines will make a pretty nifty demo of the capabilities of 360×480 256-color mode.

Extended 256-Color Modes: What's Not to Like?

When last we left 256-color programming, we had found that the standard 256-color mode, mode 13H, which officially offers 320×200 resolution, actually displays 400, not 200, scan lines, with line-doubling used to reduce the effective resolution to 320×200. By tweaking a few of the VGA's mode registers, we converted mode 13H to a true 320×400 256-color mode. As an added bonus, that 320×400 mode supports two graphics pages, a distinct improvement over the single graphics page supported by mode 13H. (We also learned how to get *four* graphics pages at 320×200 resolution, should that be needed.)

I particularly like 320×400 256-color mode for two reasons: It supports two-page graphics, which is very important for animation applications; and it doesn't require changing any of the monitor timing characteristics of the VGA. The mode bits that we changed to produce 320×400 256-color mode are pretty much guaranteed to be the same from one VGA to another, but the monitor-oriented registers are less certain to be constant, especially for VGAs that provide special support for the extended capabilities of various multiscanning monitors.

All in all, those are good arguments for 320×400 256-color mode. However, the counter-argument seems compelling as well—nothing beats higher resolution for producing striking graphics. Given that, and given that John Bridges was kind enough to make his mode set code available, I'm going to look at 360×480 256-color mode next. However, bear in mind that the drawbacks of this mode are the flip side of the strengths of 320×400 256-color mode: Only one graphics page, and direct setting of the monitor-oriented registers. Also, this mode has a peculiar and unique aspect ratio, with 480 pixels (as many as high-resolution mode 12H) vertically and only 360 horizontally. That makes for fairly poor horizontal resolution and sometimes-jagged drawing; on the other hand, the resolution is better in both directions than in mode 13H, and mode 13H itself has an odd aspect ratio, so it seems a bit petty to complain.

The single graphics page isn't a drawback if you don't need page flipping, of course, so there's not much to worry about there: If you need page flipping, don't use this mode. The direct setting of the monitor-oriented registers is another matter altogether.

I don't know how likely this code is to produce problems with clone VGAs in general; however, I did find that I had to put an older Video Seven VRAM VGA into "pure" mode—where it treats the VRAMs as DRAMs and exactly emulates a plain-vanilla IBM VGA—before 360×480 256-color mode would work properly. Now, that particular problem was due to an inherent characteristic of VRAMs, and shouldn't occur on Video Seven's Fastwrite adapter or any other VGA clone. Nonetheless, 360×480 256-color mode is a good deal different from any standard VGA mode, and while the code in this chapter runs perfectly well on all other VGAs in my experience, I can't guarantee its functionality on any particular VGA/monitor combination, unlike 320×400 256-color mode. Mind you, 360×480 256-color mode *should* work on all VGAs—there are just too many variables involved for me to be certain. Feedback from readers with broad 360×480 256-color experience is welcome.

The above notwithstanding, 360×480 256-color mode offers 64 times as many colors and nearly three times as many pixels as IBM's original CGA color graphics mode, making startlingly realistic effects possible. No mode of the VGA (at least no mode that I know of!), documented or undocumented, offers a better combination of resolution and color; even 320×400 256-color mode has 26% fewer pixels.

In other words, 360×480 256-color mode is worth considering—so let's have a look.

360x480 256-Color Mode

I'm going to start by showing you 360×480 256-color mode in action, after which we'll look at how it works. I suspect that once you see what this mode looks like, you'll be more than eager to learn how to use it.

Listing 10.1 contains three C-callable assembly functions. As you'd expect, **Set360×480Mode** places the VGA into 360×480 256-color mode. **Draw360×480Dot** draws a pixel of the specified color at the specified location. Finally, **Read360×480Dot** returns the color of the pixel at the specified location. (This last function isn't actually used in the example program in this chapter, but is included for completeness.)

Listing 10.2 contains an adaptation of some C line-drawing code I'll be presenting shortly in Chapter 14. If you're reading this book in serial fashion and haven't gotten there yet, simply take it on faith. If you really *really* need to know how the line-draw code works right *now*, by all means make a short forward call to Chapter 14 and digest it. The line-draw code presented below has been altered to select 360×480 256-color mode, and to cycle through all 256 colors that this mode supports, drawing each line in a different color.

LISTING 10.1 L10-1.ASM

```
; Borland C/C++ tiny/small/medium model-callable assembler
; subroutines to:
;       * Set 360x480 256-color VGA mode
;       * Draw a dot in 360x480 256-color VGA mode
;       * Read the color of a dot in 360x480 256-color VGA mode
;
; Assembled with TASM
;
; The 360x480 256-color mode set code and parameters were provided
; by John Bridges, who has placed them into the public domain.
;
VGA_SEGMENT         equ  0a000h          ;display memory segment
SC_INDEX            equ  3c4h            ;Sequence Controller Index register
GC_INDEX            equ  3ceh            ;Graphics Controller Index register
MAP_MASK            equ  2               ;Map Mask register index in SC
READ_MAP            equ  4               ;Read Map register index in GC
SCREEN_WIDTH        equ  360             ;# of pixels across screen
WORD_OUTS_OK        equ  1               ;set to 0 to assemble for
                                         ; computers that can't handle
                                         ; word outs to indexed VGA registers
;
_DATA   segment public byte 'DATA'
;
; 360x480 256-color mode CRT Controller register settings.
; (Courtesy of John Bridges.)
;
vptbl   dw      06b00h                   ; horz total
        dw      05901h                   ; horz displayed
        dw      05a02h                   ; start horz blanking
        dw      08e03h                   ; end horz blanking
        dw      05e04h                   ; start h sync
        dw      08a05h                   ; end h sync
        dw      00d06h                    ; vertical total
        dw      03e07h                    ; overflow
        dw      04009h                    ; cell height
        dw      0ea10h                    ; v sync start
        dw      0ac11h                    ; v sync end and protect cr0-cr7
        dw      0df12h                    ; vertical displayed
        dw      02d13h                    ; offset
        dw      00014h                    ; turn off dword mode
        dw      0e715h                    ; v blank start
        dw      00616h                    ; v blank end
        dw      0e317h                    ; turn on byte mode
vpend   label   word
_DATA   ends
;
; Macro to output a word value to a port.
;
OUT_WORD        macro
if WORD_OUTS_OK
        out     dx,ax
else
        out     dx,al
        inc     dx
        xchg    ah,al
        out     dx,al
        dec     dx
        xchg    ah,al
endif
        endm
;
_TEXT   segment byte public 'CODE'
        assume  cs:_TEXT, ds:_DATA
;
; Sets up 360x480 256-color mode.
; (Courtesy of John Bridges.)
;
; Call as: void Set360By480Mode()
;
; Returns: nothing
;
        public _Set360x480Mode
_Set360x480Mode proc near
        push    si                 ;preserve C register vars
        push    di
        mov     ax,12h             ; start with mode 12h
        int     10h                ; let the BIOS clear the video memory

        mov     ax,13h             ; start with standard mode 13h
        int     10h                ; let the BIOS set the mode

        mov     dx,3c4h            ; alter sequencer registers
        mov     ax,0604h           ; disable chain 4
        out     dx,ax

        mov     ax,0100h           ; synchronous reset
        out     dx,ax              ; asserted
        mov     dx,3c2h            ; misc output
        mov     al,0e7h            ; use 28 mHz dot clock
        out     dx,al              ; select it
        mov     dx,3c4h            ; sequencer again
        mov     ax,0300h           ; restart sequencer
        out     dx,ax              ; running again
        mov     dx,3d4h                   ; alter crtc registers

        mov     al,11h                    ; cr11
        out     dx,al                     ; current value
        inc     dx                        ; point to data
        in      al,dx                     ; get cr11 value
        and     al,7fh                    ; remove cr0 -> cr7
        out     dx,al                     ; write protect
        dec     dx                        ; point to index
        cld
        mov      si,offset vptbl
         mov      cx,((offset vpend)-(offset vptbl)) shr 1
@b:     lodsw
        out     dx,ax
        loop    @b
        pop     di                        ;restore C register vars
        pop     si
        ret
_Set360x480Mode endp
;
; Draws a pixel in the specified color at the specified
; location in 360x480 256-color mode.
;
; Call as: void Draw360x480Dot(int X, int Y, int Color)
;
; Returns: nothing
;
DParms  struc
        dw      ?                         ;pushed BP
        dw      ?                         ;return address
DrawX   dw      ?                         ;X coordinate at which to draw
DrawY   dw      ?                         ;Y coordinate at which to draw
Color   dw      ?                         ;color in which to draw (in the
                                          ; range 0-255; upper byte ignored)
DParms  ends
;
        public _Draw360x480Dot
_Draw360x480Dot proc near
        push    bp                        ;preserve caller's BP
        mov     bp,sp                     ;point to stack frame
        push    si                        ;preserve C register vars
        push    di
        mov     ax,VGA_SEGMENT
        mov     es,ax                ;point to display memory
        mov     ax,SCREEN_WIDTH/4
                                     ;there are 4 pixels at each address, so
                                     ; each 360-pixel row is 90 bytes wide
                                     ; in each plane
        mul     [bp+DrawY]                ;point to start of desired row
        mov     di,[bp+DrawX]             ;get the X coordinate
        shr     di,1                      ;there are 4 pixels at each address
        shr     di,1                      ; so divide the X coordinate by 4
        add     di,ax                     ;point to the pixel's address
        mov     cl,byte ptr [bp+DrawX]    ;get the X coordinate again
        and     cl,3                      ;get the plane # of the pixel
        mov     ah,1
        shl     ah,cl                ;set the bit corresponding to the plane
                                     ; the pixel is in
        mov     al,MAP_MASK
        mov     dx,SC_INDEX
        OUT_WORD                      ;set to write to the proper plane for
                                      ; the pixel
        mov     al,byte ptr [bp+Color];get the color
        stosb                         ;draw the pixel
        pop     di                    ;restore C register vars
        pop     si
        pop     bp                    ;restore caller's BP
        ret
_Draw360x480Dot endp
;
; Reads the color of the pixel at the specified
; location in 360x480 256-color mode.
;
; Call as: int Read360x480Dot(int X, int Y)
;
; Returns: pixel color
;
RParms  struc
        dw      ?                     ;pushed BP
        dw      ?                     ;return address
ReadX   dw      ?                     ;X coordinate from which to read
ReadY   dw      ?                     ;Y coordinate from which to read
RParms  ends
;
        public _Read360x480Dot
_Read360x480Dot proc near
        push    bp                    ;preserve caller's BP
        mov     bp,sp                 ;point to stack frame
        push    si                    ;preserve C register vars
        push    di
        mov     ax,VGA_SEGMENT
        mov     es,ax                ;point to display memory
        mov     ax,SCREEN_WIDTH/4    ;there are 4 pixels at each address, so
                                     ; each 360-pixel row is 90 bytes wide
                                     ; in each plane

        mul     [bp+DrawY]            ;point to start of desired row
        mov     si,[bp+DrawX]         ;get the X coordinate
        shr     si,1                  ;there are 4 pixels at each address
        shr     si,1                  ; so divide the X coordinate by 4
        add     si,ax                 ;point to the pixel's address
        mov     ah,byte ptr [bp+DrawX];get the X coordinate again
        and     ah,3
                                      ;get the plane # of the pixel
        mov     al,READ_MAP
        mov     dx,GC_INDEX
        OUT_WORD                      ;set to read from the proper plane for
                                      ; the pixel
        lods    byte ptr es:[si]      ;read the pixel
        sub     ah,ah                 ;make the return value a word for C
        pop     di                    ;restore C register vars
        pop     si
        pop     bp                    ;restore caller's BP
        ret
_Read360x480Dot endp
_TEXT   ends
        end
```

LISTING 10.2 L10-2.C

```
 * Sample program to illustrate VGA line drawing in 360x480
 * 256-color mode.
 *
 * Compiled with Borland C/C++.
 *
 * Must be linked with Listing 10.1 with a command line like:
 *
 *     bcc l10-2.c l10-1.asm
 *
 * By Michael Abrash
 */
#include <dos.h>                   /* contains geninterrupt */

#define TEXT_MODE         0x03
#define BIOS_VIDEO_INT    0x10
#define X_MAX             360      /* working screen width */
#define Y_MAX             480      /* working screen height */

extern void Draw360x480Dot();
extern void Set360x480Mode();

/*
 * Draws a line in octant 0 or 3 ( |DeltaX| >= DeltaY ).
 * |DeltaX|+1 points are drawn.
 */
void Octant0(X0, Y0, DeltaX, DeltaY, XDirection, Color)
unsigned int X0, Y0;            /* coordinates of start of the line */
unsigned int DeltaX, DeltaY;    /* length of the line */
int XDirection;                 /* 1 if line is drawn left to right,
                                   -1 if drawn right to left */
int Color;                      /* color in which to draw line */
{
    int DeltaYx2;
    int DeltaYx2MinusDeltaXx2;
    int ErrorTerm;

    /* Set up initial error term and values used inside drawing loop */
    DeltaYx2 = DeltaY * 2;
    DeltaYx2MinusDeltaXx2 = DeltaYx2 - (int) ( DeltaX * 2 );
    ErrorTerm = DeltaYx2 - (int) DeltaX;

    /* Draw the line */
    Draw360x480Dot(X0, Y0, Color);    /* draw the first pixel */
    while ( DeltaX-- ) {
        /* See if it's time to advance the Y coordinate */
        if ( ErrorTerm >= 0 ) {
            /* Advance the Y coordinate & adjust the error term
               back down */
            Y0++;
            ErrorTerm += DeltaYx2MinusDeltaXx2;
        } else {
            /* Add to the error term */
            ErrorTerm += DeltaYx2;
        }
        X0 += XDirection;                   /* advance the X coordinate */
        Draw360x480Dot(X0, Y0, Color);      /* draw a pixel */
    }
}
```

```
/*
 * Draws a line in octant 1 or 2 ( |DeltaX| < DeltaY ).
 * |DeltaY|+1 points are drawn.
 */
void Octant1(X0, Y0, DeltaX, DeltaY, XDirection, Color)
unsigned int X0, Y0;        /* coordinates of start of the line */
unsigned int DeltaX, DeltaY; /* length of the line */
int XDirection;             /* 1 if line is drawn left to right,
                              -1 if drawn right to left */
int Color;                  /* color in which to draw line */
{
   int DeltaXx2;
   int DeltaXx2MinusDeltaYx2;
   int ErrorTerm;

   /* Set up initial error term and values used inside drawing loop */
   DeltaXx2 = DeltaX * 2;
   DeltaXx2MinusDeltaYx2 = DeltaXx2 - (int) ( DeltaY * 2 );
   ErrorTerm = DeltaXx2 - (int) DeltaY;

   Draw360x480Dot(X0, Y0, Color);        /* draw the first pixel */
   while ( DeltaY-- ) {
     /* See if it's time to advance the X coordinate */
     if ( ErrorTerm >= 0 ) {
        /* Advance the X coordinate & adjust the error term
          back down */
        X0 += XDirection;
        ErrorTerm += DeltaXx2MinusDeltaYx2;
     } else {
        /* Add to the error term */
        ErrorTerm += DeltaXx2;
     }
     Y0++;           /* advance the Y coordinate */
     Draw360x480Dot(X0, Y0,Color); /* draw a pixel */
   }
}

/*
 * Draws a line on the EGA or VGA.
 */
void EVGALine(X0, Y0, X1, Y1, Color)
int X0, Y0;         /* coordinates of one end of the line */
int X1, Y1;         /* coordinates of the other end of the line */
unsigned char Color; /* color in which to draw line */
{
   int DeltaX, DeltaY;
   int Temp;

   /* Save half the line-drawing cases by swapping Y0 with Y1
     and X0 with X1 if Y0 is greater than Y1. As a result, DeltaY
     is always > 0, and only the octant 0-3 cases need to be
     handled. */
   if ( Y0 > Y1 ) {
     Temp = Y0;
     Y0 = Y1;
     Y1 = Temp;
     Temp = X0;
     X0 = X1;
     X1 = Temp;
   }
```

```
    /* Handle as four separate cases, for the four octants in which
       Y1 is greater than Y0 */
    DeltaX = X1 - X0;     /* calculate the length of the line
                             in each coordinate */
    DeltaY = Y1 - Y0;
    if ( DeltaX > 0 ) {
       if ( DeltaX > DeltaY ) {
           Octant0(X0, Y0, DeltaX, DeltaY, 1, Color);
       } else {
           Octant1(X0, Y0, DeltaX, DeltaY, 1, Color);
       }
    } else {
       DeltaX = -DeltaX;              /* absolute value of DeltaX */
       if ( DeltaX > DeltaY ) {
           Octant0(X0, Y0, DeltaX, DeltaY, -1, Color);
       } else {
           Octant1(X0, Y0, DeltaX, DeltaY, -1, Color);
       }
    }
}

/*
 * Subroutine to draw a rectangle full of vectors, of the
 * specified length and in varying colors, around the
 * specified rectangle center.
 */
void VectorsUp(XCenter, YCenter, XLength, YLength)
int XCenter, YCenter;    /* center of rectangle to fill */
int XLength, YLength;    /* distance from center to edge
                            of rectangle */
{
    int WorkingX, WorkingY, Color = 1;

    /* Lines from center to top of rectangle */
    WorkingX = XCenter - XLength;
    WorkingY = YCenter - YLength;
    for ( ; WorkingX < ( XCenter + XLength ); WorkingX++ )
        EVGALine(XCenter, YCenter, WorkingX, WorkingY, Color++);

    /* Lines from center to right of rectangle */
    WorkingX = XCenter + XLength - 1;
    WorkingY = YCenter - YLength;
    for ( ; WorkingY < ( YCenter + YLength ); WorkingY++ )
        EVGALine(XCenter, YCenter, WorkingX, WorkingY, Color++);

    /* Lines from center to bottom of rectangle */
    WorkingX = XCenter + XLength - 1;
    WorkingY = YCenter + YLength - 1;
    for ( ; WorkingX >= ( XCenter - XLength ); WorkingX-- )
        EVGALine(XCenter, YCenter, WorkingX, WorkingY, Color++);

    /* Lines from center to left of rectangle */
    WorkingX = XCenter - XLength;
    WorkingY = YCenter + YLength - 1;
    for ( ; WorkingY >= ( YCenter - YLength ); WorkingY-- )
        EVGALine(XCenter, YCenter, WorkingX, WorkingY, Color++);
}

/*
 * Sample program to draw four rectangles full of lines.
 */
```

```
void main()
{
   char temp;

    Set360x480Mode();

   /* Draw each of four rectangles full of vectors */
   VectorsUp(X_MAX / 4, Y_MAX / 4, X_MAX / 4, Y_MAX / 4, 1);
   VectorsUp(X_MAX * 3 / 4, Y_MAX / 4, X_MAX / 4, Y_MAX / 4, 2);
   VectorsUp(X_MAX / 4, Y_MAX * 3 / 4, X_MAX / 4, Y_MAX / 4, 3);
   VectorsUp(X_MAX * 3 / 4, Y_MAX * 3 / 4, X_MAX / 4, Y_MAX / 4, 4);

   /* Wait for the enter key to be pressed */
    scanf("%c", &temp);

   /* Back to text mode */
   _AX = TEXT_MODE;
    geninterrupt(BIOS_VIDEO_INT);
}
```

The first thing you'll notice when you run this code is that the speed of 360×480 256-color mode is pretty good, especially considering that most of the program is implemented in C.

Drawing in 360×480 256-color mode can sometimes actually be faster than in the 16-color modes, because the byte-per-pixel display memory organization of 256-color mode eliminates the need to read display memory before writing to it in order to isolate individual pixels coexisting within a single byte. In addition, 360×480 256-color mode is a variant of Mode X, which we'll encounter in detail in Chapter 32, and supports all the high-performance features of Mode X.

The second thing you'll notice is that exquisite shading effects are possible in 360×480 256-color mode; adjacent lines blend together remarkably smoothly, even with the default palette. The VGA allows you to select your 256 colors from a palette of 256K, so you could, if you wished, set up the colors to produce still finer shading albeit with fewer distinctly different colors available. For more on this and related topics, see the coverage of palette reprogramming that begins in the next chapter.

The one thing you may not notice right away is just how much detail is visible on the screen, because the blending of colors tends to obscure the superior resolution of this mode. Each of the four rectangles displayed measures 180 pixels horizontally by 240 vertically. Put another way, each *one* of those rectangles has two-thirds as many pixels as the entire mode 13H screen; in all, 360×480 256-color mode has 2.7 times as many pixels as mode 13H! As mentioned above, the resolution is unevenly distributed, with vertical resolution matching that of mode 12H but horizontal resolution barely exceeding that of mode 13H—but resolution is hot stuff, no matter how it's laid out, and 360×480 256-color mode has the highest 256-color resolution you're ever likely to see on a standard VGA. (SuperVGAs are quite another matter—but when you *require* a SuperVGA you're automatically excluding what might be a significant chunk of the market for your code.)

Now that we've seen the wonders of which our new mode is capable, let's take the time to understand how it works.

How 360x480 256-Color Mode Works

In describing 360×480 256-color mode, I'm going to assume that you're familiar with the discussion of 320×400 256-color mode in the last chapter. If not, go back to that chapter and read it; the two modes have a great deal in common, and I'm not going to bore you by repeating myself when the goods are just a few page flips (the paper kind) away.

360×480 256-color mode is essentially 320×400 256-color mode, but stretched in both dimensions. Let's look at the vertical stretching first, since that's the simpler of the two.

480 Scan Lines per Screen: A Little Slower, But No Big Deal

There's nothing unusual about 480 scan lines; standard modes 11H and 12H support that vertical resolution. The number of scan lines has nothing to do with either the number of colors or the horizontal resolution, so converting 320×400 256-color mode to 320×480 256-color mode is a simple matter of reprogramming the VGA's vertical control registers—which control the scan lines displayed, the vertical sync pulse, vertical blanking, and the total number of scan lines—to the 480-scan-line settings, and setting the polarities of the horizontal and vertical sync pulses to tell the monitor to adjust to a 480-line screen.

Switching to 480 scan lines has the effect of slowing the screen refresh rate. The VGA always displays at 70 Hz *except* in 480-scan-line modes; there, due to the time required to scan the extra lines, the refresh rate slows to 60 Hz. (VGA monitors always scan at the same rate horizontally; that is, the distance across the screen covered by the electron beam in a given period of time is the same in all modes. Consequently, adding extra lines per frame requires extra time.) 60 Hz isn't *bad*—that's the only refresh rate the EGA ever supported, and the EGA was the industry standard in its time—but it does tend to flicker a little more and so is a little harder on the eyes than 70 Hz.

360 Pixels per Scan Line: No Mean Feat

Converting from 320 to 360 pixels per scan line is more difficult than converting from 400 to 480 scan lines per screen. None of the VGA's graphics modes supports 360 pixels across the screen, or anything like it; the standard choices are 320 and 640 pixels across. However, the VGA *does* support the horizontal resolution we seek—360 pixels—in 40-column *text* mode.

Unfortunately, the register settings that select those horizontal resolutions aren't directly transferable to graphics mode. Text modes display 9 dots (the width of one character) for each time information is fetched from display memory, while graphics modes display just 4 or 8 dots per display memory fetch. (Although it's a bit confusing, it's standard terminology to refer to the interval required for one display memory fetch as a "character," and I'll follow that terminology from now on.) Consequently, both modes display either 40 or 80 characters per scan line; the only difference is that text modes display more pixels per character. Given that graphics modes *can't* display 9 dots per character (there's only enough information for eight 16-color pixels or four 256-color pixels in each memory fetch, and that's that), we'd seem to be at an impasse.

The key to solving this problem lies in recalling that the VGA is designed to drive a monitor that sweeps the electron beam across the screen at exactly the same speed, no matter what mode the VGA is in. If the monitor always sweeps at the same speed, how does the VGA manage to display both 640 pixels across the screen (in high-resolution graphics modes) and 720 pixels across the screen (in 80-column text modes)? Good question indeed—and the answer is that the VGA has not one but *two* clocks on board, and one of those clocks is just sufficiently faster than the other clock so that an extra 80 (or 40) pixels can be displayed on each scan line.

In other words, there's a slow clock (about 25 MHz) that's usually used in graphics modes to get 640 (or 320) pixels on the screen during each scan line, and a second, fast clock (about 28 MHz) that's usually used in text modes to crank out 720 (or 360) pixels per scan line. In particular, 320×400 256-color mode uses the 25 MHz clock.

I'll bet that you can see where I'm headed: We can switch from the 25 MHz clock to the 28 MHz clock in 320×480 256-color mode in order to get more pixels. It takes two clocks to produce one 256-color pixel, so we'll get 40 rather than 80 extra pixels by doing this, bringing our horizontal resolution to the desired 360 pixels.

Switching horizontal resolutions sounds easy, doesn't it? Alas, it's not. There's no standard VGA mode that uses the 28 MHz clock to draw 8 rather than 9 dots per character, so the timing parameters have to be calculated from scratch. John Bridges has already done that for us, but I want you to appreciate that producing this mode took some work. The registers controlling the total number of characters per scan line, the number of characters displayed, the horizontal sync pulse, horizontal blanking, the offset from the start of one line to the start of the next, and the clock speed all have to be altered in order to set up 360×480 256-color mode. The function **Set360×480Mode** in Listing 10.1 does all that, and sets up the registers that control vertical resolution, as well.

Once all that's done, the VGA is in 360×480 mode, awaiting our every high-resolution 256-color graphics whim.

Accessing Display Memory in 360x480 256-Color Mode

Setting up for 360×480 256-color mode proved to be quite a task. Is drawing in this mode going to be as difficult?

No. In fact, if you know how to draw in 320×400 256-color mode, you already know how to draw in 360×480 256-color mode; the conversion between the two is a simple matter of changing the working screen width from 320 pixels to 360 pixels. In fact, if you were to take the 320×400 256-color pixel reading and pixel writing code from Chapter 9 and change the **SCREEN_WIDTH** equate from 320 to 360, those routines would work perfectly in 360×480 256-color mode.

The organization of display memory in 360×480 256-color mode is almost exactly the same as in 320×400 256-color mode, which we covered in detail in the last chapter. However, as a quick refresher, each byte of display memory controls one 256-color pixel, just as in mode 13H. The VGA is reprogrammed by the mode set so that adjacent pixels lie in adjacent planes of display memory. Look back to Figure 9.1 in the last chapter to see the organization of the first few pixels on the screen; the bytes controlling those pixels run cross-plane, advancing to the next address only every fourth pixel. The address of the pixel at screen coordinate (*x*,*y*) is:

address = ((*y**360)+*x*)/4

and the plane of a given pixel is:

plane = *x* modulo 4

A new scan line starts every 360 pixels, or 90 bytes, as shown in Figure 10.1. This is the major programming difference between the 360×480 and 320×400 256-color modes; in the 320×400 mode, a new scan line starts every 80 bytes.

The other programming difference between the two modes is that the area of display memory mapped to the screen is longer in 360×480 256-color mode, which is

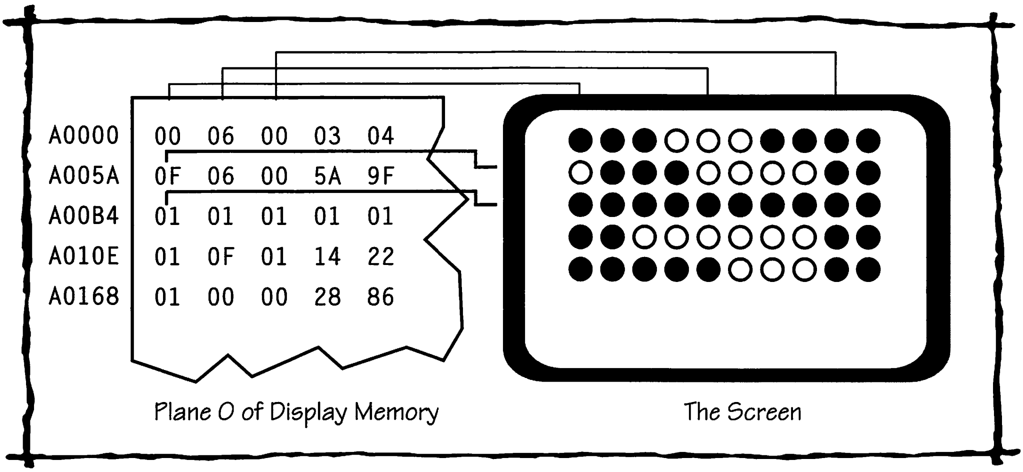


Figure 10.1 Pixel Organization in 360x480 256-Color Mode

only common sense given that there are more pixels in that mode. The exact amount of memory required in 360×480 256-color mode is 360 times 480 = 172,800 bytes. That's more than half of the VGA's 256 Kb memory complement, so page-flipping is out; however, there's no reason you couldn't use that extra memory to create a virtual screen larger than 360×480, around which you could then scroll, if you wish.

That's really all there is to drawing in 360×480 256-color mode. From a programming perspective, this mode is no more complicated than 320×400 256-color mode once the mode set is completed, and should be capable of good performance given some clever coding. It's not particular straightforward to implement bitblt, block move, or fast line-drawing code for any of the extended 256-color modes, but it can be done—and it's worth the trouble. Even the small taste we've gotten of the capabilities of these modes shows that they put the traditional CGA, EGA, and generally even VGA modes to shame.

There's more and better to come, though; in later chapters, we'll return to high-resolution 256-color programming in a big way, by exploring the tremendous potential of these modes for real time 2-D and 3-D animation.

Chapter 11

Yogi Bear and Eurythmics Confront VGA Colors

The Basics of VGA Color Generation

Kevin Mangis wants to know about the VGA's 4-bit to 8-bit to 18-bit color translation. Mansur Loloyan would like to find out how to generate a look-up table containing 256 colors and how to change the default color palette. And surely they are only the tip of the iceberg; hordes of screaming programmers from every corner of the planet are no doubt tearing the place up looking for a discussion of VGA color, and venting their frustration at my mailbox. *Let's have it*, they've said, clearly and in considerable numbers. As Eurythmics might say, who is this humble writer to disagree?

On the other hand, I hope you all know what you're getting into. To paraphrase Yogi, the VGA is smarter (and more confusing) than the average board. There's the basic 8-bit to 18-bit translation, there's the EGA-compatible 4-bit to 6-bit translation, there's the 2- or 4-bit color paging register that's used to pad 6- or 4-bit pixel values out to 8 bits, and then there's 256-color mode. Fear not, it will all make sense in the end, but it may take us a couple of additional chapters to get there—so let's get started.

Before we begin, though, I must refer you to Michael Covington's excellent article, "Color Vision and the VGA," in the June/July 1990 issue of *PC TECHNIQUES*. Michael, one of the most brilliant people it has ever been my pleasure to meet, is an expert in many areas I know nothing about, including linguistics and artificial intelligence. Add to that list the topic of color perception, for his article superbly describes the mechanisms by which we perceive color and ties that information to the VGA's capabilities. After reading Michael's article, you'll understand what colors the VGA is capable of generating, and why.

Our topic in this chapter complements Michael's article nicely. Where he focused on color perception, we'll focus on color generation; that is, the ways in which the

VGA can be programmed to generate those colors that lie within its capabilities. To find out why a VGA can't generate as pure a red as an LED, read Michael's article. If you want to find out how to flip between 16 different sets of 16 colors, though, don't touch that dial!

I would be remiss if I didn't point you in the direction of two more articles, these in the July 1990 issue of *Dr. Dobb's Journal.* "Super VGA Programming," by Chris Howard, provides a good deal of useful information about SuperVGA chipsets, modes, and programming. "Circles and the Digital Differential Analyzer," by Tim Paterson, is a good article about fast circle drawing, a topic we'll tackle soon. All in all, the dog days of 1990 were good times for graphics.

VGA Color Basics

Briefly put, the VGA color translation circuitry takes in one 4- or 8-bit pixel value at a time and translates it into three 6-bit values, one each of red, green, and blue, that are converted to corresponding analog levels and sent to the monitor. Seems simple enough, doesn't it? Unfortunately, nothing is ever that simple on the VGA, and color translation is no exception.

The Palette RAM

The color path in the VGA involves two stages, as shown in Figure 11.1. The first stage fetches a 4-bit pixel from display memory and feeds it into the EGA-compatible palette RAM (so called because it is functionally equivalent to the palette RAM color translation circuitry of the EGA), which translates it into a 6-bit value and sends it on to the DAC. The translation involves nothing more complex than the 4-bit value of a pixel being used as the address of one of the 16 palette RAM registers; a pixel value of 0 selects the contents of palette RAM register 0, a pixel value of 1 selects register 1, and so on. Each palette RAM register stores 6 bits, so each time a palette RAM register is selected by an incoming 4-bit pixel value, 6 bits of information are sent out by the palette RAM. (The operation of the palette RAM was described back in Chapter 7.)

The process is much the same in text mode, except that in text mode each 4-bit pixel value is generated based on the character's font pattern and attribute. In 256-color mode, which we'll get to eventually, the palette RAM is not a factor from the programmer's perspective and should be left alone.

The DAC

Once the EGA-compatible palette RAM has fulfilled its karma and performed 4-bit to 6-bit translation on a pixel, the resulting value is sent to the DAC (Digital/Analog Converter). The DAC performs an 8-bit to 18-bit conversion in much the same manner as the palette RAM, converts the 18-bit result to analog red, green, and blue signals

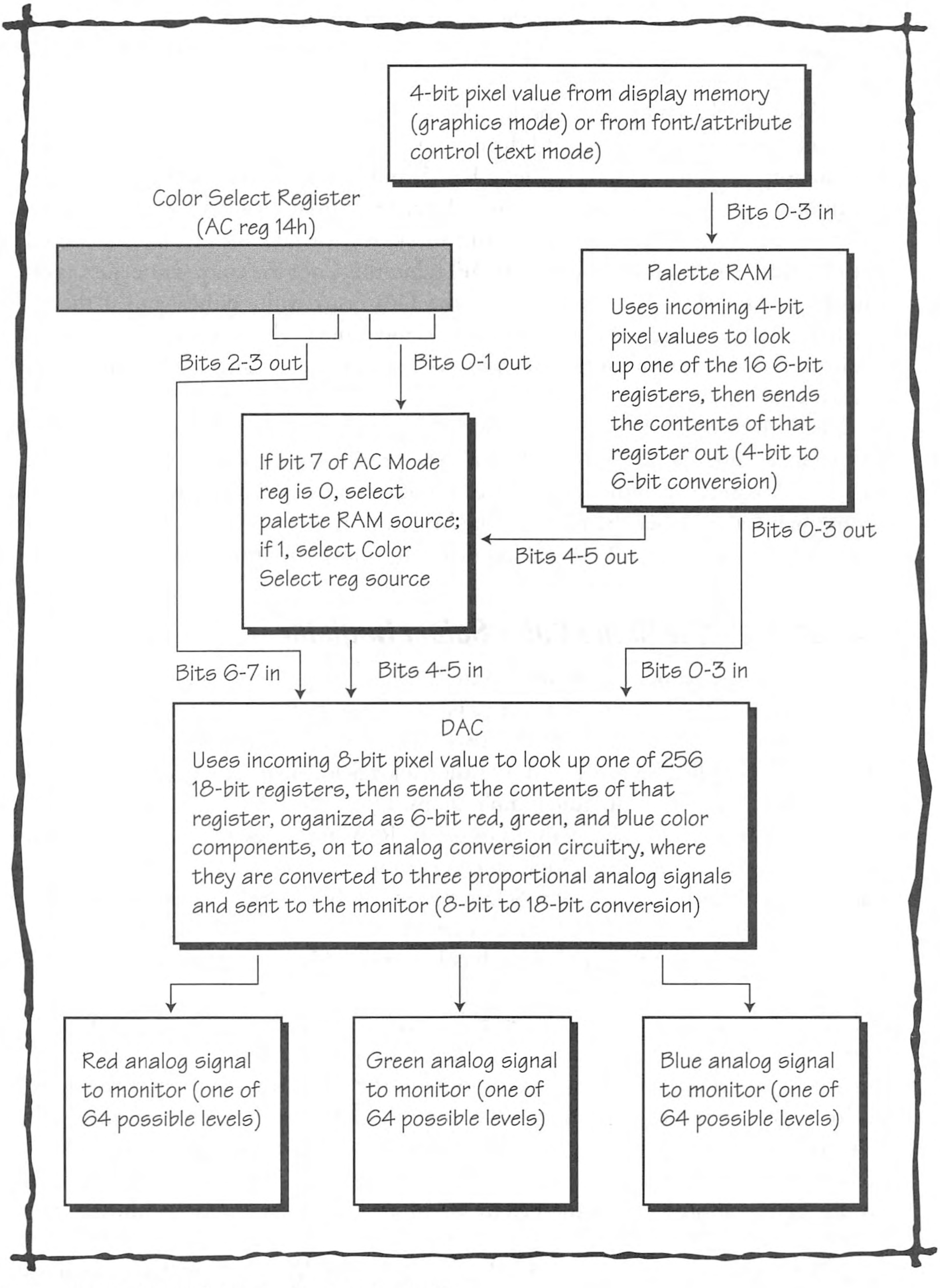

4-bit pixel value from display memory (graphics mode) or from font/attribute control (text mode)
Bits 0-3 in
Color Select Register (AC reg 14h)
Palette RAM
Uses incoming 4-bit pixel values to look up one of the 16 6-bit registers, then sends the contents of that register out (4-bit to 6-bit conversion)
Bits 2-3 out
Bits 0-1 out
If bit 7 of AC Mode reg is 0, select palette RAM source; if 1, select Color Select reg source
Bits 4-5 out
Bits 0-3 out
Bits 6-7 in
Bits 4-5 in
Bits 0-3 in
DAC
Uses incoming 8-bit pixel value to look up one of 256 18-bit registers, then sends the contents of that register, organized as 6-bit red, green, and blue color components, on to analog conversion circuitry, where they are converted to three proportional analog signals and sent to the monitor (8-bit to 18-bit conversion)
Red analog signal to monitor (one of 64 possible levels)
Green analog signal to monitor (one of 64 possible levels)
Blue analog signal to monitor (one of 64 possible levels)

Figure 11.1 The VGA Color Generation Path

(6 bits for each signal), and sends the three analog signals to the monitor. The DAC is a separate chip, external to the VGA chip, but it's an integral part of the VGA standard and is present on every VGA.

(I'd like to take a moment to point out that you can't speak of "color" at any point in the color translation process until the output stage of the DAC. The 4-bit pixel values in memory, 6-bit values in the palette RAM, and 8-bit values sent to the DAC are all attributes, not colors, because they're subject to translation by a later stage. For example, a pixel with a 4-bit value of 0 isn't black, it's attribute 0. It will be translated to 3FH if palette RAM register 0 is set to 3FH, but that's not the color white, just another attribute. The value 3FH coming into the DAC isn't white either, and if the value stored in DAC register 63 is red=7, green=0, and blue=0, the actual *color* displayed for that pixel that was 0 in display memory will be dim red. It isn't color until the DAC says it's color.)

The DAC contains 256 18-bit storage registers, used to translate one of 256 possible 8-bit values into one of 256K (262,144, to be precise) 18-bit values. The 18-bit values are actually composed of three 6-bit values, one each for red, green, and blue; for each color component, the higher the number, the brighter the color, with 0 turning that color off in the pixel and 63 (3FH) making that color maximum brightness. Got all that?

Color Paging with the Color Select Register

"Wait a minute," you say bemusedly. "Aren't you missing some bits between the palette RAM and the DAC?" Indeed I am. The palette RAM puts out 6 bits at a time, and the DAC takes in 8 bits at a time. The two missing bits—bits 6 and 7 going into the DAC—are supplied by bits 2 and 3 of the Color Select register (Attribute Controller register 14H). This has intriguing implications. In 16-color modes, pixel data can select only one of 16 attributes, which the EGA palette RAM translates into one of 64 attributes. Normally, those 64 attributes look up colors from registers 0 through 63 in the DAC, because bits 2 and 3 of the Color Select register are both zero. By changing the Color Select register, however, one of three other 64 color sets can be selected instantly. I'll refer to the process of flipping through color sets in this manner as *color paging.*

That's interesting, but frankly it seems somewhat half-baked; why bother expanding 16 attributes to 64 attributes before looking up the colors in the DAC? What we'd *really* like is to map the 16 attributes straight through the palette RAM without changing them and supply the upper *4* bits going to the DAC from a register, giving us 16 color pages. As it happens, all we have to do to make that happen is set bit 7 of the Attribute Controller Mode register (register 10H) to 1. Once that's done, bits 0 through 3 of the Color Select register go straight to bits 4 through 7 of the DAC, and only bits 3 through 0 coming out of the palette RAM are used; bits 4 and 5 from the palette RAM are ignored. In this mode, the palette RAM effectively contains 4-bit, rather than 6-bit, registers, but that's no problem because the palette RAM will be programmed to pass pixel values through unchanged by having register 0 set to 0, register 1 set to 1, and so on, a configuration in which the upper two bits of all the palette RAM registers are the same (zero) and therefore irrelevant. As a matter of fact, you'll generally want to set the palette RAM to this pass-through state when working with VGA color, whether you're using color paging or not.

Why is it a good idea to set the palette RAM to a pass-through state? It's a good idea because the palette RAM is programmed by the BIOS to EGA-compatible settings and the first 64 DAC registers are programmed to emulate the 64 colors that an EGA can display during mode sets for 16-color modes. This is done for compatibility with EGA programs, and it's useless if you're going to tinker with the VGA's colors. As a VGA programmer, you want to take a 4-bit pixel value and turn it into an 18-bit RGB value; you can do that without any help from the palette RAM, and setting the palette RAM to pass-through values effectively takes it out of the circuit and simplifies life something wonderful. The palette RAM exists solely for EGA compatibility, and serves no useful purpose that I know of for VGA-only color programming.

256-Color Mode

So far I've spoken only of 16-color modes; what of 256-color modes?

The rule in 256-color modes is: Don't tinker with the VGA palette. Period. You can select any colors you want by reprogramming the DAC, and there's no guarantee as to what will happen if you mess around with the palette RAM. There's no benefit that I know of to changing the palette RAM in 256-color mode, and the effect may vary from VGA to VGA. So don't do it unless you know something I don't.

On the other hand, feel free to alter the DAC settings to your heart's content in 256-color mode, all the more so because this is the only mode in which all 256 DAC settings can be displayed simultaneously. By the way, the Color Select register and bit 7 of the Attribute Controller Mode register are ignored in 256-color mode; all 8 bits sent from the VGA chip to the DAC come from display memory. Therefore, there is no color paging in 256-color mode. Of course, that makes sense given that all 256 DAC registers are simultaneously in use in 256-color mode.

Setting the Palette RAM

The palette RAM can be programmed either directly or through BIOS interrupt 10H, function 10H. I strongly recommend using the BIOS interrupt; a clone BIOS may mask incompatibilities with genuine IBM silicon. Such incompatibilities could include anything from flicker to trashing the palette RAM; or they may not exist at all, but why find out the hard way? My policy is to use the BIOS unless there's a clear reason not to do so, and there's no such reason that I know of in this case.

When programming specifically for the VGA, the palette RAM needs to be loaded only once, to store the pass-through values 0 through 15 in palette RAM registers 0 through 15. Setting the entire palette RAM is accomplished easily enough with subfunction 2 (AL=2) of function 10H (AH=10H) of interrupt 10H. A single call to this subfunction sets all 16 palette RAM registers (and the Overscan register) from a block of 17 bytes pointed to by ES:DX, with ES:DX pointing to the value for register 0, ES:DX+1 pointing to the value for register 1, and so on up to ES:DX+16, which points to the overscan value. The palette RAM registers store 6 bits each, so only the lower 6 bits of each of the first 16 bytes in the 17-byte block are significant. (The Overscan register, which specifies what's displayed between the area of the screen that's controlled by the values in display memory and the blanked region at the edges of the screen, is an 8-bit register, however.)

Alternatively, any one palette RAM register can be set via subfunction 0 (AL=0) of function 10H (AH=10H) of interrupt 10H. For this subfunction, BL contains the number of the palette RAM register to set and the lower 6 bits of BH contain the value to which to set that register.

Having said that, let's leave the palette RAM behind (presumably in a pass-through state) and move on to the DAC, which is the right place to do color translation on the VGA.

Setting the DAC

Like the palette RAM, the DAC registers can be set either directly or through the BIOS. Again, the BIOS should be used whenever possible, but there are a few complications here. My experience is that varying degrees of flicker and screen bounce occur on many VGAs when a large block of DAC registers is set through the BIOS. That's not a problem when the DAC is loaded just once and then left that way, as is the case in Listing 11.1, which we'll get to shortly, but it can be a serious problem when the color set is changed rapidly ("cycled") to produce on-screen effects such as rippling colors. My (limited) experience is that it's necessary to program the DAC directly in order to cycle colors cleanly, although input from readers who have worked extensively with VGA color is welcome.

At any rate, the code in this chapter will use the BIOS to set the DAC, so I'll describe the BIOS DAC-setting functions next. Later, I'll briefly describe how to set both the palette RAM and DAC registers directly, and I'll return to the topic in detail in an upcoming chapter when we discuss color cycling.

An individual DAC register can be set by interrupt 10H, function 10H (AH=10), subfunction 10H (AL=10H), with BX indicating the register to be set and the color to which that register is to be set stored in DH (6-bit red component), CH (6-bit green component), and CL (6-bit blue component).

A block of sequential DAC registers ranging in size from one register up to all 256 can be set via subfunction 12H (AL=12H) of interrupt 10H, function 10H (AH=10H).

In this case, BX contains the number of the first register to set, CX contains the number of registers to set, and ES:DX contains the address of a table of color entries to which DAC registers BX through BX+CX-1 are to be set. The color entry for each DAC register consists of three bytes; the first byte is a 6-bit red component, the second byte is a 6-bit green component, and the third byte is a 6-bit blue component, as illustrated by Listing 11.1.

If You Can't Call the BIOS, Who Ya Gonna Call?

Although the palette RAM and DAC registers should be set through the BIOS whenever possible, there are times when the BIOS is not the best choice or even a choice at all; for example, a protected-mode program may not have access to the BIOS. Also, as mentioned earlier, it may be necessary to program the DAC directly when performing color cycling. Therefore, I'll briefly describe how to set the palette RAM and DAC registers directly; in the next chapter I'll discuss programming the DAC directly in more detail.

The palette RAM registers are Attribute Controller registers 0 through 15. They are set by first reading the Input Status 1 register (at 3DAH in color mode or 3BAH in monochrome mode) to reset the Attribute Controller toggle to index mode, then loading the Attribute Controller Index register (at 3C0H) with the number (0 through 15) of the register to be loaded. Do *not* set bit 5 of the Index register to 1, as you normally would, but rather set bit 5 to 0. Setting bit 5 to 0 allows values to be written to the palette RAM registers, but it also causes the screen to blank, so you should wait for the start of vertical retrace before loading palette RAM registers if you don't want the screen to flicker. (Do you see why it's easier to go through the BIOS?) Then, write the desired register value to 3C0H, which has now toggled to become the Attribute Controller Data register. Write any desired number of additional register number/register data pairs to 3C0H, then write 20H to 3C0H to unblank the screen.

The process of loading the palette RAM registers depends heavily on the proper sequence being followed; if the Attribute Controller Index register or index/data toggle data gets changed in the middle of the loading process, you'll probably end up with a hideous display, or no display at all. Consequently, for maximum safety you may want to disable interrupts while you load the palette RAM, to prevent any sort of interference from a TSR or the like that alters the state of the Attribute Controller in the middle of the loading sequence.

The DAC registers are set by writing the number of the first register to set to the DAC Write Index register at 3C8H, then writing three bytes—the 6-bit red component, the 6-bit green component, and the 6-bit blue component, in that order—to the DAC Data register at 3C9H. The DAC Write Index register then autoincrements, so if you write another three-byte RGB value to the DAC Data register, it'll go to the next DAC register, and so on indefinitely; you can set all 256 registers by sending 256*3 = 768 bytes to the DAC Data Register.

Loading the DAC is just as sequence-dependent and potentially susceptible to interference as is loading the palette, so my personal inclination is to go through the whole process of disabling interrupts, loading the DAC Write Index, and writing a three-byte RGB value separately for each DAC register; although that doesn't take advantage of the autoincrementing feature, it seems to me to be least susceptible to outside influences. (It would be even better to disable interrupts for the entire duration of DAC register loading, but that's much too long a time to leave interrupts off.) However, I have no hard evidence to offer in support of my conservative approach to setting the DAC, just an uneasy feeling, so I'd be most interested in hearing from any readers.

A final point is that the process of loading both the palette RAM and DAC registers involves performing multiple OUTs to the same register. Many people whose opinions I respect recommend delaying between I/O accesses to the same port by performing a JMP $+2 (jumping flushes the prefetch queue and forces a memory access—or at least a cache access—to fetch the next instruction byte). In fact, some people recommend two JMP $+2 instructions between I/O accesses to the same port, and *three* jumps between I/O accesses to the same port that go in opposite directions (OUT followed by IN or IN followed by OUT). This is clearly necessary when accessing some motherboard chips, but I don't know how applicable it is when accessing VGAs, so make of it what you will. Input from knowledgeable readers is eagerly solicited.

In the meantime, if you can use the BIOS to set the DAC, do so; then you won't have to worry about the real and potential complications of setting the DAC directly.

An Example of Setting the DAC

This chapter has gotten about as big as a chapter really ought to be; the VGA color saga will continue in the next few. Quickly, then, Listing 11.1 is a simple example of setting the DAC that gives you a taste of the spectacular effects that color translation makes possible. There's nothing particularly complex about Listing 11.1; it just selects 256-color mode, fills the screen with one-pixel-wide concentric diamonds drawn with sequential attributes, and sets the DAC to produce a smooth gradient of each of the three primary colors and of a mix of red and blue. Run the program; I suspect you'll be surprised at the stunning display this short program produces. Clever color manipulation is perhaps the easiest way to produce truly eye-catching effects on the PC.

LISTING 11.1 L11-1.ASM

```
; Program to demonstrate use of the DAC registers by selecting a
; smoothly contiguous set of 256 colors, then filling the screen
; with concentric diamonds in all 256 colors so that they blend
; into one another to form a continuum of color.
;
        .model  small
        .stack  200h
        .data
```

```
; Table used to set all 256 DAC entries.
;
; Table format:
;       Byte 0: DAC register 0 red value
;       Byte 1: DAC register 0 green value
;       Byte 2: DAC register 0 blue value
;       Byte 3: DAC register 1 red value
;       Byte 4: DAC register 1 green value
;       Byte 5: DAC register 1 blue value
;       :
;       Byte 765: DAC register 255 red value
;       Byte 766: DAC register 255 green value
;       Byte 767: DAC register 255 blue value

ColorTable      labelbyte

; The first 64 entries are increasingly dim pure green.
X=0
        REPT    64
        db      0,63-X,0
X=X+1
        ENDM

; The next 64 entries are increasingly strong pure blue.
X=0
        REPT    64
        db      0,0,X
X=X+1
        ENDM

; The next 64 entries fade through violet to red.
X=0
        REPT    64
        db      X,0,63-X
X=X+1
        ENDM

; The last 64 entries are increasingly dim pure red.
X=0
        REPT    64
        db      63-X,0,0
X=X+1
        ENDM

         .code
Start:
        mov     ax,0013h                ;AH=0 selects set mode function,
                                        ; AL=13h selects 320x200 256-color
        int     10h                     ; mode

                                        ;load the DAC registers with the
                                        ; color settings
        mov     ax,@data                ;point ES to the default
        mov     es,ax                   ; data segment
        mov     dx,offset ColorTable
                                        ;point ES:DX to the start of the
                                        ; block of RGB three-byte values
                                        ; to load into the DAC registers
        mov     ax,1012h                ;AH=10h selects set color function,
                                        ; AL=12h selects set block of DAC
                                        ; registers subfunction
```

```
sub     bx,bx                     ;load the block of registers
                                  ; starting at DAC register #0
mov     cx,100h                   ;set all 256 registers
int     10h                       ;load the DAC registers

                                  ;now fill the screen with
                                  ; concentric diamonds in all 256
                                  ; color attributes
mov     ax,0a000h                 ;point DS to the display memory
mov     ds,ax                     ; segment
                                  ;
                                  ;draw diagonal lines in the upper
                                  ; left quarter of the screen
mov     al,2                      ;start with color attribute #2
mov     ah,-1                     ;cycle down through the colors
mov     bx,320                    ;draw top to bottom (distance from
                                  ; one line to the next)
mov     dx,160                    ;width of rectangle
mov     si,100                    ;height of rectangle
sub     di,di                     ;start at (0,0)
mov     bp,1                      ;draw left to right (distance from
                                  ; one column to the next)
call    FillBlock                 ;draw it
                                  ;
                                  ;draw diagonal lines in the upper
                                  ; right quarter of the screen
mov     al,2                      ;start with color attribute #2
mov     ah,-1                     ;cycle down through the colors
mov     bx,320                    ;draw top to bottom (distance from
                                  ; one line to the next)
mov     dx,160                    ;width of rectangle
mov     si,100                    ;height of rectangle
mov     di,319                    ;start at (319,0)
mov     bp,-1                     ;draw right to left (distance from
                                  ; one column to the next)
call    FillBlock                 ;draw it

                                  ;draw diagonal lines in the lower
                                  ; left quarter of the screen
mov     al,2                      ;start with color attribute #2
mov     ah,-1                     ;cycle down through the colors
mov     bx,-320                   ;draw bottom to top (distance from
                                  ; one line to the next)
mov     dx,160                    ;width of rectangle
mov     si,100                    ;height of rectangle
mov     di,199*320                ;start at (0,199)
mov     bp,1                      ;draw left to right (distance from
                                  ; one column to the next)
call    FillBlock                 ;draw it
                                  ;
                                  ;draw diagonal lines in the lower
                                  ; right quarter of the screen
mov     al,2                      ;start with color attribute #2
mov     ah,-1                     ;cycle down through the colors
mov     bx,-320                   ;draw bottom to top (distance from
                                  ; one line to the next)
mov     dx,160                    ;width of rectangle
mov     si,100                    ;height of rectangle
mov     di,199*320+319            ;start at (319,199)
mov     bp,-1                     ;draw right to left (distance from
                                  ; one column to the next)
```

```
        call    FillBlock                         ;draw it

        mov     ah,1                              ;wait for a key
        int     21h                               ;

        mov     ax,0003h                          ;return to text mode
        int     10h                               ;

        mov     ah,4ch                            ;done--return to DOS
        int     21h

; Fills the specified rectangular area of the screen with diagonal lines.
;
; Input:
;       AL = initial attribute with which to draw
;       AH = amount by which to advance the attribute from
;               one pixel to the next
;       BX = distance to advance from one pixel to the next
;       DX = width of rectangle to fill
;       SI = height of rectangle to fill
;       DS:DN = screen address of first pixel to draw
;       BP = offset from the start of one column to the start of
;               the next

FillBlock:
FillHorzLoop:
        push    di                                ;preserve pointer to top of column
        push    ax                                ;preserve initial attribute
        mov     cx,si                             ;column height
FillVertLoop:
        mov     [di],al                           ;set the pixel
        add     di,bx                             ;point to the next row in the column
        add     al,ah                             ;advance the attribute
        loop    FillVertLoop                      ;
        pop     ax                                ;restore initial attribute
        add     al,ah                             ;advance to the next attribute to
                                                  ; start the next column
        pop     di                                ;retrieve pointer to top of column
        add     di,bp                             ;point to next column
        dec     dx                                ;have we done all columns?
        jnz     FillHorzLoop                      ;no, do the next column
        ret                                       ;

        end     Start
```

Note the jagged lines at the corners of the screen when you run Listing 11.1. This shows how coarse the 320×200 resolution of mode 13H actually is. Now look at how smoothly the colors blend together in the rest of the screen. This is an excellent example of how careful color selection can boost perceived resolution, as for example when drawing antialiased lines, as discussed in Chapter 27.

Finally, note that the border of the screen turns green when Listing 11.1 is run. Listing 11.1 reprograms DAC register 0 to green, and the border attribute (in the Overscan register) happens to be 0, so the border comes out green even though we haven't touched the Overscan register. Normally, attribute 0 is black, causing the border to vanish, but the border is an 8-bit attribute that has to pass through the DAC just like any other pixel value, and it's just as subject to DAC color translation as the pixels controlled by display memory. However, the border color is not affected by the palette RAM or by the Color Select register.

In this chapter, we traced the surprisingly complex path by which the VGA turns a pixel value into RGB analog signals headed for the monitor. In the next chapter and the one that follows, it we'll look at some more code that plays with VGA color. We'll explore in more detail the process of reading and writing the palette RAM and DAC registers, and we'll observe color paging and cycling in action.

Paging Mr. VGA...

Chapter 12

More Colors in 16-Color Mode through VGA Color Paging

When last we looked, our hero had learned how to set the VGA's Digital to Analog Converter (DAC) to select 16 or 256 colors from a set of 256K colors. However, he or she (or both) still had a lot to learn about color paging, loading and reading the DAC, and color cycling, so that's where we're headed next. Before we get into any serious graphics, though, let me address a potential problem you may encounter—even with your very own C code—as you upgrade your programming tools to new technology.

Breaking Code by Upgrading Compilers

In its day, Microsoft C 6.0 was a solid compiler, but it broke much of the C graphics code I had presented in my various writings up to its release. You see, in order to set a single pixel in EGA/VGA memory, it's necessary to perform a read to latch display memory followed by a write to draw the pixel. (If you don't understand why this is the case, I suggest that you refer back to Part I of this book, but for now, just take my word for it.) Ideally we'd like to perform the read and write in close succession, with a single instruction if possible. In assembly language, that's no problem; just **XCHG**, **AND**, **XOR**, or **OR** an appropriate value with memory. In the code in question, the value actually written to memory is irrelevant, because of the way set/reset and the bit mask are set up; all that's needed is a read followed by a write with any value at all.

Matters are not so simple in C. Long ago, I tried to use code like this

```
*ScreenPtr |= 0;
```

to perform a read/write operation to display memory. Unfortunately, the optimizer in Microsoft C 5.0 (not 6.0) considered this to be a null operation, because any value

ORed with 0 remains unchanged (when the destination is system memory, that is; as described above, ORing with 0 is a useful operation when performed to VGA memory). Having concluded that it had encountered what amounted to a null operation, MSC 5.0 then declined to generate any code at all.

That was easy enough to fix. I just substituted

```
*ScreenPtr |= 0xFF;
```

which is definitely not a null operation (remember, for our purposes the value ORed with display memory is irrelevant, so 0xFF served just as well as 0). MSC 5.0 obligingly assembled the desired OR with memory, and there matters stood until the arrival of MSC 6.0.

MSC 6.0 doesn't think ***ScreenPtr |= 0xFF**; is a null operation—but it doesn't think it's an OR operation either. ORing a value with 0xFF invariably produces 0xFF as the result, so MSC 6.0 treated that code as if it were:

```
*ScreenPtr = 0xFF;
```

and assembled a **MOV** instruction, not an **OR** instruction. That eliminated the read we needed before writing to display memory, and that's what broke so much graphics code.

The solution is simple: Instead of:

```
*ScreenPtr |= 0xFF;
```

use

```
*ScreenPtr |= 0xFE;
```

and you should be all set.

There's an important point to all this beyond simply getting read-modify-write operations to work in C. Many people believe that it's possible to write low-level graphics code in C that's as efficient as code written in assembly language, and more portable, if you know exactly what code the compiler generates. This example shows why that's a fool's game; code that depends on the compiler's code generation isn't necessarily even portable from one release of the compiler to the next, let alone between compilers. Besides, the graphics adapters you're likely to encounter under MS-DOS are generally found only in x86-based computers, so it's hard to imagine what portability benefits there might be. On top of all that, I'm still waiting to encounter C graphics code that matches good assembly language code in the performance department.

All in all, my advice is to stick to assembly language for your key graphics code. And with that out of the way, let's move on to color paging.

Color Paging

As you'll recall from the previous chapter, the VGA's DAC contains 256 storage locations, each holding one 18-bit color organized as one 6-bit red component, one 6-bit green component, and one 6-bit blue component. In 256-color mode, each 8-bit pixel value in memory selects one of the 256 DAC locations, the value in that location is looked up and sent to the screen as the pixel's color, and that's that. In 16-color modes, however, each pixel is represented in display memory by a 4-bit value, so each pixel can only look up one of 16 DAC locations to be sent to the screen. What about those other 240 DAC locations? Are they useless in 16-color modes?

Not at all. Normally (as configured by the BIOS at mode set time in 16-color modes), the first 64 locations in the DAC are set to colors that are equivalent to the 64 colors an EGA can display. (The other 192 DAC locations may or may not be set to any particular values, so be sure to load them before relying on their contents.) At the same time, the EGA-compatible palette RAM is set to the same values an EGA is normally set to. This is dandy if you're writing code for an EGA, because when you tweak the palette RAM on a VGA you'll get exactly the results you'd expect on an EGA. If you're writing VGA-specific code, however, you're shortchanging yourself.

The ideal 16-color arrangement on a VGA is as follows: Load palette RAM register 0 with the value 0, palette RAM register 1 with the value 1, and so on up to palette RAM register 15, which should be set to 15. (I described how to load the palette RAM in the previous chapter, and in a little while we'll see working code that loads the palette.) The object here is to cause the palette RAM to pass pixel values through unchanged, so we can ignore it; the DAC will do all the color work.

Now load DAC locations 0 through 15 with any 16 colors you'd care to display. A pixel value of 0 in memory will cause the color in DAC location 0 to be displayed, a pixel value of 1 in memory will select DAC location 1, and so on. You can change the values stored in the DAC whenever you want to work with a different set of colors. (Loading the DAC was discussed in the previous chapter, and will be revisited in detail in the next chapter.)

Things get more exciting with the addition of color paging. If you set bit 7 of the Attribute Controller Mode register (Attribute Controller register 10H) to 1, bits 3 through 0 of the Color Select register (Attribute Controller register 14H) become bits 7 through 4 of the 8-bit values used to address locations within the DAC. The Color Select register operates in conjunction with the pixel data from display memory, which provides DAC address bits 3 through 0, as shown in Figure 12.1. I'll call this mode of operation "16-pages-of-16-colors" paging. When bit 7 of the AC Mode register is 0 (the EGA-compatible default), "4-pages-of-64-colors" paging is selected, as described in the previous chapter.

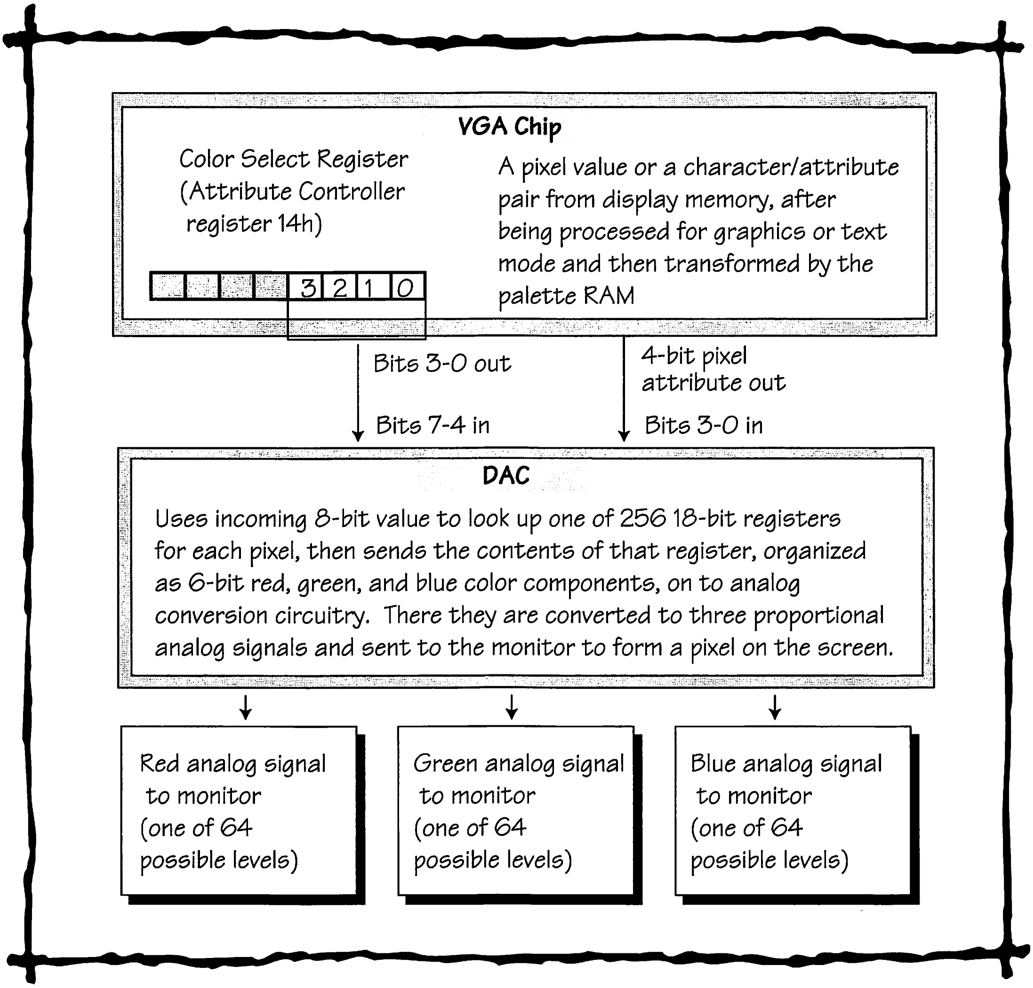

VGA Chip
Color Select Register (Attribute Controller register 14h)
3 2 1 0
A pixel value or a character/attribute pair from display memory, after being processed for graphics or text mode and then transformed by the palette RAM
Bits 3-0 out
Bits 7-4 in
4-bit pixel attribute out
Bits 3-0 in
DAC
Uses incoming 8-bit value to look up one of 256 18-bit registers for each pixel, then sends the contents of that register, organized as 6-bit red, green, and blue color components, on to analog conversion circuitry. There they are converted to three proportional analog signals and sent to the monitor to form a pixel on the screen.
Red analog signal to monitor (one of 64 possible levels)
Green analog signal to monitor (one of 64 possible levels)
Blue analog signal to monitor (one of 64 possible levels)

Figure 12.1 Color Selection with 16-Pages-of-16-Colors Paging

The Color Select register gives us the ability to perform color paging; that is, to flip instantly between color sets and thereby provide a new color interpretation for every pixel on the screen without changing the contents of display memory. If you view the DAC as consisting of 16 pages each containing 16 colors, as shown in Figure 12.2, then the Color Select register selects one of those pages and the pixel data selects one of 16 colors from within the currently selected page. (Remember that the palette RAM is set to a pass-through state, so pixel values of 0 through 15 come through the palette RAM to the DAC unaltered.) Basically, the Color Select register gives you instantaneous access to any one of 16 completely independent pages of 16 colors each. (By the way, color paging isn't available in 256-color mode. The reason should be obvious; there are only enough DAC locations for one set of 256 colors.)

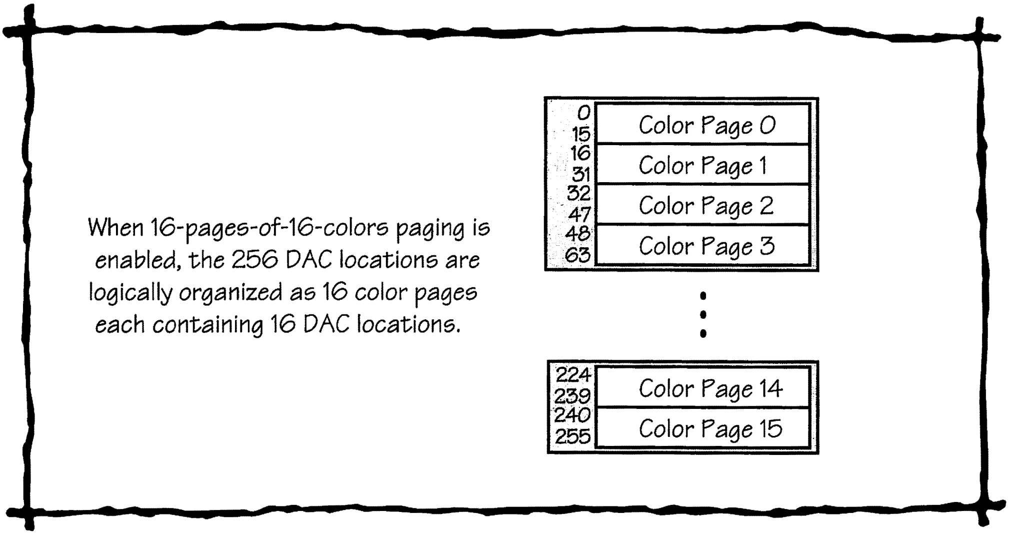

When 16-pages-of-16-colors paging is enabled, the 256 DAC locations are logically organized as 16 color pages each containing 16 DAC locations.
0
15
Color Page 0
16
31
Color Page 1
32
47
Color Page 2
48
63
Color Page 3
224
239
Color Page 14
240
255
Color Page 15

Figure 12.2 16-Pages-of-16-Colors Paging

Big deal, you say; why not just reprogram the first 16 DAC locations if you want different colors? First, it's considerably faster to program the Color Select register with a few I/O operations than it is to reprogram 16 DAC registers, a process which takes 64 **OUT** instructions. Second, it's much easier to avoid flicker when using the Color Select register; all you have to do is wait for the vertical sync pulse and set one register. In fact, you don't even have to wait for the vertical sync pulse, because the colors will change instantly, with no glitching, starting at the location of the electron beam at the very instant you set the Color Select register. The only reason to wait for the sync pulse is to make sure that all the pixels in each frame are drawn with the same color set, in order to avoid having the top and bottom of the screen appear briefly in a mismatched state.

On the other hand, loading the DAC without flicker or glitching is no picnic. The loading has to take place during non-display time; otherwise for a short time part of the screen will be drawn with a mix of the old color set and the new color set, resulting in unintended and often highly undesirable on-screen effects. However, it can be difficult on slow computers to load a large block of DAC locations during a single vertical blanking period, so there may be no way to reload the DAC cleanly between one frame and the next (although this is more of a problem in 256-color mode, where it's sometimes necessary to reload all 256 DAC locations at once). Furthermore, some BIOSes glitch or bounce the screen when called to load the DAC, and some are faster than others.

We'll return to issues of loading the DAC in the next chapter. For now, what all this amounts to is that if you need to switch color sets frequently and color paging can do the job you need done, it's far superior to constantly reloading the DAC—and easier, too.

How to Perform Color Paging

Color paging can be performed either directly or through the BIOS. As usual, the BIOS route is the better choice if there's no good reason not to use it, but there is one possible drawback that we'll come across shortly. In any case, I'll describe both techniques.

Color paging directly (without the BIOS) is a two-step process: The first step is enabling color paging, and the second step is selecting the desired color page. Enabling color paging such that you have 16 pages of 16 colors is a simple matter of setting bit 7 of the AC Mode register to 1, and is accomplished as follows:

- Read the Input Status 1 register at 3BAH (in monochrome mode) or 3DAH (in color mode) to reset the AC Index/Data toggle;
- Write 30H to the AC Index register at 3C0H to address AC register 10H, the AC Mode register (the index value is 30H rather than 10H because bit 5 of the AC Index register should always be 1 except when setting the palette RAM; when bit 5 is 0, the screen blanks);
- Read the AC Mode register setting from the AC Data register at 3C1H;
- OR 80H with the value just read to set bit 7 (this selects 16-pages-of-16-colors operation rather than 4-pages-of-64-colors operation, the default);
- Write the result to the AC Mode register via the AC Data register at 3C0H. (Remember that the AC Data register is at 3C1H for reads, but is at 3C0H on every other **OUT**—alternating with the AC Index register—for writes, in order to provide EGA compatibility.)

At this point, color paging with 16 pages of 16 colors each is enabled.

Once color paging is enabled, you can select a color page as follows:

- Read the Input Status 1 register at 3XAH to reset the AC Index/Data toggle;
- Write 34H to the AC Index register at 3C0H to address AC register 14H, the Color Select register;
- Write the desired page number (0 through 15) to the Color Select register via the AC Data register at 3C0H.

Repeat this process whenever you want to switch to another color page.

*Although it's not required, you'll generally want to wait for the leading edge of the vertical sync pulse before switching pages, as this provides the smoothest color transition, as described above. Take the vertical sync wait out of Listing 12.1 (which I'll present a little later) and set **USE_BIOS** to 0, and you'll see that the appearance of the program suffers considerably.*

Controlling color paging through the BIOS is a similar two-step process. The first step is to enable 16-pages-of-16-colors paging, and that's done by invoking interrupt 10H, the video interrupt, with AH = 10H, AL = 13H, BL = 0, and BH = 1. (If BH = 0, 4-pages-of-64-colors operation is selected.) The second step is to select the desired color page by invoking interrupt 10H with AH = 10H, AL = 13H, BL = 1, and BH = the number of the desired page, in the range 0 through 15.

Of those I've seen, at least one VGA BIOS waits for the leading edge of the vertical sync pulse before switching color pages, and at least one VGA BIOS does not. This poses a significant problem; if you wait for the leading edge of vertical sync before calling the BIOS to switch pages and then the BIOS waits for the leading edge of vertical sync before switching pages, you'll only switch pages once every two frames at most. On the other hand, if you don't wait for vertical sync and neither does the BIOS, you'll end up switching pages in the middle of frames and doing so much too often. You can determine which is the case in your color page-flipping programs by timing how long it takes the BIOS to do several color page switches at start-up, although that's certainly a nuisance. As usual, only with your own software that programs the hardware directly do you have complete control and full knowledge of what's going on.

At any rate, you can try it both ways, because Listing 12.1 supports both BIOS and direct color paging. In Listing 12.1, I assume that the BIOS does wait for the leading edge of the vertical sync pulse.

Obtaining the Color Paging State

If you want to check whether 16-pages-of-16-colors paging is enabled and which color page is currently selected, you can again do that either directly or through the BIOS. Obtaining the color paging state through the BIOS is ridiculously easy: Just invoke INT 10H with AH = 10H and AL = 1AH. On return, BL will contain the state of bit 7 of the AC Mode register (1 for 16-pages-of-16-colors paging, 0 for 4-pages-of-64-colors), and BH will contain the number of the currently selected color page.

To obtain the color paging state directly, do the following:

- Read the Input Status 1 register at 3XAH to reset the AC Index/Data toggle;
- Write 30H to the AC Index register at 3C0H to address the AC Mode register;
- Read the AC Mode register setting from the AC Data register at 3C1H. Bit 7 of this value controls the color paging state, as described above;
- Read the Input Status 1 register at 3XAH to reset the AC Index/Data toggle;
- Write 34H to the AC Index register at 3C0H to address the Color Select register;
- Read the Color Select register setting from the AC Data register at 3C1H.

An Example of Color Paging

Listing 12.1 is an example of color paging. Listing 12.1 first sets the display to 640×480 16-color graphics mode, then sets the palette RAM to a pass-through state and loads the upper 240 DAC locations with 240 colors, which are logically organized as 15 pages of 16 colors each. The palette RAM and the DAC must be set up *after* the mode set, because each mode set reprograms all of the palette RAM and at least part of the DAC. During EGA compatible mode sets, the first 64 DAC locations are programmed to match the EGA's set of colors, and during mode sets for mode 13H, 256-color mode, all 256 DAC locations are programmed.

Once the hardware is set up, Listing 12.1 draws dozens of concentric circles, using code we'll develop in Part IV of this book. I've used C rather than assembly language circle-drawing code (both versions are provided in Part IV) because drawing speed isn't an issue here; Listing 12.1 is written entirely in C, and while the drawing part of Listing 12.1 looks slow, the color paging part does not. By its very nature, which involves working with a few control registers rather than a large bitmap, color manipulation tends to produce snappy results with little effort.

LISTING 12.1 L12-1.C

```
/*
 * Illustrates color paging by color-animating a series of
 * concentric circles to produce the illusion of motion.
 * Runs on the VGA only, because color paging isn't available on
 * the EGA.
 */

#include <dos.h>

#define USE_BIOS   0   /* set to 1 to use BIOS functions to perform
                         color paging, 0 to program color paging
                        registers directly */


#define SCREEN_WIDTH_IN_BYTES  80         /* # of bytes across one scan
                                             line in mode 12h */
#define SCREEN_SEGMENT         0xA000     /* mode 12h display memory seg */
#define GC_INDEX               0x3CE      /* Graphics Controller index */
#define SET_RESET_INDEX        0          /* Set/Reset reg index in GC */
#define SET_RESET_ENABLE_INDEX 1          /* Set/Reset Enable reg index
                                             in GC */
#define BIT_MASK_INDEX         8          /* Bit Mask reg index in GC */
#define INPUT_STATUS_1         0x3DA      /* Input Status 1 port */
#define AC_INDEX               0x3C0      /* Attribute Controller index */
#define AC_DATA_W              0x3C0      /* Attribute Controller data
                                             register for writes */
#define AC_DATA_R              0x3C1      /* Attribute Controller data
                                             register for reads */

#define AC_MODE_INDEX          0x30       /* AC Mode reg index, with bit 6
                                             set to avoid blanking screen */
```

```
#define AC_COLOR_SELECT_INDEX  0x34        /* Color Select reg index, with
                                              bit 6 set to avoid blanking
                                              screen */

void main();
void DrawDot(int X, int Y);
void DrawCircle(int X, int Y, int Radius, int Color);

/* Array used to load the DAC. Organized as 256 RGB triplets */
static unsigned char DACSettings[256*3];

/* Array used to load the palette RAM to a pass-through state.
   The 17th entry sets the border color to 0 */
static unsigned char PaletteRAMSettings[] = {
   0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 0};

void main() {
    int Radius, Color, Page, Element, i;
    union REGS Regs;
    struct SREGS Sregs;
    unsigned char GreenComponent;

    /* Select VGA's hi-res 640x480 graphics mode, mode 12h */
    Regs.x.ax = 0x0012;
    int86(0x10, &Regs, &Regs);

    /* Draw concentric circles */
    for ( Radius = 10, Color = 1; Radius < 240; Radius += 2 ) {
        DrawCircle(640/2, 480/2, Radius, Color);
       if (++Color >= 16)
         Color = 1;                     /* skip color 0 */
   }

    /* Load the upper 240 DAC locations (15 pages) with one-position
       rotations of a series of increasingly green colors. Because
       page 0 is being displayed, the screen remains unchanged while
       the other 15 color pages are being loaded. */

    /* First, fill DACSettings with the desired green settings
       (because it's a static array, all locations are initialized to
       zero, so we don't need to initialize the red or green color
       components, which we want to be zero). */
    GreenComponent = 8;
    for ( Page = 1; Page <= 15; Page++ ) {
       GreenComponent = Page * 4;
       for ( Element = 1; Element <= 15; Element++ ) {
           DACSettings[Page*16*3 + Element*3 + 1] = GreenComponent;
          if ( (GreenComponent += 4) >= 64 )
             GreenComponent = 4;
      }
   }

    /* Now call the BIOS to load the upper 240 DAC locations */
    Regs.h.ah = 0x10;
    Regs.h.al = 0x12;
    Regs.x.bx = 16;
    Regs.x.cx = 240;
    Regs.x.dx = (unsigned int)(DACSettings + 16*3);
    segread(&Sregs);
    Sregs.es = Sregs.ds;         /* point ES:DX to DACSettings */
    int86x(0x10, &Regs, &Regs, &Sregs);
    /* Put the palette RAM in a pass-through state and set the Overscan
       register (border color) to 0. We've saved this for last because
       it changes the colors being displayed. */
    Regs.h.ah = 0x10;
    Regs.h.al = 2;
    Regs.x.dx = (unsigned int)PaletteRAMSettings;
    segread(&Sregs);
    Sregs.es = Sregs.ds;        /* point ES:DX to PaletteRAMSettings */
    int86x(0x10, &Regs, &Regs, &Sregs);

    /* Enable 16-pages-of-16-colors paging */
#if USE_BIOS
    Regs.h.ah = 0x10;
    Regs.h.al = 0x13;
    Regs.h.bl = 0;
    Regs.h.bh = 1;
    int86(0x10, &Regs, &Regs);
#else
    inp(INPUT_STATUS_1);
    outp(AC_INDEX, AC_MODE_INDEX);
    outp(AC_DATA_W, inp(AC_DATA_R) | 0x80);
#endif /* USE_BIOS */

    /* We're read to roll; the upper 15 pages are set up, the
       palette RAM is in a pass-through state, and 16-pages-of-16-
       colors paging is enabled. Now we'll loop through and display
       each of pages 15 through 1 and then back to 15 for one frame
       until a key is pressed. */
    for ( Page = 15, i = 0 ; i < 1000; i++ ) {

#if USE_BIOS
        /* Select the desired color page */
        Regs.h.ah = 0x10;
        Regs.h.al = 0x13;
        Regs.h.bl = 1;
        Regs.h.bh = Page;
        int86(0x10, &Regs, &Regs);
#else
        /* Wait for the leading edge of the vertical sync pulse; this
           ensures that we change color pages during vertical
           non-display time, and that the page flips are even spaced
           over time */
        while ( (inp(INPUT_STATUS_1) & 0x08) != 0 )
           ;                    /* wait for non-vertical sync time */
        while ( (inp(INPUT_STATUS_1) & 0x08) == 0 )
           ;                    /* wait for vertical sync time */
        inp(INPUT_STATUS_1);
        outp(AC_INDEX, AC_COLOR_SELECT_INDEX);
        outp(AC_DATA_W, Page);
#endif /* USE_BIOS */


        /* Cycle from page 15 down to page 1, and then back to page 15.
           Avoid page 0 entirely */
        if (--Page == 0)
           Page = 15;
    }

    /* Restore text mode and done */
    Regs.x.ax = 0x0003;
    int86(0x10, &Regs, &Regs);
}
```

```
/* Draws a pixel at screen coordinate (X,Y) */
void DrawDot(int X, int Y) {
    unsigned char far *ScreenPtr;

    /* Point to the byte the pixel is in */
#ifdef __TURBOC__
    ScreenPtr = MK_FP(SCREEN_SEGMENT,
       (Y * SCREEN_WIDTH_IN_BYTES) + (X / 8));
#else
    FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
    FP_OFF(ScreenPtr) =(Y * SCREEN_WIDTH_IN_BYTES) + (X / 8);
#endif

    /* Set the bit mask within the byte for the pixel */
    outp(GC_INDEX + 1, 0x80 >> (X & 0x07));

    /* Draw the pixel. ORed to force read/write to load latches.
       Data written doesn't matter, because set/reset is enabled
       for all planes. Note: don't OR with 0; MSC optimizes that
       statement to no operation. */
    *ScreenPtr |= 0xFF;
}

/* Draws a circle of radius Radius in color Color centered at
 * screen coordinate (X,Y) */
void DrawCircle(int X, int Y, int Radius, int Color) {
    int MajorAxis, MinorAxis;
    unsigned long RadiusSqMinusMajorAxisSq;
    unsigned long MinorAxisSquaredThreshold;

    /* Set drawing color via set/reset */
    outpw(GC_INDEX, (0x0F << 8) | SET_RESET_ENABLE_INDEX);
                                   /* enable set/reset for all planes */
    outpw(GC_INDEX, (Color << 8) | SET_RESET_INDEX);
                                   /* set set/reset (drawing) color */
    outp(GC_INDEX, BIT_MASK_INDEX);
                                   /* leave the GC Index reg pointing to
                                      the Bit Mask reg */

    /* Set up to draw the circle by setting the initial point to one
       end of the 1/8th of a circle arc we'll draw */
    MajorAxis = 0;
    MinorAxis = Radius;
    /* Set initial Radius**2 - MajorAxis**2 (MajorAxis is initially 0) */
    RadiusSqMinusMajorAxisSq = Radius * Radius;
    /* Set threshold for minor axis movement at (MinorAxis - 0.5)**2 */
    MinorAxisSquaredThreshold = MinorAxis * MinorAxis - MinorAxis;

    /* Draw all points along an arc of 1/8th of the circle, drawing
       all 8 symmetries at the same time */
    do {
       /* Draw all 8 symmetries of current point */
        DrawDot(X+MajorAxis, Y-MinorAxis);
        DrawDot(X-MajorAxis, Y-MinorAxis);
        DrawDot(X+MajorAxis, Y+MinorAxis);
        DrawDot(X-MajorAxis, Y+MinorAxis);
        DrawDot(X+MinorAxis, Y-MajorAxis);
        DrawDot(X-MinorAxis, Y-MajorAxis);
        DrawDot(X+MinorAxis, Y+MajorAxis);
        DrawDot(X-MinorAxis, Y+MajorAxis);
```

```
         /* Advance (Radius**2 - MajorAxis**2); if it equals or passes
            the MinorAxis**2 threshold, advance one pixel along the minor
            axis and set the next MinorAxis**2 threshold. */
         if ( (RadiusSqMinusMajorAxisSq -=
            MajorAxis + MajorAxis + 1) <= MinorAxisSquaredThreshold ) {
           MinorAxis--;
            MinorAxisSquaredThreshold -= MinorAxis + MinorAxis;
       }
        MajorAxis++;          /* advance one pixel along the major axis */
     } while ( MajorAxis <= MinorAxis );

     /* Reset the Bit Mask register to normal */
     outp(GC_INDEX + 1, 0xFF);

     /* Turn off set/reset enable */
      outpw(GC_INDEX, (0x00 << 8) | SET_RESET_ENABLE_INDEX);
}
```

The circles in Listing 12.1 are drawn in sequential colors 1 through 15, cycling back from 15 to 1. Color 0 is reserved for the background and is the same in all 16 color pages; otherwise the background would change color as we changed color pages, destroying the subtle color cycling effect we're striving for. The background wouldn't be the only potential problem, either; if page 0 is involved, the border could also change, creating a still more bizarre effect. Remember, the DAC modifies pixels after they've been fully processed by the VGA, and so far as the DAC is concerned, pixel attribute 0 is attribute 0, irrespective of whether it came from the Overscan (border) register, a background pixel with value 0, or, indeed, by way of translation in the palette RAM. Consequently, you should take care when performing color paging not to modify the DAC locations that the Overscan register and background colors select, unless, of course, you intend to change the border and background colors.

This is a good time to point out that the DAC is *always* available and active. It's obvious that the DAC can be used to select color sets in 256- and 16-color modes, but the DAC processes whatever comes out of the VGA in any mode. You can use the DAC to transform pixel colors in text mode, or even in modes 4 and 6, the CGA-compatible 4- and 2-color graphics modes (although in order to do that you need to understand the format in which pixels comes out of the VGA and into the DAC in those modes; once again, setting the palette to a pass-through state makes life easier). In fact, you can also use color paging in any mode other than 256-color mode. The basic principle here is that the color-processing steps that occur farther down the pipeline toward the display can modify anything that comes earlier. As the last stage in the pipeline, the DAC can modify pixels in any mode at all, and as the lead-in to the DAC stage, color paging can modify pixels in all modes except 256-color mode.

Back to Listing 12.1. Once the circles are drawn, Listing 12.1 switches from the default color page, page 0, which we haven't changed, to page 15, and then starts flipping through the color pages in the order 14, 13, and so on down to 1 and then back round to 15 at the rate of one page per frame, or 60 times per second. What does this accomplish? Well, the color pages were carefully selected as one-position rotations of increasingly bright green colors. That is, color page 1 translates a pixel value of 1 into dim green, a pixel value of 2 into next-to-dimmest green, and so on up to a pixel value of 15, which is as green a color as the VGA can produce. Color page 2 is a one-position rotation of color page 1; a pixel value of 1 produces next-to-dimmest green, a pixel value of 2 produces slightly brighter green, a pixel value of 14 produces brightest green, and a pixel value of 15 produces dimmest green. Each successive color page is a one-position rotation of the preceding page, except for color page 0, which isn't used because we need only 15 color pages to represent all possible rotations of a set of 15 colors.

Cycling through these color pages causes the circles on the screen to seem to pulse outward. The net effect is one of smooth motion, but not one pixel in display memory is being modified. This is the wonder of color manipulation: effects worthy of high-end graphics systems with little effort. Of course, there are limits to what color manipulation can do, but what it does, it does *very* well.

Listing 12.1 can perform color paging using either the direct or BIOS approach, depending on the setting of **USE_BIOS**. On my computer, both versions look exactly the same. Experiment for yourself and choose whichever you prefer.

Paging Invisible Pages

One advantage of color paging is that you can change the contents of non-displayed color pages without affecting the display in any way. Manipulating the color pages in this way is much like page flipping-based animation; while you're displaying one color page, you alter another one, then display the other one when it's ready to go. The advantage of this over simply changing the palette is that the user will see only the finished color configuration, not an intermediate state. This approach effectively expands the number of available color pages from 16 to more than 4 million (16 colors per set times 256K choices for each color; that is, every combination of 16 colors possible on the VGA).

Although it's not the main thrust of the code, Listing 12.1 does illustrate the technique of changing a non-displayed color page so as to leave the display unaffected while the DAC is being loaded. At the outset of Listing 12.1, page 0 is displayed while the DAC locations for pages 1 through 15 are loaded. Once the loading is complete, the program switches away from page 0 to begin cycling through the newly-loaded pages 15 through 1.

That brings us to the end of color paging, but certainly not to the end of color on the VGA. We still haven't looked closely at color cycling, so that's where we'll head in the next chapter.

Changing Colors without Writing Pixels

Chapter 13

Special Effects through Realtime Manipulation of DAC Colors

Sometimes, strange as it may seem, the harder you try, the less you accomplish. Brute force is fine when it suffices, but it does not always suffice, and when it does not, finesse and alternative approaches are called for. Such is the case with rapidly cycling through colors by repeatedly loading the VGA's Digital to Analog Converter (DAC). No matter how much you optimize your code, you just can't reliably load the whole DAC cleanly in a single frame, so you had best find other ways to use the DAC to cycle colors. What's more, BIOS support for DAC loading is so inconsistent that it's unusable for color cycling; direct loading through the I/O ports is the only way to go. We'll see why next, as we explore color cycling, and then finish up this chapter and this section by cleaning up some odds and ends about VGA color.

There's a lot to be said about loading the DAC, so let's dive right in and see where the complications lie.

Color Cycling

As we've learned in past chapters, the VGA's DAC contains 256 storage locations, each holding one 18-bit value representing an RGB color triplet organized as 6 bits per primary color. Each and every pixel generated by the VGA is fed into the DAC as an 8-bit value (refer to the previous two chapters to see how pixels become 8-bit values in non-256 color modes) and each 8-bit value is used to look up one of the 256 values stored in the DAC. The looked-up value is then converted to analog red, green, and blue signals and sent to the monitor to form one pixel.

That's straightforward enough, and we've produced some pretty impressive color effects by loading the DAC once and then playing with the 8-bit path into the DAC. Now, however, we want to generate color effects by dynamically changing the values stored in the DAC in real time, a technique which I'll call *color cycling.* The potential of color cycling should be obvious: Smooth motion can easily be simulated by altering the colors in an appropriate pattern, and all sorts of changing color effects can be produced without altering a single bit of display memory.

For example, a sunset can be made to color and darken by altering the DAC locations containing the colors used to draw the sunset, or a river can be made to appear to flow by cycling through the colors used to draw the river. Another use for color cycling is in providing more realistic displays for applications like realtime 3-D games, where the VGA's 256 simultaneous colors can be made to seem like many more by changing the DAC settings from frame to frame to match the changing color demands of the rendered scene. Which leaves only one question: How do we load the DAC smoothly in realtime?

Actually, so far as I know, you can't. At least you can't load the *entire* DAC—all 256 locations—frame after frame without producing distressing on-screen effects on at least some computers. In non-256 color modes, it is indeed possible to load the DAC quickly enough to cycle all displayed colors (of which there are 16 or fewer), so color cycling could be used successfully to cycle all colors in such modes. On the other hand, color paging (which flips among a number of color sets stored within the DAC in all modes other than 256 color mode, as discussed in the previous chapter) can be used in non-256 color modes to produce many of the same effects as color cycling and is considerably simpler and more reliable then color cycling, so color paging is generally superior to color cycling whenever it's available. In short, color cycling is really the method of choice for dynamic color effects only in 256-color mode—but, regrettably, color cycling is at its least reliable and capable in that mode, as we'll see next.

The Heart of the Problem

Here's the problem with loading the entire DAC repeatedly: The DAC contains 256 color storage locations, each loaded via either 3 or 4 **OUT** instructions (more on which next), so at least 768 **OUT**s are needed to load the entire DAC. That many **OUT**s take a considerable amount of time, all the more so because **OUT**s are painfully slow on 486s and Pentiums, and because the DAC is frequently on the ISA bus (although VLB and PCI are increasingly common), where wait states are inserted in fast computers. In an 8 MHz AT, 768 OUTs alone would take 288 microseconds, and the data loading and looping that are also required would take in the ballpark of 1,800 microseconds more, for a minimum of 2 milliseconds total.

As it happens, the DAC should only be loaded during vertical blanking; that is, the time between the end of displaying the bottom border and the start of displaying the top border, when no video information at all is being sent to the screen by the DAC. Otherwise, small dots of snow appear on the screen, and while an occasional dot of this sort wouldn't be a problem, the constant DAC loading required by color cycling would produce a veritable snowstorm on the screen. By the way, I do mean "border," not "frame buffer"; the overscan pixels pass through the DAC just like the pixels controlled by the frame buffer, so you can't even load the DAC while the border color is being displayed without getting snow.

The start of vertical blanking itself is not easy to find, but the leading edge of the vertical sync pulse is easy to detect via bit 3 of the Input Status 1 register at 3DAH; when bit 3 is 1, the vertical sync pulse is active. Conveniently, the vertical sync pulse starts partway through but not too far into vertical blanking, so it serves as a handy way to tell when it's safe to load the DAC without producing snow on the screen.

So we wait for the start of the vertical sync pulse, then begin to load the DAC. There's a catch, though. On many computers—Pentiums, 486s, and 386s sometimes, 286s most of the time, and 8088s all the time—there just isn't enough time between the start of the vertical sync pulse and the end of vertical blanking to load all 256 DAC locations. That's the crux of the problem with the DAC, and shortly we'll get to a tool that will let you explore for yourself the extent of the problem on computers in which you're interested. First, though, we must address *another* DAC loading problem: the BIOS.

Loading the DAC via the BIOS

The DAC can be loaded either directly or through subfunctions 10H (for a single DAC register) or 12H (for a block of DAC registers) of the BIOS video service interrupt 10H, function 10H, described in Chapter 11. For cycling the contents of the entire DAC, the block-load function (invoked by executing **INT** 10H with AH = 10H and AL = 12H to load a block of CX DAC locations, starting at location BX, from the block of RGB triplets—3 bytes per triplet—starting at ES:DX into the DAC) would be the better of the two, due to the considerably greater efficiency of calling the BIOS once rather than 256 times. At any rate, we'd like to use one or the other of the BIOS functions for color cycling, because we know that whenever possible, one should use a BIOS function in preference to accessing hardware directly, in the interests of avoiding compatibility problems. In the case of color cycling, however, it is emphatically *not* possible to use either of the BIOS functions, for they have problems. Serious problems.

The difficulty is this: IBM's BIOS specification describes exactly how the parameters passed to the BIOS control the loading of DAC locations, and all clone BIOSes meet that specification scrupulously, which is to say that if you invoke **INT** 10H, function 10H, subfunction 12H with a given set of parameters, you can be sure that you will end up with the same values loaded into the same DAC locations on all VGAs from all vendors. IBM's spec does *not*, however, describe whether vertical retrace should be waited for before loading the DAC, nor does it mention whether video should be left enabled while loading the DAC, leaving cloners to choose whatever approach they desire—and, alas, every VGA cloner seems to have selected a different approach.

I tested four clone VGAs from different manufacturers, some in a 20 MHz 386 machine and some in a 10 MHz 286 machine. Two of the four waited for vertical retrace before loading the DAC; two didn't. Two of the four blanked the display while loading the DAC, resulting in flickering bars across the screen. One showed speckled pixels spattered across the top of the screen while the DAC was being loaded. Also, not one was able to load all 256 DAC locations without showing *some* sort of garbage on the screen for at least one frame, but that's not the BIOS's fault; it's a problem endemic to the VGA.

The above findings lead me inexorably to the conclusion that the BIOS should not be used to load the DAC dynamically. That is, if you're loading the DAC just once in preparation for a graphics session—sort of a DAC mode set—by all means load by way of the BIOS. No one will care that some garbage is displayed for a single frame; heck, I have boards that bounce and flicker and show garbage every time I do a mode set, and the amount of garbage produced by loading the DAC once is far less noticeable. If, however, you intend to load the DAC repeatedly for color cycling, avoid the BIOS DAC load functions like the plague. They will bring you only heartache.

As but one example of the unsuitability of the BIOS DAC-loading functions for color cycling, imagine that you want to cycle all 256 colors 70 times a second, which is once per frame. In order to accomplish that, you would normally wait for the start of the vertical sync signal (marking the end of the frame), then call the BIOS to load the DAC. On some boards—boards with BIOSes that don't wait for vertical sync before loading the DAC—that will work pretty well; you will, in fact, load the DAC once a frame. On other boards, however, it will work very poorly indeed; your program will wait for the start of vertical sync, and then the BIOS will wait for the start of the next vertical sync, with the result being that the DAC gets loaded only once every *two* frames. Sadly, there's no way, short of actually profiling the performance of BIOS DAC loads, for you to know which sort of BIOS is installed in a particular computer, so unless you can always control the brand of VGA your software will run on, you really can't afford to color cycle by calling the BIOS.

Which is not to say that loading the DAC directly is a picnic either, as we'll see next.

Loading the DAC Directly

So we must load the DAC directly in order to perform color cycling. The DAC is loaded directly by sending (with an OUT instruction) the number of the DAC location to be loaded to the DAC Write Index register at 3C8H and then performing three **OUT**s to write an RGB triplet to the DAC Data register at 3C9H. This approach must be repeated 256 times to load the entire DAC, requiring over a thousand **OUT**s in all.

There is another, somewhat faster approach, but one that has its risks. After an RGB triplet is written to the DAC Data register, the DAC Write Index register automatically increments to point to the next DAC location, and this repeats indefinitely as successive RGB triplets are written to the DAC. By taking advantage of this feature, the entire DAC can be loaded with just 769 **OUT**s: one **OUT** to the DAC Write Index register and 768 **OUT**s to the DAC Data register.

So what's the drawback? Well, imagine that as you're loading the DAC, an interrupt-driven TSR (such as a program switcher or multitasker) activates and writes to the DAC; you could end up with quite a mess on the screen, especially when your program resumes and continues writing to the DAC—but in all likelihood to the wrong locations. No problem, you say; just disable interrupts for the duration. Good idea—but it takes much longer to load the DAC than interrupts should be disabled for. If, on the other hand, you set the index for each DAC location separately, you can disable interrupts 256 times, once as each DAC location is loaded, without problems.

As I commented two chapters back, I don't have any gruesome tale to relate that mandates taking the slower but safer road and setting the index for each DAC location separately while interrupts are disabled. I'm merely hypothesizing as to what ghastly mishaps *could* happen. However, it's been my experience that anything that can happen on the PC *does* happen eventually; there are just too dang many PCs out there for it to be otherwise. However, load the DAC any way you like; just don't blame me if you get a call from someone who's claims that your program sometimes turns their screen into something resembling month-old yogurt. It's not really your fault, of course—but try explaining that to *them!*

A Test Program for Color Cycling

Anyway, the choice of how to load the DAC is yours. Given that I'm not providing you with any hard-and-fast rules (mainly because there don't seem to be any), what you need is a tool so that you can experiment with various DAC-loading approaches for yourself, and that's exactly what you'll find in Listing 13.1.

Listing 13.1 draws a band of vertical lines, each one pixel wide, across the screen. The attribute of each vertical line is one greater than that of the preceding line, so there's a smooth gradient of attributes from left to right. Once everything is set up, the program starts cycling the colors stored in however many DAC locations are specified by the **CYCLE_SIZE** equate; as many as all 256 DAC locations can be cycled. (Actually, **CYCLE_SIZE**-1 locations are cycled, because location 0 is kept constant in order to keep the background and border colors from changing, but **CYCLE_SIZE** locations are *loaded*, and it's the number of locations we can load without problems that we're interested in.)

LISTING 13.1 L13-1.ASM

```
; Fills a band across the screen with vertical bars in all 256
; attributes, then cycles a portion of the palette until a key is
; pressed.
; Assemble with MASM or TASM

USE_BIOS               equ   1   ;set to 1 to use BIOS functions to access the
                                 ; DAC, 0 to read and write the DAC directly
GUARD_AGAINST_INTS     equ   1   ;1 to turn off interrupts and set write index
                                 ; before loading each DAC location, 0 to rely
                                 ; on the DAC auto-incrementing
WAIT_VSYNC             equ   1   ;set to 1 to wait for the leading edge of
                                 ; vertical sync before accessing the DAC, 0
                                 ; not to wait
NOT_8088               equ   0       ;set to 1 to use REP INSB and REP OUTSB when
                                     ; accessing the  DAC directly, 0 to use
                                     ;  IN/STOSB and LODSB/OUT
CYCLE_SIZE             equ   256     ;# of DAC locations to cycle, 256 max
SCREEN_SEGMENT         equ   0a000h  ;mode 13h display memory segment
SCREEN_WIDTH_IN_BYTES  equ   320     ;# of bytes across the screen in mode 13h
INPUT_STATUS_1         equ   03dah   ;input status 1 register port
DAC_READ_INDEX         equ   03c7h   ;DAC Read Index register
DAC_WRITE_INDEX        equ   03c8h   ;DAC Write Index register
DAC_DATA               equ   03c9h   ;DAC Data register

if NOT_8088
        .286
endif   ;NOT_8088

        .model  small
        .stack  100h
        .data
;Storage for all 256 DAC locations, organized as one three-byte
; (actually three 6-bit values; upper two bits of each byte aren't
; significant) RGB triplet per color.
PaletteTemp     db   256*3 dup(?)
        .code
start:
        mov     ax,@data
        mov     ds,ax

;Select VGA's standard 256-color graphics mode, mode 13h.
        mov     ax,0013h                      ;AH = 0: set mode function,
        int     10h                           ; AL = 13h: mode # to set

;Read all 256 DAC locations into PaletteTemp (3 6-bit values, one
; each for red, green, and blue, per DAC location).

if WAIT_VSYNC
;Wait for the leading edge of the vertical sync pulse; this ensures
; that we read the DAC starting during the vertical non-display
; period.
        mov     dx,INPUT_STATUS_1
WaitNotVSync:                            ;wait to be out of vertical sync
        in      al,dx
        and     al,08h
        jnz     WaitNotVSync
WaitVSync:                               ;wait until vertical sync begins
        in      al,dx
        and     al,08h
        jz      WaitVSync
endif                                     ;WAIT_VSYNC

if USE_BIOS
        mov     ax,1017h                  ;AH = 10h: set DAC function,
                                          ; AL = 17h: read DAC block
subfunction
        sub     bx,bx                     ;start with DAC location 0
        mov     cx,256                    ;read out all 256 locations
        mov     dx,seg PaletteTemp
        mov     es,dx
        mov     dx,offset PaletteTemp     ;point ES:DX to array in which
                                          ; the DAC values are to be stored
        int     10h                       ;read the DAC
else                                      ;!USE_BIOS
 if GUARD_AGAINST_INTS
        mov     cx,CYCLE_SIZE             ;# of DAC locations to load
        mov     di,seg PaletteTemp
        mov     es,di
        mov     di,offset PaletteTemp     ;dump the DAC into this array
        sub     ah,ah                     ;start with DAC location 0
DACStoreLoop:
        mov     dx,DAC_READ_INDEX
        mov     al,ah
        cli
        out     dx,al                     ;set the DAC location #
        mov     dx,DAC_DATA
        in      al,dx                     ;get the red component
        stosb
        in      al,dx                     ;get the green component
        stosb
        in      al,dx                     ;get the blue component
        stosb
        sti
        inc     ah
        loop    DACStoreLoop
 else   ;!GUARD_AGAINST_INTS
        mov     dx,DAC_READ_INDEX
        sub     al,al
        out     dx,al                     ;set the initial DAC location to 0
        mov     di,seg PaletteTemp
        mov     es,di
        mov     di,offset PaletteTemp     ;dump the DAC into this array
        mov     dx,DAC_DATA
  if NOT_8088
        mov     cx,CYCLE_SIZE*3
        rep     insb                      ;read CYCLE_SIZE DAC locations at
once
  else ;!NOT_8088
        mov     cx,CYCLE_SIZE             ;# of DAC locations to load
DACStoreLoop:
        in      al,dx                     ;get the red component
        stosb
        in      al,dx                     ;get the green component
        stosb
        in      al,dx                     ;get the blue component
        stosb
        loop    DACStoreLoop
  endif                             ;NOT_8088
 endif                              ;GUARD_AGAINST_INTS
endif   ;USE_BIOS
```

```
;Draw a series of 1-pixel-wide vertical bars across the screen in
; attributes 1 through 255.
        mov     ax,SCREEN_SEGMENT
        mov     es,ax
        mov     di,50*SCREEN_WIDTH_IN_BYTES     ;point ES:DI to the start
                                                ; of line 50 on the screen
        cld
        mov     dx,100                          ;draw 100 lines high
RowLoop:
        mov     al,1                            ;start each line with attr 1
        mov     cx,SCREEN_WIDTH_IN_BYTES        ;do a full line across
ColumnLoop:
        stosb                                   ;draw a pixel
        add     al,1                            ;increment the attribute
        adc     al,0                            ;if the attribute just turned
                                                ; over to 0, increment it to 1
                                                ; because we're not going to
                                                ; cycle DAC location 0, so
                                                ; attribute 0 won't change
        loop    ColumnLoop
        dec     dx
        jnz     RowLoop

;Cycle the specified range of DAC locations until a key is pressed.
CycleLoop:
;Rotate colors 1-255 one position in the PaletteTemp array;
; location 0 is always left unchanged so that the background
; and border don't change.
        push    word ptr PaletteTemp+(1*3)      ;set aside PaletteTemp
        push    word ptr PaletteTemp+(1*3)+2    ; setting for attr 1
        mov     cx,254
        mov     si,offset PaletteTemp+(2*3)
        mov     di,offset PaletteTemp+(1*3)
        mov     ax,ds
        mov     es,ax
        mov     cx,254*3/2
        rep     movsw                           ;rotate PaletteTemp settings
                                                ; for attrs 2 through 255 to
                                                ; attrs 1 through 254
        pop     bx                              ;get back original settings
        pop     ax                              ; for attribute 1 and move
        stosw                                   ; them to the PaletteTemp
        mov     es:[di],bl                      ; location for attribute 255

if WAIT_VSYNC
;Wait for the leading edge of the vertical sync pulse; this ensures
; that we reload the DAC starting during the vertical non-display
; period.
        mov     dx,INPUT_STATUS_1
WaitNotVSync2:                          ;wait to be out of vertical sync
        in      al,dx
        and     al,08h
        jnz     WaitNotVSync2
WaitVSync2:                             ;wait until vertical sync begins
        in      al,dx
        and     al,08h
        jz      WaitVSync2
endif   ;WAIT_VSYNC

if USE_BIOS
```

```
;Set the new, rotated palette.
        mov     ax,1012h                ;AH = 10h: set DAC function,
                                        ; AL = 12h: set DAC block subfunction
        sub     bx,bx                   ;start with DAC location 0
        mov     cx,CYCLE_SIZE           ;# of DAC locations to set
        mov     dx,seg PaletteTemp
        mov     es,dx
        mov     dx,offset PaletteTemp   ;point ES:DX to array from which
                                        ; to load the DAC
        int     10h                     ;load the DAC
else    ;!USE_BIOS
 if GUARD_AGAINST_INTS
        mov     cx,CYCLE_SIZE           ;# of DAC locations to load
        mov     si,offset PaletteTemp   ;load the DAC from this array
        sub     ah,ah                   ;start with DAC location 0
DACLoadLoop:
        mov     dx,DAC_WRITE_INDEX
        mov     al,ah
        cli
        out     dx,al                   ;set the DAC location #
        mov     dx,DAC_DATA
        lodsb
        out     dx,al                   ;set the red component
        lodsb
        out     dx,al                   ;set the green component
        lodsb
        out     dx,al                   ;set the blue component
        sti
        inc     ah
        loop    DACLoadLoop
 else   ;!GUARD_AGAINST_INTS
        mov     dx,DAC_WRITE_INDEX
        sub     al,al
        out     dx,al                   ;set the initial DAC location to 0
        mov     si,offset PaletteTemp   ;load the DAC from this array
        mov     dx,DAC_DATA
  if NOT_8088
        mov     cx,CYCLE_SIZE*3
        rep     outsb              ;load CYCLE_SIZE DAC locations at once
  else  ;!NOT_8088
        mov     cx,CYCLE_SIZE           ;# of DAC locations to load
DACLoadLoop:
        lodsb
        out     dx,al                   ;set the red component
        lodsb
        out     dx,al                   ;set the green component
        lodsb
        out     dx,al                   ;set the blue component
        loop    DACLoadLoop
  endif ;NOT_8088
 endif  ;GUARD_AGAINST_INTS
endif   ;USE_BIOS

;See if a key has been pressed.
        mov     ah,0bh                  ;DOS check standard input status fn
        int     21h
        and     al,al                   ;is a key pending?
        jz      CycleLoop               ;no, cycle some more

;Clear the keypress.
        mov     ah,1                    ;DOS keyboard input fn
        int     21h
```

```
;Restore text mode and done.
        mov     ax,0003h                        ;AH = 0: set mode function,
        int     10h                             ; AL = 03h: mode # to set
        mov     ah,4ch                          ;DOS terminate process fn
        int     21h

        end     start
```

The big question is, How does Listing 13.1 cycle colors? Via the BIOS or directly? With interrupts enabled or disabled? *Et cetera*?

However you like, actually. Four equates at the top of Listing 13.1 select the sort of color cycling performed; by changing these equates and **CYCLE_SIZE**, you can get a feel for how well various approaches to color cycling work with whatever combination of computer system and VGA you care to test.

The **USE_BIOS** equate is simple. Set **USE_BIOS** to 1 to load the DAC through the block-load-DAC BIOS function, or to 0 to load the DAC directly with **OUT**s.

If **USE_BIOS** is 1, the only other equate of interest is **WAIT_VSYNC**. If **WAIT_VSYNC** is 1, the program waits for the leading edge of vertical sync before loading the DAC; if **WAIT_VSYNC** is 0, the program doesn't wait before loading. The effect of setting or not setting **WAIT_VSYNC** depends on whether the BIOS of the VGA the program is running on waits for vertical sync before loading the DAC. You may end up with a double wait, causing color cycling to proceed at half speed, you may end up with no wait at all, causing cycling to occur far too rapidly (and almost certainly with hideous on-screen effects), or you may actually end up cycling at the proper one-cycle-per-frame rate.

If **USE_BIOS** is 0, **WAIT_VSYNC** still applies. However, you will always want to set **WAIT_VSYNC** to 1 when **USE_BIOS** is 0; otherwise, cycling will occur much too fast, and a good deal of continuous on-screen garbage is likely to make itself evident as the program loads the DAC non-stop.

If **USE_BIOS** is 0, **GUARD_AGAINST_INTS** determines whether the possibility of the DAC loading process being interrupted is guarded against by disabling interrupts and setting the write index once for every location loaded and whether the DAC's autoincrementing feature is relied upon or not.

If **GUARD_AGAINST_INTS** is 1, the following sequence is followed for the loading of each DAC location in turn: Interrupts are disabled, the DAC Write Index register is set appropriately, the RGB triplet for the location is written to the DAC Data register, and interrupts are enabled. This is the slow but safe approach described earlier.

Matters get still more interesting if **GUARD_AGAINST_INTS** is 0. In that case, if **NOT_8088** is 0, then an autoincrementing load is performed in a straightforward fashion; the DAC Write Index register is set to the index of the first location to load and the RGB triplet is sent to the DAC by way of three **LODSB/OUT DX,AL** pairs, with **LOOP** repeating the process for each of the locations in turn.

If, however, **NOT_8088** is 1, indicating that the processor is a 286 or better (perhaps **AT_LEAST_286** would have been a better name), then after the initial DAC

Write Index value is set, all 768 DAC locations are loaded with a single **REP OUTSB**. This is clearly the fastest approach, but it runs the risk, albeit remote, that the loading sequence will be interrupted and the DAC registers will become garbled.

My own experience with Listing 13.1 indicates that it is sometimes possible to load all 256 locations cleanly but sometimes it is not; it all depends on the processor, the bus speed, the VGA, and the DAC, as well as whether autoincrementation and **REP OUTSB** are used. I'm not going to bother to report how many DAC locations I *could* successfully load with each of the various approaches, for the simple reason that I don't have enough data points to make reliable suggestions, and I don't want you acting on my comments and running into trouble down the pike. You now have a versatile tool with which to probe the limitations of various DAC-loading approaches; use it to perform your own tests on a sampling of the slowest hardware configurations you expect your programs to run on, then leave a generous safety margin.

One thing's for sure, though—you're not going to be able to cycle all 256 DAC locations cleanly once per frame on a reliable basis across the current generation of PCs. That's why I said at the outset that brute force isn't appropriate to the task of color cycling. That doesn't mean that color cycling can't be used, just that subtler approaches must be employed. Let's look at some of those alternatives.

Color Cycling Approaches that Work

First of all, I'd like to point out that when color cycling does work, it's a thing of beauty. Assemble Listing 13.1 so that it doesn't use the BIOS to load the DAC, doesn't guard against interrupts, and uses 286-specific instructions if your computer supports them. Then tinker with **CYCLE_SIZE** until the color cycling is perfectly clean on your computer. Color cycling looks stunningly smooth, doesn't it? And this is crude color cycling, working with the default color set; switch over to a color set that gradually works its way through various hues and saturations, and you could get something that looks for all the world like true-color animation (albeit working with a small subset of the full spectrum at any one time).

Given that, how can we take advantage of color cycling within the limitations of loading the DAC? The simplest approach, and my personal favorite, is that of cycling a portion of the DAC while using the rest of the DAC locations for other, non-cycling purposes. For example, you might allocate 32 DAC locations to the aforementioned sunset, reserve 160 additional locations for use in drawing a static mountain scene, and employ the remaining 64 locations to draw images of planes, cars, and the like in the foreground. The 32 sunset colors could be cycled cleanly, and the other 224 colors would remain the same throughout the program, or would change only occasionally.

That suggests a second possibility: If you have several different color sets to be cycled, interleave the loading so that only one color set is cycled per frame. Suppose you are animating a night scene, with stars twinkling in the background, meteors streaking across the sky, and a spaceship moving across the screen with its jets flaring. One way to produce most of the necessary effects with little effort would be to draw the stars in several attributes and then cycle the colors for those attributes, draw the meteor paths in successive attributes, one for each pixel, and then cycle the colors for *those* attributes, and do much the same for the jets. The only remaining task would be to animate the spaceship across the screen, which is not a particularly difficult task.

The key to getting all the color cycling to work in the above example, however, would be to assign each color cycling task a different part of the DAC, with each part cycled independently as needed. If, as is likely, the total number of DAC locations cycled proved to be too great to manage in one frame, you could simply cycle the colors of the stars after one frame, the colors of the meteors after the next, and the colors of the jets after yet another frame, then back around to cycling the colors of the stars. By splitting up the DAC in this manner and interleaving the cycling tasks, you can perform a great deal of seemingly complex color animation without loading very much of the DAC during any one frame.

Yet another and somewhat odder workaround is that of using only 128 DAC locations and page flipping. (Page flipping in 256-color modes involves using the VGA's undocumented 256-color modes; see Chapters 9, 28, and 32 for details.) In this mode of operation, you'd first display page 0, which is drawn entirely with colors 0-127. Then you'd draw page 1 to look just like page 0, except that colors 128-255 are used instead. You'd load DAC locations 128-255 with the next cycle settings for the 128 colors you're using, then you'd switch to display the second page with the new colors. Then you could modify page 0 as needed, drawing in colors 0-127, load DAC locations 0-127 with the next color cycle settings, and flip back to page 0.

The idea is that you modify only those DAC locations that are not used to display any pixels on the current screen. The advantage of this is *not*, as you might think, that you don't generate garbage on the screen when modifying undisplayed DAC locations; in fact, you do, for a spot of interference will show up if you set a DAC location, displayed or not, during display time. No, you still have to wait for vertical sync and load only during vertical blanking before loading the DAC when page flipping with 128 colors; the advantage is that since none of the DAC locations you're modifying is currently displayed, you can spread the loading out over two or more vertical blanking periods—however long it takes. If you did this without the 128-color page flipping, you might get odd on-screen effects as some of the colors changed after one frame, some after the next, and so on—or you might not; changing the entire DAC in chunks over several frames is another possibility worth considering.

Yet another approach to color cycling is that of loading a bit of the DAC during each horizontal blanking period. Combine that with counting scan lines, and you could vastly expand the number of simultaneous on-screen colors by cycling colors *as* *a frame is displayed*, so that the color set changes from scan line to scan line down the screen.

The possibilities are endless. However, were I to be writing 256-color software that used color cycling, I'd find out how many colors could be cycled after the start of vertical sync on the slowest computer I expected the software to run on, I'd lop off at least 10 percent for a safety margin, and I'd structure my program so that no color cycling set exceeded that size, interleaving several color cycling sets if necessary.

That's what *I'd* do. Don't let yourself be held back by my limited imagination, though! Color cycling may be the most complicated of all the color control techniques, but it's also the most powerful.

Odds and Ends

In my experience, when relying on the autoincrementing feature while loading the DAC, the Write Index register wraps back from 255 to 0, and likewise when you load a block of registers through the BIOS. So far as I know, this is a characteristic of the hardware, and should be consistent; also, Richard Wilton documents this behavior for the BIOS in the VGA bible, *Programmer's Guide to PC Video Systems, Second Edition* (Microsoft Press), so you should be able to count on it. Not that I see that DAC index wrapping is especially useful, but it never hurts to understand exactly how your resources behave, and I never know when one of you might come up with a serviceable application for any particular quirk.

The DAC Mask

There's one register in the DAC that I haven't mentioned yet, the DAC Mask register, at 03C6H. The operation of this register is simple but powerful; it can mask off any or all of the 8 bits of pixel information coming into the DAC from the VGA. Whenever a bit of the DAC Mask register is 1, the corresponding bit of pixel information is passed along to the DAC to be used in looking up the RGB triplet to be sent to the screen. Whenever a bit of the DAC Mask register is 0, the corresponding pixel bit is ignored, and a 0 is used for that bit position in all look-ups of RGB triplets. At the extreme, a DAC Mask setting of 0 causes all 8 bits of pixel information to be ignored, so DAC location 0 is looked up for every pixel, and the entire screen displays the color stored in DAC location 0. This makes setting the DAC Mask register to 0 a quick and easy way to blank the screen.

Reading the DAC

The DAC can be read directly, via the DAC Read Index register at 3C7H and the DAC Data register at 3C9H, in much the same way as it can be written directly by way of the DAC Write Index register—complete with autoincrementing the DAC Read

Index register after every three reads. Everything I've said about writing to the DAC applies to reading from the DAC. In fact, reading from the DAC can even cause snow, just as loading the DAC does, so it should ideally be performed during vertical blanking.

The DAC can also be read by way of the BIOS in either of two ways. **INT** 10H, function 10H (AH=10H), subfunction 15H (AL=15H) reads out a single DAC location, specified by BX; this function returns the RGB triplet stored in the specified location with the red component in the lower 6 bits of DH, the green component in the lower 6 bits of CH, and the blue component in the lower 6 bits of CL.

INT 10H, function 10H (AH=10H), subfunction 17H (AL=17H) reads out a block of DAC locations of length CX, starting with the location specified by BX. ES:DX must point to the buffer in which the RGB values from the specified block of DAC locations are to be stored. The form of this buffer (RGB, RGB, RGB ..., with three bytes per RGB triple) is exactly the same as that of the buffer used when calling the BIOS to load a block of registers.

Listing 13.1 illustrates reading the DAC both through the BIOS block-read function and directly, with the direct-read code capable of conditionally assembling to either guard against interrupts or not and to use **REP INSB** or not. As you can see, reading the DAC settings is very much symmetric with setting the DAC.

Cycling Down

And so, at long last, we come to the end of our discussion of color control on the VGA. If it has been more complex than anyone might have imagined, it has also been most rewarding. There's as much obscure but very real potential in color control as there is anywhere on the VGA, which is to say that there's a very great deal of potential indeed. Put color cycling or color paging together with the page flipping and image drawing techniques explored elsewhere in this book, and you'll leave the audience gasping and wondering "How the heck did they *do* that?"

Bresenham Is Fast, and Fast Is Good

Chapter 14

Implementing and Optimizing Bresenham's Line-Drawing Algorithm

For all the complexity of graphics design and programming, surprisingly few primitive functions lie at the heart of most graphics software. Heavily-used primitives include routines that draw dots, circles, area fills, bit block logical transfers, and, of course, lines. For many years, computer graphics were created primarily with specialized line-drawing hardware, so lines are in a way the *lingua franca* of computer graphics. Lines are used in a wide variety of microcomputer graphics applications today, notably CAD/CAM and computer-aided engineering.

Probably the best-known formula for drawing lines on a computer display is called Bresenham's line-drawing algorithm. (We have to be specific here because there is also a less-well-known Bresenham's circle-drawing algorithm.) In this chapter, I'll present two implementations for the EGA and VGA of Bresenham's line-drawing algorithm, which provides decent line quality and excellent drawing speed.

The first implementation is in rather plain C, with the second in not-so-plain assembly, and they're both pretty good code. The assembly implementation is damned good code, in fact, but if you want to know whether it's the fastest Bresenham's implementation possible, I must tell you that it isn't. First of all, the code could be sped up a bit by shuffling and combining the various error-term manipulations, but that results in *truly* cryptic code. I wanted you to be able to relate the original algorithm to the final code, so I skipped those optimizations. Also, write mode 3, which is unique to the VGA, could be used for considerably faster drawing. I've described write mode 3 in earlier chapters, and I strongly recommend its use in VGA-only line drawing.

Second, horizontal, vertical, and diagonal lines could be special-cased, since those particular lines require little calculation and can be drawn very rapidly. (This is especially true of horizontal lines, which can be drawn 8 pixels at a time.)

Third, run-length slice line drawing could be used to significantly reduce the number of calculations required per pixel, as I'll demonstrate in the next two chapters.

Finally, unrolled loops and/or duplicated code could be used to eliminate most of the branches in the final assembly implementation, and because x86 processors are notoriously slow at branching, that would make quite a difference in overall performance. If you're interested in unrolled loops and similar assembly techniques, I refer you to my recent book on high-performance assembler programming, *Zen of Code Optimization.*

That brings us neatly to my final point: Even if I didn't know that there were further optimizations to be made to my line-drawing implementation, I'd *assume* that there were. As I'm sure the experienced assembly programmers among you know, there are dozens of ways to tackle any problem in assembly, and someone else always seems to have come up with a trick that never occurred to you. I've incorporated a suggestion made by Jim Mackraz in the code in this chapter, and I'd be most interested in hearing of any other tricks or tips you may have.

Notwithstanding, the line-drawing implementation in Listing 14.3 is plenty fast enough for most purposes, so let's get the discussion underway.

The Task at Hand

There are two important characteristics of any line-drawing function. First, it must draw a reasonable approximation of a line. A computer screen has limited resolution, and so a line-drawing function must actually approximate a straight line by drawing a series of pixels in what amounts to a jagged pattern that generally proceeds in the desired direction. That pattern of pixels must reliably suggest to the human eye the true line it represents. Second, to be usable, a line-drawing function must be *fast.* Minicomputers and mainframes generally have hardware that performs line drawing, but most microcomputers offer no such assistance. True, nowadays graphics accelerators such as the S3 and ATI chips have line drawing hardware, but some other accelerators don't; when drawing lines on the latter sort of chip, when drawing on the CGA, EGA, and VGA, and when drawing sorts of lines not supported by line-drawing hardware as well, the PC's CPU must draw lines on its own, and, as many users of graphics-oriented software know, that can be a slow process indeed.

Line drawing quality and speed derive from two factors: The algorithm used to draw the line and the implementation of that algorithm. The first implementation (written in Borland C++) that I'll be presenting in this chapter illustrates the workings of the algorithm and draws lines at a good rate. The second implementation, written in assembly language and callable directly from Borland C++, draws lines at extremely high speed, on the order of three to six times faster than the C version. Between them, the two implementations illuminate Bresenham's line-drawing algorithm and provide high-performance line-drawing capability.

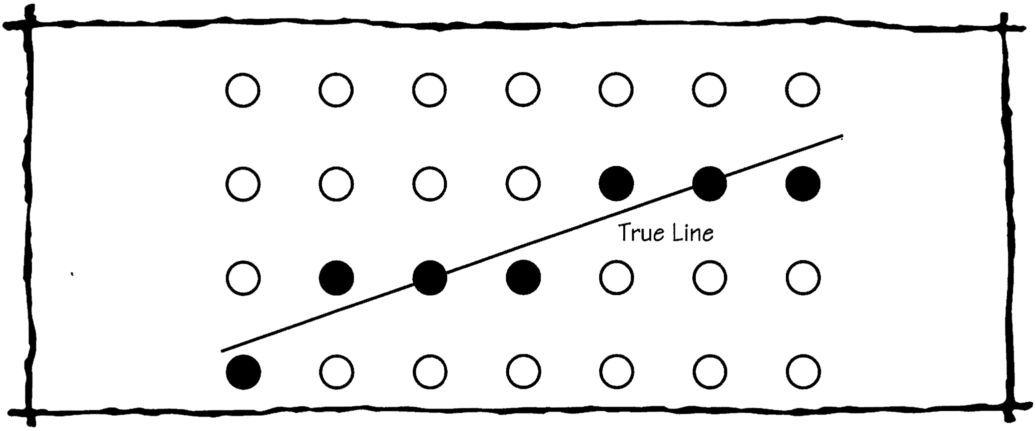


Figure 14.1 Approximating a True Line from a Pixel Array

The difficulty in drawing a line lies in generating a set of pixels that, taken together, are a reasonable facsimile of a true line. Only horizontal, vertical, and 1:1 diagonal lines can be drawn precisely along the true line being represented; all other lines must be approximated from the array of pixels that a given video mode supports, as shown in Figure 14.1.

Considerable thought has gone into the design of line-drawing algorithms, and a number of techniques for drawing high-quality lines have been developed. Unfortunately, most of these techniques were developed for powerful, expensive graphics workstations and require very high resolution, a large color palette, and/or floating-point hardware. These techniques tend to perform poorly and produce less visually impressive results on all but the best-endowed PCs.

Bresenham's line-drawing algorithm, on the other hand, is uniquely suited to microcomputer implementation in that it requires no floating-point operations, no divides, and no multiplies inside the line-drawing loop. Moreover, it can be implemented with surprisingly little code.

Bresenham's Line-Drawing Algorithm

The key to grasping Bresenham's algorithm is to understand that when drawing an approximation of a line on a finite-resolution display, each pixel drawn will lie either exactly on the true line or to one side or the other of the true line. The amount by which the pixel actually drawn deviates from the true line is the *error* of the line drawing at that point. As the drawing of the line progresses from one pixel to the next, the error can be used to tell when, given the resolution of the display, a more accurate approximation of the line can be drawn by placing a given pixel one unit of screen resolution away from its predecessor in either the horizontal or the vertical direction, or both.

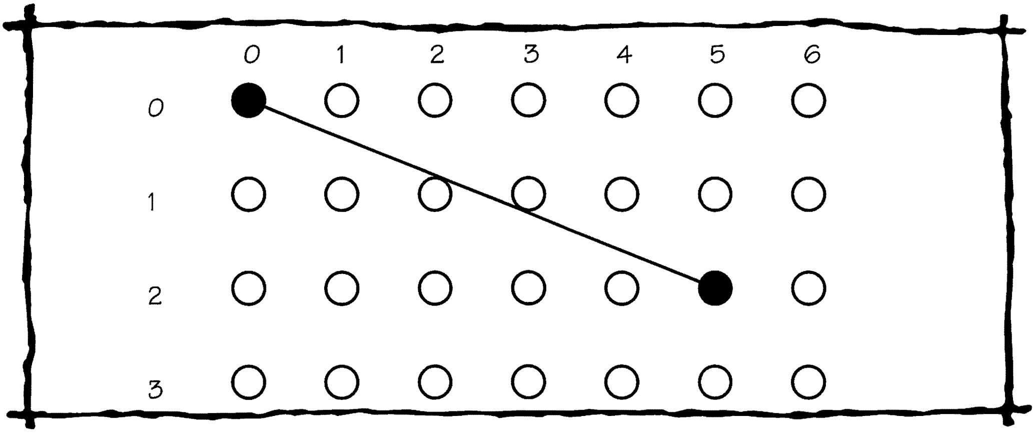


Figure 14.2 Drawing between Two Pixel Endpoints

Let's examine the case of drawing a line where the horizontal, or X length of the line is greater than the vertical, or Y length, and both lengths are greater than 0. For example, suppose we are drawing a line from (0,0) to (5,2), as shown in Figure 14.2. Note that Figure 14.2 shows the upper left-hand corner of the screen as (0,0), rather than placing (0,0) at its more traditional lower left-hand corner location. Due to the way in which the PC's graphics are mapped to memory, it is simpler to work within this framework, although a translation of Y from increasing downward to increasing upward could be effected easily enough by simply subtracting the Y coordinate from the screen height minus 1; if you are more comfortable with the traditional coordinate system, feel free to modify the code in Listings 14.1 and 14.3.

In Figure 14.2, the endpoints of the line fall exactly on displayed pixels. However, no other part of the line squarely intersects the center of a pixel, meaning that all other pixels will have to be plotted as approximations of the line. The approach to approximation that Bresenham's algorithm takes is to move exactly 1 pixel along the major dimension of the line each time a new pixel is drawn, while moving 1 pixel along the minor dimension each time the line moves more than halfway between pixels along the minor dimension.

In Figure 14.2, the X dimension is the major dimension. This means that 6 dots, one at each of X coordinates 0, 1, 2, 3, 4, and 5, will be drawn. The trick, then, is to decide on the correct Y coordinates to accompany those X coordinates.

It's easy enough to select the Y coordinates by eye in Figure 14.2. The appropriate Y coordinates are 0, 0, 1, 1, 2, 2, based on the Y coordinate closest to the line for each X coordinate. Bresenham's algorithm makes the same selections, based on the same criterion. The manner in which it does this is by keeping a running record of the error of the line—that is, how far from the true line the current Y coordinate is—at each X coordinate, as shown in Figure 14.3. When the running error of the line indicates that the current Y coordinate deviates from the true line to the extent that the adjacent Y coordinate would be closer to the line, then the current Y coordinate is changed to that adjacent Y coordinate.

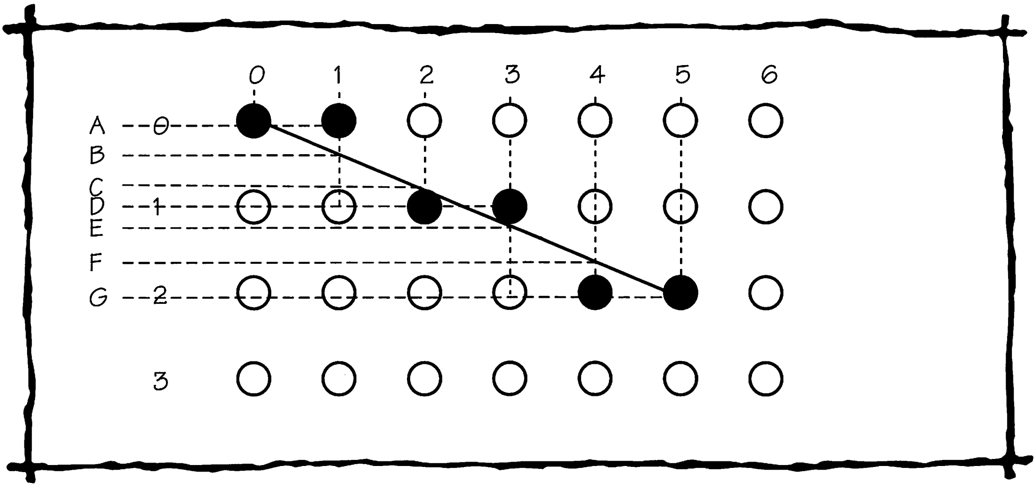


Figure 14.3 The Error Term in Bresenham's Algorithm

Let's take a moment to follow the steps Bresenham's algorithm would go through in drawing the line in Figure 14.3. The initial pixel is drawn at (0,0), the starting point of the line. At this point the error of the line is 0.

Since X is the major dimension, the next pixel has an X coordinate of 1. The Y coordinate of this pixel will be whichever of 0 (the last Y coordinate) or 1 (the adjacent Y coordinate in the direction of the end point of the line) the true line at this X coordinate is closer to. The running error at this point is B minus A, as shown in Figure 14.3. This amount is less than 1/2 (that is, less than halfway to the next Y coordinate), so the Y coordinate does not change at X equal to 1. Consequently, the second pixel is drawn at (1,0).

The third pixel has an X coordinate of 2. The running error at this point is C minus A, which is greater than 1/2 and therefore closer to the next than to the current Y coordinate. The third pixel is drawn at (2,1), and 1 is subtracted from the running error to compensate for the adjustment of one pixel in the current Y coordinate. The running error of the pixel actually drawn at this point is C minus D.

The fourth pixel has an X coordinate of 3. The running error at this point is E minus D; since this is less than 1/2, the current Y coordinate doesn't change. The fourth pixel is drawn at (3,1).

The fifth pixel has an X coordinate of 4. The running error at this point is F minus D; since this is greater than 1/2, the current Y coordinate advances. The third pixel is drawn at (4,2), and 1 is subtracted from the running error. The error of the pixel drawn at this point is G minus F.

Finally, the sixth pixel is the end point of the line. This pixel has an X coordinate of 5. The running error at this point is G minus G, or 0, indicating that this point is squarely on the true line, as of course it should be given that it's the end point, so the current Y coordinate remains the same. The end point of the line is drawn at (5,2), and the line is complete.

That's really all there is to Bresenham's algorithm. The algorithm is a process of drawing a pixel at each possible coordinate along the major dimension of the line, each with the closest possible coordinate along the minor dimension. The running error is used to keep track of when the coordinate along the minor dimension must change in order to remain as close as possible to the true line. The above description of the case where X is the major dimension, Y is the minor dimension, and both dimensions are greater than zero is readily generalized to all eight octants in which lines could be drawn, as we will see in the C implementation.

The above discussion summarizes the nature rather than the exact mechanism of Bresenham's line-drawing algorithm. I'll provide a brief seat-of-the-pants discussion of the algorithm in action when we get to the C implementation of the algorithm; for a full mathematical treatment, I refer you to pages 433–436 of Foley and Van Dam's *Fundamentals of Interactive Computer Graphics* (Addison-Wesley, 1982), or pages 72–78 of the second edition of that book, which was published under the name *Computer Graphics: Principles and Practice* (Addison-Wesley, 1990). These sources provide the derivation of the integer-only, divide-free version of the algorithm, as well as Pascal code for drawing lines in one of the eight possible octants.

Strengths and Weaknesses

The overwhelming strength of Bresenham's line-drawing algorithm is speed. With no divides, no floating-point operations, and no need for variables that won't fit in 16 bits, it is perfectly suited for PCs.

The weakness of Bresenham's algorithm is that it produces relatively low-quality lines by comparison with most other line-drawing algorithms. In particular, lines generated with Bresenham's algorithm can tend to look a little jagged. On the PC, however, jagged lines are an inevitable consequence of relatively low resolution and a small color set, so lines drawn with Bresenham's algorithm don't look all that much different from lines drawn in other ways. Besides, in most applications, users are far more interested in the overall picture than in the primitive elements from which that picture is built. As a general rule, any collection of pixels that trend from point A to point B in a straight fashion is accepted by the eye as a line. Bresenham's algorithm is successfully used by many current PC programs, and by the standard of this wide acceptance the algorithm is certainly good enough.

Then, too, users hate waiting for their computer to finish drawing. By any standard of drawing performance, Bresenham's algorithm excels.

An Implementation in C

It's time to get down and look at some actual working code. Listing 14.1 is a C implementation of Bresenham's line-drawing algorithm for modes 0EH, 0FH, 10H, and

12H of the VGA, called as function **EVGALine.** Listing 14.2 is a sample program to demonstrate the use of **EVGALine.**

LISTING 14.1 L14-1.C

```
/*
 * C implementation of Bresenham's line drawing algorithm
 * for the EGA and VGA. Works in modes 0xE, 0xF, 0x10, and 0x12.
 *
 * Compiled with Borland C++
 *
 * By Michael Abrash
 */

#include <dos.h>           /* contains MK_FP macro */

#define EVGA_SCREEN_WIDTH_IN_BYTES       80
                                          /* memory offset from start of
                                             one row to start of next */
#define EVGA_SCREEN_SEGMENT              0xA000
                                          /* display memory segment */
#define GC_INDEX                         0x3CE
                                          /* Graphics Controller
                                             Index register port */
#define GC_DATA                          0x3CF
                                          /* Graphics Controller
                                             Data register port */
#define SET_RESET_INDEX                  0  /* indexes of needed */
#define ENABLE_SET_RESET_INDEX           1  /* Graphics Controller */
#define BIT_MASK_INDEX                   8  /* registers */

/*
 * Draws a dot at (X0,Y0) in whatever color the EGA/VGA hardware is
 * set up for. Leaves the bit mask set to whatever value the
 * dot required.
 */
void EVGADot(X0, Y0)
unsigned int X0;      /* coordinates at which to draw dot, with */
unsigned int Y0;      /* (0,0) at the upper left of the screen */
{
    unsigned char far *PixelBytePtr;
    unsigned char PixelMask;

    /* Calculate the offset in the screen segment of the byte in
       which the pixel lies */
    PixelBytePtr = MK_FP(EVGA_SCREEN_SEGMENT,
       ( Y0 * EVGA_SCREEN_WIDTH_IN_BYTES ) + ( X0 / 8 ));

    /* Generate a mask with a 1 bit in the pixel's position within the
       screen byte */
    PixelMask = 0x80 >> ( X0 & 0x07 );

    /* Set up the Graphics Controller's Bit Mask register to allow
       only the bit corresponding to the pixel being drawn to
       be modified */
    outportb(GC_INDEX, BIT_MASK_INDEX);
    outportb(GC_DATA, PixelMask);
```

```
   /* Draw the pixel. Because of the operation of the set/reset
       feature of the EGA/VGA, the value written doesn't matter.
       The screen byte is ORed in order to perform a read to latch the
       display memory, then perform a write in order to modify it. */
    *PixelBytePtr |= 0xFE;
}

/*
 * Draws a line in octant 0 or 3 ( |DeltaX| >= DeltaY ).
 */
void Octant0(X0, Y0, DeltaX, DeltaY, XDirection)
unsigned int X0, Y0;          /* coordinates of start of the line */
unsigned int DeltaX, DeltaY; /* length of the line (both > 0) */
int XDirection;               /* 1 if line is drawn left to right,
                                 -1 if drawn right to left */
{
    int DeltaYx2;
    int DeltaYx2MinusDeltaXx2;
    int ErrorTerm;

    /* Set up initial error term and values used inside drawing loop */
    DeltaYx2 = DeltaY * 2;
    DeltaYx2MinusDeltaXx2 = DeltaYx2 - (int) ( DeltaX * 2 );
    ErrorTerm = DeltaYx2 - (int) DeltaX;

    /* Draw the line */
    EVGADot(X0, Y0);                /* draw the first pixel */
    while ( DeltaX-- ) {
        /* See if it's time to advance the Y coordinate */
        if ( ErrorTerm >= 0 ) {
            /* Advance the Y coordinate & adjust the error term
               back down */
           Y0++;
            ErrorTerm += DeltaYx2MinusDeltaXx2;
        } else {
           /* Add to the error term */
           ErrorTerm += DeltaYx2;
        }
        X0 += XDirection;           /* advance the X coordinate */
        EVGADot(X0, Y0);           /* draw a pixel */
    }
}

/*
 * Draws a line in octant 1 or 2 ( |DeltaX| < DeltaY ).
 */
void Octant1(X0, Y0, DeltaX, DeltaY, XDirection)
unsigned int X0, Y0;          /* coordinates of start of the line */
unsigned int DeltaX, DeltaY; /* length of the line (both > 0) */
int XDirection;               /* 1 if line is drawn left to right,
                                 -1 if drawn right to left */
{
    int DeltaXx2;
    int DeltaXx2MinusDeltaYx2;
    int ErrorTerm;

    /* Set up initial error term and values used inside drawing loop */
    DeltaXx2 = DeltaX * 2;
    DeltaXx2MinusDeltaYx2 = DeltaXx2 - (int) ( DeltaY * 2 );
    ErrorTerm = DeltaXx2 - (int) DeltaY;
    EVGADot(X0, Y0);             /* draw the first pixel */
    while ( DeltaY-- ) {
        /* See if it's time to advance the X coordinate */
        if ( ErrorTerm >= 0 ) {
            /* Advance the X coordinate & adjust the error term
               back down */
            X0 += XDirection;
            ErrorTerm += DeltaXx2MinusDeltaYx2;
        } else {
            /* Add to the error term */
            ErrorTerm += DeltaXx2;
        }
        Y0++;                       /* advance the Y coordinate */
        EVGADot(X0, Y0);            /* draw a pixel */
    }
}

/*
 * Draws a line on the EGA or VGA.
 */
void EVGALine(X0, Y0, X1, Y1, Color)
int X0, Y0;     /* coordinates of one end of the line */
int X1, Y1;     /* coordinates of the other end of the line */
char Color;     /* color to draw line in */
{
    int DeltaX, DeltaY;
    int Temp;

    /* Set the drawing color */

    /* Put the drawing color in the Set/Reset register */
    outportb(GC_INDEX, SET_RESET_INDEX);
    outportb(GC_DATA, Color);
    /* Cause all planes to be forced to the Set/Reset color */
    outportb(GC_INDEX, ENABLE_SET_RESET_INDEX);
    outportb(GC_DATA, 0xF);

    /* Save half the line-drawing cases by swapping Y0 with Y1
       and X0 with X1 if Y0 is greater than Y1. As a result, DeltaY
       is always > 0, and only the octant 0-3 cases need to be
       handled. */
    if ( Y0 > Y1 ) {
        Temp = Y0;
        Y0 = Y1;
        Y1 = Temp;
        Temp = X0;
        X0 = X1;
        X1 = Temp;
    }

    /* Handle as four separate cases, for the four octants in which
       Y1 is greater than Y0 */
    DeltaX = X1 - X0;     /* calculate the length of the line
                             in each coordinate */
    DeltaY = Y1 - Y0;
    if ( DeltaX > 0 ) {
        if ( DeltaX > DeltaY ) {
            Octant0(X0, Y0, DeltaX, DeltaY, 1);
        } else {
            Octant1(X0, Y0, DeltaX, DeltaY, 1);
        }
    } else {
        DeltaX = -DeltaX;                /* absolute value of DeltaX */
        if ( DeltaX > DeltaY ) {
            Octant0(X0, Y0, DeltaX, DeltaY, -1);
        } else {
            Octant1(X0, Y0, DeltaX, DeltaY, -1);
        }
    }

    /* Return the state of the EGA/VGA to normal */
    outportb(GC_INDEX, ENABLE_SET_RESET_INDEX);
    outportb(GC_DATA, 0);
    outportb(GC_INDEX, BIT_MASK_INDEX);
    outportb(GC_DATA, 0xFF);
}
```

LISTING 14.2 L14-2.C

```
/*
 * Sample program to illustrate EGA/VGA line drawing routines.
 *
 * Compiled with Borland C++
 *
 * By Michael Abrash
 */

#include <dos.h>       /* contains geninterrupt */

#define GRAPHICS_MODE    0x10
#define TEXT_MODE        0x03
#define BIOS_VIDEO_INT   0x10
#define X_MAX            640       /* working screen width */
#define Y_MAX            348       /* working screen height */

extern void EVGALine();

/*
 * Subroutine to draw a rectangle full of vectors, of the specified
 * length and color, around the specified rectangle center.
 */
void VectorsUp(XCenter, YCenter, XLength, YLength, Color)
int XCenter, YCenter;    /* center of rectangle to fill */
int XLength, YLength;    /* distance from center to edge
                             of rectangle */
int Color;                /* color to draw lines in */
{
    int WorkingX, WorkingY;

    /* Lines from center to top of rectangle */
    WorkingX = XCenter - XLength;
    WorkingY = YCenter - YLength;
    for ( ; WorkingX < ( XCenter + XLength ); WorkingX++ )
        EVGALine(XCenter, YCenter, WorkingX, WorkingY, Color);

    /* Lines from center to right of rectangle */
    WorkingX = XCenter + XLength - 1;
    WorkingY = YCenter - YLength;
    for ( ; WorkingY < ( YCenter + YLength ); WorkingY++ )
        EVGALine(XCenter, YCenter, WorkingX, WorkingY, Color);
    /* Lines from center to bottom of rectangle */
    WorkingX = XCenter + XLength - 1;
    WorkingY = YCenter + YLength - 1;
    for ( ; WorkingX >= ( XCenter - XLength ); WorkingX-- )
         EVGALine(XCenter, YCenter, WorkingX, WorkingY, Color);

    /* Lines from center to left of rectangle */
    WorkingX = XCenter - XLength;
    WorkingY = YCenter + YLength - 1;
    for ( ; WorkingY >= ( YCenter - YLength ); WorkingY-- )
         EVGALine(XCenter, YCenter, WorkingX, WorkingY, Color );
}

/*
 * Sample program to draw four rectangles full of lines.
 */
void main()
{
    char temp;

    /* Set graphics mode */
    _AX = GRAPHICS_MODE;
     geninterrupt(BIOS_VIDEO_INT);

    /* Draw each of four rectangles full of vectors */
    VectorsUp(X_MAX / 4, Y_MAX / 4, X_MAX / 4,
       Y_MAX / 4, 1);
    VectorsUp(X_MAX * 3 / 4, Y_MAX / 4, X_MAX / 4,
       Y_MAX / 4, 2);
    VectorsUp(X_MAX / 4, Y_MAX * 3 / 4, X_MAX / 4,
       Y_MAX / 4, 3);
    VectorsUp(X_MAX * 3 / 4, Y_MAX * 3 / 4, X_MAX / 4,
       Y_MAX / 4, 4);

    /* Wait for the enter key to be pressed */
     scanf("%c", &temp);

    /* Return back to text mode */
    _AX = TEXT_MODE;
     geninterrupt(BIOS_VIDEO_INT);
}
```

Looking at EVGALine

The **EVGALine** function itself performs four operations. **EVGALine** first sets up the VGA's hardware so that all pixels drawn will be in the desired color. This is accomplished by setting two of the VGA's registers, the Enable Set/Reset register and the Set/Reset register. Setting the Enable Set/Reset to the value 0FH, as is done in **EVGALine**, causes all drawing to produce pixels in the color contained in the Set/Reset register. Setting the Set/Reset register to the passed color, in conjunction with the Enable Set/Reset setting of 0FH, causes all drawing done by **EVGALine** and the functions it calls to generate the passed color. In summary, setting up the Enable Set/Reset and Set/Reset registers in this way causes the remainder of **EVGALine** to draw a line in the specified color.

EVGALine next performs a simple check to cut in half the number of line orientations that must be handled separately. Figure 14.4 shows the eight possible line orientations among which a Bresenham's algorithm implementation must distinguish. (In interpreting Figure 14.4, assume that lines radiate outward from the center of the figure, falling into one of eight octants delineated by the horizontal and vertical axes and the two diagonals.) The need to categorize lines into these octants falls out of the major/minor axis nature of the algorithm; the orientations are distinguished by which coordinate forms the major axis and by whether each of X and Y increases or decreases from the line start to the line end.

*A moment of thought will show, however, that four of the line orientations are redundant. Each of the four orientations for which **DeltaY**, the Y component of the line, is less than 0 (that is, for which the line start Y coordinate is greater than the line end Y coordinate) can be transformed into one of the four orientations for which the line start Y coordinate is less than the line end Y coordinate simply by reversing the line start and end coordinates, so that the line is drawn in the other direction. **EVGALine** does this by swapping (X0,Y0) (the line start coordinates) with (X1,Y1) (the line end coordinates) whenever Y0 is greater than Y1.*

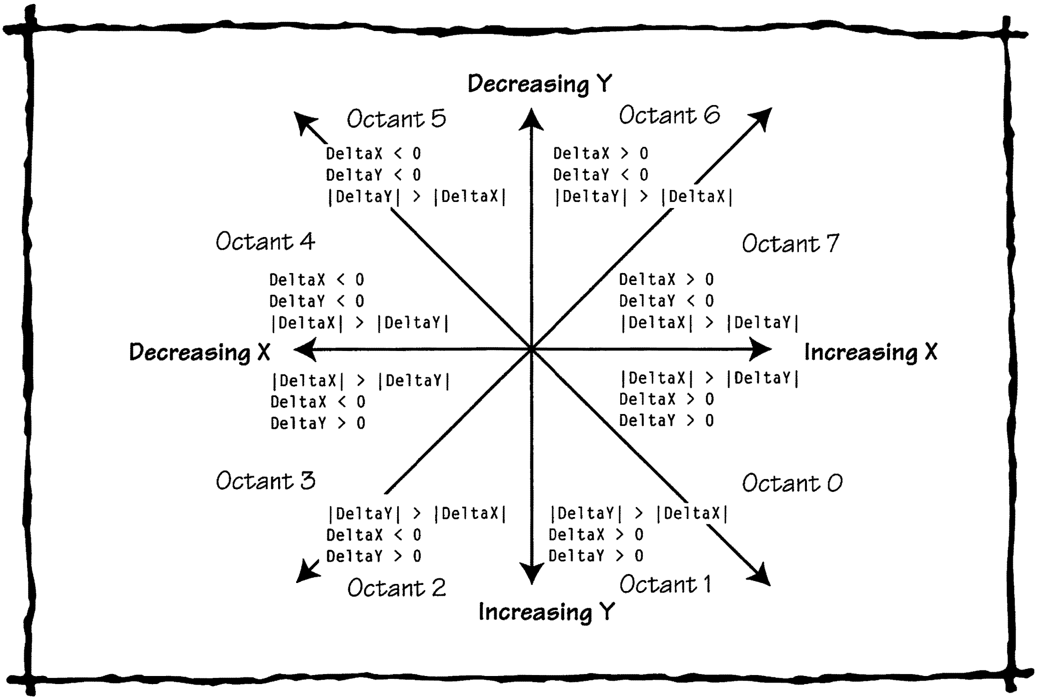


Figure 14.4 Bresenham's Eight Possible Line Orientations

This accomplished, **EVGALine** must still distinguish among the four remaining line orientations. Those four orientations form two major categories, orientations for which the X dimension is the major axis of the line and orientations for which the Y dimension is the major axis. As shown in Figure 14.4, octants 1 (where X increases from start to finish) and 2 (where X decreases from start to finish) fall into the latter category, and differ in only one respect, the direction in which the X coordinate moves when it changes. Handling of the running error of the line is exactly the same for both cases, as one would expect given the symmetry of lines differing only in the sign of **DeltaX**, the X coordinate of the line. Consequently, for those cases where **DeltaX** is less than zero, the direction of X movement is made negative, and the absolute value of **DeltaX** is used for error term calculations.

Similarly, octants 0 (where X increases from start to finish) and 3 (where X decreases from start to finish) differ only in the direction in which the X coordinate moves when it changes. The difference between line drawing in octants 0 and 3 and line drawing in octants 1 and 2 is that in octants 0 and 3, since X is the major axis, the X coordinate changes on every pixel of the line and the Y coordinate changes only when the running error of the line dictates. In octants 1 and 2, the Y coordinate changes on every pixel and the X coordinate changes only when the running error dictates, since Y is the major axis.

There is one line-drawing function for octants 0 and 3, **Octant0**, and one line-drawing function for octants 1 and 2, **Octant1**. A single function with **if** statements could certainly be used to handle all four octants, but at a significant performance cost. There is, on the other hand, very little performance cost to grouping octants 0 and 3 together and octants 1 and 2 together, since the two octants in each pair differ only in the direction of change of the X coordinate.

EVGALine determines which line-drawing function to call and with what value for the direction of change of the X coordinate based on two criteria: whether **DeltaX** is negative or not, and whether the absolute value of **DeltaX** (**|DeltaX|**) is less than **DeltaY** or not, as shown in Figure 14.5. Recall that the value of **DeltaY**, and hence the direction of change of the Y coordinate, is guaranteed to be non-negative as a result of the earlier elimination of four of the line orientations.

After calling the appropriate function to draw the line (more on those functions shortly), **EVGALine** restores the state of the Enable Set/Reset register to its default of zero. In this state, the Set/Reset register has no effect, so it is not necessary to restore the state of the Set/Reset register as well. **EVGALine** also restores the state of the Bit Mask register (which, as we will see, is modified by **EVGADot**, the pixel-drawing routine actually used to draw each pixel of the lines produced by **EVGALine**) to its default of 0FFH. While it would be more modular to have **EVGADot** restore the state of the Bit Mask register after drawing each pixel, it would also be considerably slower to do so. The same could be said of having **EVGADot** set the Enable Set/Reset and Set/Reset registers for each pixel: While modularity would improve, speed would suffer markedly.

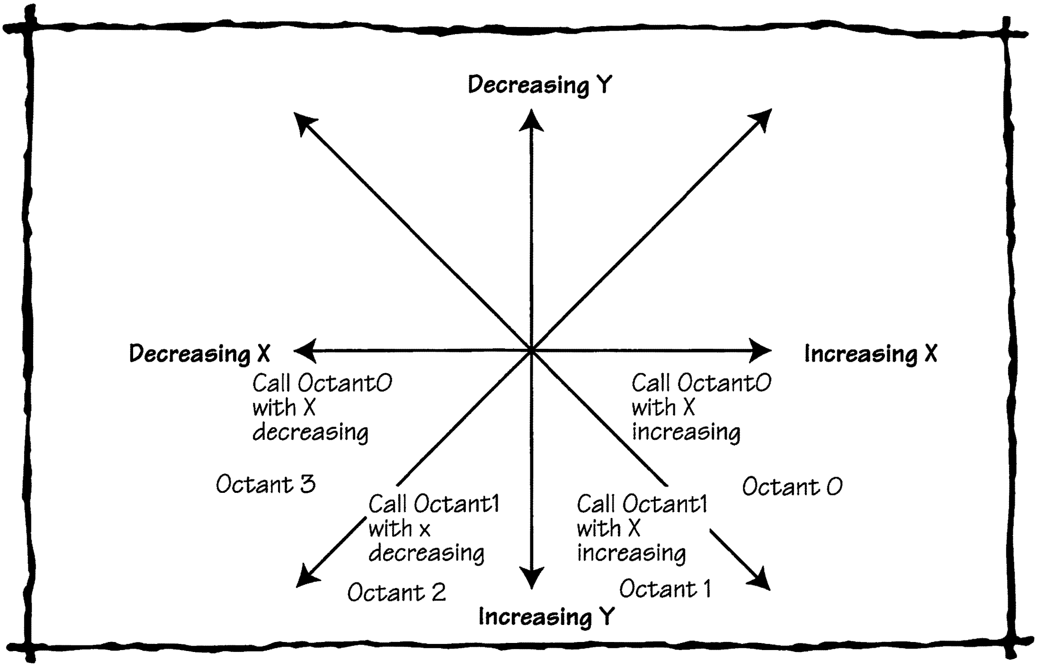

Decreasing Y
Decreasing X
Increasing X
Call Octant0 with X decreasing
Call Octant0 with X increasing
Octant 3
Octant 0
Call Octant1 with x decreasing
Call Octant1 with X increasing
Octant 2
Octant 1
Increasing Y

Figure 14.5 EVGALine's Decision Logic

Drawing Each Line

The **Octant0** and **Octantl** functions draw lines for which |**DeltaX**| is greater than **DeltaY** and lines for which |**DeltaX**| is less than or equal to **DeltaY**, respectively. The parameters to **Octant0** and **Octant1** are the starting point of the line, the length of the line in each dimension, and **XDirection**, the amount by which the X coordinate should be changed when it moves. **XDirection** must be either 1 (to draw toward the right edge of the screen) or –1 (to draw toward the left edge of the screen). No value is required for the amount by which the Y coordinate should be changed; since **DeltaY** is guaranteed to be positive, the Y coordinate always changes by 1 pixel.

Octant0 draws lines for which |**DeltaX**| is greater than **DeltaY**. For such lines, the X coordinate of each pixel drawn differs from the previous pixel by either 1 or –1, depending on the value of **XDirection**. (This makes it possible for **Octant0** to draw lines in both octant 0 and octant 3.) Whenever **ErrorTerm** becomes non-negative, indicating that the next Y coordinate is a better approximation of the line being drawn, the Y coordinate is increased by 1.

Octantl draws lines for which |**DeltaX**| is less than or equal to **DeltaY**. For these lines, the Y coordinate of each pixel drawn is 1 greater than the Y coordinate of the previous pixel. Whenever **ErrorTerm** becomes non-negative, indicating that the next X coordinate is a better approximation of the line being drawn, the X coordinate is advanced by either 1 or –1, depending on the value of **XDirection**. (This makes it possible for **Octantl** to draw lines in both octant 1 and octant 2.)

Drawing Each Pixel

At the core of **Octant0** and **Octant1** is a pixel-drawing function, **EVGADot. EVGADot** draws a pixel at the specified coordinates in whatever color the hardware of the VGA happens to be set up for. As described earlier, since the entire line drawn by **EVGALine** is of the same color, line-drawing performance is improved by setting the VGA's hardware up once in **EVGALine** before the line is drawn, and then drawing all the pixels in the line in the same color via **EVGADot.**

EVGADot makes certain assumptions about the screen. First, it assumes that the address of the byte controlling the pixels at the start of a given row on the screen is 80 bytes after the start of the row immediately above it. In other words, this implementation of **EVGADot** only works for screens configured to be 80 bytes wide. Since this is the standard configuration of all of the modes **EVGALine** is designed to work in, the assumption of 80 bytes per row should be no problem. If it is a problem, however, **EVGADot** could easily be modified to retrieve the BIOS integer variable at address 0040:004A, which contains the number of bytes per row for the current video mode.

Second, **EVGADot** assumes that screen memory is organized as a linear bitmap starting at address A000:0000, with the pixel at the upper left of the screen controlled by bit 7 of the byte at offset 0, the next pixel to the right controlled by bit 6, the ninth pixel controlled by bit 7 of the byte at offset 1, and so on. Further, it assumes that the graphics adapter's hardware is configured such that setting the Bit Mask register to allow modification of only the bit controlling the pixel of interest and then ORing a value of 0FEH with display memory will draw that pixel correctly without affecting any other dots. (Note that 0FEH is used rather than 0FFH or 0 because some optimizing compilers turn ORs with the latter values into simpler operations or optimize them away entirely. As explained later, however, it's not the value that's ORed that matters, given the way we've set up the VGA's hardware; it's the act of ORing itself, and the value 0FEH forces the compiler to perform the OR operation.) Again, this is the normal way in which modes 0EH, 0FH, 10H, and 12H operate. As described earlier, **EVGADot** also assumes that the VGA is set up so that each pixel drawn in the above-mentioned manner will be drawn in the correct color.

Given those assumptions, **EVGADot** becomes a surprisingly simple function. First, **EVGADot** builds a far pointer that points to the byte of display memory controlling the pixel to be drawn. Second, a mask is generated consisting of zeros for all bits except the bit controlling the pixel to be drawn. Third, the Bit Mask register is set to that mask, so that when display memory is read and then written, all bits except the one that controls the pixel to be drawn will be left unmodified.

Finally, 0FEH is ORed with the display memory byte controlling the pixel to be drawn. ORing with 0FEH first reads display memory, thereby loading the VGA's internal latches with the contents of the display memory byte controlling the pixel to be drawn, and then writes to display memory with the value 0FEH. Because of the unusual way in which the VGA's data paths work and the way in which **EVGALine** sets up the VGA's Enable Set/Reset and Set/Reset registers, the value that is written by the

OR instruction is ignored. Instead, the value that actually gets placed in display memory is the color that was passed to **EVGALine** and placed in the Set/Reset register. The Bit Mask register, which was set up in step three above, allows only the single bit controlling the pixel to be drawn to be set to this color value. For more on the various machineries the VGA brings to bear on graphics data, look back to Chapter 3.

The result of all this is simply a single pixel drawn in the color set up in **EVGALine**. **EVGADot** may seem excessively complex for a function that does nothing more that draw one pixel, but programming the VGA isn't trivial (as we've seen in the early chapters of this book). Besides, while the explanation of **EVGADot** is lengthy, the code itself is only five lines long.

Line drawing would be somewhat faster if the code of **EVGADot** were made an inline part of **Octant0** and **Octant1**, thereby saving the overhead of preparing parameters and calling the function. Feel free to do this if you wish; I maintained **EVGADot** as a separate function for clarity and for ease of inserting a pixel-drawing function for a different graphics adapter, should that be desired. If you do install a pixel-drawing function for a different adapter, or a fundamentally different mode such as a 256-color SuperVGA mode, remember to remove the hardware-dependent **outportb** lines in **EVGALine** itself.

Comments on the C Implementation

EVGALine does no error checking whatsoever. My assumption in writing **EVGALine** was that it would be ultimately used as the lowest-level primitive of a graphics software package, with operations such as error checking and clipping performed at a higher level. Similarly, **EVGALine** is tied to the VGA's screen coordinate system of (0,0) to (639,199) (in mode 0EH), (0,0) to (639,349) (in modes 0FH and 10H), or (0,0) to (639,479) (in mode 12H), with the upper left corner considered to be (0,0). Again, transformation from any coordinate system to the coordinate system used by **EVGALine** can be performed at a higher level. **EVGALine** is specifically designed to do one thing: draw lines into the display memory of the VGA. Additional functionality can be supplied by the code that calls **EVGALine**.

The version of **EVGALine** shown in Listing 14.1 is reasonably fast, but it is not as fast as it might be. Inclusion of **EVGADot** directly into **Octant0** and **Octant1**, and, indeed, inclusion of **Octant0** and **Octant1** directly into **EVGALine** would speed execution by saving the overhead of calling and parameter passing. Handpicked register variables might speed performance as well, as would the use of word OUTs rather than byte OUTs. A more significant performance increase would come from eliminating separate calculation of the address and mask for each pixel. Since the location of each pixel relative to the previous pixel is known, the address and mask could simply be adjusted from one pixel to the next, rather than recalculated from scratch.

These enhancements are not incorporated into the code in Listing 14.1 for a couple of reasons. One reason is that it's important that the workings of the algorithm be clearly visible in the code, for learning purposes. Once the implementation is understood, rewriting it for improved performance would certainly be a worthwhile exercise. Another reason is that when flat-out speed is needed, assembly language is the best way to go. Why produce hard-to-understand C code to boost speed a bit when assembly-language code can perform the same task at two or more times the speed?

Given which, a high-speed assembly language version of **EVGALine** would seem to be a logical next step.

Bresenham's Algorithm in Assembly

Listing 14.3 is a high-performance implementation of Bresenham's algorithm, written entirely in assembly language. The code is callable from C just as is Listing 14.1, with the same name, **EVGALine**, and with the same parameters. Either of the two can be linked to any program that calls **EVGALine**, since they appear to be identical to the calling program. The only difference between the two versions is that the sample program in Listing 14.2 runs over three times as fast on a 486 with an ISA-bus VGA when calling the assembly-language version of **EVGALine** as when calling the C version, and the difference would be considerably greater yet on a local bus, or with the use of write mode 3. Link each version with Listing 14.2 and compare performance—the difference is startling.

LISTING 14.3 L14-3.ASM

```
; Fast assembler implementation of Bresenham's line-drawing algorithm
; for the EGA and VGA. Works in modes 0Eh, 0Fh, 10h, and 12h.
; Borland C++ near-callable.
; Bit mask accumulation technique when |DeltaX| >= |DeltaY|
;  suggested by Jim Mackraz.
;
; Assembled with TASM
;
; By Michael Abrash
;
;****************************************************************
; C-compatible line-drawing entry point at _EVGALine.           *
; Near C-callable as:                                           *
;       EVGALine(X0, Y0, X1, Y1, Color);                        *
;****************************************************************
;

    model small
    .code

;
; Equates.
;
EVGA_SCREEN_WIDTH_IN_BYTES      equ  80        ;memory offset from start of
                                               ; one row to start of next
                                               ; in display memory
EVGA_SCREEN_SEGMENT             equ  0a000h    ;display memory segment
```

```
GC_INDEX                  equ     3ceh     ;Graphics Controller
                                           ; Index register port
SET_RESET_INDEX           equ     0        ;indexes of needed
ENABLE_SET_RESET_INDEX    equ     1        ; Graphics Controller
BIT_MASK_INDEX            equ     8        ; registers

;
; Stack frame.
;
EVGALineParms   struc
                dw      ?                  ;pushed BP
                dw      ?                  ;pushed return address (make double
                                           ; word for far call)
X0              dw      ?                  ;starting X coordinate of line
Y0              dw      ?                  ;starting Y coordinate of line
X1              dw      ?                  ;ending X coordinate of line
Y1              dw      ?                  ;ending Y coordinate of line
Color           db      ?                  ;color of line
                db      ?                  ;dummy to pad to word size
EVGALineParms   ends

;****************************************************************
; Line drawing macros.                                          *
;****************************************************************

;
; Macro to loop through length of line, drawing each pixel in turn.
; Used for case of |DeltaX| >= |DeltaY|.
; Input:
;       MOVE_LEFT: 1 if DeltaX < 0, 0 else
;       AL: pixel mask for initial pixel
;       BX: |DeltaX|
;       DX: address of GC data register, with index register set to
;               index of Bit Mask register
;       SI: DeltaY
;       ES:DI: display memory address of byte containing initial
;               pixel
;
LINE1   macro   MOVE_LEFT
        local   LineLoop, MoveXCoord, NextPixel, Line1End
        local   MoveToNextByte, ResetBitMaskAccumulator
        mov     cx,bx               ;# of pixels in line
        jcxz    Line1End            ;done if there are no more pixels
                                    ; (there's always at least the one pixel
                                    ; at the start location)
        shl     si,1                ;DeltaY * 2
        mov     bp,si               ;error term
        sub     bp,bx               ;error term starts at DeltaY * 2 - DeltaX
        shl     bx,1                ;DeltaX * 2
        sub     si,bx               ;DeltaY * 2 - DeltaX * 2 (used in loop)
        add     bx,si               ;DeltaY * 2 (used in loop)
        mov     ah,al               ;set aside pixel mask for initial pixel
                                    ; with AL (the pixel mask accumulator) set
                                    ; for the initial pixel
LineLoop:
;
; See if it's time to advance the Y coordinate yet.
;
        and     bp,bp               ;see if error term is negative
        js      MoveXCoord          ;yes, stay at the same Y coordinate
;
```

```
; Advance the Y coordinate, first writing all pixels in the current
; byte, then move the pixel mask either left or right, depending
; on MOVE_LEFT.
;
        out     dx,al                ;set up bit mask for pixels in this byte
        xchg    byte ptr [di],al
                                ;load latches and write pixels, with bit mask
                                     ; preserving other latched bits. Because
                                     ; set/reset is enabled for all planes, the
                                     ; value written actually doesn't matter
        add     di,EVGA_SCREEN_WIDTH_IN_BYTES   ;increment Y coordinate
        add     bp,si                ;adjust error term back down
;
; Move pixel mask one pixel (either right or left, depending
; on MOVE_LEFT), adjusting display memory address when pixel mask wraps.
;
if MOVE_LEFT
        rol     ah,1                 ;move pixel mask 1 pixel to the left
else
        ror     ah,1                 ;move pixel mask 1 pixel to the right
endif
        jnc     ResetBitMaskAccumulator ;didn't wrap to next byte
        jmp     short MoveToNextByte    ;did wrap to next byte
;
; Move pixel mask one pixel (either right or left, depending
; on MOVE_LEFT), adjusting display memory address and writing pixels
; in this byte when pixel mask wraps.
;
MoveXCoord:
        add     bp,bx                ;increment error term & keep same
if MOVE_LEFT
        rol     ah,1                 ;move pixel mask 1 pixel to the left
else
        ror     ah,1                 ;move pixel mask 1 pixel to the right
endif
        jnc     NextPixel            ;if still in same byte, no need to
                                     ; modify display memory yet
        out     dx,al                ;set up bit mask for pixels in this byte.
        xchg    byte ptr [di],al
                                ;load latches and write pixels, with bit mask
                                ; preserving other latched bits. Because
                                ; set/reset is enabled for all planes, the
                                ; value written actually doesn't matter
MoveToNextByte:
if MOVE_LEFT
        dec     di                   ;next pixel is in byte to left
else
        inc     di                   ;next pixel is in byte to right
endif
ResetBitMaskAccumulator:
        sub     al,al                ;reset pixel mask accumulator
NextPixel:
        or      al,ah                ;add the next pixel to the pixel mask
                                     ; accumulator
        loop    LineLoop
;
; Write the pixels in the final byte.
;
Line1End:
        out     dx,al                ;set up bit mask for pixels in this byte
        xchg    byte ptr [di],al
```

```
                               ;load latches and write pixels, with bit mask
                               ; preserving other latched bits. Because
                               ; set/reset is enabled for all planes, the
                               ; value written actually doesn't matter
        endm

;
; Macro to loop through length of line, drawing each pixel in turn.
; Used for case of DeltaX < DeltaY.
; Input:
;       MOVE_LEFT: 1 if DeltaX < 0, 0 else
;       AL: pixel mask for initial pixel
;       BX: |DeltaX|
;       DX: address of GC data register, with index register set to
;               index of Bit Mask register
;       SI: DeltaY
;       ES:DI: display memory address of byte containing initial
;               pixel
;
LINE2   macro   MOVE_LEFT
        local   LineLoop, MoveYCoord, ETermAction, Line2End
        mov     cx,si                   ;# of pixels in line
        jcxz    Line2End                ;done if there are no more pixels
        shl     bx,1                    ;DeltaX * 2
        mov     bp,bx                   ;error term
        sub     bp,si                   ;error term starts at DeltaX * 2 - DeltaY
        shl     si,1                    ;DeltaY * 2
        sub     bx,si                   ;DeltaX * 2 - DeltaY * 2 (used in loop)
        add     si,bx                   ;DeltaX * 2 (used in loop)
;
; Set up initial bit mask & write initial pixel.
;
        out     dx,al
        xchg    byte ptr [di],ah
                               ;load latches and write pixel, with bit mask
                                    ; preserving other latched bits. Because
                                    ; set/reset is enabled for all planes, the
                                    ; value written actually doesn't matter
LineLoop:
;
; See if it's time to advance the X coordinate yet.
;
        and     bp,bp                        ;see if error term is negative
        jns     ETermAction                  ;no, advance X coordinate
        add     bp,si                        ;increment error term & keep same
        jmp     short MoveYCoord             ; X coordinate
ETermAction:
;
; Move pixel mask one pixel (either right or left, depending
; on MOVE_LEFT), adjusting display memory address when pixel mask wraps.
;
if MOVE_LEFT
        rol     al,1
        sbb     di,0
else
        ror     al,1
        adc     di,0
endif
        out     dx,al                        ;set new bit mask
        add     bp,bx                        ;adjust error term back down
;
```

```
; Advance Y coordinate.
;
MoveYCoord:
        add     di,EVGA_SCREEN_WIDTH_IN_BYTES
;
; Write the next pixel.
;
        xchg    byte ptr [di],ah
                                ;load latches and write pixel, with bit mask
                                ; preserving other latched bits. Because
                                ; set/reset is enabled for all planes, the
                                ; value written actually doesn't matter
;
        loop    LineLoop
Line2End:
        endm

;***************************************************************
; Line drawing routine.                                        *
;***************************************************************

        public  _EVGALine
_EVGALine       proc    near
        push    bp
        mov     bp,sp
        push    si                      ;preserve register variables
        push    di
        push    ds
;
; Point DS to display memory.
;
        mov     ax,EVGA_SCREEN_SEGMENT
        mov     ds,ax
;
; Set the Set/Reset and Set/Reset Enable registers for
; the selected color.
;
        mov     dx,GC_INDEX
        mov     al,SET_RESET_INDEX
        out     dx,al
        inc     dx
        mov     al,[bp+Color]
        out     dx,al
        dec     dx
        mov     al,ENABLE_SET_RESET_INDEX
        out     dx,al
        inc     dx
        mov     al,0ffh
        out     dx,al
;
; Get DeltaY.
;
        mov     si,[bp+Y1]              ;line Y start
        mov     ax,[bp+Y0]              ;line Y end, used later in
                                        ;calculating the start address
        sub     si,ax                   ;calculate DeltaY
        jns     CalcStartAddress        ;if positive, we're set
;
; DeltaY is negative -- swap coordinates so we're always working
; with a positive DeltaY.
;
```

```
        mov     ax,[bp+Y1]          ;set line start to Y1, for use
                                    ; in calculating the start address
        mov     dx,[bp+X0]
        xchg    dx,[bp+X1]
        mov     [bp+X0],dx          ;swap X coordinates
        neg     si                  ;convert to positive DeltaY
;
; Calculate the starting address in display memory of the line.
; Hardwired for a screen width of 80 bytes.
;
CalcStartAddress:
        shl     ax,1                ;Y0 * 2 ;Y0 is already in AX
        shl     ax,1                ;Y0 * 4
        shl     ax,1                ;Y0 * 8
        shl     ax,1                ;Y0 * 16
        mov     di,ax
        shl     ax,1                ;Y0 * 32
        shl     ax,1                ;Y0 * 64
        add     di,ax               ;Y0 * 80
        mov     dx,[bp+X0]
        mov     cl,dl               ;set aside lower 3 bits of column for
        and     cl,7                ; pixel masking
        shr     dx,1
        shr     dx,1
        shr     dx,1                ;get byte address of column (X0/8)
        add     di,dx               ;offset of line start in display segment
;
; Set up GC Index register to point to the Bit Mask register.
;
        mov     dx,GC_INDEX
        mov     al,BIT_MASK_INDEX
        out     dx,al
        inc     dx                  ;leave DX pointing to the GC Data register
;
; Set up pixel mask (in-byte pixel address).
;
        mov     al,80h
        shr     al,cl
;
; Calculate DeltaX.
;
        mov     bx,[bp+X1]
        sub     bx,[bp+X0]
;
; Handle correct one of four octants.
;
        js      NegDeltaX
        cmp     bx,si
        jb      Octant1
;
; DeltaX >= DeltaY >= 0.
;
        LINE1   0
        jmp     EVGALineDone
;
; DeltaY > DeltaX >= 0.
;
Octant1:
        LINE2   0
        jmp     short EVGALineDone
;
```

```
NegDeltaX:
        neg     bx      ;|DeltaX|
        cmp     bx,si
        jb      Octant2
;
; |DeltaX| >= DeltaY and DeltaX < 0.
;
        LINE1   1
        jmp     short EVGALineDone
;
; |DeltaX| < DeltaY and DeltaX < 0.
;
Octant2:
        LINE2   1
;
EVGALineDone:
;
; Restore EVGA state.
;
        mov     al,0ffh
        out     dx,al                   ;set Bit Mask register to 0ffh
        dec     dx
        mov     al,ENABLE_SET_RESET_INDEX
        out     dx,al
        inc     dx
        sub     al,al
        out     dx,al                   ;set Enable Set/Reset register to 0
;
        pop     ds
        pop     di
        pop     si
        pop     bp
        ret
_EVGALine       endp

        end
```

An explanation of the workings of the code in Listing 14.3 would be a lengthy one, and would be redundant since the basic operation of the code in Listing 14.3 is no different from that of the code in Listing 14.1, although the implementation is much changed due to the nature of assembly language and also due to designing for speed rather than for clarity. Given that you thoroughly understand the C implementation in Listing 14.1, the assembly language implementation in Listing 14.3, which is well-commented, should speak for itself.

One point I do want to make is that Listing 14.3 incorporates a clever notion for which credit is due Jim Mackraz, who described the notion in a letter written in response to an article I wrote long ago in the late and lamented *Programmer's Journal*. Jim's suggestion was that when drawing lines for which |**DeltaX**| is greater than |**DeltaY**|, bits set to 1 for each of the pixels controlled by a given byte can be accumulated in a register, rather than drawing each pixel individually. All the pixels controlled by that byte can then be drawn at once, with a single access to display memory, when all pixel processing associated with that byte has been completed. This approach can save many OUTs and many display memory reads and writes when drawing nearly-horizontal lines, and that's important because EGAs and VGAs hold the CPU up for a considerable period of time on each I/O operation and display memory access.

All too many PC programmers fall into the high-level-language trap of thinking that a good algorithm guarantees good performance. Not so: As our two implementations of Bresenham's algorithm graphically illustrate (pun not originally intended, but allowed to stand once recognized), truly great PC code requires both a good algorithm *and* a good assembly implementation. In Listing 14.3, we've got both—and my-oh-my, isn't it fun?

The Good, the Bad, and the Run-Sliced

Chapter 15

Faster Bresenham Lines with Run-Length Slice Line Drawing

Years ago, I worked at a company that asked me to write blazingly fast line-drawing code for an AutoCAD driver. I implemented the basic Bresenham's line-drawing algorithm; streamlined it as much as possible; special-cased horizontal, diagonal, and vertical lines; broke out separate, optimized routines for lines in each octant; and massively unrolled the loops. When I was done, I had line drawing down to a mere five or six instructions per pixel, and I handed the code over to the AutoCAD driver person, content in the knowledge that I had pushed the theoretical limits of the Bresenham's algorithm on the 80×86 architecture, and that this was as fast as line drawing could get on a PC. That feeling lasted for about a week, until Dave Miller, who these days is a Windows display-driver whiz at Engenious Solutions, casually mentioned Bresenham's faster run-length slice line-drawing algorithm.

Remember Bill Murray's safety tip in *Ghostbusters* ? It goes something like this. Harold Ramis tells the Ghostbusters not to cross the beams of the antighost guns. "Why?" Murray asks.

"It would be bad," Ramis says.

Murray says, "I'm fuzzy on the whole good/bad thing. What exactly do you mean by 'bad'?" It turns out that what Ramis means by bad is basically the destruction of the universe.

"Important safety tip," Murray comments dryly.

I learned two important safety tips from my line-drawing experience; neither involves the possible destruction of the universe, so far as I know, but they are nonetheless worth keeping in mind. First, never, never, never think you've written the fastest possible code. Odds are, you haven't. Run your code past another good programmer, and he or she will probably say, "But why don't you do this?" and you'll realize that you could indeed do that, and your code would then be faster. Or relax and come back to your code later, and you may well see another, faster approach. There are a million ways to implement code for any task, and you can almost always find a faster way if you need to.

Second, when performance matters, never have your code perform the same calculation more than once. This sounds obvious, but it's astonishing how often it's ignored. For example, consider this snippet of code:

```
for (i=0; i<RunLength; i++)
{
    *WorkingScreenPtr = Color;
    if (XDelta > 0)
    {
        WorkingScreenPtr++;
    }
    else
    {
        WorkingScreenPtr--;
    }
}
```

Here, the programmer knows which way the line is going before the main loop begins—but nonetheless performs that test every time through the loop, when calculating the address of the next pixel. Far better to perform the test only once, outside the loop, as shown here:

```
if (XDelta > 0)
{
    for (i=0; i<RunLength; i++)
    {
        *WorkingScreenPtr++ = Color;
    }
}
else
{
    for (i=0; i<RunLength; i++)
    {
        *WorkingScreenPtr-- = Color;
    }
}
```

Think of it this way: A program is a state machine. It takes a set of inputs and produces a corresponding set of outputs by passing through a set of states. Your primary job as a programmer is to implement the desired state machine. Your additional job as a performance programmer is to minimize the lengths of the paths through the state machine. This means performing as many tests and calculations as possible outside the loops, so that the loops themselves can do as little work—that is, pass through as few states—as possible.

Which brings us full circle to Bresenham's run-length slice line-drawing algorithm, which just happens to be an excellent example of a minimized state machine. In case you're fuzzy on the good/bad performance thing, that's "good"—as in *fast.*

Run-Length Slice Fundamentals

First off, I have a confession to make: I'm not sure that the algorithm I'll discuss is actually, precisely Bresenham's run-length slice algorithm. It's been a long time since I read about this algorithm; in the intervening years, I've misplaced Bresenham's article, and have been unable to unearth it. As a result, I had to derive the algorithm from scratch, which was admittedly more fun than reading about it, and also ensured that I understood it inside and out. The upshot is that what I discuss may or may not be Bresenham's run-length slice algorithm—but it surely is fast.

The place to begin understanding the run-length slice algorithm is the standard Bresenham's line-drawing algorithm. (I discussed the standard Bresenham's line-drawing algorithm at length in the previous chapter.) The basis of the standard approach is stepping one pixel at a time along the major axis (the longer dimension of the line), while maintaining an integer error term that indicates at each major-axis step how close the line is to advancing halfway to the next pixel along the minor axis. Figure 15.1 illustrates standard Bresenham's line drawing. The key point here is that a calculation and a test are performed once for each step along the major axis.

The run-length slice algorithm rotates matters 90 degrees, with salubrious results. The basis of the run-length slice algorithm is stepping one pixel at a time along the minor axis (the shorter dimension), while maintaining an integer error term indicating how close the line is to advancing an extra pixel along the major axis, as illustrated by Figure 15.2.

Consider this: When you're called upon to draw a line with an X-dimension of 35 and a Y-dimension of 10, you have a great deal of information available, some of which is ignored by standard Bresenham's. In particular, because the slope is between 1/3 and

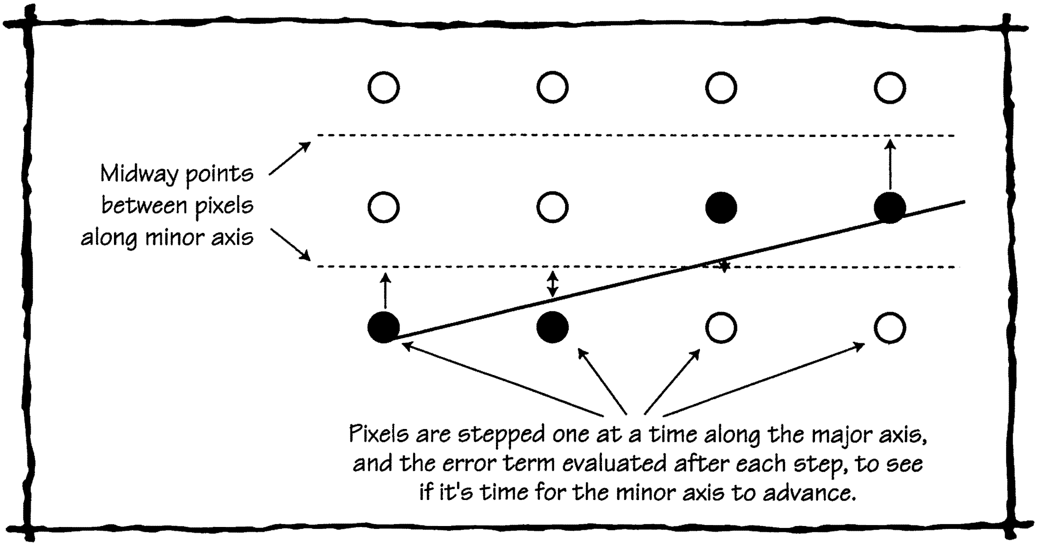

Midway points
between pixels
along minor axis
Pixels are stepped one at a time along the major axis,
and the error term evaluated after each step, to see
if it's time for the minor axis to advance.

Figure 15.1 Standard Bresenham's Line Drawing

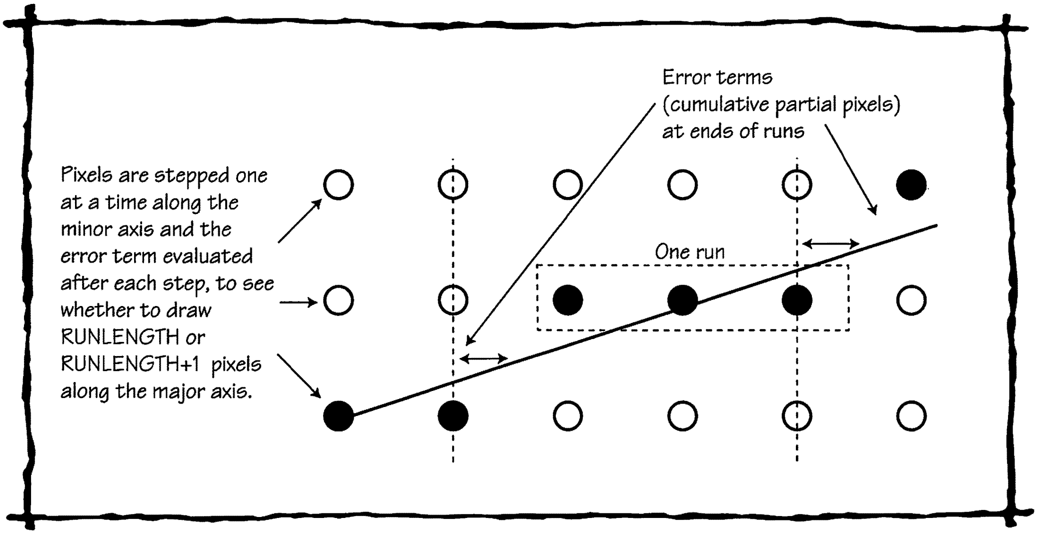

Error terms
(cumulative partial pixels)
at ends of runs
Pixels are stepped one at a time along the minor axis and the error term evaluated after each step, to see whether to draw RUNLENGTH or RUNLENGTH+1 pixels along the major axis.
One run

Figure 15.2 Run-Length Slice Line Drawing

1/4, you know that every single run—a *run* being a set of pixels at the same minor-axis coordinate—must be either three or four pixels long. No other length is possible, as shown in Figure 15.3 (apart from the first and last runs, which are special cases that I'll discuss shortly). Therefore, for this line, there's no need to perform an error-term calculation and test for each pixel. Instead, we can just perform one test per run, to see whether the run is three or four pixels long, thereby eliminating about 70 percent of the calculations in drawing this line.

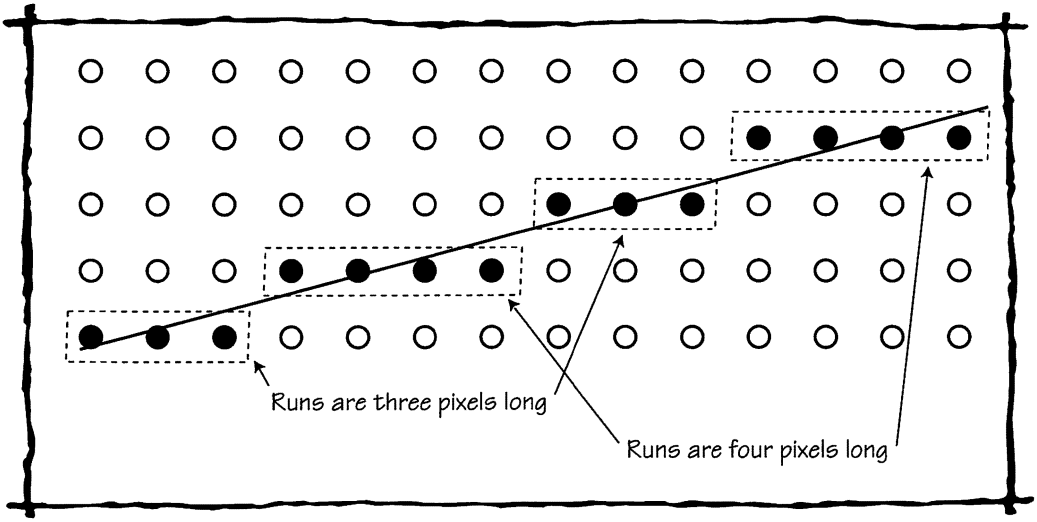


Figure 15.3 Runs in a Slope 1/3.5 Line

Take a moment to let the idea behind run-length slice drawing soak in. Periodic decisions must be made to control pixel placement. The key to speed is to make those decisions as infrequently and as quickly as possible. Of course, it will work to make a decision at each pixel—that's standard Bresenham's. However, most of those per-pixel decisions are redundant, and in fact we have enough information before we begin drawing to know which are the redundant decisions. Run-length slice drawing is exactly equivalent to standard Bresenham's, but it pares the decision-making process down to a minimum. It's somewhat analogous to the difference between finding the greatest common divisor of two numbers using Euclid's algorithm and finding it by trying every possible divisor. Both approaches produce the desired result, but that which takes maximum advantage of the available information and minimizes redundant work is preferable.

Run-Length Slice Implementation

We know that for any line, a given run will always be one of two possible lengths. How, though, do we know which length to select? Surprisingly, this is easy to determine. For the following discussion, assume that we have a slope of 1/3.5, so that X is the major axis; however, the discussion also applies to Y-major lines, with X and Y reversed.

The minimum possible length for any run in an X-major line is **int(XDelta/YDelta)**, where **XDelta** is the X-dimension of the line and **YDelta** is the Y-dimension. The maximum possible length is **int(XDelta/YDelta)+ 1**. The trick, then, is knowing which of these two lengths to select for each run. To see how we can make this selection, refer to Figure 15.4. For each one-pixel step along the minor axis (Y, in this case), we advance at

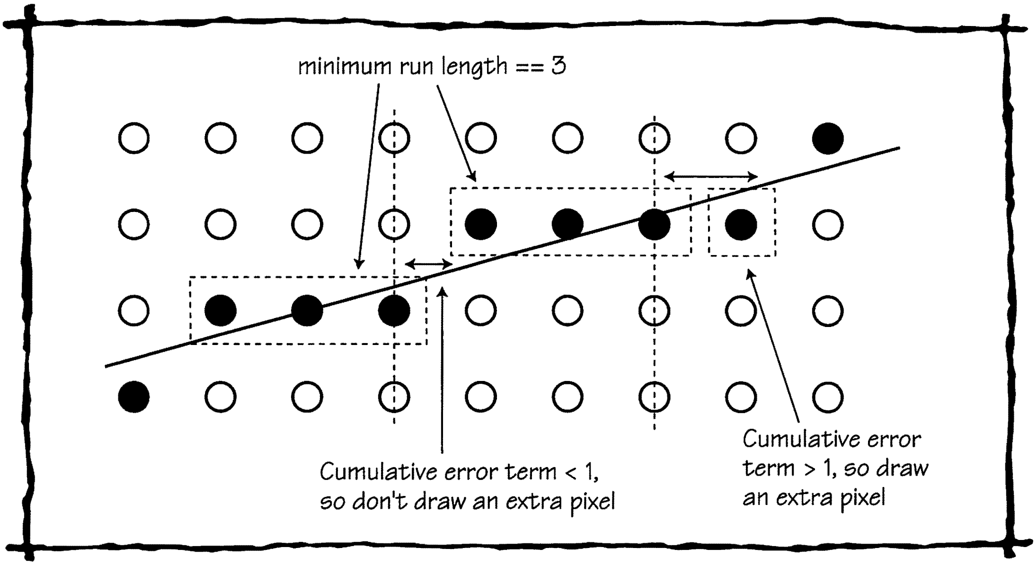

minimum run length == 3
Cumulative error term < 1, so don't draw an extra pixel
Cumulative error term > 1, so draw an extra pixel

Figure 15.4 How the Error Term Determines Run Length

least three pixels. The full advance distance along X (the major axis) is actually three-plus pixels, because there is also a fractional portion to the advance along X for a single-pixel Y step. This fractional advance is the key to deciding when to add an extra pixel to a run. The fraction indicates what portion of an extra pixel we advance along X (the major axis) during each run. If we keep a running sum of the fractional parts, we have a measure of how close we are to needing an extra pixel; when the fractional sum reaches 1, it's time to add an extra pixel to the current run. Then, we can subtract 1 from the running sum (because we just advanced one pixel), and continue on.

Practically speaking, however, we can't work with fractions because floating-point arithmetic is slow and fixed-point arithmetic is imprecise. Therefore, we take a cue from standard Bresenham's and scale all the error-term calculations up so that we can work with integers. The fractional X (major axis) advance per one-pixel Y (minor axis) advance is the fractional portion of **XDelta/YDelta**. This value is exactly equivalent **to (XDelta % YDelta)/YDelta**. We'll scale this up by multiplying it by **YDelta*2**, so that the amount by which we adjust the error term up for each one-pixel minor-axis advance is **(XDelta % YDelta)*2**.

We'll similarly scale up the one pixel by which we adjust the error term down after it turns over, so our downward error-term adjustment is **YDelta*2**. Therefore, before drawing each run, we'll add **(XDelta % YDelta)*2** to the error term. If the error term runs over (reaches one full pixel), we'll lengthen the run by 1, and subtract **YDelta*2** from the error term. (All values are multiplied by 2 so that the initial error term, which involves a 0.5 term, can be scaled up to an integer, as discussed next.)

This is not a complicated process; it involves only integer addition and subtraction and a single test, and it lends itself to many and varied optimizations. For example, you could break out hardwired optimizations for drawing each possible pair of run lengths. For the aforementioned line with a slope of 1/3.5, for example, you could have one routine hardwired to blast in a run of three pixels as quickly as possible, and another hardwired to blast in a run of four pixels. These routines would ideally have no looping, but rather just a series of instructions customized to draw the desired number of pixels at maximum speed. Each routine would know that the only possibilities for the length of the next run would be three and four, so they could increment the error term, then jump directly to the appropriate one of the two routines depending on whether the error term turned over. Properly implemented, it should be possible to reduce the average per-run overhead of line drawing to less than one branch, with only two additions and two tests (the number of runs must also be counted down), plus a subtraction half the time. On a 486, this amounts to something on the order of 150 nanoseconds of overhead per pixel, exclusive of the time required to actually write the pixel to display memory.

That's good.

Run-Length Slice Details

A couple of run-length slice implementation details yet remain. First is the matter of how error-term turnover is detected. This is done in much the same way as it is with standard Bresenham's: The error term is maintained as a negative valve and advances for each step; when the error term reaches 0, it's time to add an extra pixel to the current run. This means that we only have to test for carry after advancing the error term to determine whether or not to add an extra pixel to each run. (Actually, the code in this chapter tests for the error term being greater than zero, but the assembly code in the next chapter will use the very efficient carry approach.)

The second and more difficult detail is balancing the runs so that they're centered around the ideal line, and therefore draw the same pixels that standard Bresenham's would draw. If we just drew full-length runs from the start, we'd end up with an unbalanced line, as shown in Figure 15.5. Instead, we have to split the initial pixel plus one

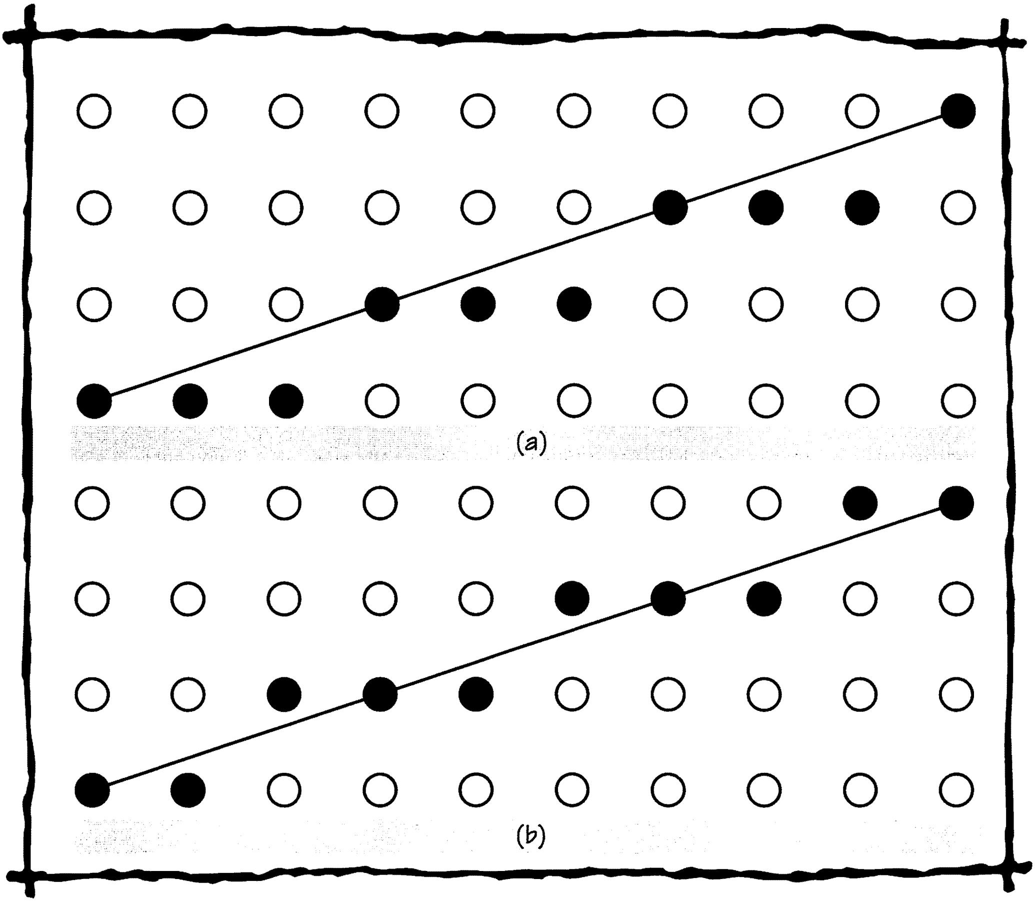


Figure 15.5 Balancing Run-Length Slice Lines: a) Unbalanced; b) Balanced

full run as evenly as possible between the first and last runs of the line, and adjust the initial error term appropriately for the initial half-run.

The initial error term is advanced by one-half of the normal per-step fractional advance, because the initial step is only one-half pixel along the minor axis. This half-step gets us exactly halfway between the initial pixel and the next pixel along the minor axis. All the error-term adjustments are scaled up by two times precisely so that we can scale up this halved error term for the initial run by two times, and thereby make it an integer.

The other trick here is that if an odd number of pixels are allocated between the first and last partial runs, we'll end up with an odd pixel, since we are unable to draw a half-pixel. This odd pixel is accounted for by adding half a pixel to the error term.

That's all there is to run-length slice line drawing; the partial first and last runs are the only tricky part. Listing 15.1 is a run-length slice implementation in C. This is not an optimized implementation, nor is it meant to be; this listing is provided so that you can see how the run-length slice algorithm works. In the next chapter, I'll move on to an optimized version, but for now, Listing 15.1 will make it much easier to grasp the principles of run-length slice drawing, and to understand the optimized code I'll present in the next chapter.

LISTING 15.1 L15-1.C

```
/* Run-length slice line drawing implementation for mode 0x13, the VGA's
320x200 256-color mode. Not optimized! Tested with Borland C++ in
the small model. */

#include <dos.h>

#define SCREEN_WIDTH    320
#define SCREEN_SEGMENT  0xA000

void DrawHorizontalRun(char far **ScreenPtr, int XAdvance, int RunLength,
                       int Color);
void DrawVerticalRun(char far **ScreenPtr, int XAdvance, int RunLength,
                       int Color);
/* Draws a line between the specified endpoints in color Color. */
void LineDraw(int XStart, int YStart, int XEnd, int YEnd, int Color)
{
   int Temp, AdjUp, AdjDown, ErrorTerm, XAdvance, XDelta, YDelta;
   int WholeStep, InitialPixelCount, FinalPixelCount, i, RunLength;
   char far *ScreenPtr;

   /* We'll always draw top to bottom, to reduce the number of cases we have to
   handle, and to make lines between the same endpoints draw the same pixels */
   if (YStart > YEnd) {
      Temp = YStart;
      YStart = YEnd;
      YEnd = Temp;
      Temp = XStart;
      XStart = XEnd;
      XEnd = Temp;
   }
   /* Point to the bitmap address first pixel to draw */
   ScreenPtr = MK_FP(SCREEN_SEGMENT, YStart * SCREEN_WIDTH + XStart);
```

```
/* Figure out whether we're going left or right, and how far we're
   going horizontally */
if ((XDelta = XEnd - XStart) < 0)
{
   XAdvance = -1;
   XDelta = -XDelta;
}
else
{
   XAdvance = 1;
}
/* Figure out how far we're going vertically */
YDelta = YEnd - YStart;

/* Special-case horizontal, vertical, and diagonal lines, for speed
   and to avoid nasty boundary conditions and division by 0 */
if (XDelta == 0)
{
   /* Vertical line */
   for (i=0; i<=YDelta; i++)
   {
      *ScreenPtr = Color;
      ScreenPtr += SCREEN_WIDTH;
   }
   return;
}
if (YDelta == 0)
{
   /* Horizontal line */
   for (i=0; i<=XDelta; i++)
   {
      *ScreenPtr = Color;
      ScreenPtr += XAdvance;
   }
   return;
}
if (XDelta == YDelta)
{
   /* Diagonal line */
   for (i=0; i<=XDelta; i++)
   {
      *ScreenPtr = Color;
      ScreenPtr += XAdvance + SCREEN_WIDTH;
   }
   return;
}

/* Determine whether the line is X or Y major, and handle accordingly */
if (XDelta >= YDelta)
{
   /* X major line */
   /* Minimum # of pixels in a run in this line */
   WholeStep = XDelta / YDelta;

   /* Error term adjust each time Y steps by 1; used to tell when one
      extra pixel should be drawn as part of a run, to account for
      fractional steps along the X axis per 1-pixel steps along Y */
   AdjUp = (XDelta % YDelta) * 2;

   /* Error term adjust when the error term turns over, used to factor
      out the X step made at that time */
   AdjDown = YDelta * 2;
```

```
      /* Initial error term; reflects an initial step of 0.5 along the Y
         axis */
      ErrorTerm = (XDelta % YDelta) - (YDelta * 2);

      /* The initial and last runs are partial, because Y advances only 0.5
         for these runs, rather than 1. Divide one full run, plus the
         initial pixel, between the initial and last runs */
      InitialPixelCount = (WholeStep / 2) + 1;
      FinalPixelCount = InitialPixelCount;

      /* If the basic run length is even and there's no fractional
         advance, we have one pixel that could go to either the initial
         or last partial run, which we'll arbitrarily allocate to the
         last run */
      if ((AdjUp == 0) && ((WholeStep & 0x01) == 0))
      {
         InitialPixelCount--;
      }
      /* If there're an odd number of pixels per run, we have 1 pixel that can't
         be allocated to either the initial or last partial run, so we'll add 0.5
         to error term so this pixel will be handled by the normal full-run loop */
         if ((WholeStep & 0x01) != 0)
      {
         ErrorTerm += YDelta;
      }
      /* Draw the first, partial run of pixels */
      DrawHorizontalRun(&ScreenPtr, XAdvance, InitialPixelCount, Color);
      /* Draw all full runs */
      for (i=0; i<(YDelta-1); i++)
      {
         RunLength = WholeStep;  /* run is at least this long */
         /* Advance the error term and add an extra pixel if the error
            term so indicates */
         if ((ErrorTerm += AdjUp) > 0)
         {
            RunLength++;
            ErrorTerm -= AdjDown;   /* reset the error term */
         }
         /* Draw this scan line's run */
         DrawHorizontalRun(&ScreenPtr, XAdvance, RunLength, Color);
      }
      /* Draw the final run of pixels */
      DrawHorizontalRun(&ScreenPtr, XAdvance, FinalPixelCount, Color);
      return;
   }
   else
   {
      /* Y major line */

      /* Minimum # of pixels in a run in this line */
      WholeStep = YDelta / XDelta;

      /* Error term adjust each time X steps by 1; used to tell when 1 extra
         pixel should be drawn as part of a run, to account for
         fractional steps along the Y axis per 1-pixel steps along X */
      AdjUp = (YDelta % XDelta) * 2;

      /* Error term adjust when the error term turns over, used to factor
         out the Y step made at that time */
      AdjDown = XDelta * 2;
      /* Initial error term; reflects initial step of 0.5 along the X axis */
      ErrorTerm = (YDelta % XDelta) - (XDelta * 2);

      /* The initial and last runs are partial, because X advances only 0.5
         for these runs, rather than 1. Divide one full run, plus the
         initial pixel, between the initial and last runs */
      InitialPixelCount = (WholeStep / 2) + 1;
      FinalPixelCount = InitialPixelCount;

      /* If the basic run length is even and there's no fractional advance, we
         have 1 pixel that could go to either the initial or last partial run,
         which we'll arbitrarily allocate to the last run */
      if ((AdjUp == 0) && ((WholeStep & 0x01) == 0))
      {
         InitialPixelCount--;
      }
      /* If there are an odd number of pixels per run, we have one pixel
         that can't be allocated to either the initial or last partial
         run, so we'll add 0.5 to the error term so this pixel will be
         handled by the normal full-run loop */
      if ((WholeStep & 0x01) != 0)
      {
         ErrorTerm += XDelta;
      }
      /* Draw the first, partial run of pixels */
      DrawVerticalRun(&ScreenPtr, XAdvance, InitialPixelCount, Color);

      /* Draw all full runs */
      for (i=0; i<(XDelta-1); i++)
      {
         RunLength = WholeStep;  /* run is at least this long */
         /* Advance the error term and add an extra pixel if the error
            term so indicates */
         if ((ErrorTerm += AdjUp) > 0)
         {
            RunLength++;
            ErrorTerm -= AdjDown;   /* reset the error term */
         }
         /* Draw this scan line's run */
         DrawVerticalRun(&ScreenPtr, XAdvance, RunLength, Color);
      }
      /* Draw the final run of pixels */
      DrawVerticalRun(&ScreenPtr, XAdvance, FinalPixelCount, Color);
      return;
   }
}
/* Draws a horizontal run of pixels, then advances the bitmap pointer to
   the first pixel of the next run. */
void DrawHorizontalRun(char far **ScreenPtr, int XAdvance,
   int RunLength, int Color)
{
   int i;
   char far *WorkingScreenPtr = *ScreenPtr;

   for (i=0; i<RunLength; i++)
   {
      *WorkingScreenPtr = Color;
      WorkingScreenPtr += XAdvance;
   }
   /* Advance to the next scan line */
   WorkingScreenPtr += SCREEN_WIDTH;
   *ScreenPtr = WorkingScreenPtr;
}
/* Draws a vertical run of pixels, then advances the bitmap pointer to
   the first pixel of the next run. */
void DrawVerticalRun(char far **ScreenPtr, int XAdvance,
   int RunLength, int Color)
{
   int i;
   char far *WorkingScreenPtr = *ScreenPtr;

   for (i=0; i<RunLength; i++)
   {
      *WorkingScreenPtr = Color;
      WorkingScreenPtr += SCREEN_WIDTH;
   }
   /* Advance to the next column */
   WorkingScreenPtr += XAdvance;
   *ScreenPtr = WorkingScreenPtr;
}
```

Notwithstanding that it's not optimized, Listing 15.1 is reasonably fast. If you run Listing 15.2 (a sample line-drawing program that you can use to test-drive Listing 15.1), you may be as surprised as I was at how quickly the screen fills with vectors, considering that Listing 15.1 is entirely in C and has some redundant divides. Or perhaps you won't be surprised—in which case I suggest you *not* miss the next chapter.

LISTING 15.2 L15-2.C

```
/* Sample line-drawing program. Uses the optimized
line-drawing functions coded in LListing L15.1.C.
Tested with Borland C++ in the small model. */

#include <dos.h>

#define GRAPHICS_MODE   0x13
#define TEXT_MODE       0x03
#define BIOS_VIDEO_INT  0x10
#define X_MAX           320      /* working screen width */
#define Y_MAX           200      /* working screen height */

extern void LineDraw(int XStart, int YStart, int XEnd, int YEnd, int Color);

/* Subroutine to draw a rectangle full of vectors, of the specified
 * length and color, around the specified rectangle center.  */
void VectorsUp(XCenter, YCenter, XLength, YLength, Color)
int XCenter, YCenter;   /* center of rectangle to fill */
int XLength, YLength;   /* distance from center to edge of rectangle */
int Color;              /* color to draw lines in */
{
   int WorkingX, WorkingY;

   /* lines from center to top of rectangle */
   WorkingX = XCenter - XLength;
   WorkingY = YCenter - YLength;
   for ( ; WorkingX < ( XCenter + XLength ); WorkingX++ )
   {
      LineDraw(XCenter, YCenter, WorkingX, WorkingY, Color);
   }
   /* lines from center to right of rectangle */
   WorkingX = XCenter + XLength - 1;
   WorkingY = YCenter - YLength;
   for ( ; WorkingY < ( YCenter + YLength ); WorkingY++ )
   {
      LineDraw(XCenter, YCenter, WorkingX, WorkingY, Color);
   }
   /* lines from center to bottom of rectangle */
   WorkingX = XCenter + XLength - 1;
   WorkingY = YCenter + YLength - 1;
   for ( ; WorkingX >= ( XCenter - XLength ); WorkingX-- )
   {
      LineDraw(XCenter, YCenter, WorkingX, WorkingY, Color);
   }
   /* lines from center to left of rectangle */
   WorkingX = XCenter - XLength;
   WorkingY = YCenter + YLength - 1;
   for ( ; WorkingY >= ( YCenter - YLength ); WorkingY-- )
   {
      LineDraw(XCenter, YCenter, WorkingX, WorkingY, Color);
   }
}
/* Sample program to draw four rectangles full of lines.  */
int main()
{
   union REGS regs;

   /* Set graphics mode */
   regs.x.ax = GRAPHICS_MODE;
   int86(BIOS_VIDEO_INT, &regs, &regs);

   /* Draw each of four rectangles full of vectors */
   VectorsUp(X_MAX / 4, Y_MAX / 4, X_MAX / 4, Y_MAX / 4, 1);
   VectorsUp(X_MAX * 3 / 4, Y_MAX / 4, X_MAX / 4, Y_MAX / 4, 2);
   VectorsUp(X_MAX / 4, Y_MAX * 3 / 4, X_MAX / 4, Y_MAX / 4, 3);
   VectorsUp(X_MAX * 3 / 4, Y_MAX * 3 / 4, X_MAX / 4, Y_MAX / 4, 4);

   /* Wait for a key to be pressed */
   getch();

   /* Return back to text mode */
   regs.x.ax = TEXT_MODE;
   int86(BIOS_VIDEO_INT, &regs, &regs);
}
```

Dead Cats and Lightning Lines

Chapter 16

Optimizing Run-Length Slice Line Drawing in a Major Way

As I write this, the wife, the kid, and I are in the throes of yet another lightning-quick transcontinental move, this time to Redmond, Washington to work for You Know Who. Moving is never fun, but what makes it worse for us is the pets. Getting them into kennels and to the airport is hard; there's always the possibility that they might not be allowed to fly because of the weather; and, worst of all, they might not make it. Animals don't usually end up injured or dead, but it does happen.

In a (not notably successful) effort to cheer me up about the prospect of shipping my animals, a friend told me the following story, which he swears actually happened to a friend of his. I don't know—to me, it has the ring of an urban legend, which is to say it makes a good story, but you can never track down the person it really happened to; it's always a friend of a friend. But maybe it is true, and anyway, it's a good story.

This friend of a friend (henceforth referred to as FOF), worked in an air-freight terminal. Consequently, he handled a lot of animals, which was fine by him, because he liked animals; in fact, he had quite a few cats at home. You can imagine his dismay when, one day, he took a kennel off the plane to find that the cat it carried was quite thoroughly dead. (No, it wasn't resting, nor pining for the fjords; this cat was bloody *deceased.*)

FOF knew how upset the owner would be, and came up with a plan to make everything better. At home, he had a cat of the same size, shape, and markings. He would substitute that cat, and since all cats treat all humans with equal disdain, the owner would never know the difference, and would never suffer the trauma of the loss of her cat. So FOF drove home, got his cat, put it in the kennel, and waited for the owner to show up—at which point, she took one look at the kennel and said, "This isn't my cat. My cat is dead."

As it turned out, she had shipped her recently deceased feline home to be buried. History does not record how our FOF dug himself out of this one.

Okay, but what's the point? The point is, if it isn't broken, don't fix it. And if it is broken, maybe that's all right, too. Which brings us, neat as a pin, to the topic of drawing lines in a serious hurry.

Fast Run-Length Slice Line Drawing

In the last chapter, we examined the principles of run-length slice line drawing, which draws lines a run at a time rather than a pixel at a time, a run being a series of pixels along the major (longer) axis. It's time to turn theory into useful practice by developing a fast assembly version. Listing 16.1 is the assembly version, in a form that's plug-compatible with the C code from the previous chapter.

LISTING 16.1 L16-1.ASM

```
; Fast run-length slice line drawing implementation for mode 0x13, the VGA's
; 320x200 256-color mode.
; Draws a line between the specified endpoints in color Color.
; C near-callable as:
;  void LineDraw(int XStart, int YStart, int XEnd, int YEnd, int Color)
; Tested with TASM

SCREEN_WIDTH          equ 320
SCREEN_SEGMENT        equ 0a000h
    .model  small
    .code

; Parameters to call.
parms    struc
         dw   ?                      ;pushed BP
         dw   ?                      ;pushed return address
XStart   dw   ?                      ;X start coordinate of line
YStart   dw   ?                      ;Y start coordinate of line
XEnd     dw   ?                      ;X end coordinate of line
YEnd     dw   ?                      ;Y end coordinate of line
Color    db   ?                      ;color in which to draw line
         db   ?                      ;dummy byte because Color is really a word
parmsends

; Local variables.
AdjUp                 equ -2    ;error term adjust up on each advance
AdjDown               equ -4    ;error term adjust down when error term turns over
WholeStep             equ -6    ;minimum run length
XAdvance              equ -8    ;1 or -1, for direction in which X advances
LOCAL_SIZE            equ  8
    public  _LineDraw
_LineDraw  proc  near
      cld
      push      bp                   ;preserve caller's stack frame
      mov       bp,sp                ;point to our stack frame
      sub sp,   LOCAL_SIZE           ;allocate space for local variables
      push      si                   ;preserve C register variables
      push      di
      push      ds                   ;preserve caller's DS
```

```
; We'll draw top to bottom, to reduce the number of cases we have to handle,
; and to make lines between the same endpoints always draw the same pixels.
      mov        ax,[bp].YStart
      cmp        ax,[bp].YEnd
      jle        LineIsTopToBottom
      xchg       [bp].YEnd,ax                 ;swap endpoints
      mov        [bp].YStart,ax
      mov        bx,[bp].XStart
      xchg       [bp].XEnd,bx
      mov        [bp].XStart,bx
LineIsTopToBottom:
; Point DI to the first pixel to draw.
      mov        dx,SCREEN_WIDTH
      mul        dx    '                      ;YStart * SCREEN_WIDTH
      mov        si,[bp].XStart
      mov        di,si
      add        di,ax                        ;DI = YStart * SCREEN_WIDTH + XStart
                                              ; = offset of initial pixel
; Figure out how far we're going vertically (guaranteed to be positive).
      mov        cx,[bp].YEnd
      sub        cx,[bp].YStart               ;CX = YDelta
; Figure out whether we're going left or right, and how far we're going
; horizontally. In the process, special-case vertical lines, for speed and
; to avoid nasty boundary conditions and division by 0.
      mov        dx,[bp].XEnd
      sub        dx,si                        ;XDelta
      jnz        NotVerticalLine              ;XDelta == 0 means vertical line
                                              ;it is a vertical line
                                              ;yes, special case vertical line
      mov        ax,SCREEN_SEGMENT
      mov        ds,ax                        ;point DS:DI to the first byte to draw
      mov        al,[bp].Color
VLoop:
      mov        [di],al
      add        di,SCREEN_WIDTH
      dec        cx
      jns        VLoop
      jmp        Done
; Special-case code for horizontal lines.
      align      2
IsHorizontalLine:
      mov        ax,SCREEN_SEGMENT
      mov        es,ax                        ;point ES:DI to the first byte to draw
      mov        al,[bp].Color
      mov        ah,al                        ;duplicate in high byte for word access
      and        bx,bx                        ;left to right?
      jns        DirSet                       ;yes
      sub        di,dx                        ;currently right to left, point to left
                                              ; end so we can go left to right
                                              ; (avoids unpleasantness withright to
                                              ;  left REP STOSW)
DirSet:
      mov        cx,dx
      inc        cx                                ;# of pixels to draw
      shr        cx,1                              ;# of words to draw
      rep        stosw                             ;do as many words as possible
      adc        cx,cx
      rep        stosb                             ;do the odd byte, if there is one
      jmp        Done
; Special-case code for diagonal lines.
      align      2
```

```
IsDiagonalLine:
      mov        ax,SCREEN_SEGMENT
      mov        ds,ax                  ;point DS:DI to the first byte to draw
      mov        al,[bp].Color
      add        bx,SCREEN_WIDTH        ;advance distance from one pixel to next
DLoop:
      mov        [di],al
      add        di,bx
      dec        cx
      jns        DLoop
      jmp        Done

      align      2
NotVerticalLine:
      mov        bx,1                   ;assume left to right, so XAdvance = 1
                                        ;***leaves flags unchanged***
      jns        LeftToRight            ;left to right, all set
      neg        bx                     ;right to left, so XAdvance = -1
      neg        dx                     ;|XDelta|
LeftToRight:
; Special-case horizontal lines.
      and        cx,cx                  ;YDelta == 0?
      jz         IsHorizontalLine       ;yes
; Special-case diagonal lines.
      cmp        cx,dx                  ;YDelta == XDelta?
      jz         IsDiagonalLine         ;yes
; Determine whether the line is X or Y major, and handle accordingly.
      cmp        dx,cx
      jae        XMajor
      jmp        YMajor
; X-major (more horizontal than vertical) line.
      align      2
XMajor:
      mov        ax,SCREEN_SEGMENT
      mov        es,ax                  ;point ES:DI to the first byte to draw
      and        bx,bx                  ;left to right?
      jns        DFSet                  ;yes, CLD is already set
      std                               ;right to left, so draw backwards
DFSet:
      mov        ax,dx                  ;XDelta
      sub        dx,dx                  ;prepare for division
      div        cx                     ;AX = XDelta/YDelta
                                        ; (minimum # of pixels in a run in this line)
                                        ;DX = XDelta % YDelta
      mov        bx,dx                  ;error term adjust each time Y steps by 1;
      add        bx,bx                  ; used to tell when one extra pixel should be
      mov        [bp].AdjUp,bx          ; drawn as part of a run, to account for
                                        ; fractional steps along the X axis per
                                        ; 1-pixel steps along Y
      mov        si,cx                  ;error term adjust when the error term turns
      add        si,si                  ; over, used to factor out the X step made at
      mov        [bp].AdjDown,si        ; that time
; Initial error term; reflects an initial step of 0.5 along the Y axis.
      sub        dx,si                  ;(XDelta % YDelta) - (YDelta * 2)
                                        ;DX = initial error term
; The initial and last runs are partial, because Y advances only 0.5 for
; these runs, rather than 1. Divide one full run, plus the initial pixel,
; between the initial and last runs.
      mov        si,cx                  ;SI = YDelta
      mov        cx,ax                  ;whole step (minimum run length)
      shr        cx,1
```

```
     inc        cx                     ;initial pixel count = (whole step / 2) + 1;
                                       ; (may be adjusted later). This is also the
                                       ; final run pixel count
     push       cx                     ;remember final run pixel count for later
; If the basic run length is even and there's no fractional advance, we have
; one pixel that could go to either the initial or last partial run, which
; we'll arbitrarily allocate to the last run.
; If there is an odd number of pixels per run, we have one pixel that can't
; be allocated to either the initial or last partial run, so we'll add 0.5 to
; the error term so this pixel will be handled by the normal full-run loop.
     add        dx,si                  ;assume odd length, add YDelta to error term
                                       ; (add 0.5 of a pixel to the error term)
     test       al,1                   ;is run length even?
     jnz        XMajorAdjustDone       ;no, already did work for odd case, all set
     sub        dx,si                  ;length is even, undo odd stuff we just did
     and        bx,bx                  ;is the adjust up equal to 0?
     jnz        XMajorAdjustDone       ;no (don't need to check for odd length,
                                       ; because of the above test)
     dec        cx                     ;both conditions met; make initial run 1
                                       ; shorter
XMajorAdjustDone:
     mov        [bp].WholeStep,ax      ;whole step (minimum run length)
     mov        al,[bp].Color          ;AL = drawing color
; Draw the first, partial run of pixels.
     rep        stosb                  ;draw the final run
     add        di,SCREEN_WIDTH        ;advance along the minor axis (Y)
; Draw all full runs.
     cmp        si,1                   ;are there more than 2 scans, so there are
                                       ; some full runs? (SI = # scans - 1)
     jna        XMajorDrawLast         ;no, no full runs
     dec        dx                     ;adjust error term by -1 so we can use
                                       ; carry test
     shr        si,1                   ;convert from scan to scan-pair count
     jnc        XMajorFullRunsOddEntry ;if there is an odd number of scans,
                                       ; do the odd scan now
XMajorFullRunsLoop:
     mov        cx,[bp].WholeStep      ;run is at least this long
     add        dx,bx                  ;advance the error term and add an extra
     jnc        XMajorNoExtra          ; pixel if the error term so indicates
     inc        cx                     ;one extra pixel in run
     sub        dx,[bp].AdjDown        ;reset the error term
XMajorNoExtra:
     rep        stosb                  ;draw this scan line's run
     add        di,SCREEN_WIDTH        ;advance along the minor axis (Y)
XMajorFullRunsOddEntry:                ;enter loop here if there is an odd number
                                       ; of full runs
     mov        cx,[bp].WholeStep      ;run is at least this long
     add        dx,bx                  ;advance the error term and add an extra
     jnc        XMajorNoExtra2         ; pixel if the error term so indicates
     inc        cx                     ;one extra pixel in run
     sub        dx,[bp].AdjDown        ;reset the error term
XMajorNoExtra2:
     rep        stosb                  ;draw this scan line's run
     add        di,SCREEN_WIDTH        ;advance along the minor axis (Y)

     dec        si
     jnz        XMajorFullRunsLoop
; Draw the final run of pixels.
XMajorDrawLast:
     pop        cx                     ;get back the final run pixel length
     rep        stosb                  ;draw the final run
```

```
      cld                                ;restore normal direction flag
      jmp        Done
; Y-major (more vertical than horizontal) line.
      align      2
YMajor:
      mov        [bp].XAdvance,bx             ;remember which way X advances
      mov        ax,SCREEN_SEGMENT
      mov        ds,ax                   ;point DS:DI to the first byte to draw
      mov        ax,cx                   ;YDelta
      mov        cx,dx                   ;XDelta
      sub        dx,dx                   ;prepare for division
      div        cx                      ;AX = YDelta/XDelta
                                         ; (minimum # of pixels in a run in this line)
                                         ;DX = YDelta % XDelta
      mov        bx,dx                   ;error term adjust each time X steps by 1;
      add        bx,bx                   ; used to tell when one extra pixel should be
      mov        [bp].AdjUp,bx           ; drawn as part of a run, to account for
                                         ; fractional steps along the Y axis per
                                         ; 1-pixel steps along X
      mov        si,cx                   ;error term adjust when the error term turns
      add        si,si                   ; over, used to factor out the Y step made at
      mov        [bp].AdjDown,si         ; that time

; Initial error term; reflects an initial step of 0.5 along the X axis.
      sub        dx,si                   ;(YDelta % XDelta) - (XDelta * 2)
                                         ;DX = initial error term
; The initial and last runs are partial, because X advances only 0.5 for
; these runs, rather than 1. Divide one full run, plus the initial pixel,
; between the initial and last runs.
      mov        si,cx                   ;SI = XDelta
      mov        cx,ax                   ;whole step (minimum run length)
      shr        cx,1
      inc        cx                      ;initial pixel count = (whole step / 2) + 1;
                                         ; (may be adjusted later)
      push       cx                      ;remember final run pixel count for later

; If the basic run length is even and there's no fractional advance, we have
; one pixel that could go to either the initial or last partial run, which
; we'll arbitrarily allocate to the last run.
; If there is an odd number of pixels per run, we have one pixel that can't
; be allocated to either the initial or last partial run, so we'll add 0.5 to
; the error term so this pixel will be handled by the normal full-run loop.
      add        dx,si                   ;assume odd length, add XDelta to error term
      test       al,1                    ;is run length even?
      jnz        YMajorAdjustDone        ;no, already did work for odd case, all set
      sub        dx,si                   ;length is even, undo odd stuff we just did
      and        bx,bx                   ;is the adjust up equal to 0?
      jnz        YMajorAdjustDone        ;no (don't need to check for odd length,
                                         ; because of the above test)
      dec        cx                      ;both conditions met; make initial run 1
                                         ; shorter
YMajorAdjustDone:
      mov        [bp].WholeStep,ax       ;whole step (minimum run length)
      mov        al,[bp].Color           ;AL = drawing color
      mov        bx,[bp].XAdvance        ;which way X advances
; Draw the first, partial run of pixels.
YMajorFirstLoop:
      mov        [di],al                 ;draw the pixel
      add        di,SCREEN_WIDTH         ;advance along the major axis (Y)
      dec        cx
      jnz        YMajorFirstLoop
      add        di,bx                 ;advance along the minor axis (X)
          ; Draw all full runs.
      cmp        si,1                  ;# of full runs. Are there more than 2
                                       ; columns, so there are some full runs?
                                       ; (SI = # columns - 1)
      jna        YMajorDrawLast        ;no, no full runs
      dec        dx                    ;adjust error term by -1 so we can use
                                       ; carry test
      shr        si,1                  ;convert from column to column-pair count
      jnc        YMajorFullRunsOddEntry;if there is an odd number of
                                       ; columns, do the odd column now
YMajorFullRunsLoop:
      mov        cx,[bp].WholeStep     ;run is at least this long
      add        dx,[bp].AdjUp         ;advance the error term and add an extra
      jnc        YMajorNoExtra         ; pixel if the error term so indicates
      inc        cx                    ;one extra pixel in run
      sub        dx,[bp].AdjDown       ;reset the error term
YMajorNoExtra:
  ;draw the run
YMajorRunLoop:
      mov        [di],al               ;draw the pixel
      add        di,SCREEN_WIDTH       ;advance along the major axis (Y)
      dec        cx
      jnz        YMajorRunLoop
      add        di,bx                 ;advance along the minor axis (X)
YMajorFullRunsOddEntry:                ;enter loop here if there is an odd number
                                       ; of full runs
      mov        cx,[bp].WholeStep     ;run is at least this long
      add        dx,[bp].AdjUp         ;advance the error term and add an extra
      jnc        YMajorNoExtra2        ; pixel if the error term so indicates
      inc        cx                    ;one extra pixel in run
      sub        dx,[bp].AdjDown       ;reset the error term
YMajorNoExtra2:
  ;draw the run
YMajorRunLoop2:
      mov        [di],al               ;draw the pixel
      add        di,SCREEN_WIDTH       ;advance along the major axis (Y)
      dec        cx
      jnz        YMajorRunLoop2
      add        di,bx                 ;advance along the minor axis (X)

      dec        si
      jnz        YMajorFullRunsLoop
; Draw the final run of pixels.
YMajorDrawLast:
      pop        cx                    ;get back the final run pixel length
YMajorLastLoop:
      mov        [di],al               ;draw the pixel
      add        di,SCREEN_WIDTH       ;advance along the major axis (Y)
      dec        cx
      jnz        YMajorLastLoop
Done:
      pop        ds                          ;restore caller's DS
      pop        di
      pop        si                          ;restore C register variables
      mov        sp,bp                       ;deallocate local variables
      pop        bp                          ;restore caller's stack frame
      ret
  _LineDraw   endp
      end
```

How Fast Is Fast?

Your first question is likely to be the following: Just how fast is Listing 16.1? Is it optimized to the hilt, or just pretty fast? The quick answer is: It's *fast.* Listing 16.1 draws lines at a rate of nearly 1 million pixels per second on my 486/33, and is capable of still faster drawing, as I'll discuss shortly. (The heavily optimized AutoCAD line-drawing code that I mentioned in the last chapter drew 150,000 pixels per second on an EGA in a 386/16, and I thought I had died and gone to Heaven. Such is progress.) The full answer is a more complicated one, and ties in to the principle that if it is broken, maybe that's okay—and to the principle of looking before you leap, also known as profiling before you optimize.

When I went to speed up run-length slice lines, I initially manually converted the last chapter's C code into assembly. Then I streamlined the register usage and used **REP STOS** wherever possible. Listing 16.1 is that code. At that point, line drawing was surely faster, although I didn't know exactly how much faster. Equally surely, there were significant optimizations yet to be made, and I was itching to get on to them, for they were bound to be a lot more interesting than a basic C-to-assembly port.

Ego intervened at this point, however. I wanted to know how much of a speed-up I had already gotten, so I timed the performance of the C code and compared it to the assembly code. To my horror, I found that I had not gotten even a two-times improvement! I couldn't understand how that could be—the C code was decidedly unoptimized—until I hit on the idea of measuring the maximum memory speed of the VGA to which I was drawing.

Bingo. The Paradise VGA in my 486/33 is fast for a single display-memory write, because it buffers the data, lets the CPU go on its merry way, and finishes the write when display memory is ready. However, the maximum rate at which data can be written to the adapter turns out to be no more than one byte every microsecond. Put another way, you can only write one byte to this adapter every 33 clock cycles on a 486/33. Therefore, no matter how fast I made the line-drawing code, it could never draw more than 1,000,000 pixels per second in 256-color mode in my system. The C code was already drawing at about half that rate, so the potential speed-up for the assembly code was limited to a maximum of two times, which is pretty close to what Listing 16.1 did, in fact, achieve. When I compared the C and assembly implementations drawing to normal system (nondisplay) memory, I found that the assembly code was actually four times as fast as the C code.

In fact, Listing 16.1 draws VGA lines at about 92 percent of the maximum possible rate in my system—that is, it draws very nearly as fast as the VGA hardware will allow. All the optimization in the world would get me less than 10 percent faster line drawing—and only if I eliminated all overhead, an unlikely proposition at best. The code isn't fully optimized, but so what?

Now it's true that faster line-drawing code would likely be more beneficial on faster VGAs, especially local-bus VGAs, and in slower systems. For that reason, I'll list a variety of potential optimizations to Listing 16.1. On the other hand, it's also true that Listing 16.1 is capable of drawing lines at a rate of 2.2 million pixels per second on a 486/ 33, given fast enough VGA memory, so it should be able to drive almost any non-local-bus VGA at nearly full speed. In short, Listing 16.1 is very fast, and, in many systems, further optimization is basically a waste of time.

Profile before you optimize.

Further Optimizations

Following is a quick tour of some of the many possible further optimizations to Listing 16.1.

The run-handling loops could be unrolled more than the current two times. However, bear in mind that a two-times unrolling gets more than half the maximum unrolling benefit with less overhead than a more heavily unrolled loop.

BX could be freed up in the Y-major code by breaking out separate loops for X advances of 1 and –1. DX could be freed up by using AH as the counter for the run loops, although this would limit the maximum line length that could be handled. The freed registers could be used to keep more of the whole-step and error variables in registers. Alternatively, the freed registers could be used to implement more esoteric approaches like unrolling the Y-major inner loop; such unrolling could take advantage of the knowledge that only two run lengths are possible for any given line. Strangely enough, on the 486 it might also be worth unrolling the X-major inner loop, which consists of **REP STOSB**, because of the slow start-up time of **REP** relative to the speed of branching on that processor.

Special code could be implemented for lines with integral slopes, because all runs are exactly the same length in such lines. Also, the X-major code could try to write an aligned word at a time to display memory whenever possible; this would improve the maximum possible performance on some 16-bit VGAs.

One weakness of Listing 16.1 is that for lines with slopes between 0.5 and 2, the average run length is less than two, rendering run-length slicing ineffective. This can be remedied by viewing lines in that range as being composed of diagonal, rather than horizontal or vertical runs. I haven't space to take this idea any further in this book, but it's not very complicated, and it guarantees a minimum run length of 2, which renders run drawing considerably more efficient, and makes techniques such as unrolling the inner run-drawing loops more attractive.

Finally, be aware that run-length slice drawing is best for long lines, because it has more and slower setup than a standard Bresenham's line draw, including a divide. Run-length slice is great for 100-pixel lines, but not necessarily for 20-pixel lines, and it's a sure thing that it's not terrific for 3-pixel lines. Both approaches will work, but if line-drawing performance is critical, whether you'll want to use run-length slice or standard

Bresenham's depends on the typical lengths of the lines you'll be drawing. For lines of widely varying lengths, you might want to implement both approaches, and choose the best one for each line, depending on the line length—assuming, of course, that your display memory is fast enough and your application demanding enough to make that level of optimization worthwhile.

If your code looks broken from a performance perspective, think before you fix it; that particular cat may be dead for a perfectly good reason. I'll say it again: *Profile before you optimize.*

Circling Around the VGA

Chapter 17

Understanding Hardenburgh's Algorithm for Fast Circles

Whenever I pick up one of the classic books about graphics algorithms, I come away thinking that those guys must be awfully smart, because *I* sure as heck don't understand what they're talking about. The explanations are cryptic, difficult to follow, and often leave key elements as the legendary "exercise for the reader." Worse, they're difficult to relate to the real world; the authors tell you how to derive an algorithm, when what you really want to know is how it works and how to implement it efficiently—and that final and most important step is, sadly, often omitted, or, at best, shown in marginally useful pseudocode.

I don't know why this state of affairs exists, but exist it does. One theory is that academics think in abstractions, not implementations. Maybe so. Another, more cynical, school of thought holds that academics must publish "major" works in order to get degrees, tenure, grants, and the like, so they dress up relatively simple concepts with a great deal of theory to make them seem more important or profound than they might be. Again, maybe so. At any rate, you and I are left holding the bag, with graphics code waiting to be written on the one hand and cryptic, highly theoretical explanations on the other, and a yawning gap in between.

It is against this background that I received a letter from Hal Hardenberg (who many may remember from his wild and wildly entertaining "DTACK Grounded" newsletter and "Offramp" column in *Programmer's Journal* some years ago) regarding an article I wrote on line drawing. Hal's letter began thusly:

"*Ten pages of typeset text on drawing a LINE???* Yikes! I had in mind 5 pages on drawing three kinds of curves!" (Hal is inordinately fond of italics and exclamation points.)

This gentle missive was followed by a call from Hal asking whether I'd be interested in writing an article with him about drawing circles and ellipses. He felt strongly that there was nothing particularly complicated about any of the above, and that one article should do it for both.

In a world of people who puff themselves up by making the simple complex, I was more than slightly intrigued to meet someone who promised to make the complex simple. Hal and I got together, and while he decided to leave the article writing to me (he merely instructed me in the concepts and gave me his 68000 circle and ellipse drawing code; the man is remarkably generous with his considerable knowledge), he did indeed make the whole topic seem simple. Not quite so simple that it'll fit in one chapter—I'm going to spend two chapters on circle drawing and two on ellipses—but remarkably simpler than the graphics books would make it seem to be, and the credit for the concepts in these installments goes enthusiastically to Hal.

Hal thinks his approach may be the one used by Bresenham's circle-drawing algorithm, but he's not sure; he got fed up with the turgid nature of the standard references and derived his own approach. That's our good fortune, for Hal's approach is both fast—almost in a class with line drawing—and easy to understand.

With the credits and history out of the way, let's get started with circle drawing. We'll spend this chapter and the next on circles and then progress to the more flexible but more complicated ellipses. In the process, we'll do a good deal of the sort of low-level C and assembly optimization that I've demonstrated many times before in my articles, columns, and books like *Zen of Code Optimization* (Coriolis Group Books, 1994); we'll also learn more than a little about the sort of optimization that springs from understanding the operation of an algorithm thoroughly and then reshaping it to match the PC's capabilities. Only by applying both sorts of optimization can we test the limits of the PC's performance.

Why and when Circles and Ellipses Matter

Circles and ellipses rank no better than fourth on the list of most-used graphics elements, after bitblts, lines, and area fills. Nonetheless, they are used for many sorts of drawing, particularly in CAD and CAE applications, and their importance is magnified because most software takes so darn *long* to draw them.

True circles—that is, objects for which every point, as measured in *pixels*, not screen distance, is the same distance from the center—are useful only on screens that offer square pixels (pixels spaced equidistant along both axes). On any other sort of screen, true circles come out squashed or distended along one axis or the other. Fortunately, all graphics modes in common use today—640×480, 800×600, and 1024×768—offer square pixels on popular displays, or close enough to square pixels as makes no difference.

Just to be sure we're all speaking the same language, let me define some terms. *Ellipses* are ovals drawn around two foci, with a constant combined distance from the two foci to each point on the ellipse. For the purposes of this book, ellipses will further be defined to have symmetry around the X and Y axes (the foci share either a common

Y coordinate or a common X coordinate). That is, their major axes are either vertical or horizontal. Tilted ellipses, which I'm not going to tackle here, need not have symmetry around any axis. Basically, ellipses are specific 90-degree alignments of tilted ellipses, and circles are ellipses where the foci are both at the same point. As a final definition, I'll discuss all drawing of circles and ellipses in terms of pixels, not screen distance, except where otherwise noted, because pixels are the units with which we'll always work directly.

For this chapter and the next, we'll put ellipses aside and focus on circles.

The Basics of Drawing a Circle

Drawing a circle is actually pretty easy. The basic equation for a circle is

$$Radius^2 = X^2 + Y^2$$

which is nothing more than a way of saying that every point on a circle is exactly **Radius** distance away from the center of the circle. (X and Y form two legs of a right triangle, with **Radius** as the hypotenuse. If you know your Pythagoras, you know how to draw circles.)

Viewing circle drawing in computer implementation terms, we can first cut our workload by realizing that we actually only need to generate 1/8th of a circle; symmetry does the rest. Next, we can generate that 1/8th-circle arc by starting at the zero setting for the major axis (the axis which advances more rapidly) and the maximum setting (**Radius**) for the minor axis, then advancing one pixel along the major axis at a time, and using the following formula to calculate the corresponding minor axis point, as shown in Figure 17.1:

$$MinorAxis = sqrt(Radius^2 - MajorAxis^2)$$

Note that I'm using the terms "major axis" and "minor axis" rather than X and Y because the eight-way symmetry allows us to use the same arc calculations when either X or Y is the major axis. The arc is complete when the major axis coordinate equals or exceeds the minor axis coordinate for a point. The arc can be regenerated for each of the eight symmetries, but it's easier and less calculation-intensive to draw all eight symmetries for each point at once.

That sounds a little complicated, but is in fact less so than you might think. Listing 17.1 shows a straightforward C implementation of the above approach for 16-color modes such as modes 10H and 12H. As you can see, the code isn't very long or complicated at all, and what complication there is largely results from controlling the VGA's bit mask and set/reset features. Basically, Listing 17.1 advances one pixel along the major axis, calculates the corresponding minor axis point, and then translates that result to all eight symmetries, drawing the eight points one after another through a dot-plot routine.

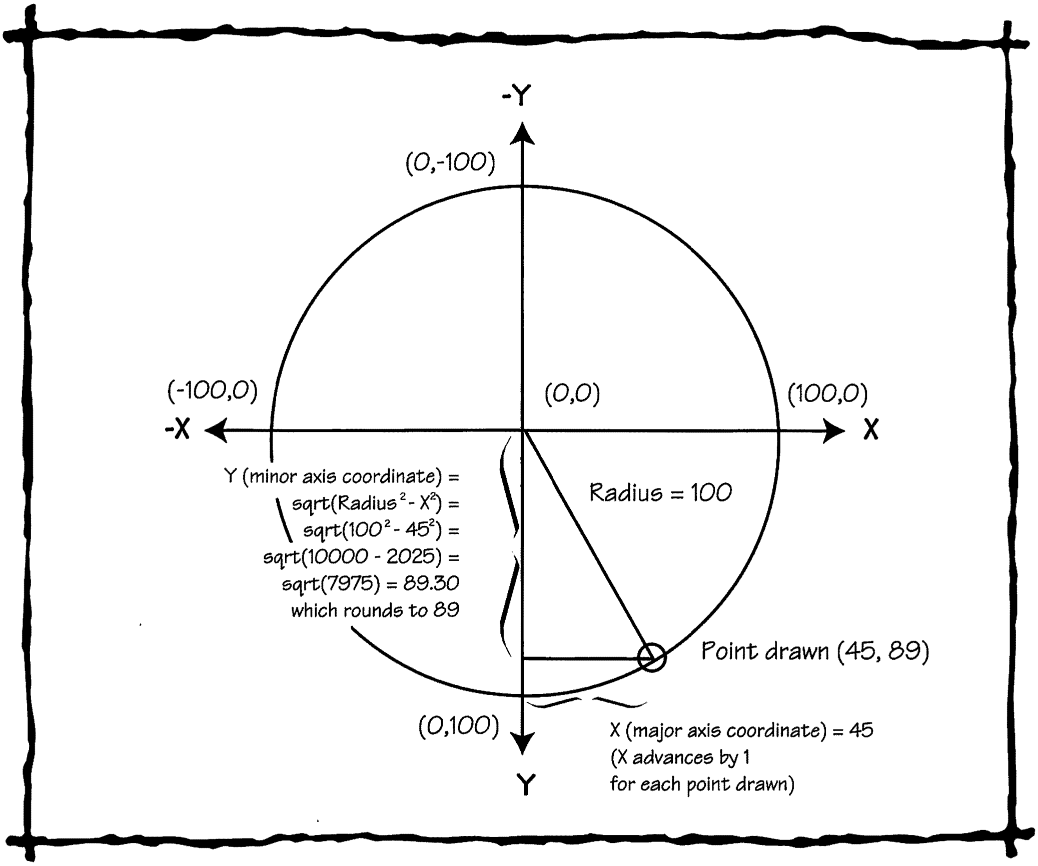


Figure 17.1 Calculating the Arc

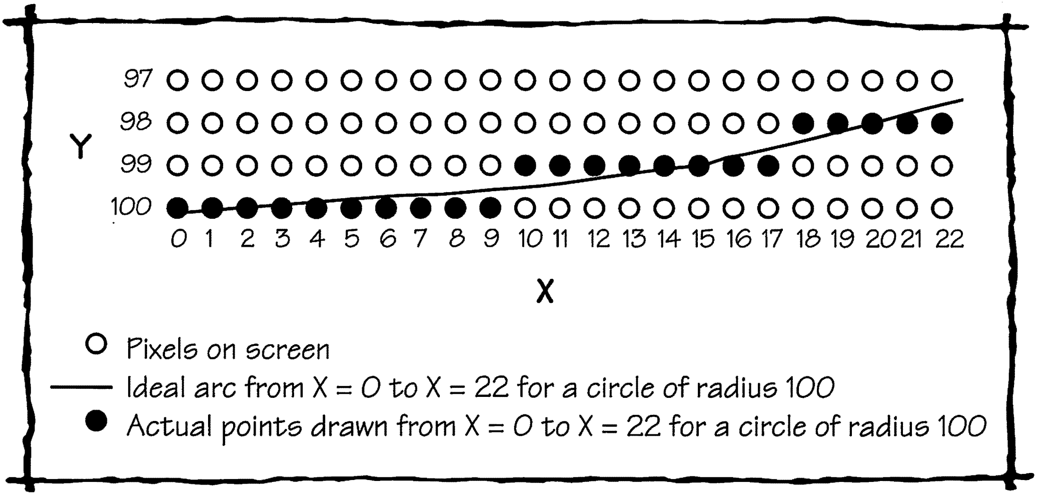

Y
97
98
99
100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
X
○ Pixels on screen
—— Ideal arc from X = 0 to X = 22 for a circle of radius 100
● Actual points drawn from X = 0 to X = 22 for a circle of radius 100

Figure 17.2 Incremental Arc Drawing

Listing 17.2 is a demonstration program for Listing 17.1. It calls the function in Listing 17.1 to draw a screen full of multicolored concentric circles. If you run Listing 17.2, you'll find that it does indeed draw circles, albeit none too quickly.

LISTING 17.1. L17-1.C

```
/*
 * Draws a circle of the specified radius and color.
 * Compiles with either Borland or Microsoft compilers.
 * Will work on VGA or EGA in 16-color mode.
 */

#include <math.h>
#include <dos.h>

/* Handle differences between Borland and Micrsoft. Note that Borland accepts
   outp as a synonym for outportb, but not outpw for outport. */
#ifdef __TURBOC__
#define outpw   outport
#endif

#define SCREEN_WIDTH_IN_BYTES    80        /* # of bytes across one scan
                                              line in mode 12h */
#define SCREEN_SEGMENT           0xA000    /* mode 12h display memory seg */
#define GC_INDEX                 0x3CE     /* Graphics Controller port */
#define SET_RESET_INDEX          0         /* Set/Reset reg index in GC */
#define SET_RESET_ENABLE_INDEX   1         /* Set/Reset enable reg index in GC */
#define BIT_MASK_INDEX           8         /* Bit Mask reg index in GC */

/* Draws a pixel at screen coordinate (X,Y) */
void DrawDot(int X, int Y) {
     unsigned char far *ScreenPtr;

   /* Point to the byte the pixel is in */
#ifdef __TURBOC__
   ScreenPtr = MK_FP(SCREEN_SEGMENT,
   (Y * SCREEN_WIDTH_IN_BYTES) + (X / 8));
#else
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) =(Y * SCREEN_WIDTH_IN_BYTES) + (X / 8);
#endif

    /* Set the bit mask within the byte for the pixel */
    outp(GC_INDEX + 1, 0x80 >> (X & 0x07));

    /* Draw the pixel. ORed to force read/write to load latches.
       Data written doesn't matter, because set/reset is enabled
       for all planes. Note: don't OR with 0; MSC optimizes that
       statement to no operation. */
    *ScreenPtr |= 0xFE;
}

/* Draws a circle of radius Radius in color Color centered at
   screen coordinate (X,Y) */
void DrawCircle(int X, int Y, int Radius, int Color) {
     int MajorAxis, MinorAxis;
   double RadiusSquared = (double) Radius * Radius;
   /* Set drawing color via set/reset */
   outpw(GC_INDEX, (0x0F << 8) | SET_RESET_ENABLE_INDEX);
                                       /* enable set/reset for all planes */
   outpw(GC_INDEX, (Color << 8) | SET_RESET_INDEX);
                                       /* set set/reset (drawing) color */
   outp(GC_INDEX, BIT_MASK_INDEX);
                                       /* leave the GC pointing to Bit Mask reg */

   /* Set up to draw the circle by setting the initial point to one
      end of the 1/8th of a circle arc we'll draw */
   MajorAxis = 0;
   MinorAxis = Radius;

   /* Draw all points along an arc of 1/8th of the circle, drawing
      all 8 symmetries at the same time */
   do {
   /* Draw all 8 symmetries of current point */
      DrawDot(X+MajorAxis, Y-MinorAxis);
      DrawDot(X-MajorAxis, Y-MinorAxis);
      DrawDot(X+MajorAxis, Y+MinorAxis);
      DrawDot(X-MajorAxis, Y+MinorAxis);
      DrawDot(X+MinorAxis, Y-MajorAxis);
      DrawDot(X-MinorAxis, Y-MajorAxis);
      DrawDot(X+MinorAxis, Y+MajorAxis);
      DrawDot(X-MinorAxis, Y+MajorAxis);
      MajorAxis++;                        /* advance one pixel along major axis */
      MinorAxis =
        sqrt(RadiusSquared - ((double) MajorAxis * MajorAxis)) + 0.5;
      /* calculate corresponding point along minor axis */
  } while ( MajorAxis <= MinorAxis );

  /* Reset the Bit Mask register to normal */
  outp(GC_INDEX + 1, 0xFF);

  /* Turn off set/reset enable */
  outpw(GC_INDEX, (0x00 << 8) | SET_RESET_ENABLE_INDEX);
}
```

LISTING 17.2 L17-2.C

```
/*
 * Draws a series of concentric circles.
 * For VGA only, because mode 12h is unique to VGA.
 * Compile and link with L17-X (1 or 3) with Borland C++:
 *   Bcc L17 - X.C  L17 - 2.C
 *
 */

#include <dos.h>

main() {
   int     Radius, Temp, Color;
   union   REGS Regs;

   /* Select VGA's hi-res 640x480 graphics mode, mode 12h */
   Regs.x.ax = 0x0012;
   int86(0x10, &Regs, &Regs);
   /* Draw concentric circles */
   for ( Radius = 10, Color = 7; Radius < 240; Radius += 2 ) {
      DrawCircle(640/2, 480/2, Radius, Color);
      Color = (Color + 1) & 0x0F; /* cycle through 16 colors */
   }

   /* Wait for a key, restore text mode, and done */
   scanf("%c", &Temp);
   Regs.x.ax = 0x0003;
   int86(0x10, &Regs, &Regs);
}
```

Drawing a Circle More Efficiently

Now that we know how to draw a circle, let's think about how we might do it better. There are two paths to take, algorithmic refinement and implementation optimization (that is, converting to assembly, code massaging, fine-tuning, things like that). When given this choice, always take the algorithmic approach first, for it's easy to fine-tune after settling on an algorithm, but it's very difficult to change algorithms without wasting effort once you've fine-tuned. We'll concentrate on algorithmic refinement for the remainder of this chapter, continuing to work in C code with a dot-plot routine so that the operation of the algorithm is apparent. Then, in the next chapter, we'll tighten up the C code by eliminating the independent plotting of each point, and we'll finally arrive at a high-speed assembly implementation.

The optimization we'll make to Listing 17.1 is this: Rather than calculating each minor axis point by taking an extremely time-consuming floating-point square root, we'll use purely integer calculations to determine when it's time to advance one pixel along the minor axis. (Granted, a floating-point coprocessor would speed up the square root calculation, but integer approaches are faster still, and even in these days where the 486 is the baseline Intel CPU, much of the installed base still doesn't have floating-point coprocessors.) In this respect, the faster circle-drawing implementation will be similar to the line-drawing code presented in Chapter 14; knowing as we do that the minor axis can only advance zero pixels or one pixel, we'll use an *integer threshold variable* (which we called an *error term variable* in line drawing) to determine when to advance along the minor axis. However, the circle drawing approach is a tad more complicated, because it involves squares.

Let's take a moment to work out the internals of our new, faster approach. This approach will also serve as a beautiful illustration of the point that you can only max out the performance of your code if you really understand what that code is doing (rather than blindly implementing an algorithm you've looked up), to the point where you can alter it into forms that are radically different and better suited to the PC, but nonetheless functionally equivalent.

An Incremental Circle Drawing Approach

Here's the trick to integer-only circle drawing: Use expansions of squared elements to keep track of when the minor axis should advance. In other words, rather than calculating each minor axis point independently through this expression

```
MinorAxis = sqrt(Radius² - MajorAxis²)
```

maintain the running states of **MinorAxis**^{2} and **Radius**^{2} – **MajorAxis**^{2}, and decrement the minor axis by one pixel whenever **MinorAxis**^{2} drops below **Radius**^{2} – **MajorAxis**^{2}.

Okay, I admit it's a *little* more complicated than that, but not much. Consider this: Suppose that we're drawing a circle of radius 100, centered about (0,0), and we're drawing the arc starting at (0,100), as shown in Figure 17.1. A simple multiply gives us **Radius**^{2} (10,000), which also happens to be **Radius**^{2} – X^2, because X is zero. Now, as we advance X (the major axis) one pixel at a time, we want to know when it's time to advance Y one pixel; that occurs when Y (which equals **sqrt(Radius**^{2} – X^2**)**) drops below 99.5 (that is, moves more than halfway from the initial Y of 100 to the next pixel along the Y axis, at 99). Another way to express that is to say that we want to advance Y when Y^2 (which equals **Radius**^{2} – X^2) drops below 99.5^2—or, more conveniently for us, we want to advance Y when **Radius**^{2} – X^2 drops below 9900.25.

Why is that convenient? Well, we already know the initial **Radius**^{2} – X^2, which is 10,000. It's easy to maintain **Radius**^{2} – X^2 as X advances, because (X + 1)^2 is simply X^2 + 2X + 1, a simple integer calculation given X^2 and X. Consequently, **Radius**^{2} – (X + 1)^2 can be calculated as **Radius**^{2} – (X^2 + 2X + 1), with no floating-point arithmetic needed.

Now that we know **Radius**^{2} – X^2 for each X as we move to the right, all we need to know is the threshold value for **Radius**^{2} – X^2 below which we must advance Y. Initially, that threshold value is the value we calculated earlier, 9900.25, which is 99.5^2.

We seem to have a problem here, in that our threshold is not an integer. That's easily dealt with, however, as follows: First of all, that initial threshold is calculated as (Y – 0.5)^2 (the square of the coordinate of the midpoint between Y and Y – 1). That expression expands to Y^2 – Y + 0.25. Now, Y^2 – Y is an easily-calculated integer expression; it's only the 0.25 that's a sticking point. It turns out, however, that we can just ignore the 0.25, because the **Radius**^{2} – X^2 values we'll compare to the Y thresholds are always integers. If a given **Radius**^{2} – X^2 value matches the integer portion of a Y^2 – Y + 0.25 value, we'll know that it actually is less than the threshold, because of the 0.25 we'll be carrying along.

For the example in Figure 17.2, the initial point plotted is (0,100) relative to the center of the circle. (We'll always do our calculations relative to the center of the circle, and then adjust for the center of the circle and perform symmetry calculations later.) **Radius**^{2} – X^2 is 10,000 at this point, and the initial threshold, (Y – 0.5)^2, is 9900.25—but we'll use Y^2 – Y to derive a working threshold of 9,900.

Next, X advances one pixel to coordinate 1. **Radius**^{2} – X^2 goes to 10,000 – (2X + 1), which is 9,999 (X refers to the last X drawn, which is zero at the moment.) That still exceeds the threshold of 9,900, so Y doesn't change. X then advances to coordinate 2. **Radius**^{2} – X^2 goes to 9,999 – (2X + 1), which is 9,996, so Y still doesn't advance. **Radius**^{2} – X^2 then advances to 9,991, 9,984, 9,975, 9,964, 9,951, 9,936, 9,919, and finally to 9,900 as X advances to 10. Remember, we've only performed integer addition and subtraction as X has moved, and a mere two integer multiplications were required to set up the squared terms at the outset.

When X equals 10, **Radius**^{2} – X^2 has finally matched our threshold for advancing Y; in fact, because of the implied 0.25 we've been carrying around, we know that **Radius**^{2} – X^2 has passed the threshold. Consequently, we subtract 1 from Y to advance to the next pixel along the Y axis, and draw the next point at (10,99). That's precisely what we want, since the rounded integer portion of **sqrt**(100^2 – 10^2) (which is **Radius**^{2} – X^2) is 99.

Our only remaining task is to reset the threshold so that we know when to advance Y again. That's accomplished by calculating the new threshold as (Y – 1)^2; much as we did earlier with X, we can expand this to Y^2 – 2Y + 1 in order to perform integer-only arithmetic. Given that we already know the Y^2 for the threshold we just reached, it's a simple matter to calculate (Y – 1)^2 for the next threshold each time we advance Y.

There's a trick here, though: The Y we use in the threshold isn't the Y we just advanced to *or* the Y we just advanced from--it's the Y of the threshold we just reached; 99.5 is our sample case. Consequently, when Y advances to 99, the threshold advances to 9,900 – (99.5 * 2) + 1, which is 9,702. The 0.5 element doesn't mean we have to perform floating-point arithmetic, because 0.5 * 2 is always 1, so the above equation can also be expressed as 9,900 – (100 * 2 – 1) + 1. Consequently, the formula we'll use to advance the threshold is Y^2 – 2Y, where Y^2 is the last threshold value and Y is the Y coordinate of the last pixel drawn.

That's really all there is to it; reread the last section and work through an example or two of your own and you'll see how straightforward integer-only circle drawing is. It's remarkably easy to implement this approach, too; Listing 17.3, which is such an implementation, is scarcely longer than Listing 17.1. Listing 17.3 is functionally equivalent to Listing 17.1—except that it runs *more than five times faster than Listing 17.1.*

Integer arithmetic is a wonderful thing, isn't it?

LISTING 17.3 L17-3.C

```
/*
 * Draws a circle of the specified radius and color, using a fast
 * integer-only & square-root-free approach.
 * Compiles with Borland or Microsoft
 * Will work on VGA, or EGA in 16-color mode.
 */

#include <dos.h>
#include <math.h>

/* Handle differences between Borland and Microsft compilers. Note that Borland
    accepts outp as a synonym for outportb, but not outpw for outport. */
#ifdef __TURBOC__
```

```
#define outpw  outport
#endif

#define SCREEN_WIDTH_IN_BYTES     80         /* # of bytes across one scan
                                                line in mode 12h */
#define SCREEN_SEGMENT            0xA000     /* mode 12h display memory seg */
#define GC_INDEX                  0x3CE      /* Graphics Controller port */
#define SET_RESET_INDEX           0          /* Set/Reset reg index in GC */
#define SET_RESET_ENABLE_INDEX    1          /* Set/Reset enable reg index
                                                in GC */
#define  BIT_MASK_INDEX           8          /* Bit Mask reg index in GC */

/* Draws a pixel at screen coordinate (X,Y) */
void DrawDot(int X, int Y) {
   unsigned char far *ScreenPtr;

   /* Point to the byte the pixel is in */
#ifdef __TURBOC__
   ScreenPtr = MK_FP(SCREEN_SEGMENT,
      (Y * SCREEN_WIDTH_IN_BYTES) + (X / 8));
#else
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) =(Y * SCREEN_WIDTH_IN_BYTES) + (X / 8);
#endif

   /* Set the bit mask within the byte for the pixel */
   outp(GC_INDEX + 1, 0x80 >> (X & 0x07));

   /* Draw the pixel. ORed to force read/write to load latches.
      Data written doesn't matter, because set/reset is enabled
      for all planes. Note: don't OR with 0; MSC optimizes that
      statement to no operation. */
   *ScreenPtr |= 0xFE;
}

/* Draws a circle of radius Radius in color Color centered at
 * screen coordinate (X,Y) */
void DrawCircle(int X, int Y, int Radius, int Color) {
   int MajorAxis, MinorAxis;
   unsigned long RadiusSqMinusMajorAxisSq;
   unsigned long MinorAxisSquaredThreshold;

   /* Set drawing color via set/reset */
   outpw(GC_INDEX, (0x0F << 8) | SET_RESET_ENABLE_INDEX);
                                             /* enable set/reset for all planes */
   outpw(GC_INDEX, (Color << 8) | SET_RESET_INDEX);
                                             /* set set/reset (drawing) color */
   outp(GC_INDEX, BIT_MASK_INDEX);
                                             /* leave the GC pointing to Bit Mask
                                                reg */

   /* Set up to draw the circle by setting the initial point to one
      end of the 1/8th of a circle arc we'll draw */
   MajorAxis = 0;
   MinorAxis = Radius;
   /* Set initial Radius**2 - MajorAxis**2 (MajorAxis is initially 0 */
   RadiusSqMinusMajorAxisSq = (unsigned long) Radius * Radius;
   /* Set threshold for minor axis movement at (MinorAxis - 0.5)**2 */
   MinorAxisSquaredThreshold =
        (unsigned long) MinorAxis * MinorAxis - MinorAxis;
   /* Draw all points along an arc of 1/8th of the circle, drawing
      all 8 symmetries at the same time */
   do {
      /* Draw all 8 symmetries of current point */
      DrawDot(X+MajorAxis, Y-MinorAxis);
      DrawDot(X-MajorAxis, Y-MinorAxis);
      DrawDot(X+MajorAxis, Y+MinorAxis);
      DrawDot(X-MajorAxis, Y+MinorAxis);
      DrawDot(X+MinorAxis, Y-MajorAxis);
      DrawDot(X-MinorAxis, Y-MajorAxis);
      DrawDot(X+MinorAxis, Y+MajorAxis);
      DrawDot(X-MinorAxis, Y+MajorAxis);
      MajorAxis++;                     /* advance one pixel along major axis */
      if ( (RadiusSqMinusMajorAxisSq -=
         MajorAxis + MajorAxis - 1) <= MinorAxisSquaredThreshold ) {
         MinorAxis--;
         MinorAxisSquaredThreshold -= MinorAxis + MinorAxis;
      }
   } while ( MajorAxis <= MinorAxis );

   /* Reset the Bit Mask register to normal */
   outp(GC_INDEX + 1, 0xFF);

   /* Turn off set/reset enable */
   outpw(GC_INDEX, (0x00 << 8) | SET_RESET_ENABLE_INDEX);
}
```

Notes on the Implementation

The obvious question about Listing 17.3 is, Does it work? It's certainly fast, but if it doesn't draw circles properly, it's of little use.

I'm confident that Listing 17.3 does indeed work. The theory is sound, and I compared all coordinates generated by Listing 17.1 when linked to Listing 17.2 to the coordinates generated by Listing 17.3, and they were the same for all circles drawn.

Listing 17.3 uses long integers, an unavoidable consequence of lugging around squared terms of values that exceed 255. Long arithmetic is relatively slow; it might be worthwhile to special-case circles with radii less than 256 and draw them with a separate routine that uses short integers.

Listing 17.3 also treats the Y coordinates of circle centers as increasing from the top of the screen to the bottom, contrary to the normal graphing convention. If necessary, the sense of the Y axis can be inverted by subtracting each Y coordinate from the screen height minus 1; that's the only adjustment necessary, because circles are symmetric about the X axis.

Continuing in Circles

That takes us halfway through our exploration of circle drawing. Coming up in the next chapter is the other portion of our optimization agenda: fine-tuning for the VGA and conversion to assembly. The end result should be an additional improvement of at least three times, bringing the total to at least *15 times* over that of Listing 17.1!

Circling in for the Kill

Chapter 18

Optimizing Hardenburgh's Circle Algorithm with a Vengeance

Two years back, I set out to write the fastest possible line-drawing code for the PC. I took Bresenham's algorithm apart piece by piece until I understood it completely, then unleashed all the assembly-language skills I had on the task of implementing that algorithm. When I was done, I had boosted performance by about two times over a standard Bresenham's assembly-language implementation, and I couldn't for the life of me imagine how the code could be improved one iota. In other words, I was confident that I had written just about the fastest possible code.

That was an incorrect conclusion—to put it mildly.

Over the years, it seems as though every graphics programmer I know has decided to clue me in on his or her favorite way to draw lines. I've heard about state-machine line drawing, run-based line drawing, fixed-point line drawing, and even a technique that lets the floating-point processor perform a single division while the line-drawing routine sets up, then uses the bits of the floating-point remainder to control line drawing. Wildly different as these approaches are, they have one thing in common—they're all faster than my original "optimized" code.

Which brings us to this chapter. In the previous chapter, we learned how to draw circles, then we vastly improved performance by switching from floating-point code to Hal Hardenbergh's integer-only algorithm that requires multiplication and division only during the initial setup. That was step 1 of graphics optimization: selection of algorithm. Steps 2 (matching the algorithm to the hardware) and 3 (conversion of critical code to assembly language) are coming up next. When we're done, we'll have circle-drawing code that's more than 20 times as fast as the original implementation. Our final circle-drawing code will be more than 3 times as fast as the faster routine we developed last time, *even though both routines use exactly the same algorithm.* Clearly, there is more to performance than selecting the right algorithm, although that is an essential starting point.

Fast as our final implementation will be, however, I wouldn't dream of calling it optimized. As I said in the opening to this chapter, it's presumptuous indeed to think you've come up with the best possible graphics code, and circle drawing is no exception. In fact, the code could easily be speeded up by using unrolled loops to draw multiple pixels without looping, and could possibly be made faster yet with fixed-point arithmetic or by encoding the pixel list in a more readily usable format. There are also many small improvements—simplified calculations, eliminated redundancies, and the like—to be made throughout the code, although optimizing outside the inner loops tends to be a waste of time and effort.

My point is this: Don't take the code in this chapter as gospel. It's fast, but it could be at least a little faster—and maybe a *lot* faster. Understand what I've done, then try to come up with a way to do it better; one of the great things about PC graphics programming is that it's almost always possible to do exactly that.

Slimming Down the Main Loop

In order to be able to focus on specific optimizations in this chapter, I'm going to assume that you're familiar with circle drawing in general. If not, I suggest you read the previous chapter, which discussed the fundamentals of circle drawing and described in detail Hal Hardenburgh's integer-only algorithm that we'll use here.

The question at hand is this: How can we speed up the circle-drawing code we saw at the end of the previous chapter, which used integer-only calculations and required no multiplication or division inside the main loop? If you refer back to that code, you'll see that while the main loop is quite compact, it calls a separate routine to draw each pixel, and it's there that we can save a whole slew of processor cycles.

The pixel-drawing routine in the previous chapter was short, but it performed two time-consuming and avoidable tasks. First, it calculated each pixel's display memory offset from scratch, requiring both a multiply and the construction of a far pointer. Similarly, it generated each pixel's bit mask from scratch with a little arithmetic and a shift. As it turns out, neither of those actions is actually necessary, because with the circle-drawing approach we were using (and will continue to use) the offset and mask for each pixel can be calculated incrementally from the offset and mask for the *previous* pixel.

In other words, once we've drawn pixel *n*, we can generate the bit mask for pixel *n*+1 with at most a single-bit rotation. Likewise, we can calculate the offset for pixel *n*+1 with at most an increment or decrement followed by an addition. Those simpler calculations can save many cycles relative to calculating each pixel from scratch. We can also save some cycles by moving the code that draws each pixel into the drawing loop and eliminating the call to and return from the drawing function.

Reflecting Octants

There's another, less obvious optimization we can make. Consider this: The process of calculating adjacent points along one-eighth of a circle is nothing more than a matter of deciding whether to move along both axes after each pixel or only along the major axis; making these moves and drawing the corresponding pixels illuminates precisely those pixels closest to the desired arc. Given that, it should be clear that it's possible to calculate the set of moves from one pixel to the next and store that set in an array, then play back the array with varying major and minor axis directions eight times in order to draw the circle. Put another way, we could calculate and store the information needed to determine when to advance along the minor axis just once for a given circle, then play back that information eight times to draw the eight symmetric arcs that make up the circle, interpreting the information slightly differently each time.

What does that buy us? It lets us separate the arc calculation code from the arc drawing code so that each can be better optimized. Truth to tell, that's not such a big deal in C; we could just calculate each point and draw all eight symmetries on the spot, as we did in the last chapter, although that would require maintaining eight display memory pointers and eight masks. When we get to assembly language, however, separation of calculation and drawing will stand us in good stead; by reducing complexity it will allow us to keep all variables in registers for the duration of both the calculation and drawing loops—and that will translate directly into better performance.

I don't know whether the separation of calculation from drawing has a similarly large advantage in C, or indeed any advantage at all. However, given that the major purpose of the C code in this chapter is to prototype and illuminate the assembler code, I'll use the same approach of separating calculation and drawing in the C code that I'll use later in the assembly code.

Faster Circles in C

Listing 18.1 shows a C circle-drawing function that uses the separate calculation and drawing approach, along with the incremental offset and mask calculation technique described earlier. Arcs with horizontal major axes are handled separately from arcs with vertical major axes because the process of advancing across a scan line of EGA/VGA memory is fundamentally different from that of advancing from one scan line to the next. When compiled and linked to Listing 18.2, which repeats the drawing of a set of circles 20 times for timing purposes, Listing 18.1 is about 40 percent faster than Listing 17.3 in the previous chapter, which was our speed champ until now, as shown in Table 18.1. That's nowhere near the improvement that Listing 17.3 produced over Listing 17.1, but it's certainly significant.

Table 18.1 Hardenburg Circles versus Optimized Hardenburgh Circles

	Compiler/Processor			
	Microsoft C 5.0		Turbo C 2.0	
Listing	286	386	286	386
17.1 (C/floating point)	468 sec	175 sec	339 sec	127 sec
17.3 (C/integer)	44 sec	16 sec	47 sec	18 sec
18.1 (C/incremental pixel addressing)	31 sec	12 sec	32 sec	13 sec
18.3/4 (ISVGA=0) (ASM)	14 sec	7 sec	14 sec	7 sec
18.3/4 (ISVGA=1) (ASM/write mode 3)	13 sec	5.5 sec	13 sec	5.5 sec

Notes: The execution times shown are for the various circle-drawing implementations in this chapter and the last when linked to Listing 18.2. Maximum optimization (/Ox for Microsoft C, -G -O -Z -r for Turbo C) was used to compile all C code. Times in the columns labelled "286" were recorded on a Video Seven VRAM VGA running on a 10-MHz 1-wait-state AT clone (a monochrome adapter was also installed, making the VGA an 8-bit device); times in the columns labelled "386" were recorded on a the built-in Paradise VGA in a 20-MHz, 32K-0-wait-state-cache Toshiba 5200 (a monochrome adapter was also installed). No floating-point processor was installed in either computer. Results could vary considerably on different hardware.

LISTING 18.1 L18-1.C

```
/*
 * Draws a circle of the specified radius and color, using a fast
 * integer-only & square-root-free approach, and generating the
 * arc for one octant into a buffer, then drawing all 8 symmetries
 * from that buffer.
 * Compiles with either Borland or Microsoft.
 * Will work on VGA or EGA, but will draw what appears to be an
 * ellipse in non-square-pixel modes.
 */

#include <dos.h>

/* Handle differences between Borland and Micrsoft. Note that Borland accepts
   outp as a synonym for outportb, but not outpw for outport */
#ifdef __TURBOC__
#define outpw  outport
#endif

#define SCREEN_WIDTH_IN_BYTES   80        /* # of bytes across one scan
                                             line in mode 12h */
#define SCREEN_SEGMENT          0xA000    /* mode 12h display memory seg */
#define GC_INDEX                0x3CE     /* Graphics Controller port */
#define SET_RESET_INDEX         0         /* Set/Reset reg index in GC */
```

```
#define SET_RESET_ENABLE_INDEX    1    /* Set/Reset Enable reg index in GC */
#define BIT_MASK_INDEX            8    /* Bit Mask reg index in GC */

unsigned char PixList[SCREEN_WIDTH_IN_BYTES*8/2];
                                       /* maximum major axis length is
                                          1/2 screen width, because we're
                                          assuming no clipping is needed */

/* Draws the arc for an octant in which Y is the major axis. (X,Y) is the
   starting point of the arc. HorizontalMoveDirection selects whether the
   arc advances to the left or right horizontally (0=left, 1=right).
   RowOffset contains the offset in bytes from one scan line to the next,
   controlling whether the arc is drawn up or down. Length is the
   vertical length in pixels of the arc, and DrawList is a list
   containing 0 for each point if the next point is vertically aligned,
   and 1 if the next point is 1 pixel diagonally to the left or right. */

void DrawVOctant(int X, int Y, int Length, int RowOffset,
   int HorizontalMoveDirection, unsigned char *DrawList)
{
   unsigned char far *ScreenPtr, BitMask;

   /* Point to the byte the initial pixel is in */
#ifdef __TURBOC__
   ScreenPtr = MK_FP(SCREEN_SEGMENT,
      (Y * SCREEN_WIDTH_IN_BYTES) + (X / 8));
#else
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) =(Y * SCREEN_WIDTH_IN_BYTES) + (X / 8);
#endif
   /* Set the initial bit mask */
   BitMask = 0x80 >> (X & 0x07);

   /* Draw all points in DrawList */
   while ( Length-- ) {
      /* Set the bit mask for the pixel */
      outp(GC_INDEX + 1, BitMask);
      /* Draw the pixel. ORed to force read/write to load latches.
         Data written doesn't matter, because set/reset is enabled
         for all planes. Note: don't OR with 0; MSC optimizes that
         statement to no operation. */
      *ScreenPtr |= 0xFE;
      /* Now advance to the next pixel based on DrawList. */
      if ( *DrawList++ ) {
         /* Advance horizontally to produce a diagonal move. Rotate
            the bit mask, advancing one byte horizontally if the bit
            mask wraps. */
         if ( HorizontalMoveDirection == 1 ) {
            /* Move right */
            if ( (BitMask >>= 1) == 0 ) {
               BitMask = 0x80;         /* wrap the mask */
               ScreenPtr++;            /* advance 1 byte to the right */
            }
         } else {
            /* Move left */
            if ( (BitMask <<= 1) == 0 ) {
               BitMask = 0x01;         /* wrap the mask */
               ScreenPtr--;            /* advance 1 byte to the left */
            }
         }
      }
      ScreenPtr += RowOffset; /* advance to the next scan line */
   }
}

/* Draws the arc for an octant in which X is the major axis. (X,Y) is the
   starting point of the arc. HorizontalMoveDirection selects whether the
   arc advances to the left or right horizontally (0=left, 1=right).
   RowOffset contains the offset in bytes from one scan line to the next,
   controlling whether the arc is drawn up or down. Length is the
   horizontal length in pixels of the arc, and DrawList is a list
   containing 0 for each point if the next point is horizontally aligned,
   and 1 if the next point is 1 pixel above or below diagonally. */

void DrawHOctant(int X, int Y, int Length, int RowOffset,
   int HorizontalMoveDirection, unsigned char *DrawList)
{
   unsigned char far *ScreenPtr, BitMask;

   /* Point to the byte the initial pixel is in */
#ifdef __TURBOC__
   ScreenPtr = MK_FP(SCREEN_SEGMENT,
      (Y * SCREEN_WIDTH_IN_BYTES) + (X / 8));
#else
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) =(Y * SCREEN_WIDTH_IN_BYTES) + (X / 8);
#endif
   /* Set the initial bit mask */
   BitMask = 0x80 >> (X & 0x07);

   /* Draw all points in DrawList */
   while ( Length-- ) {
      /* Set the bit mask for the pixel */
      outp(GC_INDEX + 1, BitMask);
      /* Draw the pixel (see comments above for details) */
      *ScreenPtr |= 0xFE;
      /* Now advance to the next pixel based on DrawList */
      if ( *DrawList++ ) {
         /* Advance vertically to produce a diagonal move */
         ScreenPtr += RowOffset; /* advance to the next scan line */
      }
      /* Advance horizontally. Rotate the bit mask, advancing one
         byte horizontally if the bit mask wraps */
      if ( HorizontalMoveDirection == 1 ) {
         /* Move right */
         if ( (BitMask >>= 1) == 0 ) {
            BitMask = 0x80;   /* wrap the mask */
            ScreenPtr++;      /* advance 1 byte to the right */
         }
      } else {
         /* Move left */
         if ( (BitMask <<= 1) == 0 ) {
            BitMask = 0x01;   /* wrap the mask */
            ScreenPtr--;      /* advance 1 byte to the left */
         }
      }
   }
}

/* Draws a circle of radius Radius in color Color centered at
   screen coordinate (X,Y) */
```

```
void DrawCircle(int X, int Y, int Radius, int Color) {
   int MajorAxis, MinorAxis;
   unsigned long RadiusSqMinusMajorAxisSq, MinorAxisSquaredThreshold;
   unsigned char *PixListPtr;

   /* Set drawing color via set/reset */
   outpw(GC_INDEX, (0x0F << 8) | SET_RESET_ENABLE_INDEX);
                                 /* enable set/reset for all planes */
   outpw(GC_INDEX, (Color << 8) | SET_RESET_INDEX);
                                 /* set set/reset (drawing) color */
   outp(GC_INDEX, BIT_MASK_INDEX); /* leave the GC Index reg pointing
                                       to the Bit Mask reg */

   /* Set up to draw the circle by setting the initial point to one
      end of the 1/8th of a circle arc we'll draw */
   MajorAxis = 0;
   MinorAxis = Radius;
   /* Set initial Radius**2 - MajorAxis**2 (MajorAxis is initially 0) */
   RadiusSqMinusMajorAxisSq = (unsigned long) Radius * Radius;
   /* Set threshold for minor axis movement at (MinorAxis - 0.5)**2 */
   MinorAxisSquaredThreshold = (unsigned long) MinorAxis * MinorAxis -
      MinorAxis;

   /* Calculate all points along an arc of 1/8th of the circle and
      store that info in PixList for later drawing */
   PixListPtr = PixList;
   do {
      /* Advance (Radius**2 - MajorAxis**2); if it equals or passes
         the MinorAxis**2 threshold, advance one pixel along both the
         major and minor axes and set the next MinorAxis**2 threshold;
         otherwise, advance one pixel only along the major axis. */
      RadiusSqMinusMajorAxisSq -=
         MajorAxis + MajorAxis + 1;
      if ( RadiusSqMinusMajorAxisSq <= MinorAxisSquaredThreshold ) {
         /* Advance 1 pixel along both the major and minor axes */
         MinorAxis--;
         MinorAxisSquaredThreshold -= MinorAxis + MinorAxis;
         *PixListPtr++ = 1;   /* advance along both axes */
      } else {
         *PixListPtr++ = 0;   /* advance only along the major axis */
      }
      MajorAxis++;   /* always advance one pixel along the major axis */
   } while ( MajorAxis <= MinorAxis );

   /* Now draw each of the 8 symmetries of the octant in turn */
   /* Draw the octants for which Y is the major axis */
   DrawVOctant(X-Radius,Y,MajorAxis,-SCREEN_WIDTH_IN_BYTES,1,PixList);
   DrawVOctant(X-Radius,Y,MajorAxis,SCREEN_WIDTH_IN_BYTES,1,PixList);
   DrawVOctant(X+Radius,Y,MajorAxis,-SCREEN_WIDTH_IN_BYTES,0,PixList);
   DrawVOctant(X+Radius,Y,MajorAxis,SCREEN_WIDTH_IN_BYTES,0,PixList);

   /* Draw the octants for which X is the major axis */
   DrawHOctant(X,Y-Radius,MajorAxis,SCREEN_WIDTH_IN_BYTES,0,PixList);
   DrawHOctant(X,Y-Radius,MajorAxis,SCREEN_WIDTH_IN_BYTES,1,PixList);
   DrawHOctant(X,Y+Radius,MajorAxis,-SCREEN_WIDTH_IN_BYTES,0,PixList);
   DrawHOctant(X,Y+Radius,MajorAxis,-SCREEN_WIDTH_IN_BYTES,1,PixList);

   /* Reset the Bit Mask register to normal */
   outp(GC_INDEX + 1, 0xFF);
   /* Turn off set/reset enable */
   outpw(GC_INDEX, (0x00 << 8) | SET_RESET_ENABLE_INDEX);
}
```

It's worth noting that Listings 18.1 and 17.3 both use the same integer-only algorithm presented in the previous chapter. The performance difference between the two listings comes from understanding the code the compiler generates for each and the performance implications of that code. In particular, Listing 18.1 virtually eliminates multiplication, multi-bit shifts, and call and return instructions, all of which are relatively slow on x86 processors.

LISTING 18.2 L18-2.C

```
/*
 * Draws a series of concentric circles.
 * For VGA only, because mode 12h is unique to VGA.
 * Compile and link using Borland C++ with accompanying listings as follows:
 *    bcc -ms l18-1 l18-2            (or)
 *    bcc -ms l18-3 l18-2 l18-4.asm
 *
 *
 *
 */
#include <dos.h>

main() {
   int Radius, Temp, Color, i;
   union REGS Regs;

   /* Select VGA's hi-res 640x480 graphics mode, mode 12h. */
   Regs.x.ax = 0x0012;
   int86(0x10, &Regs, &Regs);

   /* Draw 20 sets of concentric circles for timing purposes. */
   for (i = 0; i < 20; i++) {
      for ( Radius = 10, Color = 7; Radius < 240; Radius += 2 ) {
         DrawCircle(640/2, 480/2, Radius, Color);
         Color = (Color + 1) & 0x0F;   /* cycle through 16 colors */
      }
   }

   /* Wait for a key, restore text mode, and done. */
   scanf("%c", &Temp);
   Regs.x.ax = 0x0003;
   int86(0x10, &Regs, &Regs);
}
```

Notes on the C Implementation

Listing 18.1, like Listing 17.3, uses long integers because the squared values used can grow too large for short integers. The performance cost of long integers can be avoided by special-casing circles with radii less than 256. In order for circles with radii less than 256 to work with short integers, however, short *unsigned* integers must be used, or comparisons may not work correctly when squared quantities exceed 32,767.

Listing 18.1 (and, indeed, all the listings in this chapter and the previous one) assumes that no clipping is needed. If that's not the case, the approach of generating a pixel list and then drawing the eight symmetries from the list would lend itself well to clipping, because the drawing routine could use the list to skip quickly over any initial portion of an octant that's outside a clip region, and could terminate processing immediately when the far edge of the clip region is reached. At the very least, clipping from a pixel list is surely more manageable than attempting to draw and clip all eight symmetries simultaneously, and is undoubtedly more efficient than calculating and drawing the clipped arcs for each of the eight octants separately.

Circles to the Metal: Assembly Language

I believe that the critical code for graphics primitives should be written in assembly language, and circle drawing is no exception. Listings 18.3 and 18.4 show a C/assembly language hybrid circle-drawing routine that is a good deal faster yet than Listing 18.1; as Table 18.1 shows, the code in Listings 18.3 and 18.4 is about twice as fast as Listing 18.1.

LISTING 18.3 L18-3.C

```
/*
 * Draws a circle of the specified radius and color, using a fast
 * integer-only & square-root-free approach, and generating the
 * arc for one octant into a buffer, then drawing all 8 symmetries
 * from that buffer. Uses assembly language for inner loops of octant
 * generation & drawing.
 * Compiles with either Borland or Microsoft.
 * Will work on VGA or EGA, but will draw what appears to be an
 * ellipse in non-square-pixel modes.
 */
#define ISVGA  0                            /* set to 1 to use VGA write mode 3*/
                                            /* keep synchronized with Listing 4 */
#include <dos.h>

/* Handle differences between Borland and Microsoft. Note that Borland accepts
   outp as a synonym for outportb, but not outpw for outport. */
#ifdef __TURBOC__
#define outpw  outport
#endif

#define SCREEN_WIDTH_IN_BYTES    80         /* # of bytes across one scan
                                               line in mode 12h */
#define SCREEN_SEGMENT           0xA000     /* mode 12h display memory seg */
#define GC_INDEX                 0x3CE      /* Graphics Controller port */
#define SET_RESET_INDEX          0          /* Set/Reset reg index in GC */
#define SET_RESET_ENABLE_INDEX   1          /* Set/Reset Enable reg index in GC */
#define GC_MODE_INDEX            5          /* Graphics Mode reg index in GC */
#define COLOR_DONT_CARE          7          /* Color Don't Care reg index in GC */
#define BIT_MASK_INDEX           8          /* Bit Mask reg index in GC */

unsigned char PixList[SCREEN_WIDTH_IN_BYTES*8/2];
                                            /* maximum major axis length is
                                               1/2 screen width, because we're
                                               assuming no clipping is needed */
/* Draws a circle of radius Radius in color Color centered at
 * screen coordinate (X,Y) */
```

```
void DrawCircle(int X, int Y, int Radius, int Color) {
   int MajorAxis, MinorAxis;
   unsigned long RadiusSqMinusMajorAxisSq, MinorAxisSquaredThreshold;
   unsigned char *PixListPtr, OriginalGCMode;

   /* Set drawing color via set/reset */
   outpw(GC_INDEX, (0x0F << 8) | SET_RESET_ENABLE_INDEX);
                                 /* enable set/reset for all planes */
   outpw(GC_INDEX, (Color << 8) | SET_RESET_INDEX);
                                 /* set set/reset (drawing) color */
#if ISVGA
   /* Remember original read/write mode & select
      read mode 1/write mode 3, with Color Don't Care
      set to ignore all planes and therefore always return 0xFF */
   outp(GC_INDEX, GC_MODE_INDEX);
   OriginalGCMode = inp(GC_INDEX + 1);
   outp(GC_INDEX+1, OriginalGCMode | 0x0B);
   outpw(GC_INDEX, (0x00 << 8) | COLOR_DONT_CARE);
   outpw(GC_INDEX, (0xFF << 8) | BIT_MASK_INDEX);
#else
   outp(GC_INDEX, BIT_MASK_INDEX); /* leave the GC Index reg pointing
                                       to the Bit Mask reg */
#endif

   /* Set up to draw the circle by setting the initial point to one
      end of the 1/8th of a circle arc we'll draw */
   MajorAxis = 0;
   MinorAxis = Radius;
   /* Set initial Radius**2 - MajorAxis**2 (MajorAxis is initially 0) */
   RadiusSqMinusMajorAxisSq = (unsigned long) Radius * Radius;
   /* Set threshold for minor axis movement at (MinorAxis - 0.5)**2 */
   MinorAxisSquaredThreshold = (unsigned long) MinorAxis * MinorAxis -
      MinorAxis;

   /* Calculate all points along an arc of 1/8th of the circle.
      Results are placed in PixList */
   MajorAxis = GenerateOctant(PixList, MajorAxis, MinorAxis,
      RadiusSqMinusMajorAxisSq, MinorAxisSquaredThreshold);

   /* Now draw each of the 8 symmetries of the octant in turn */
   /* Draw the octants for which Y is the major axis */
   DrawVOctant(X-Radius,Y,MajorAxis,-SCREEN_WIDTH_IN_BYTES,1,PixList);
   DrawVOctant(X-Radius,Y,MajorAxis,SCREEN_WIDTH_IN_BYTES,1,PixList);
   DrawVOctant(X+Radius,Y,MajorAxis,-SCREEN_WIDTH_IN_BYTES,0,PixList);
   DrawVOctant(X+Radius,Y,MajorAxis,SCREEN_WIDTH_IN_BYTES,0,PixList);

   /* Draw the octants for which X is the major axis */
   DrawHOctant(X,Y-Radius,MajorAxis,SCREEN_WIDTH_IN_BYTES,0,PixList);
   DrawHOctant(X,Y-Radius,MajorAxis,SCREEN_WIDTH_IN_BYTES,1,PixList);
   DrawHOctant(X,Y+Radius,MajorAxis,-SCREEN_WIDTH_IN_BYTES,0, PixList);
   DrawHOctant(X,Y+Radius,MajorAxis,-SCREEN_WIDTH_IN_BYTES,1, PixList);

#if ISVGA
   /* Restore original write mode */
   outpw(GC_INDEX, (OriginalGCMode << 8) | GC_MODE_INDEX);
   /* Restore normal Color Don't Care setting */
   outpw(GC_INDEX, (0x0F << 8) | COLOR_DONT_CARE);
#else
   /* Reset the Bit Mask register to normal */
   outp(GC_INDEX + 1, 0xFF);
#endif
```

```
   /* Turn off set/reset enable */
   outpw(GC_INDEX, (0x00 << 8) | SET_RESET_ENABLE_INDEX);
}
```

LISTING 18.4 L18-4.ASM

```
; Contains 3 C-callable routines: GenerateOctant, DrawVOctant, and
;       DrawHOctant. See individual routines for comments.
;
; Works with TASM or MASM
;
ISVGA   equ     0       ;set to 1 to use VGA write mode 3
                        ; keep synchronized with Listing 3
        .model small
        .code
;*********************************************************************
; Generates an octant of the specified circle, placing the results in
; PixList, with a 0 in PixList meaning draw pixel & move only along
; major axis, and a 1 in PixList meaning draw pixel & move along both
; axes.
; C near-callable as:
;  int GenerateOctant(unsigned char *PixList, int MajorAxis,
;       int MinorAxis, unsigned long RadiusSqMinusMajorAxisSq,
;       unsigned long MinorAxisSquaredThreshold);
;
; Return value = MajorAxis
;
GenerateOctantParms       struc
          dw      ?       ;pushed BP
          dw      ?       ;return address
PixList   dw      ?       ;pointer to list to store draw control data in
MajorAxis dw      ?       ;initial major/minor axis coords relative to
MinorAxis dw      ?       ; to the center of the circle
RadiusSqMinusMajorAxisSq  dd ?   ;initial Radius**2 - MajorAxis**2
MinorAxisSquaredThreshold dd ?   ;initial threshhold for minor axis
GenerateOctantParms       ends   ; movement is MinorAxis**2 - MinorAxis
;
        public _GenerateOctant
_GenerateOctant proc    near
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to our stack frame
        push    si              ;preserve C register variables
        push    di
;                                       ;get all parms into registers
        mov     di,[PixList+bp]         ;point DI to PixList
        mov     ax,[MajorAxis+bp]       ;AX=MajorAxis
        mov     bx,[MinorAxis+bp]       ;BX=MinorAxis
        mov     cx,word ptr [RadiusSqMinusMajorAxisSq+bp]
        mov     dx,word ptr [RadiusSqMinusMajorAxisSq+bp+2]
                                        ;DX:CX=RadiusSqMinusMajorAxisSq
        mov     si,word ptr [MinorAxisSquaredThreshold+bp]
        mov     bp,word ptr [MinorAxisSquaredThreshold+bp+2]
                                        ;BP:SI=MinorAxisSquaredThreshold
GenLoop:
        sub     cx,1            ;subtract MajorAxis + MajorAxis + 1 from
        sbb     dx,0            ; RadiusSqMinusMajorAxisSq
        sub     cx,ax
        sbb     dx,0
        sub     cx,ax
        sbb     dx,0
        cmp     dx,bp           ;if RadiusSqMinusMajorAxisSq <=
        jb      IsMinorMove     ; MinorAxisSquaredThreshold, move along
        ja      NoMinorMove     ; minor as well as major, otherwise move
        cmp     cx,si           ; only along major
        ja      NoMinorMove
IsMinorMove:                    ;move along minor as well as major
        dec     bx              ;decrement MinorAxis
        sub     si,bx           ;subtract MinorAxis + MinorAxis from
        sbb     bp,0            ; MinorAxisSquaredThreshold
        sub     si,bx
        sbb     bp,0
        mov     byte ptr [di],1 ;enter 1 (move both axes) in PixList
        inc     di              ;advance PixList pointer
        inc     ax              ;increment MajorAxis
        cmp     ax,bx           ;done if MajorAxis > MinorAxis, else
        jbe     GenLoop         ; continue generating PixList entries
        jmp     short Done
NoMinorMove:
        mov     byte ptr [di],0 ;enter 0 (move only major) in PixList
        inc     di              ;advance PixList pointer
        inc     ax              ;increment MajorAxis
        cmp     ax,bx           ;done if MajorAxis > MinorAxis, else
        jbe     GenLoop         ; continue generating PixList entries
Done:
        pop     di              ;restore C register variables
        pop     si
        pop     bp
        ret
_GenerateOctant endp
;********************************************************************
; Draws the arc for an octant in which Y is the major axis. (X,Y) is the
; starting point of the arc. HorizontalMoveDirection selects whether the
; arc advances to the left or right horizontally (0=left, 1=right).
; RowOffset contains the offset in bytes from one scan line to the next,
; controlling whether the arc is drawn up or down. DrawLength is the
; vertical length in pixels of the arc, and DrawList is a list
; containing 0 for each point if the next point is vertically aligned,
; and 1 if the next point is 1 pixel diagonally to the left or right.
;
; The Graphics Controller Index register must already point to the Bit
; Mask register.
;
; C near-callable as:
;  void DrawVOctant(int X, int Y, int DrawLength, int RowOffset,
;       int HorizontalMoveDirection, unsigned char *DrawList);
;
DrawParms       struc
        dw      ?       ;pushed BP
        dw      ?       ;return address
X       dw      ?       ;initial coordinates
Y       dw      ?
DrawLength dw   ?       ;vertical length
RowOffset dw    ?       ;distance from one scan line to the next
HorizontalMoveDirection dw ? ;1 to move right, 0 to move left
DrawList dw     ?       ;pointer to list containing 1 to draw
DrawParms       ends    ; diagonally, 0 to draw vertically for
                                ; each point
SCREEN_SEGMENT  equ     0a000h  ;display memory segment in mode 12h
SCREEN_WIDTH_IN_BYTES equ 80    ;distance from one scan line to next
GC_INDEX        equ     3ceh    ;GC Index register address
;
        public _DrawVOctant
```

```
_DrawVOctant    proc    near
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to our stack frame
        push    si              ;preserve C register variables
        push    di
;Point ES:DI to the byte the initial pixel is in.
        mov     ax,SCREEN_SEGMENT
        mov     es,ax
        mov     ax,SCREEN_WIDTH_IN_BYTES
        mul     [bp+Y]  ;Y*SCREEN_WIDTH_IN_BYTES
        mov     di,[bp+X] ;X
        mov     cx,di   ;set X aside in CX
        shr     di,1
        shr     di,1
        shr     di,1    ;X/8
        add     di,ax   ;screen offset = Y*SCREEN_WIDTH_IN_BYTES+X/8
        and     cl,07h  ;X modulo 8
if ISVGA                ;--VGA--
        mov     ah,80h  ;keep VGA bit mask in AH
        shr     ah,cl   ;initial bit mask = 80h shr (X modulo 8);
        cld             ;for LODSB, used below
else                    ;--EGA--
        mov     al,80h  ;keep EGA bit mask in AL
        shr     al,cl   ;initial bit mask = 80h shr (X modulo 8);
        mov     dx,GC_INDEX+1 ;point DX to GC Data reg/bit mask
endif                   ;--------
        mov     si,[bp+DrawList] ;SI points to list to draw from
        sub     bx,bx           ;so we have the constant 0 in a reg
        mov     cx,[bp+DrawLength] ;CX=# of pixels to draw
        jcxz    VDrawDone       ;skip this if no pixels to draw
        cmp     [bp+HorizontalMoveDirection],0 ;draw right or left
        mov     bp,[bp+RowOffset] ;BP=offset to next row
        jz      VGoLeft         ;draw from right to left
VDrawRightLoop:                 ;draw from left to right
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3,
                                ; set/reset provides color
        lodsb                   ;get next draw control byte
        and     al,al           ;move right?
        jz      VAdvanceOneLineRight ;no move right
        ror     ah,1            ;move right
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter (set/reset provides
                                ; color); just force read then write
        cmp     [si],bl         ;check draw control byte; move right?
        jz      VAdvanceOneLineRight ;no move right
        ror     al,1            ;move right
endif                           ;--------
        adc     di,bx   ;move one byte to the right if mask wrapped
VAdvanceOneLineRight:
ife ISVGA                       ;--EGA--
        inc     si              ;advance draw control list pointer
endif                           ;--------
        add     di,bp           ;move to the next scan line up or down
        loop    VDrawRightLoop  ;do next pixel, if any
        jmp     short VDrawDone ;done
VGoLeft:                        ;draw from right to left
VDrawLeftLoop:
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
        lodsb                   ;get next draw control byte
        and     al,al           ;move left?
        jz      VAdvanceOneLineLeft ;no move left
        rol     ah,1            ;move left
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
        cmp     [si],bl         ;check draw control byte; move left?
        jz      VAdvanceOneLineLeft ;no move left
        rol     al,1            ;move left
endif                           ;--------
        sbb     di,bx           ;move one byte to the left if mask wrapped
VAdvanceOneLineLeft:
ife ISVGA                       ;--EGA--
        inc     si              ;advance draw control list pointer
endif                           ;--------
        add     di,bp           ;move to the next scan line up or down
        loop    VDrawLeftLoop   ;do next pixel, if any
VDrawDone:
        pop     di              ;restore C register variables
        pop     si
        pop     bp
        ret
_DrawVOctant    endp
;********************************************************************
; Draws the arc for an octant in which X is the major axis. (X,Y) is the
; starting point of the arc. HorizontalMoveDirection selects whether the
; arc advances to the left or right horizontally (0=left, 1=right).
; RowOffset contains the offset in bytes from one scan line to the next,
; controlling whether the arc is drawn up or down. DrawLength is the
; horizontal length in pixels of the arc, and DrawList is a list
; containing 0 for each point if the next point is horizontally aligned,
; and 1 if the next point is 1 pixel above or below diagonally.
;
; Graphics Controller Index register must already point to the Bit Mask
; register.
;
; C near-callable as:
;  void DrawHOctant(int X, int Y, int DrawLength, int RowOffset,
;       int HorizontalMoveDirection, unsigned char *DrawList)
;
; Uses same parameter structure as DrawVOctant().
;
        public _DrawHOctant
_DrawHOctant    proc    near
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to our stack frame
        push    si              ;preserve C register variables
        push    di
;Point ES:DI to the byte the initial pixel is in.
        mov     ax,SCREEN_SEGMENT
        mov     es,ax
        mov     ax,SCREEN_WIDTH_IN_BYTES
        mul     [bp+Y]  ;Y*SCREEN_WIDTH_IN_BYTES
        mov     di,[bp+X] ;X
        mov     cx,di   ;set X aside in CX
        shr     di,1
        shr     di,1
        shr     di,1    ;X/8
        add     di,ax   ;screen offset = Y*SCREEN_WIDTH_IN_BYTES+X/8
        and     cl,07h  ;X modulo 8
        mov     bh,80h
        shr     bh,cl   ;initial bit mask = 80h shr (X modulo 8);
```

```
if ISVGA                ;--VGA--
        cld             ;for LODSB, used below
else                    ;--EGA--
        mov     dx,GC_INDEX+1 ;point DX to GC Data reg/bit mask
endif                    ;--------
        mov     si,[bp+DrawList] ;SI points to list to draw from
        sub     bl,bl           ;so we have the constant 0 in a reg
        mov     cx,[bp+DrawLength] ;CX=# of pixels to draw
        jcxz    HDrawDone       ;skip this if no pixels to draw
if ISVGA                        ;--VGA--
        sub     ah,ah           ;clear bit mask accumulator
else                            ;--EGA--
        sub     al,al           ;clear bit mask accumulator
endif                           ;--------
        cmp     [bp+HorizontalMoveDirection],0 ;draw right or left
        mov     bp,[bp+RowOffset] ;BP=offset to next row
        jz      HGoLeft         ;draw from right to left
HDrawRightLoop:                 ;draw from left to right
if ISVGA                        ;--VGA--
        or      ah,bh           ;put this pixel in bit mask accumulator
        lodsb                   ;get next draw control byte
        and     al,al           ;move up/down?
else                            ;--EGA--
        or      al,bh           ;put this pixel in bit mask accumulator
        cmp     [si],bl         ;check draw control byte; move up/down?
endif                           ;--------
        jz      HAdvanceOneLineRight ;no move up/down
                        ;move up/down; first draw accumulated pixels
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
        sub     ah,ah           ;clear bit mask accumulator
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
        sub     al,al           ;clear bit mask accumulator
endif                           ;--------
        add     di,bp           ;move to the next scan line up or down
HAdvanceOneLineRight:
ife ISVGA                       ;--EGA--
        inc     si              ;advance draw control list pointer
endif                           ;--------
        ror     bh,1            ;move to right; shift mask
        jnc     HDrawLoopRightBottom ;didn't wrap to the next byte
                        ;move to next byte; 1st draw accumulated pixels
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
        sub     ah,ah           ;clear bit mask accumulator
else
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
        sub     al,al           ;clear bit mask accumulator
endif                           ;--------
        inc     di              ;move 1 byte to the right
HDrawLoopRightBottom:
        loop    HDrawRightLoop  ;draw next pixel, if any
        jmp     short HDrawDone ;done
HGoLeft:                        ;draw from right to left
HDrawLeftLoop:
if ISVGA                        ;--VGA--
        or      ah,bh           ;put this pixel in bit mask accumulator
        lodsb                   ;get next draw control byte
        and     al,al           ;move up/down?
```

```
else                            ;--EGA--
        or      al,bh           ;put this pixel in bit mask accumulator
        cmp     [si],bl         ;check draw control byte; move up/down?
endif                           ;--------
        jz      HAdvanceOneLineLeft ;no move up/down
                        ;move up/down; first draw accumulated pixels
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
        sub     ah,ah           ;clear bit mask accumulator
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
        sub     al,al           ;clear bit mask accumulator
endif                           ;--------
        add     di,bp           ;move to the next scan line up or down
HAdvanceOneLineLeft:
ife ISVGA                       ;--EGA--
        inc     si              ;advance draw control list pointer
endif                           ;--------
        rol     bh,1            ;move to left; shift mask
        jnc     HDrawLoopLeftBottom ;didn't wrap to next byte
                        ;move to next byte; 1st draw accumulated pixels
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
        sub     ah,ah           ;clear bit mask accumulator
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
        sub     al,al           ;clear bit mask accumulator
endif                           ;--------
        dec     di              ;move 1 byte to the left
HDrawLoopLeftBottom:
        loop    HDrawLeftLoop   ;draw next pixel, if any
HDrawDone:
                                ;draw any remaining accumulated pixels
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
endif                           ;--------
        pop     di              ;restore C register variables
        pop     si
        pop     bp
        ret
_DrawHOctant    endp
        end
```

Why didn't I use pure assembly language? Primarily because it's rarely worth using assembly outside of heavily-used loops. The overall performance improvement resulting from assembly language used anywhere else is generally imperceptible and hard to justify; assembly is difficult to write and harder to read and change. Listings 18.3 and 18.4 strike a good balance between performance, ease of coding and comprehension, and maintainability.

Listings 18.3 and 18.4 generally correspond directly to Listing 18.1, although that may be obscured by the considerable optimization performed in Listing 18.4. Two aspects of Listings 18.3 and 18.4 do not correspond to Listing 18.1, however, and bear further discussion.

When the major axis is horizontal, multiple horizontally adjacent pixels are often drawn. Whenever multiple adjacent pixels are controlled by the same display memory byte, it is possible to draw all the pixels that reside in that byte with a single display memory read/write operation. This is highly desirable because display memory is extremely slow relative to normal system memory, especially on 386 and later computers. Consequently, Listing 18.4 accumulates pixels that reside in the same byte when drawing horizontal-major-axis arcs, and accesses display memory only when all pixels that could possibly belong in a given byte have been processed. (See Chapter 14 for the application of this technique to straight-line drawing.) Pixel accumulation is a good example of matching an algorithm to the hardware; the basic operation of the algorithm is unchanged, but the code is fine-tuned so that the implementation suffers less from the poor performance of display memory.

Supporting VGA Write Mode 3

Listings 18.3 and 18.4 contain another example of matching the circle-drawing algorithm to the hardware: Optional support for write mode 3, which only the VGA supports. When the **ISVGA** symbols in both Listing 18.3 and Listing 18.4 are set to 1 (make sure both symbols are the same at all times), write mode 3 is used to draw pixels, improving overall performance by as much as 25 percent. **ISVGA** makes Listing 18.4 in particular a little hard to follow—but I hope that you'll agree that the performance improvement and the exposure to a useful VGA-specific optimization are worth the trouble.

The virtue of write mode 3 is that it ANDs the Bit Mask register with the byte written by the CPU to form the working bit mask; that in turn means that there's no need to do an **OUT** when write mode 3 is used, thereby eliminating both an instruction and the many wait states that occur during I/O to most VGAs. What's more, by eliminating the need to perform **OUT**s we free up AL and DX for other purposes, in this case making it possible to use **LODSB**. (Note, though, that **LODSB** is not as fast as

```
MOV AL,[SI]
INC SI
```

on 486 and Pentium computers.) See Chapter 4 for more information about write mode 3.

In order for write mode 3 to work properly, the desired bit mask must be written to memory. (The set/reset circuitry provides the pixel color.) First, however, display memory must be read to latch the surrounding pixels, so that the bit mask can work its magic. An efficient way to both read from and write to display memory is to do so in a single instruction with **AND**, **OR**, or **XCHG**. (On 486s and Pentiums, using one **MOV** to read display memory followed by another **MOV** to write to display memory is a little faster than the single-instruction solutions, but it makes for more instruction bytes and destroys the contents of a register.) However, **XCHG** wipes out the register containing the working copy of the bit mask, and **AND** with any value other than 0FFH or **OR** with any value other than 0 normally alters the value written to memory so that it no longer sets the desired bit mask. (We just want to write the desired bit mask straight from the register to display memory.) This is solved by selecting read mode 1 (color compare mode) and setting the Color Don't Care register to 0, with the result that 0FFH is always read from display memory. Once that is done, we can **AND** the desired bit mask with display memory without altering either the value written to memory or the register containing the working copy of the bit mask. (See Chapter 6 for a discussion of this application of read mode 1.)

By the way, Listings 18.3 and 18.4 run just as well on VGAs as on EGAs if both **ISVGA** symbols are set to zero—they just run more slowly than if compiled/assembled specifically for the VGA.

There's no reason that the C code in Listing 18.1 couldn't be made faster by using both the write mode 3/read mode 1 and pixel accumulation techniques we've applied in the assembler code. However, such approaches, which save an approximately fixed number of cycles, have a greater percentage impact on overall performance after all other aspects of the code have been streamlined, and so are most worth using in high-performance assembler code.

When graphics code is truly streamlined across the board, as in Listing 18.4, the characteristics of the display adapter can affect performance significantly. For example, the 286 timings in Table 1 were all performed in a 10-MHz AT with both a Video Seven VRAM VGA and a monochrome adapter installed. It's a little-known fact that when a monochrome adapter is present, all VGAs must revert to being 8-bit memory devices. When the monochrome adapter was removed from the test-unit AT, allowing the VRAM VGA to become a 16-bit device, the time for the non-VGA specific version of Listings 18.3 and 18.4 dropped from 14 seconds to 12.5 seconds—an improvement of more than 10%. This means that Listing 18.4 has reached the point where it is starting to bump up against the hardware's inherent limits—a sure sign of high-performance code, and an indication that perceptible performance variations from one make of VGA to the next are likely to occur.

Circles? Done

In the last two chapters, we've seen performance improvements of as much as 36 times from our initial circle-drawing implementation. Viewing this in terms of the three optimization steps I described at the outset, that very roughly breaks down as 5 to 10 times improvement from algorithm selection; 1.5 to 2.5 times improvement from matching the algorithm to the hardware; and 1.5 to 2 times improvement from conversion to assembly.

The conclusions are two: 1) algorithm selection is indeed important, but processor- and hardware-specific optimizations are important too, and 2) circles, not normally considered to be one of the speedier graphics primitives, can be drawn surprisingly rapidly, in the ballpark with if not quite so fast as lines.

Circles? Done. Now it's on to ellipses.

Circles that Squish

Chapter 19

An Efficient Algorithm for Drawing Ellipses

First things first. The best circle-drawing routine I know of gets faster seemingly by the day, so much so that I'm beginning to think that the ultimate circle-drawing routine will consist of nothing more than a single **NOP** once we figure out how to trim away all the superfluous instructions. Consider this:

Hal Hardenbergh's circle-drawing approach (presented in this space over the last two chapters) drew circles faster than I would have thought was possible. Even so, in the previous chapter I went to great pains to point out that I did *not* think that my implementation of Hal's approach was the fastest possible way to draw circles, but rather just one good way among many. Good thing, too, because not long after I wrote those words, I chanced to talk once again with Hal. I mentioned that there was really no need for even the few multiplications used in his algorithm; the squared terms cancelled out right at the beginning, allowing circles to be drawn without a single multiply or divide. Hal went home, thought about that for a while, and realized that, given the elimination of the squared terms, we didn't need 32-bit integers any more; plain old 16-bit integers would do just fine. Whereupon he devised yet another circle-drawing algorithm, this one using 16-bit integers and requiring less than 10 instructions per point to generate a circle arc.

To put that in more readily-understood terms, I suspect that Hal's new algorithm can be used to draw circles faster than the Bresenham's line-drawing algorithm I presented back in Chapter 14 draws lines!

I'm not going to present Hal's new circle-drawing algorithm here, for a couple of reasons: I've probably overdosed you on circles by this point, and Hal may want to publish his new findings himself. If you know what you're doing, it should be easy enough to apply the above information to my discussions in the last two chapters to derive the new approach.

At any rate, the moral is clear. If you think your code is optimized to the limit, *maybe* it is—but don't bet your house on it.

And with that in mind, let's get on with learning how to draw ellipses pretty doggone fast.

A Quick Primer on Ellipses

An ellipse is an oval, which is to say a squished (or, possibly, non-squished) circle. Ellipses are centered around two foci; the sum of the distances from the two foci to any point on a given ellipse is a constant. A circle is actually a special case of ellipse for which every point is equidistant from the center, where both foci reside atop one another.

A circle has a single radius that is the distance from the center to every point on the circle. An ellipse has two basic radii, one that is the distance from the center of the ellipse to the edge along the X axis, and one that is the distance along the Y axis, as shown in Figure 19.1. These two distances, which we'll call the X radius (of length A) and the Y radius (of length B), along with the center of the ellipse (the point at which the X and Y radii meet) are the fundamental parameters with which we'll work; we won't concern ourselves with the foci or distances from the foci from now on. You might think of ellipses as being defined by the smallest rectangle that contains them; however, for our purposes there's an additional limitation that A and B must be integers, so the encompassing rectangle must have even dimensions to allow the center to fall squarely on a pixel. (It's quite possible to support ellipses with fractionally-located centers, but it's generally not necessary and complicates matters, so we'll avoid it.)

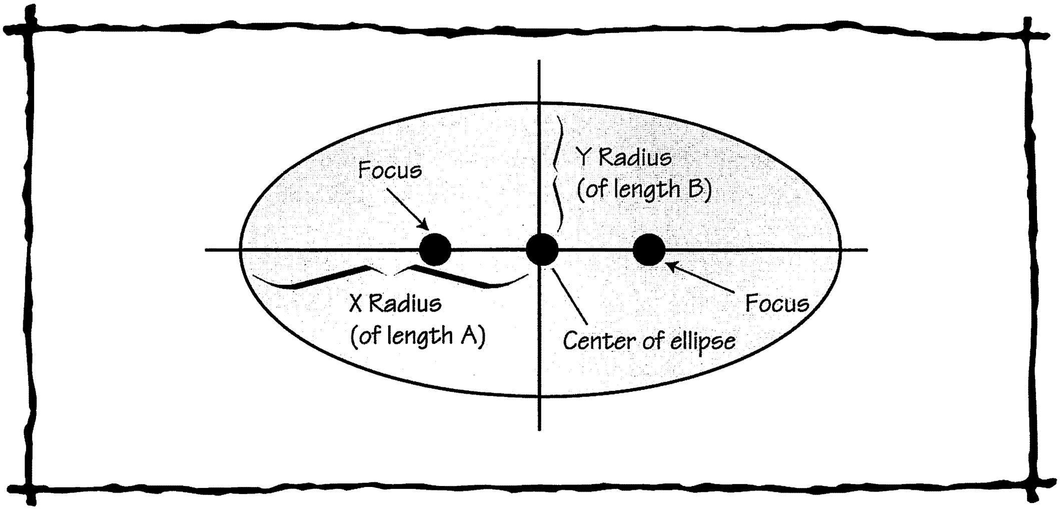


Figure 19.1 The Geometry of an Ellipse

Circles are certainly faster and easier to calculate than ellipses; whereas the equation for a circle is

$$X^2 + Y^2 = R^2$$

the equation for an ellipse is:

$$X^2/A^2 + Y^2/B^2 = 1$$

(Make A and B the same and you get a circle.) By the way, the equation above is for non-tilted ellipses—that is, ellipses with horizontal and vertical axes, where the foci share either a common X coordinate or a common Y coordinate—and that's all we'll work with in this book. Tilted ellipses are both flexible and useful, but they're also slower, more complicated, and generally quite a different kettle of fish from non-tilted ellipses.

Why Ellipses Matter

The question, as always, is how to get a PC to draw the object implied by the above equation for a non-tilted ellipse as quickly as possible, and that's what we'll spend this chapter and the next figuring out. It's well worth knowing how to draw ellipses quickly, for they're extremely useful. Of course, it's often necessary to draw ovals, and ellipses are handy for that alone, but there's more to it than that. You see, true circles, of the sort we learned to draw in the previous two chapters, are useless on displays with non-square pixels (that is, displays with aspect ratios other than 1:1.) On such displays, true circles, which space pixels evenly in both directions, appear as ellipses. Examples of such displays are Hercules graphics, all CGA and EGA graphics modes, and all standard VGA graphics modes except 640×480. In other words, you can't use a true circle-drawing algorithm to draw circles in any standard IBM mode except one.

You *can* use ellipses to draw circles in all those modes, though; just adjust the ratio of the X and Y radii of each ellipse to balance the aspect ratio of the display, and bingo; you have a circle. For example, the aspect ratio of the mode 10H display is about 4:3 (4 pixels in the X direction covers the same physical distance on the screen as 3 pixels in the Y direction), so if you draw an ellipse with an eccentricity (A/B ratio) of 4/3, it will appear as a circle in mode 10H. We'll see an example of this shortly. The important point is that the capability to draw ellipses is not only useful for drawing ovals but essential for drawing circles in many PC graphics modes.

Learning to Draw Ellipses Fast: Divide and Conquer

Now that we've established that ellipses are good stuff, how will we draw them fast? The path we'll take will be familiar to those of you who have followed the past two chapters on circles. First, we'll learn how to draw ellipses using the basic ellipse equation and floating-point arithmetic. Next, we'll derive a far more efficient algorithm, one which uses no non-integer arithmetic or square roots and requires no multiplies or divides in the main loops, and implement it in C. That will take us to the end of this chapter. In the next chapter, we'll tune the C implementation to the quirks of the EGA and VGA, and finally we'll convert the critical code to assembly language.

So, let's start learning how to draw ellipses. We'll start by drawing them slowly, but you can be sure that *that* will change.

Drawing an Ellipse the Easy—and Slow—Way

The straightforward way to draw an ellipse is implemented in Listing 19.1. This listing takes advantage of the four-way symmetry of non-tilted ellipses, shown in Figure 19.2, by generating one arc in which X is the major axis (that is, the X coordinate advances faster) and drawing all four symmetries at once via four calls to a dot-plot function, then generating one arc in which Y is the major axis and drawing all four symmetries the same way.

Arc generation is accomplished by starting at the point where the major axis is 0 relative to the center of the ellipse and the minor axis is the maximum distance from the center, then stepping the major axis by 1 pixel each time and calculating the corresponding minor axis point via floating-point arithmetic according to the ellipse equation I stated earlier. This continues until the arc reaches the point at which the major axis changes, which is the point at which the slope of the arc reaches 45 degrees.

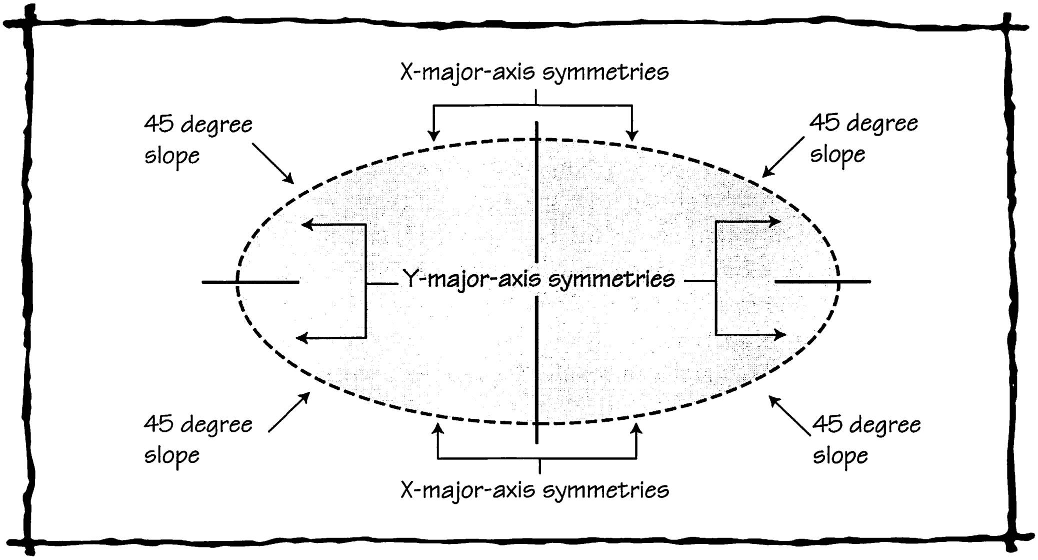


Figure 19.2 The Symmetry of Non-Tilted Ellipses

So, for example, when drawing an arc for which X is the major axis, the initial point drawn would be (0,B). The next point drawn would be (1,*y*), where *y* is calculated as follows:

$$x^2/A^2 + y^2/B^2 = 1$$
$$y^2/B^2 = 1 - x^2/A^2$$
$$y^2 = B^2 - B^2*x^2/A^2$$

Therefore,

$$y = \mathrm{sqrt}(B^2 - B^2*x^2/A^2)$$

rounded to the nearest integer. The same calculation is repeated for each and every *x* as *x* is incremented along the arc, with the calculated coordinates reflected around the ellipse. (All *x* and *y* coordinates discussed are relative to the center of the ellipse.) That's easy enough, eh? The only trick is knowing when to stop, and that happens when the *y* component of

$$x^2/A^2 + y^2/B^2 = 1$$

is no longer the larger component, as detected by

$$y^2/B^2 <= x^2/A^2$$

As you'd expect, the same thing is done for the arc where *y* advances faster, but with *x* and *y*, A and B swapped in the calculations.

LISTING 19.1 L19-1.C

```
/*
 * Draws an ellipse of the specified X and Y axis radii and color,
 * using floating-point calculations.
 * Compiles with either Borland or Microsoft.
 * VGA or EGA.
 */

#include <math.h>
#include <dos.h>

/* Borland accepts outp for outportb, but not outpw for outport */
#ifdef __TURBOC__
#define outpw  outport
#endif

#define SCREEN_WIDTH_IN_BYTES    80        /* # of bytes across one scan
                                              line in modes 10h and 12h */
#define SCREEN_SEGMENT           0xA000    /* mode 10h/12h display memory seg */
#define GC_INDEX                 0x3CE     /* Graphics Controller Index port */
#define SET_RESET_INDEX          0         /* Set/Reset reg index in GC */
#define SET_RESET_ENABLE_INDEX   1         /* Set/Reset Enable reg index in GC */
#define BIT_MASK_INDEX           8         /* Bit Mask reg index in GC */
```

```
/* Draws a pixel at screen coordinate (X,Y) */
void DrawDot(int X, int Y) {
   unsigned char far *ScreenPtr;

   /* Point to the byte the pixel is in */
#ifdef __TURBOC__
   ScreenPtr = MK_FP(SCREEN_SEGMENT, (Y*SCREEN_WIDTH_IN_BYTES) + (X/8));
#else
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) = (Y * SCREEN_WIDTH_IN_BYTES) + (X / 8);
#endif

   /* Set the bit mask within the byte for the pixel */
   outp(GC_INDEX + 1, 0x80 >> (X & 0x07));

   /* Draw the pixel. ORed to force read/write to load latches.
      Data written doesn't matter, because set/reset is enabled
      for all planes. Note: don't OR with 0; MSC optimizes that
      statement to no operation. */
   *ScreenPtr |= 0xFE;
}

/* Draws an ellipse of X axis radius A and Y axis radius B in
 * color Color centered at screen coordinate (X,Y). Radii must
 * both be non-zero. */
void DrawEllipse(int X, int Y, int A, int B, int Color) {
   int WorkingX, WorkingY;
   double ASquared = (double) A * A;
   double BSquared = (double) B * B;
   double Temp;

   /* Set drawing color via set/reset */
   outpw(GC_INDEX, (0x0F << 8) | SET_RESET_ENABLE_INDEX);
                                 /* enable set/reset for all planes */
   outpw(GC_INDEX, (Color << 8) | SET_RESET_INDEX);
                                 /* set set/reset (drawing) color */
   outp(GC_INDEX, BIT_MASK_INDEX); /* leave the GC Index reg pointing
                                      to the Bit Mask reg */

   /* Draw the four symmetric arcs for which X advances faster (that is,
      for which X is the major axis) */
   /* Draw the initial top & bottom points */
   DrawDot(X, Y+B);
   DrawDot(X, Y-B);

   /* Draw the four arcs */
   for (WorkingX = 0; ; ) {
      /* Advance one pixel along the X axis */
      WorkingX++;

      /* Calculate the corresponding point along the Y axis. Guard
         against floating-point roundoff making the intermediate term
         less than 0 */
      Temp = BSquared - (BSquared *
         (double)WorkingX * (double)WorkingX / ASquared);
      if ( Temp >= 0 ) {
         WorkingY = sqrt(Temp) + 0.5;
      } else {
         WorkingY = 0;
      }
      /* Stop if X is no longer the major axis (the arc has passed the
         45-degree point) */
      if (((double)WorkingY/BSquared) <= ((double)WorkingX/ASquared))
         break;

      /* Draw the 4 symmetries of the current point */
      DrawDot(X+WorkingX, Y-WorkingY);
      DrawDot(X-WorkingX, Y-WorkingY);
      DrawDot(X+WorkingX, Y+WorkingY);
      DrawDot(X-WorkingX, Y+WorkingY);
   }

   /* Draw the four symmetric arcs for which Y advances faster (that is,
      for which Y is the major axis) */
   /* Draw the initial left & right points */
   DrawDot(X+A, Y);
   DrawDot(X-A, Y);

   /* Draw the four arcs */
   for (WorkingY = 0; ; ) {
      /* Advance one pixel along the Y axis */
      WorkingY++;

      /* Calculate the corresponding point along the X axis. Guard
         against floating-point roundoff making the intermediate term
         less than 0 */
      Temp = ASquared - (ASquared *
         (double)WorkingY * (double)WorkingY / BSquared);
      if ( Temp >= 0 ) {
         WorkingX = sqrt(Temp) + 0.5;
      } else {
         WorkingX = 0;           /* floating-point roundoff */
      }

      /* Stop if Y is no longer the major axis (the arc has passed the
         45-degree point) */
      if (((double)WorkingX/ASquared) < ((double)WorkingY/BSquared))
         break;

      /* Draw the 4 symmetries of the current point */
      DrawDot(X+WorkingX, Y-WorkingY);
      DrawDot(X-WorkingX, Y-WorkingY);
      DrawDot(X+WorkingX, Y+WorkingY);
      DrawDot(X-WorkingX, Y+WorkingY);
   }

   /* Reset the Bit Mask register to normal */
   outp(GC_INDEX + 1, 0xFF);

   /* Turn off set/reset enable */
   outpw(GC_INDEX, (0x00 << 8) | SET_RESET_ENABLE_INDEX);
}
```

LISTING 19.2 L19-2.C

```
/*
 * Draws a series of concentric ellipses that should appear to be
 * circles in the EGA's hi-res mode, mode 10h. (They may not appear
 * to be circles on monitors that don't display mode 10h with the
 * same aspect ratio as the Enhanced Color Display.)
 * For EGA or VGA.
 * Compile and link (using Borland C++) with l19-X.c (where X is 1 or 4) with:
 *    bcc -ms -eL19-2X.EXE  L19-2.C  L19-X.C
 *
 */

#include <dos.h>

main() {
   int BaseRadius, Temp, Color;
   union REGS Regs;

   /* Select EGA's hi-res 640x350 graphics mode, mode 10h */
   Regs.x.ax = 0x0010;
   int86(0x10, &Regs, &Regs);

   /* Draw concentric ellipses */
   for ( BaseRadius = 2, Color = 7; BaseRadius < 58; BaseRadius++ ) {
      DrawEllipse(640/2, 350/2, BaseRadius*4, BaseRadius*3, Color);
      Color = (Color + 1) & 0x0F;   /* cycle through 16 colors */
   }

   /* Wait for a key, restore text mode, and done */
   scanf("%c", &Temp);
   Regs.x.ax = 0x0003;
   int86(0x10, &Regs, &Regs);
}
```

LISTING 19.3 L19-3.C

```
/*
 * Draws nested ellipses of varying eccentricities in the VGA's
 * hi-res mode, mode 12h.
 * For VGA only.
 * Compile and link (using Borland C++) with l19-X.c (where X is 1 or 4) with:
 *    bcc -ms -eL19-3X.EXE  L19-3.C  L19-X.C
 *
 */

#include <dos.h>

main() {
   int XRadius, YRadius, Temp, Color;
   union REGS Regs;

   /* Select VGA's hi-res 640x480 graphics mode, mode 12h */
   Regs.x.ax = 0x0012;
   int86(0x10, &Regs, &Regs);

   /* Draw nested ellipses */
   for ( XRadius = 100, YRadius = 2, Color = 7; YRadius < 240;
         XRadius++, YRadius += 2 ) {
      DrawEllipse(640/2, 480/2, XRadius, YRadius, Color);
      Color = (Color + 1) & 0x0F;   /* cycle through 16 colors */
   }

   /* Wait for a key, restore text mode, and done */
   scanf("%c", &Temp);
   Regs.x.ax = 0x0003;
   int86(0x10, &Regs, &Regs);
}
```

Link Listing 19.1 to Listing 19.2 to see ellipses drawn to appear as circles in mode 10H. Some multiscanning monitors don't provide a 4:3 aspect ratio in mode 10H, so the ellipses may not look all that circular. Trust me, they do have an eccentricity of 1.33. Link Listing 19.1 to Listing 19.3 to see ellipses drawn with a variety of eccentricities. When you run these listings, you will see that ellipses drawn by stepping the major axis tend to look rather jagged; that's the cost of performance, and the appearance of these ellipses is nonetheless perfectly acceptable. The alternative is antialiased drawing, which can produce stunning results in 256-color and high-color modes, but would be orders of magnitude slower than the step-based ellipse drawing we'll see shortly.

As you can see, drawing an ellipse is no great trick. However, drawing an ellipse with reasonable performance requires a little more thought.

Ellipse Drawing: An Incremental Approach

Remember the incremental, integer-only algorithm we used to speed up circle drawing two chapters back? I hope so, because fast ellipse drawing, as implemented in Listing 19.4, is strikingly similar, if slightly more complicated, and I'm not going to discuss the process in as much detail this time. Basically, instead of calculating the minor axis coordinate from scratch for each pixel, the incremental approach calculates it as a delta from the last pixel.

LISTING 19.4 L19-4.C

```
/*
 * Draws an ellipse of the specified X and Y axis radii and color,
 * using a fast integer-only & square-root-free approach.
 * Compiles with either Borland or Microsoft.
 * VGA or EGA.
 */

#include <math.h>
#include <dos.h>

/* Borland accepts outp for outportb, but not outpw for outport */
#ifdef __TURBOC__
#define outpw  outport
#endif

#define SCREEN_WIDTH_IN_BYTES    80         /* # of bytes across one scan
                                               line in modes 10h and 12h */
#define SCREEN_SEGMENT           0xA000     /* mode 10h/12h display memory seg */
#define GC_INDEX                 0x3CE      /* Graphics Controller Index port */
#define SET_RESET_INDEX          0          /* Set/Reset reg index in GC */
#define SET_RESET_ENABLE_INDEX   1          /* Set/Reset Enable reg index in GC */
#define BIT_MASK_INDEX           8          /* Bit Mask reg index in GC */

/* Draws a pixel at screen coordinate (X,Y) */
void DrawDot(int X, int Y) {
   unsigned char far *ScreenPtr;
   /* Point to the byte the pixel is in */
#ifdef __TURBOC__
   ScreenPtr = MK_FP(SCREEN_SEGMENT, (Y*SCREEN_WIDTH_IN_BYTES) + (X/8));
#else
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) = (Y * SCREEN_WIDTH_IN_BYTES) + (X / 8);
#endif

   /* Set the bit mask within the byte for the pixel */
   outp(GC_INDEX + 1, 0x80 >> (X & 0x07));

   /* Draw the pixel. ORed to force read/write to load latches.
      Data written doesn't matter, because set/reset is enabled
      for all planes. Note: don't OR with 0; MSC optimizes that
      statement to no operation. */
   *ScreenPtr |= 0xFE;
}

/* Draws an ellipse of X axis radius A and Y axis radius B in
 * color Color centered at screen coordinate (X,Y). Radii must
 * both be non-zero. */
void DrawEllipse(int X, int Y, int A, int B, int Color) {
   int WorkingX, WorkingY;
   long Threshold;
   long ASquared = (long) A * A;
   long BSquared = (long) B * B;
   long XAdjust, YAdjust;

   /* Set drawing color via set/reset */
   outpw(GC_INDEX, (0x0F << 8) | SET_RESET_ENABLE_INDEX);
                                 /* enable set/reset for all planes */
   outpw(GC_INDEX, (Color << 8) | SET_RESET_INDEX);
                                 /* set set/reset (drawing) color */
   outp(GC_INDEX, BIT_MASK_INDEX); /* leave the GC Index reg pointing
                                       to the Bit Mask reg */

   /* Draw the four symmetric arcs for which X advances faster (that is,
      for which X is the major axis) */
   /* Draw the initial top & bottom points */
   DrawDot(X, Y+B);
   DrawDot(X, Y-B);

   /* Draw the four arcs; set draw parameters for initial point (0,B) */
   WorkingX = 0;
   WorkingY = B;
   XAdjust = 0;
   YAdjust = ASquared * 2 * B;
   Threshold = ASquared / 4 - ASquared * B;

   for (;;) {
      /* Advance the threshold to the value for the next X point
         to be drawn */
      Threshold += XAdjust + BSquared;

      /* If the threshold has passed 0, then the Y coordinate has
         advanced more than halfway to the next pixel and it's time
         to advance the Y coordinate by 1 and set the next threhold
         accordingly */
      if ( Threshold >= 0 ) {
         YAdjust -= ASquared * 2;
         Threshold -= YAdjust;
      WorkingY--;
   }

   /* Advance the X coordinate by 1 */
   XAdjust += BSquared * 2;
   WorkingX++;

   /* Stop if X is no longer the major axis (the arc has passed the
      45-degree point) */
   if ( XAdjust >= YAdjust )
      break;

   /* Draw the 4 symmetries of the current point */
   DrawDot(X+WorkingX, Y-WorkingY);
   DrawDot(X-WorkingX, Y-WorkingY);
   DrawDot(X+WorkingX, Y+WorkingY);
   DrawDot(X-WorkingX, Y+WorkingY);
}

/* Draw the four symmetric arcs for which Y advances faster (that is,
   for which Y is the major axis) */
/* Draw the initial left & right points */
DrawDot(X+A, Y);
DrawDot(X-A, Y);

/* Draw the four arcs; set draw parameters for initial point (A,0) */
WorkingX = A;
WorkingY = 0;
XAdjust = BSquared * 2 * A;
YAdjust = 0;
Threshold = BSquared / 4 - BSquared * A;

for (;;) {
   /* Advance the threshold to the value for the next Y point
      to be drawn */
   Threshold += YAdjust + ASquared;

   /* If the threshold has passed 0, then the X coordinate has
      advanced more than halfway to the next pixel and it's time
      to advance the X coordinate by 1 and set the next threhold
      accordingly */
   if ( Threshold >= 0 ) {
      XAdjust -= BSquared * 2;
      Threshold = Threshold - XAdjust;
      WorkingX--;
   }

   /* Advance the Y coordinate by 1 */
   YAdjust += ASquared * 2;
   WorkingY++;

   /* Stop if Y is no longer the major axis (the arc has passed the
      45-degree point) */
   if ( YAdjust > XAdjust )
      break;

   /* Draw the 4 symmetries of the current point */
   DrawDot(X+WorkingX, Y-WorkingY);
   DrawDot(X-WorkingX, Y-WorkingY);
   DrawDot(X+WorkingX, Y+WorkingY);
   DrawDot(X-WorkingX, Y+WorkingY);
}
```

```
   /* Reset the Bit Mask register to normal */
   outp(GC_INDEX + 1, 0xFF);
   /* Turn off set/reset enable */
   outpw(GC_INDEX, (0x00 << 8) | SET_RESET_ENABLE_INDEX);
}
```

The tremendous advantage of the incremental approach is that all terms used can be maintained as integers rather than floating-point values. Better yet, no multiplication or division is required to advance from one point to the next (not counting multiplication by 2, which is really an add or shift). The incremental approach isn't quite as fast for ellipses as for circles, but it nonetheless makes ellipses *nearly* as fast as the circles we've drawn in the last two chapters, and that's remarkably fast.

That said, let's take a quick trip through the math of the incremental ellipse-drawing approach for those of you with a mind to do some tinkering on your own.

A Thumbnail Derivation of the Incremental Approach

As with the floating-point approach, the incremental approach draws ellipses by generating an arc for which X advances more rapidly and then drawing the four symmetries, then doing the same for Y. Also like the floating-point approach, the coordinate which advances more rapidly—the major axis for the arc being drawn—is incremented by 1 each time, and the corresponding minor axis point is drawn. The only difference between the two approaches lies in the way that the minor axis coordinate is determined. Where the floating-point approach recalculates the minor axis coordinate, the incremental approach merely decides whether the minor axis coordinate has changed from the previous point, and advances that coordinate by 1 if that is the case.

The trick to the incremental approach, then, lies in deciding when it's time to advance the minor axis coordinate. Here, in a nutshell, is how that works. The equation for an ellipse is

$$x^2/A^2 + y^2/B^2 = 1$$

which can be expressed as:

$$B^2*x^2 + A^2*y^2 - A^2*B^2 = 0$$

When drawing an arc for which x is the major axis, all we'll do is evaluate the above equation initially for $x = 0$ and $y = B - 0.5$, which will give us a measure of how far off x is from the value at which y does equal B - 0.5 (B - 0.5 being the point at which y gets closer to the next pixel and advances). Then, we'll reevaluate the equation for x+1 each time x advances one pixel. When the result becomes positive, we'll have passed the point at which y is closer to the next pixel, so we'll decrement y and adjust the equation for the new y value, then start looking in the same way for the next time y advances. That's really all there is to it.

So, when drawing an arc for which x advances faster, we'll set the initial y to B - 0.5 and the initial x to 0, which, plugged into the above equation, gives us

$$B^2*0^2 + A^2*(B-0.5)^2 - A^2*B^2 = 0$$

which is to say (squaring B - 0.5)

$$0.25*A^2 - A^2*B = 0$$

so the initial threshold is

$$A^2/4 - A^2*B.$$

This is easy enough to calculate with integer arithmetic. True, we're ignoring a possible fractional term from $A^2/4$, but that's no problem; we'll simply choose to advance y if the threshold becomes exactly 0, thereby correctly handling the case where there's an implied fractional value.

Now that we have an initial threshold, we have to adjust it each time we advance x until it becomes positive, indicating a change in y. That's done by advancing the x-based component of the threshold from

$$B^2*x^2$$

to

$$B^2*(x+1)^2$$

which can be expressed as

$$B^2*(x^2+2*x+1)$$

or

$$B^2*x^2 + B^2*2*x + B^2$$

B^2*x^2 is already in the current threshold equation, so

$$B^2*2*x + B^2$$

is added to the x-based term each time x advances, and that quantity can be maintained with integer arithmetic on an ongoing basis.

When the threshold is reached or exceeded, the y coordinate is decremented by 1, and the threshold must be adjusted back down in preparation for the next advance. This is done by adjusting the y component of the ellipse equation to

$$B^2*(y-1)^2$$

which is

$$B^2*(y^2-2*y+1)$$

or

$$B^2*y^2 - B^2*2*y + B^2$$

Since B^2*y^2 is the value we're adjusting from, the incremental portion of this equation is simply $-B^2*2*y + B^2$, and, like the *x* component above, that value is easily maintained with integer arithmetic as *y* advances. (Note, however, that the *y* in the above equation has a fractional component of 0.5 that ends up cancelling the B^2 added at the end of the equation. See Chapter 17 for a more detailed discussion of this phenomenon in the context of circles.)

Drawing stops when the 45 degree point is reached. That condition is detected when the minor axis adjustment equals or exceeds the major axis adjustment, thereby becoming the dominant component in calculating the threshold and causing the arc to advance more rapidly along the minor axis.

I've gone fast here, because we covered this approach in detail when we discussed circles, but everything you really need to know to understand how the incremental approach works for ellipses is laid out above. If you had trouble following along, you might refer back to the lengthier explanation of the incremental approach for circles in Chapter 17.

Or you might not. After all, what you really need to know is how to draw ellipses fast, and Listing 19.4 does that, with far better yet to come in the next chapter.

Notes and Caveats on the Code

Unlike our circle-drawing code, the ellipse-drawing code in Listing 19.4 won't handle radii as large as 32K; the limit varies depending on the radii combination, but is never less than 1K. Given that 800 is the largest usable non-clipped radius on the highest-resolution SuperVGA available, a limit of 1K shouldn't pose any problem. If a greater range is needed, integers larger than 32 bits could be used, although that's more easily done in assembly language than in C. Along the same lines, calculations for smaller ellipses could potentially be performed using smaller integers. In general, no particular attempt was made to optimize the code presented in this chapter. In the next chapter we'll worry about fine-tuning, which is pointless without the foundation of a good algorithm such as the one we've developed here.

The incremental approach used in Listing 19.4 is not Hal Hardenbergh's ellipse-drawing approach. Hal has come up with a fixed-point technique that is slightly less precise due to fractional roundoff but looks to be faster than the approach I've presented. I derived the approach I've presented from the circle-drawing approach we've already covered, because I prefer exact plotting when I can get it at little cost and because I thought it would be easier for readers to understand an extension of what we've already covered than something new.

Notwithstanding that this is not Hal's approach, he patiently let me bounce it off him and kept me from getting wildly off track, for which I am most grateful.

How Fast Is It?

The big question, of course, is: How much faster is the incremental approach? *Plenty.* Listing 19.2 runs about 20 times faster when linked to the version of **DrawEllipse** in Listing 19.4 than to the version in Listing 19.1, and Listing 19.3 produces similar results. A numeric coprocessor would help Listing 19.1, but not *that* much; anyway, you can't count on every system having a coprocessor. And we've only begun to kick ellipse drawing into high gear. In the next chapter we'll tackle the two remaining legs of the optimization sequence by tailoring the code to the EGA/VGA and converting to assembler. Based on our experience with circle drawing, I'd expect a performance improvement of an additional two to three times, with the tally for our final code running at around 40 to 60 times faster than Listing 19.1.

Ellipses that Rip

Chapter 20

Optimizing Ellipse Drawing with a Draw List for Each Octant

Do you believe in coincidence? You don't have to, you know; there's no rule that says there has to be any such thing, and many people choose to believe otherwise. They think that all events are interrelated; what appears to be coincidence actually reflects deeper meaning in the universe. Personally, I prefer to believe in random coincidence, because if coincidences are meaningful, the universe has been trying to send me a *very* meaningful message lately—and while I can't imagine what that message could possibly be, I'm not sure I want to find out!

To wit: In the previous chapter, I began by telling you that I seemed to be encountering faster circle implementations almost daily, and I mentioned Hal Hardenbergh's extremely fast, 16-bit- integer-only circle-drawing approach. A few days after I wrote the original article from which that chapter was derived, in what was either one hell of a coincidence or a telegram from the Twilight Zone, an article by Tim Paterson in the July, 1990 *Dr. Dobb's Journal* crossed my desk. The topic of the article: drawing circles. Fast. With no multiplies and no divides and plain old 16-bit integers.

Sound familiar?

Tim covers ground that we've already been over, but he looks at circle drawing from a different and interesting perspective. Although the code is in C, you could convert it to assembly language easily enough. The message? One (which pointedly includes that fellow I) should never be too sure that he or she has in fact nailed any topic for all time, from all perspectives.

With that lesson firmly in mind, let's draw some ellipses. Fast. *Very* fast, in fact. Nonetheless, I'm sure there's something faster yet; in my experience, there always is.

Ellipses, Continued

Last time we learned how to draw ellipses without using any multiplies, divides, or floating-point numbers, thanks to an integer-only incremental algorithm. This time I'll better attune that code to the hardware of the EGA and VGA by eliminating the separate calculation of the screen address for each and every point. Instead, I'll generate *a draw list* for an octant, that is, a set of commands to either advance or not advance along the minor axis each time drawing advances one pixel along the major axis. Then I'll draw the four symmetries of that draw list (the four octants which share the same major axis—that is, advance more rapidly along the same axis) one at a time, using specialized code that calculates the bit mask and offset for each pixel as a function of the last pixel, thereby eliminating all multiplications and multi-bit rotations. I'll then repeat the process for the four octants in which the other coordinate is the major axis. Finally, I'll rewrite in assembly language the code that generates draw lists, and I'll do the same for the code that draws octants from draw lists.

Ellipse Drawing Made Fast

Without further ado, let's get to the code. Listing 20.1 is C ellipse-drawing code, differing from Listing 19.4 in that Listing 20.1 generates a draw list and draws the four symmetries of that list, then does the whole thing again for the other axis, as described above. That change produces a performance improvement of about 35 percent, as shown in Table 20.1. Listing 20.2 is a sample C program that can call any of the ellipse-drawing functions in this chapter and the last; Listing 20.2 was used for timing the various implementations. (Because this chapter brings together a lot of familiar stuff, I made the sample program a little more interesting than the standard concentric ellipses. It's not a big deal—it's kind of a circle with pointy ears—but it gives you an idea of the sorts of shapes that are easily created with sets of ellipses; run it yourself and see.)

LISTING 20.1 L20-1.C

```
/*
 * Draws an ellipse of the specified X and Y axis radii and color,
 * using a fast integer-only & square-root-free approach, and
 * generating the arc for one octant into a buffer, drawing four
 * symmetries from that buffer, then doing the same for the other
 * axis.
 * Compiles with either Borland or Microsoft.
 * VGA or EGA.
 */
#include <dos.h>

/* Handle differences between Borland and Microsoft. Note that Borland accepts
   outp as a synonym for outportb, but not outpw for outport */
#ifdef __TURBOC__
#define outpw  outport
```

Table 20.1 Ellipse-Drawing Performance Comparison

	Processor	
Listing	286	386
19.1 (C/floating point)	1088 sec	406 sec
19.4 (C/integer)	46 sec	17 sec
20.1 (C/incremental pixel addressing)	33 sec	13 sec
20.3/4 (ISVGA=0) (ASM)	14 sec	7 sec
20.3/4 (ISVGA=1) (ASM/write mode 3)	13 sec	5 sec

Notes: These are the execution times of the various ellipse-drawing implementations in Chapters 19 and 20 when linked to Listing 20.2. Borland C was used to compile all C code, with maximum optimization (-G -O -Z -r) enabled. Times in the columns labelled "286" were recorded on a Video Seven VRAM VGA running as a 16-bit device on a 10-MHz 1-wait-state AT clone; times in the columns labelled "386" were recorded on a the built- in Paradise VGA in a 20-MHz, 32K-0-wait-state-cache Toshiba 5200 (a monochrome adapter was also installed). No floating-point processor was installed in either computer. Results could vary considerably on different hardware.

```
#endif

#define SCREEN_WIDTH_IN_BYTES     80          /* # of bytes across one scan
                                                 line in mode 12h */
#define SCREEN_SEGMENT            0xA000      /* mode 12h display memory seg */
#define GC_INDEX                  0x3CE       /* Graphics Controller port */
#define SET_RESET_INDEX           0           /* Set/Reset reg index in GC */
#define SET_RESET_ENABLE_INDEX    1           /* Set/Reset Enable reg index
                                                 in GC */
#define BIT_MASK_INDEX            8           /* Bit Mask reg index in GC */

unsigned char PixList[SCREEN_WIDTH_IN_BYTES*8/2];
                                              /* maximum major axis length is
                                                 1/2 screen width, because we're
                                                 assuming no clipping is needed */

/* Draws the arc for an octant in which Y is the major axis. (X,Y) is the
   starting point of the arc. HorizontalMoveDirection selects whether the
   arc advances to the left or right horizontally (0=left, 1=right).
   RowOffset contains the offset in bytes from one scan line to the next,
   controlling whether the arc is drawn up or down. Length is the
   vertical length in pixels of the arc, and DrawList is a list
   containing 0 for each point if the next point is vertically aligned,
   and 1 if the next point is 1 pixel diagonally to the left or right. */
void DrawVOctant(int X, int Y, int Length, int RowOffset,
   int HorizontalMoveDirection, unsigned char *DrawList)
{
   unsigned char far *ScreenPtr, BitMask;

   /* Point to the byte the initial pixel is in. */
```

```
#ifdef __TURBOC__
   ScreenPtr = MK_FP(SCREEN_SEGMENT,
      (Y * SCREEN_WIDTH_IN_BYTES) + (X / 8));
#else
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) =(Y * SCREEN_WIDTH_IN_BYTES) + (X / 8);
#endif
   /* Set the initial bit mask */
   BitMask = 0x80 >> (X & 0x07);

   /* Draw all points in DrawList */
   while ( Length-- ) {
      /* Set the bit mask for the pixel */
      outp(GC_INDEX + 1, BitMask);
      /* Draw the pixel. ORed to force read/write to load latches.
         Data written doesn't matter, because set/reset is enabled
         for all planes. Note: don't OR with 0; MSC optimizes that
         statement to no operation */
      *ScreenPtr |= 0xFE;
      /* Now advance to the next pixel based on DrawList. */
      if ( *DrawList++ ) {
         /* Advance horizontally to produce a diagonal move. Rotate
            the bit mask, advancing one byte horizontally if the bit
            mask wraps */
         if ( HorizontalMoveDirection == 1 ) {
            /* Move right */
            if ( (BitMask >>= 1) == 0 ) {
               BitMask = 0x80;   /* wrap the mask */
               ScreenPtr++;      /* advance 1 byte to the right */
            }
         } else {
            /* Move left */
            if ( (BitMask <<= 1) == 0 ) {
               BitMask = 0x01;   /* wrap the mask */
               ScreenPtr--;      /* advance 1 byte to the left */
            }
         }
      }
      ScreenPtr += RowOffset; /* advance to the next scan line */
   }
}

/* Draws the arc for an octant in which X is the major axis. (X,Y) is the
   starting point of the arc. HorizontalMoveDirection selects whether the
   arc advances to the left or right horizontally (0=left, 1=right).
   RowOffset contains the offset in bytes from one scan line to the next,
   controlling whether the arc is drawn up or down. Length is the
   horizontal length in pixels of the arc, and DrawList is a list
   containing 0 for each point if the next point is horizontally aligned,
   and 1 if the next point is 1 pixel above or below diagonally. */
void DrawHOctant(int X, int Y, int Length, int RowOffset,
   int HorizontalMoveDirection, unsigned char *DrawList)
{
   unsigned char far *ScreenPtr, BitMask;

   /* Point to the byte the initial pixel is in */
#ifdef __TURBOC__
   ScreenPtr = MK_FP(SCREEN_SEGMENT,
      (Y * SCREEN_WIDTH_IN_BYTES) + (X / 8));
#else
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) =(Y * SCREEN_WIDTH_IN_BYTES) + (X / 8);
#endif
   /* Set the initial bit mask */
   BitMask = 0x80 >> (X & 0x07);

   /* Draw all points in DrawList */
   while ( Length-- ) {
      /* Set the bit mask for the pixel */
      outp(GC_INDEX + 1, BitMask);
      /* Draw the pixel (see comments above for details) */
      *ScreenPtr |= 0xFE;
      /* Now advance to the next pixel based on DrawList */
      if ( *DrawList++ ) {
         /* Advance vertically to produce a diagonal move */
         ScreenPtr += RowOffset; /* advance to the next scan line */
      }
      /* Advance horizontally. Rotate the bit mask, advancing one
         byte horizontally if the bit mask wraps */
      if ( HorizontalMoveDirection == 1 ) {
         /* Move right */
         if ( (BitMask >>= 1) == 0 ) {
            BitMask = 0x80;   /* wrap the mask */
            ScreenPtr++;      /* advance 1 byte to the right */
         }
      } else {
         /* Move left */
         if ( (BitMask <<= 1) == 0 ) {
            BitMask = 0x01;   /* wrap the mask */
            ScreenPtr--;      /* advance 1 byte to the left */
         }
      }
   }
}

/* Draws an ellipse of X axis radius A and Y axis radius B in
 * color Color centered at screen coordinate (X,Y). Radii must
 * both be non-zero. */
void DrawEllipse(int X, int Y, int A, int B, int Color) {
   int WorkingX, WorkingY;
   long Threshold;
   long ASquared = (long) A * A;
   long BSquared = (long) B * B;
   long XAdjust, YAdjust;
   unsigned char *PixListPtr;

   /* Set drawing color via set/reset */
   outpw(GC_INDEX, (0x0F << 8) | SET_RESET_ENABLE_INDEX);
                                 /* enable set/reset for all planes */
   outpw(GC_INDEX, (Color << 8) | SET_RESET_INDEX);
                                 /* set set/reset (drawing) color */
   outp(GC_INDEX, BIT_MASK_INDEX); /* leave the GC Index reg pointing
                                       to the Bit Mask reg */

   /* Draw the four symmetric arcs for which X advances faster (that is,
      for which X is the major axis) */

   /* Draw the four arcs; set draw parameters for initial point (0,B) */
   /* Calculate all points along an arc of 1/8th of the ellipse and
      store that info in PixList for later drawing */
   PixListPtr = PixList;
   WorkingX = 0;
```

```
XAdjust = 0;
YAdjust = ASquared * 2 * B;
Threshold = ASquared / 4 - ASquared * B;

for (;;) {
   /* Advance the threshold to the value for the next X point
      to be drawn */
   Threshold += XAdjust + BSquared;

   /* If the threshold has passed 0, then the Y coordinate has
      advanced more than halfway to the next pixel and it's time
      to advance the Y coordinate by 1 and set the next threshold
      accordingly */
   if ( Threshold >= 0 ) {
      YAdjust -= ASquared * 2;
      Threshold -= YAdjust;
      *PixListPtr++ = 1;   /* advance along both axes */
   } else {
      *PixListPtr++ = 0;   /* advance only along the X axis */
   }

   /* Advance the X coordinate by 1 */
   XAdjust += BSquared * 2;
   WorkingX++;

   /* Stop if X is no longer the major axis (the arc has passed the
      45-degree point) */
   if ( XAdjust >= YAdjust )
      break;
}

/* Now draw each of 4 symmetries of the octant in turn, the
   octants for which X is the major axis. Adjust every other arc
   so that there's no overlap. */
DrawHOctant(X,Y-B,WorkingX,SCREEN_WIDTH_IN_BYTES,0,PixList);
DrawHOctant(X+1,Y-B+(*PixList),WorkingX-1,SCREEN_WIDTH_IN_BYTES,1,
   PixList+1);
DrawHOctant(X,Y+B,WorkingX,-SCREEN_WIDTH_IN_BYTES,0,PixList);
DrawHOctant(X+1,Y+B-(*PixList),WorkingX-1,-SCREEN_WIDTH_IN_BYTES,1,
   PixList+1);

/* Draw the four symmetric arcs for which X advances faster (that is,
   for which Y is the major axis) */

/* Draw the four arcs; set draw parameters for initial point (A,0) */
/* Calculate all points along an arc of 1/8th of the ellipse and
   store that info in PixList for later drawing */
PixListPtr = PixList;
WorkingY = 0;
XAdjust = BSquared * 2 * A;
YAdjust = 0;
Threshold = BSquared / 4 - BSquared * A;

for (;;) {
   /* Advance the threshold to the value for the next Y point
      to be drawn */
   Threshold += YAdjust + ASquared;

   /* If the threshold has passed 0, then the X coordinate has
      advanced more than halfway to the next pixel and it's time
      to advance the X coordinate by 1 and set the next threhold
      accordingly */
      if ( Threshold >= 0 ) {
         XAdjust -= BSquared * 2;
         Threshold = Threshold - XAdjust;
         *PixListPtr++ = 1;   /* advance along both axes */
      } else {
         *PixListPtr++ = 0;   /* advance only along the X axis */
      }

      /* Advance the Y coordinate by 1 */
      YAdjust += ASquared * 2;
      WorkingY++;

      /* Stop if Y is no longer the major axis (the arc has passed the
         45-degree point) */
      if ( YAdjust > XAdjust )
         break;
   }

   /* Now draw each of 4 symmetries of the octant in turn, the
      octants for which Y is the major axis. Adjust every other arc
      so that there's no overlap. */
   DrawVOctant(X-A,Y,WorkingY,-SCREEN_WIDTH_IN_BYTES,1,PixList);
   DrawVOctant(X-A+(*PixList),Y+1,WorkingY-1,SCREEN_WIDTH_IN_BYTES,1,
      PixList+1);
   DrawVOctant(X+A,Y,WorkingY,-SCREEN_WIDTH_IN_BYTES,0,PixList);
   DrawVOctant(X+A-(*PixList),Y+1,WorkingY-1,SCREEN_WIDTH_IN_BYTES,0,
      PixList+1);

   /* Reset the Bit Mask register to normal */
   outp(GC_INDEX + 1, 0xFF);
   /* Turn off set/reset enable */
   outpw(GC_INDEX, (0x00 << 8) | SET_RESET_ENABLE_INDEX);
}
```

LISTING 20.2   L20-2.C

```
/*
 * Draws ellipses of varying eccentricities in the VGA's hi-res mode,
 * mode 12h.
 * For VGA only.
 * Compile and link (using Borland C++) with listing L20-X.C (where X is 1 or 4)
 * with:
 *    bcc -ms L20-X.C  L20-2.C
 *
 */

#include <dos.h>
#include <stdio.h>

main() {
   int XRadius, YRadius, Temp, Color, i;
   union REGS Regs;

   /* Select VGA's hi-res 640x480 graphics mode, mode 12h */
   Regs.x.ax = 0x0012;
   int86(0x10, &Regs, &Regs);

   /* Repeat 10 times */
   for ( i = 0; i < 10; i++ ) {
      /* Draw nested ellipses */
      for ( XRadius = 319, YRadius = 1, Color = 7; YRadius < 240;
            XRadius -= 1, YRadius += 2 ) {
         DrawEllipse(640/2, 480/2, XRadius, YRadius, Color);
         Color = (Color + 1) & 0x0F;   /* cycle through 16 colors */
      }
   }

   /* Wait for a key, restore text mode, and done */
   scanf("%c", &Temp);
   Regs.x.ax = 0x0003;
   int86(0x10, &Regs, &Regs);
}
```

I am well aware that Listing 20.1 is not fully optimized; for one thing, it doesn't take advantage of the write mode 3 and pixel-accumulation techniques used by the assembly code in Listing 20.4. Listing 20.1 is intended as an illustrative bridge between the standard ellipse-drawing code of the previous chapter and the fast but hard to understand code in Listing 20.4, so I've leaned toward comprehension rather than maximum speed in Listing 20.1. To my mind, it's wasted effort to spend time squeezing cycles out of Listing 20.1 when Listings 20.3 and 20.4 will always be faster no matter how well-optimized Listing 20.1 is.

Listing 20.3 is the C portion of the final and fastest ellipse-drawing routine. Listing 20.3 calls functions in the assembly language module shown in Listing 20.4 in order to perform the two critical aspects of ellipse drawing: draw list generation and the actual octant drawing.

Listings 20.3 and 20.4 together are about twice as fast as Listing 20.1. They are in the range of 2.5 to 3.5 times faster than Listing 19.4. Lastly, they are 60 or so times faster than the floating-point based implementation in Listing 19.1.

See what a little forethought and attention to detail can do?

LISTING 20.3 L20-3.C

```
/*
 * Draws an ellipse of the specified X and Y axis radii and color,
 * using a fast integer-only & square-root-free approach, and
 * generating the arc for one octant into a buffer, drawing four
 * symmetries from that buffer, then doing the same for the other
 * axis. Uses assembly language for inner loops of octant generation
 * & drawing. Link to Listing 20.4.
 *
 * Compiles with either Borland or Microsoft.
 * VGA or EGA.
 */
#define ISVGA  0              /* set to 1 to use VGA write mode 3*/
                              /* keep synchronized with Listing 4 */
#include <dos.h>

/* Handle differences between Borland and Micrmedian. Note that Borland accepts
   outp as a synonym for outportb, but not outpw for outport */
#ifdef __TURBOC__
#define outpw  outport
#endif
```

```
#define SCREEN_WIDTH_IN_BYTES     80         /* # of bytes across one scan
                                                line in mode 12h */
#define SCREEN_SEGMENT            0xA000     /* mode 12h display memory seg */
#define GC_INDEX                  0x3CE      /* Graphics Controller port */
#define SET_RESET_INDEX           0          /* Set/Reset reg index in GC */
#define SET_RESET_ENABLE_INDEX    1          /* Set/Reset Enable reg index
                                                in GC */
#define GC_MODE_INDEX             5          /* Graphics Mode reg index in GC */
#define COLOR_DONT_CARE           7          /* Color Don't Care reg index in GC */
#define BIT_MASK_INDEX            8          /* Bit Mask reg index in GC */

unsigned char PixList[SCREEN_WIDTH_IN_BYTES*8/2];
                                             /* maximum major axis length is
                                                1/2 screen width, because we're
                                                assuming no clipping is needed */

/* Draws an ellipse of X axis radius A and Y axis radius B in
 * color Color centered at screen coordinate (X,Y). Radii must
 * both be non-zero. */
void DrawEllipse(int X, int Y, int A, int B, int Color) {
   int Length;
   long Threshold;
   long ASquared = (long) A * A;
   long BSquared = (long) B * B;
   long XAdjust, YAdjust;
   unsigned char *PixListPtr, OriginalGCMode;

   /* Set drawing color via set/reset */
   outpw(GC_INDEX, (0x0F << 8) | SET_RESET_ENABLE_INDEX);
                                 /* enable set/reset for all planes */
   outpw(GC_INDEX, (Color << 8) | SET_RESET_INDEX);
                                 /* set set/reset (drawing) color */
#if ISVGA
   /* Remember original read/write mode & select
      read mode 1/write mode 3, with Color Don't Care
      set to ignore all planes and therefore always return 0xFF */
   outp(GC_INDEX, GC_MODE_INDEX);
   OriginalGCMode = inp(GC_INDEX + 1);
   outp(GC_INDEX+1, OriginalGCMode | 0x0B);
   outpw(GC_INDEX, (0x00 << 8) | COLOR_DONT_CARE);
   outpw(GC_INDEX, (0xFF << 8) | BIT_MASK_INDEX);
#else
   outp(GC_INDEX, BIT_MASK_INDEX); /* leave the GC Index reg pointing
                                       to the Bit Mask reg */
#endif

   /* Draw the four symmetric arcs for which X advances faster (that is,
      for which X is the major axis) */
   /* Generate the draw list for 1 octant */
   Length = GenerateEOctant(PixList, (long) ASquared * 2 * B,
      (long) ASquared / 4 - ASquared * B, ASquared, BSquared);

   /* Now draw each of 4 symmetries of the octant in turn, the
      octants for which X is the major axis. Adjust every other arc
      so that there's no overlap. */
   DrawHOctant(X,Y-B,Length,SCREEN_WIDTH_IN_BYTES,0,PixList);
   DrawHOctant(X+1,Y-B+(*PixList),Length-1,SCREEN_WIDTH_IN_BYTES,1,
      PixList+1);
   DrawHOctant(X,Y+B,Length,-SCREEN_WIDTH_IN_BYTES,0,PixList);
   DrawHOctant(X+1,Y+B-(*PixList),Length-1,-SCREEN_WIDTH_IN_BYTES,1,
      PixList+1);
   /* Draw the four symmetric arcs for which Y advances faster (that is,
      for which Y is the major axis) */
   /* Generate the draw list for 1 octant */
   Length = GenerateEOctant(PixList, (long) BSquared * 2 * A,
      (long) BSquared / 4 - BSquared * A, BSquared, ASquared);

   /* Now draw each of 4 symmetries of the octant in turn, the
      octants for which X is the major axis. Adjust every other arc
      so that there's no overlap. */
   DrawVOctant(X-A,Y,Length,-SCREEN_WIDTH_IN_BYTES,1,PixList);
   DrawVOctant(X-A+(*PixList),Y+1,Length-1,SCREEN_WIDTH_IN_BYTES,1,
      PixList+1);
   DrawVOctant(X+A,Y,Length,-SCREEN_WIDTH_IN_BYTES,0,PixList);
   DrawVOctant(X+A-(*PixList),Y+1,Length-1,SCREEN_WIDTH_IN_BYTES,0,
      PixList+1);

#if ISVGA
   /* Restore original write mode */
   outpw(GC_INDEX, (OriginalGCMode << 8) | GC_MODE_INDEX);
   /* Restore normal Color Don't Care setting */
   outpw(GC_INDEX, (0x0F << 8) | COLOR_DONT_CARE);
#else
   /* Reset the Bit Mask register to normal */
   outp(GC_INDEX + 1, 0xFF);
#endif
   /* Turn off set/reset enable */
   outpw(GC_INDEX, (0x00 << 8) | SET_RESET_ENABLE_INDEX);
}
```

LISTING 20.4 L20-4.ASM

```
; Contains 3 C-callable routines: GenerateEOctant, DrawVOctant, and
;       DrawHOctant. See individual routines for comments. Link to
;       Listing 20.3.
;
; Works with TASM or MASM
;
ISVGA   equ     0       ;set to 1 to use VGA write mode 3
                        ; keep synchronized with Listing 3
        .model small
        .code
;********************************************************************
; Generates an octant of the specified ellipse, placing the results in
; PixList, with a 0 in PixList meaning draw pixel & move only along
; major axis, and a 1 in PixList meaning draw pixel & move along both
; axes.
; C near-callable as:
;  int GenerateEOctant(unsigned char *PixList, long MinorAdjust,
;       long Threshold, long MajorSquared, long MinorSquared);
;
; Return value = PixelCount (# of points)
;
; Passed parameters:
;
GenerateOctantParms     struc
        dw      ?       ;pushed BP
        dw      ?       ;return address pushed by call
PixList dw      ?       ;pointer to list to store draw control data in
MinorAdjust dd  ?       ;initially MajorAxis**2 * 2 * MinorAxis, used
```

```
                        ; to adjust threshold after minor axis move
Threshold dd    ?       ;initially MajorAxis**2 / 4 + MajorAxis**2 *
                        ; MinorAxis, used to determine when to advance
                        ; along the minor axis
MajorSquared dd ?       ;MajorAxis**2
MinorSquared dd ?       ;MinorAxis**2
GenerateOctantParms     ends
;
; Local variables (offsets relative to BP in stack frame):
;
PixelCount      equ     -2      ;running major axis coordinate
                                ; relative to center
MajorAdjust     equ     -6      ;used to adjust threshold after major
                                ; axis move
MajorSquaredTimes2 equ  -10     ;MajorSquared * 2
MinorSquaredTimes2 equ  -14     ;MinorSquared * 2
;
        public _GenerateEOctant
_GenerateEOctant proc    near
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to our stack frame
        add     sp,MinorSquaredTimes2
                                ;allocate room for local vars
        push    si              ;preserve C register variables
        push    di
;Initialize local variables.
        mov     word ptr [bp+PixelCount],0 ;initialize count of pixels
                                        ; to zero
        mov     ax,word ptr [bp+MajorSquared] ;set MajorSquaredTimes2
        shl     ax,1                    ;lower word times 2
        mov     word ptr [bp+MajorSquaredTimes2],ax
        mov     ax,word ptr [bp+MajorSquared+2]
        rcl     ax,1                    ;upper word times 2
        mov     word ptr [bp+MajorSquaredTimes2+2],ax

        mov     ax,word ptr [bp+MinorSquared] ;set MinorSquaredTimes2
        shl     ax,1                    ;lower word times 2
        mov     word ptr [bp+MinorSquaredTimes2],ax
        mov     ax,word ptr [bp+MinorSquared+2]
        rcl     ax,1                    ;upper word times 2
        mov     word ptr [bp+MinorSquaredTimes2+2],ax
;Set up registers for loop.
        mov     di,[PixList+bp]         ;point DI to PixList
; Set MajorAdjust to 0.
        sub     cx,cx
        mov     si,cx                   ;SI:CX = MajorAdjust

        mov     bx,word ptr [bp+Threshold]      ;DX:BX = threshold
        mov     dx,word ptr [bp+Threshold+2]
; At this point:
;  DX:BX = threshold
;  SI:CX = MajorAdjust
;  DI = PixList pointer
GenLoop:
; Advance the threshold by MajorAdjust + MinorAxis**2.
        add     bx,cx
        adc     dx,si
        add     bx,word ptr [bp+MinorSquared]
        adc     dx,word ptr [bp+MinorSquared+2]
; If the threshold has passed 0, then the minor coordinate has
; advanced more than halfway to the next pixel and it's time to
; advance the minor coordinate by 1 and set the next threshold
; accordingly.
        mov     byte ptr [di],0 ;assume we won't move along the
                                ; minor axis
        js      MoveMajor       ;and, in fact, we won't move minor
; Minor coordinate has advanced.
; Adjust the minor axis adjust value.
        mov     ax,word ptr [bp+MajorSquaredTimes2]
        sub     word ptr [bp+MinorAdjust],ax
        mov     ax,word ptr [bp+MajorSquaredTimes2+2]
        sbb     word ptr [bp+MinorAdjust+2],ax
; Adjust the threshold for the minor axis move
        sub     bx,word ptr [bp+MinorAdjust]
        sbb     dx,word ptr [bp+MinorAdjust+2]
        mov     byte ptr [di],1
MoveMajor:
        inc     di
; Count this point.
        inc     word ptr [bp+PixelCount]
; Adjust the major adjust for the new point.
        add     cx,word ptr [bp+MinorSquaredTimes2]
        adc     si,word ptr [bp+MinorSquaredTimes2+2]
; Stop if the major axis has switched (the arc has passed the
; 45-degree point).
        cmp     si,word ptr [bp+MinorAdjust+2]
        ja      Done
        jb      GenLoop
        cmp     cx,word ptr [bp+MinorAdjust]
        jb      GenLoop
Done:
        mov     ax,[bp+PixelCount]      ;return # of points
        pop     di              ;restore C register variables
        pop     si
        mov     sp,bp           ;deallocate local vars
        pop     bp              ;restore caller's stack frame
        ret
_GenerateEOctant endp
;*********************************************************************
; Draws the arc for an octant in which Y is the major axis. (X,Y) is the
; starting point of the arc. HorizontalMoveDirection selects whether the
; arc advances to the left or right horizontally (0=left, 1=right).
; RowOffset contains the offset in bytes from one scan line to the next,
; controlling whether the arc is drawn up or down. DrawLength is the
; vertical length in pixels of the arc, and DrawList is a list
; containing 0 for each point if the next point is vertically aligned,
; and 1 if the next point is 1 pixel diagonally to the left or right.
;
; The Graphics Controller Index register must already point to the Bit
; Mask register.
;
; C near-callable as:
;  void DrawVOctant(int X, int Y, int DrawLength, int RowOffset,
;       int HorizontalMoveDirection, unsigned char *DrawList);
;
DrawParms       struc
        dw      ?       ;pushed BP
        dw      ?       ;return address
X       dw      ?       ;initial coordinates
Y       dw      ?
DrawLength dw   ?       ;vertical length
RowOffset dw    ?       ;distance from one scan line to the next
HorizontalMoveDirection dw ? ;1 to move right, 0 to move left
```

```
DrawList dw     ?       ;pointer to list containing 1 to draw
DrawParms       ends    ; diagonally, 0 to draw vertically for
                        ; each point
SCREEN_SEGMENT  equ     0a000h  ;display memory segment in mode 12h
SCREEN_WIDTH_IN_BYTES equ 80    ;distance from one scan line to next
GC_INDEX        equ     3ceh    ;GC Index register address
;
        public _DrawVOctant
_DrawVOctant    proc    near
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to our stack frame
        push    si              ;preserve C register variables
        push    di
;Point ES:DI to the byte the initial pixel is in.
        mov     ax,SCREEN_SEGMENT
        mov     es,ax
        mov     ax,SCREEN_WIDTH_IN_BYTES
        mul     [bp+Y]  ;Y*SCREEN_WIDTH_IN_BYTES
        mov     di,[bp+X] ;X
        mov     cx,di   ;set X aside in CX
        shr     di,1
        shr     di,1
        shr     di,1    ;X/8
        add     di,ax   ;screen offset = Y*SCREEN_WIDTH_IN_BYTES+X/8
        and     cl,07h  ;X modulo 8
if ISVGA                ;--VGA--
        mov     ah,80h  ;keep VGA bit mask in AH
        shr     ah,cl   ;initial bit mask = 80h shr (X modulo 8);
        cld             ;for LODSB, used below
else                    ;--EGA--
        mov     al,80h  ;keep EGA bit mask in AL
        shr     al,cl   ;initial bit mask = 80h shr (X modulo 8);
        mov     dx,GC_INDEX+1 ;point DX to GC Data reg/bit mask
endif                   ;--------
        mov     si,[bp+DrawList] ;SI points to list to draw from
        sub     bx,bx           ;so we have the constant 0 in a reg
        mov     cx,[bp+DrawLength] ;CX=# of pixels to draw
        jcxz    VDrawDone       ;skip this if no pixels to draw
        cmp     [bp+HorizontalMoveDirection],0 ;draw right or left
        mov     bp,[bp+RowOffset] ;BP=offset to next row
        jz      VGoLeft         ;draw from right to left
VDrawRightLoop:                 ;draw from left to right
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3,
                                ; set/reset provides color
        lodsb                   ;get next draw control byte
        and     al,al           ;move right?
        jz      VAdvanceOneLineRight ;no move right
        ror     ah,1            ;move right
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter (set/reset provides
                                ; color); just force read then write
        cmp     [si],bl         ;check draw control byte; move right?
        jz      VAdvanceOneLineRight ;no move right
        ror     al,1            ;move right
endif                           ;--------
        adc     di,bx           ;move one byte to the right if mask wrapped
VAdvanceOneLineRight:
ife ISVGA                       ;--EGA--
        inc     si              ;advance draw control list pointer
```

```
endif                           ;--------
        add     di,bp           ;move to the next scan line up or down
        loop    VDrawRightLoop  ;do next pixel, if any
        jmp     short VDrawDone ;done
VGoLeft:                        ;draw from right to left
VDrawLeftLoop:
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
        lodsb                   ;get next draw control byte
        and     al,al           ;move left?
        jz      VAdvanceOneLineLeft ;no move left
        rol     ah,1            ;move left
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
        cmp     [si],bl         ;check draw control byte; move left?
        jz      VAdvanceOneLineLeft ;no move left
        rol     al,1            ;move left
endif                           ;--------
        sbb     di,bx           ;move one byte to the left if mask wrapped
VAdvanceOneLineLeft:
ife ISVGA                       ;--EGA--
        inc     si              ;advance draw control list pointer
endif                           ;--------
        add     di,bp           ;move to the next scan line up or down
        loop    VDrawLeftLoop   ;do next pixel, if any
VDrawDone:
        pop     di              ;restore C register variables
        pop     si
        pop     bp
        ret
_DrawVOctant    endp
;*********************************************************************
; Draws the arc for an octant in which X is the major axis. (X,Y) is the
; starting point of the arc. HorizontalMoveDirection selects whether the
; arc advances to the left or right horizontally (0=left, 1=right).
; RowOffset contains the offset in bytes from one scan line to the next,
; controlling whether the arc is drawn up or down. DrawLength is the
; horizontal length in pixels of the arc, and DrawList is a list
; containing 0 for each point if the next point is horizontally aligned,
; and 1 if the next point is 1 pixel above or below diagonally.
;
; Graphics Controller Index register must already point to the Bit Mask
; register.
;
; C near-callable as:
;  void DrawHOctant(int X, int Y, int DrawLength, int RowOffset,
;       int HorizontalMoveDirection, unsigned char *DrawList)
;
; Uses same parameter structure as DrawVOctant().
;
        public _DrawHOctant
_DrawHOctant    proc    near
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to our stack frame
        push    si              ;preserve C register variables
        push    di
;Point ES:DI to the byte the initial pixel is in.
        mov     ax,SCREEN_SEGMENT
        mov     es,ax
        mov     ax,SCREEN_WIDTH_IN_BYTES
        mul     [bp+Y]  ;Y*SCREEN_WIDTH_IN_BYTES
        mov     di,[bp+X] ;X
        mov     cx,di   ;set X aside in CX
        shr     di,1
        shr     di,1
        shr     di,1    ;X/8
        add     di,ax   ;screen offset = Y*SCREEN_WIDTH_IN_BYTES+X/8
        and     cl,07h  ;X modulo 8
        mov     bh,80h
        shr     bh,cl   ;initial bit mask = 80h shr (X modulo 8);
if ISVGA                ;--VGA--
        cld             ;for LODSB, used below
else                    ;--EGA--
        mov     dx,GC_INDEX+1 ;point DX to GC Data reg/bit mask
endif                    ;--------
        mov     si,[bp+DrawList] ;SI points to list to draw from
        sub     bl,bl           ;so we have the constant 0 in a reg
        mov     cx,[bp+DrawLength] ;CX=# of pixels to draw
        jcxz    HDrawDone       ;skip this if no pixels to draw
if ISVGA                        ;--VGA--
        sub     ah,ah           ;clear bit mask accumulator
else                            ;--EGA--
        sub     al,al           ;clear bit mask accumulator
endif                           ;--------
        cmp     [bp+HorizontalMoveDirection],0 ;draw right or left
        mov     bp,[bp+RowOffset] ;BP=offset to next row
        jz      HGoLeft         ;draw from right to left
HDrawRightLoop:                 ;draw from left to right
if ISVGA                        ;--VGA--
        or      ah,bh           ;put this pixel in bit mask accumulator
        lodsb                   ;get next draw control byte
        and     al,al           ;move up/down?
else                            ;--EGA--
        or      al,bh           ;put this pixel in bit mask accumulator
        cmp     [si],bl         ;check draw control byte; move up/down?
endif                           ;--------
        jz      HAdvanceOneLineRight ;no move up/down
                                ;move up/down; first draw accumulated pixels
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
        sub     ah,ah           ;clear bit mask accumulator
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
        sub     al,al           ;clear bit mask accumulator
endif                           ;--------
        add     di,bp           ;move to the next scan line up or down
HAdvanceOneLineRight:
ife ISVGA                       ;--EGA--
        inc     si              ;advance draw control list pointer
endif                           ;--------
        ror     bh,1            ;move to right; shift mask
        jnc     HDrawLoopRightBottom ;didn't wrap to the next byte
                                ;move to next byte; 1st draw accumulated pixels
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
        sub     ah,ah           ;clear bit mask accumulator
else
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
        sub     al,al           ;clear bit mask accumulator
```

```
endif                           ;--------
        inc     di              ;move 1 byte to the right
HDrawLoopRightBottom:
        loop    HDrawRightLoop  ;draw next pixel, if any
        jmp     short HDrawDone ;done
HGoLeft:                        ;draw from right to left
HDrawLeftLoop:
if ISVGA                        ;--VGA--
        or      ah,bh           ;put this pixel in bit mask accumulator
        lodsb                   ;get next draw control byte
        and     al,al           ;move up/down?
else                            ;--EGA--
        or      al,bh           ;put this pixel in bit mask accumulator
        cmp     [si],bl         ;check draw control byte; move up/down?
endif                           ;--------
        jz      HAdvanceOneLineLeft ;no move up/down
                                ;move up/down; first draw accumulated pixels
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
        sub     ah,ah           ;clear bit mask accumulator
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
        sub     al,al           ;clear bit mask accumulator
endif                           ;--------
        add     di,bp           ;move to the next scan line up or down
HAdvanceOneLineLeft:
ife ISVGA                       ;--EGA--
        inc     si              ;advance draw control list pointer
endif                           ;--------
        rol     bh,1            ;move to left; shift mask
        jnc     HDrawLoopLeftBottom ;didn't wrap to next byte
                                ;move to next byte; 1st draw accumulated pixels
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
        sub     ah,ah           ;clear bit mask accumulator
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
        sub     al,al           ;clear bit mask accumulator
endif                           ;--------
        dec     di              ;move 1 byte to the left
HDrawLoopLeftBottom:
        loop    HDrawLeftLoop   ;draw next pixel, if any
HDrawDone:
                                ;draw any remaining accumulated pixels
if ISVGA                        ;--VGA--
        and     es:[di],ah      ;AH becomes bit mask in write mode 3
else                            ;--EGA--
        out     dx,al           ;set the desired bit mask
        and     es:[di],al      ;data doesn't matter; force read/write
endif                           ;--------
        pop     di              ;restore C register variables
        pop     si
        pop     bp
        ret
_DrawHOctant    endp
        end
```

Notes on the Ellipse-Drawing Implementations

This chapter is truly a synthesis of what has come before. We spent the previous chapter developing the incremental ellipse-drawing approach, and the chapter before that developing the draw-list approach for circles. In fact, not only is there nothing particularly new, but there's a bit of optimization overkill in Listing 20.4.

> *I must in all honesty point out that it's scarcely worth bothering with converting the draw list generation code to assembly language at all. First, drawing from the draw list is likely to take much longer than generating the draw list, because four octants are drawn for each draw list generated and because drawing is usually slowed considerably by video wait states. That means that draw list generation doesn't represent a very large fraction of total execution time, and therefore isn't a particularly fruitful place to expend optimization effort.*

Second, draw list generation involves many 32-bit variables, too many to be able to keep them all in the registers; when that's the case, particularly in fairly straightforward add-subtract-compare code like that used in draw list generation, I've found that there's not likely to be much difference between good assembly code and the code produced by a good C compiler. Sure, the assembly-language code is better, but again the difference isn't likely to translate into a sizable improvement in overall performance.

When you optimize code, it's important to understand where in your code the effort will pay off best. In Listings 20.3 and 20.4, optimization effort is better spent in trying to draw octants from draw lists faster than in trying to generate the draw lists themselves faster.

Why Optimizing Isn't a Science

There is one slightly tricky element to Listing 20.4. If you look closely, you'll note that each draw list element is *always* set to 0. Later, that same element may be set again, this time to 1, meaning that a single element may be set twice, incurring an extra instruction and an extra memory access. Is this wise?

In this case, it probably is, although the truth of the matter is far from clear; the question illustrates the hazards of optimizing in today's multi-platform (286, 386, 486, and Pentium, with a variety of memory architectures) world. Presetting each element to 0 allows us to branch and be done with it if there is no minor move, although it also requires us to perform a second set for each element for which there *is* a minor move. The alternative would be something like this:

```
js    NoMoveMinor
<advance minor coordinate>
mov   byte ptr [di],1
```

```
     jmp   short MoveMajor
NoMoveMinor:
     mov   byte ptr [di],0
MoveMajor:
     inc   di
```

This code only sets each draw list element once, but also requires a branch in the case where the minor coordinate advances. That means that the latter approach saves one **MOV BYTE PTR [DI],0** when the minor coordinate advances, but adds one **JMP SHORT MoveMajor** at the same time—not a good trade on *any* 80x86 processor. Although in actual use, instruction fetching can alter those cycle counts somewhat; any variation is usually to the relative detriment of **JMP**, which empties the prefetch queue.

Well, then, why not load 1 or 0 into a register and then store the register, eliminating a memory access? That code would look like this:

```
     sub   al,al       ;assume there's no minor move
     js    NoMoveMinor
     <advance minor coordinate>
     inc   ax          ;upper byte doesn't matter, but word INC
                       ; is more efficient than byte INC
NoMoveMinor:
     stosb
```

This last approach might be faster—or it might not. It all depends on the processor and the memory architecture. On an 8088, there's no question but that the last approach is faster; the 8088 instruction set favors both string instructions like **STOSB** and keeping values in registers. On a 386, however, **MOV [DI],0** takes just 2 cycles, and **INC DI** takes another 2; **STOSB** takes 4, so there's no advantage to **STOSB** there. (On a 486 and Pentium, **STOSB** is almost always a loser to **MOV/INC**.) However, the latter approach requires not only **STOSB** but also **SUB AL,AL** and possibly **INC AX**, so it's actually 2 cycles slower on a 386 in both cases.

At this point we get into issues such as whether the system has a cache, and if so whether the code is in the cache and whether it's a write-back or write-through cache, and if not whether we've hit a ready-to-go interleaved memory bank or the current column in static-column RAM. In short, there's no clear answer as to which code is fastest here unless you know not only your target processor but also your target memory architecture. The only thing that's constant across all 80x86-family processors is that branching is slow, so all of the alternative approaches we've discussed are faster than the obvious approach that we first discussed, the approach of not preloading or presetting at all and branching in both cases.

I'd like to be able to pull a clear, simple lesson out of all this, but the life of an optimizing PC programmer is neither simple nor clear. If there's a moral here, it would be: aim down the middle. That is, try to write code that provides good performance (by assembly language standards) on every common 80x86 processor, and terrible performance on none. In this particular example, that translates into not branching any more than you absolutely must.

The Polygon Primeval

Chapter 21

Drawing Polygons Efficiently and Quickly

"Give me but one firm spot on which to stand, and I will move the Earth."
—Archimedes

Were Archimedes alive today, he might say, "Give me but one fast polygon-fill routine on which to call, and I will draw the Earth." Programmers often think of pixel drawing as being the basic graphics primitive, but filled polygons are equally fundamental and far more useful. Filled polygons can be used for constructs as diverse as a single pixel or a 3-D surface, and virtually everything in between.

I'll spend some time in this chapter and the next several developing routines to draw filled polygons and building more sophisticated graphics operations atop those routines. Once we have that foundation, I'll get into 2-D manipulation and animation of polygon-based entities as preface to an exploration of 3-D graphics. You can't get there from here without laying some groundwork, though, so in this chapter I'll begin with the basics of filling a polygon. In the next chapter, we'll see how to draw a polygon considerably faster. That's my general approach for this sort of topic: High-level exploration of a graphics topic first, followed by a speedy hardware-specific implementation for the IBM PC/VGA combination, the most widely used graphics system around. Abstract, machine-independent graphics is a thing of beauty, but only by understanding graphics at all levels, including the hardware, can you boost performance into the realm of the sublime.

And slow computer graphics is scarcely worth the bother.

Filled Polygons

A polygon is simply a shape formed by lines laid end to end to form a continuous, closed path. A polygon is filled by setting all pixels within the polygon's boundaries to a color or pattern. For now, we'll work only with polygons filled with solid colors.

You can divide polygons into three categories: convex, nonconvex, and complex, as shown in Figure 21.1. Convex polygons include what you'd normally think of as "convex" and more; as far as we're concerned, a convex polygon is one for which any horizontal line drawn through the polygon encounters the right edge exactly once and the left edge exactly once, excluding horizontal and zero-length edge segments. Put another way, neither the right nor left edge of a convex polygon ever reverses direction from up to down, or vice-versa. Also, the right and left edges of a convex polygon may not cross one another, although they may touch so long as the right edge never crosses over to the left side of the left edge. (Check out the second polygon drawn in Listing 21.3, which certainly isn't convex in the normal sense.) The boundaries of nonconvex polygons, on the other hand, can go in whatever directions they please, so long as they never cross. Complex polygons can have any boundaries you might imagine, which makes for interesting problems in deciding which interior spaces to fill and which not to fill. Each category is a superset of the previous one.

(See Chapter 24 for a more detailed discussion of polygon types and naming.)

Why bother to distinguish between convex, nonconvex, and complex polygons? Easy: performance, especially when it comes to filling convex polygons. We're going to start with filled convex polygons; they're widely useful and will serve well to introduce some of the subtler complexities of polygon drawing, not the least of which is the slippery concept of "inside."

Which Side Is Inside?

The basic principle of polygon filling is decomposing each polygon into a series of horizontal lines, one for each horizontal row of pixels, or scan line, within the polygon (a process I'll call *scan conversion*), and drawing the horizontal lines. I'll refer to the entire process as rasterization. Rasterization of convex polygons is easily done by starting at

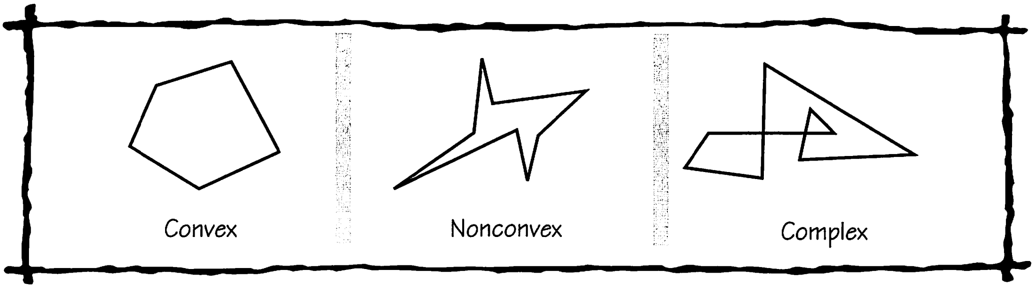


Figure 21.1 Convex, Nonconvex, and Complex Polygons

the top of the polygon and tracing down the left and right sides, one scan line (one vertical pixel) at a time, filling the extent between the two edges on each scan line, until the bottom of the polygon is reached. At first glance, rasterization does not seem to be particularly complicated, although it should be apparent that this simple approach is inadequate for nonconvex polygons.

There are a couple of complications, however. The lesser complication is how to rasterize the polygon efficiently, given that it's difficult to write fast code that simultaneously traces two edges and fills the space between them. The solution is to decouple the process of scan-converting the polygon into a list of horizontal lines from that of drawing the horizontal lines. One device-independent routine can trace along the two edges and build a list of the beginning and end coordinates of the polygon on each raster line. Then a second, device-specific, routine can draw from the list after the entire polygon has been scanned. We'll see this in action shortly.

The second, greater complication arises because the definition of which pixels are "within" a polygon is a more complicated matter than you might imagine. You might think that scan-converting an edge of a polygon is analogous to drawing a line from one vertex to the next, but this is not so. A line by itself is a one-dimensional construct, and as such is approximated on a display by drawing the pixels nearest to the line on either side of the true line. A line serving as a polygon boundary, on the other hand, is part of a two-dimensional object. When filling a polygon, we want to draw the pixels within the polygon, but a standard vertex-to-vertex line-drawing algorithm will draw many pixels outside the polygon, as shown in Figure 21.2.

It's no crime to use standard lines to trace out a polygon, rather than drawing only interior pixels. In fact, there are certain advantages: For example, the edges of a filled polygon will match the edges of the same polygon drawn unfilled. Such polygons will

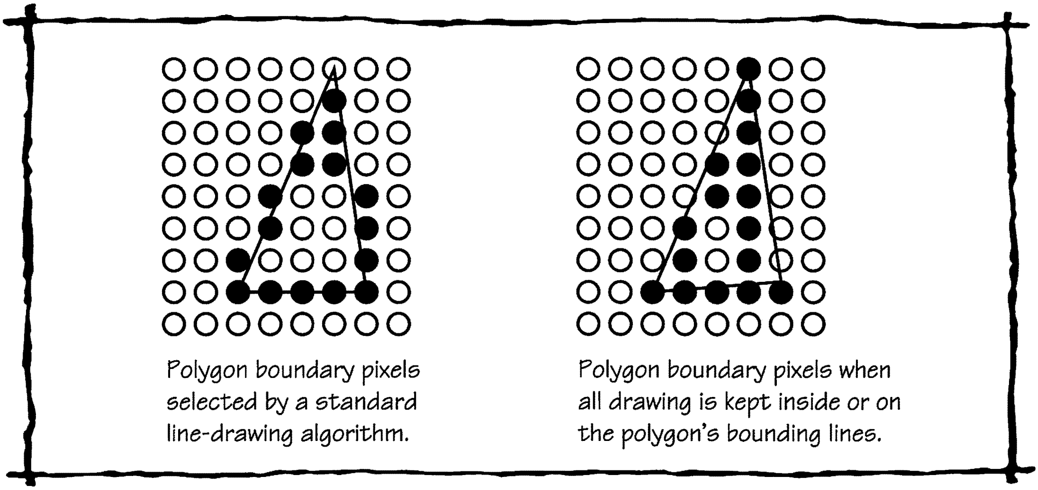

Polygon boundary pixels selected by a standard line-drawing algorithm.
Polygon boundary pixels when all drawing is kept inside or on the polygon's bounding lines.

Figure 21.2 Drawing Polygons with Standard Line-Drawing Algorithms

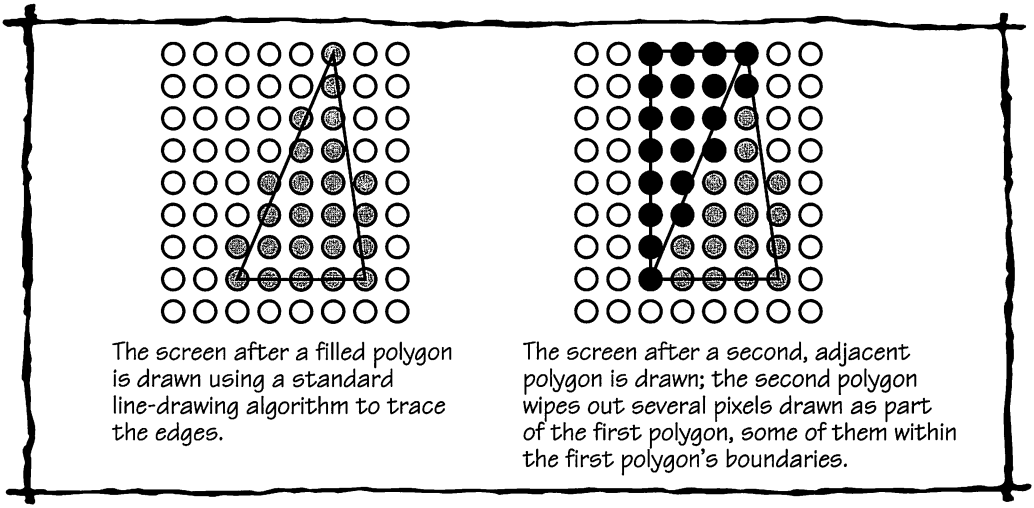

The screen after a filled polygon is drawn using a standard line-drawing algorithm to trace the edges.
The screen after a second, adjacent polygon is drawn; the second polygon wipes out several pixels drawn as part of the first polygon, some of them within the first polygon's boundaries.

Figure 21.3 The Adjacent Polygons Problem

look pretty much as they're supposed to, and all drawing on raster displays is, after all, only an approximation of an ideal.

There's one great drawback to tracing polygons with standard lines, however: Adjacent polygons won't fit together properly, as shown in Figure 21.3. If you use six equilateral triangles to make a hexagon, for example, the edges of the triangles will overlap when traced with standard lines, and more recently drawn triangles will wipe out portions of their predecessors. Worse still, odd color effects will show up along the polygon boundaries if XOR drawing is used. Consequently, filling out to the boundary lines just won't do for drawing images composed of fitted-together polygons. And because fitting polygons together is exactly what I have in mind, we need a different approach.

How Do You Fit Polygons Together?

How, then, do you fit polygons together? *Very* carefully. First, the line-tracing algorithm must be adjusted so that it selects only those pixels that are truly inside the polygon. This basically requires shifting a standard line-drawing algorithm horizontally by one half-pixel toward the polygon's interior. That leaves the issue of how to handle points that are exactly on the boundary, and points that lie at vertices, so that those points are drawn once and only once. To deal with that, we're going to adopt the following rules:

- Points located exactly on nonhorizontal edges are drawn only if the interior of the polygon is directly to the right (left edges are drawn, right edges aren't).
- Points located exactly on horizontal edges are drawn only if the interior of the polygon is directly below them (horizontal top edges are drawn, horizontal bottom edges aren't).

- A vertex is drawn only if all lines ending at that point meet the above conditions (no right or bottom edges end at that point).

All edges of a polygon except those that are flat tops or flat bottoms will be considered either right edges or left edges, regardless of slope. The left edge is the one that starts with the leftmost line down from the top of the polygon.

These rules ensure that no pixel is drawn more than once when adjacent polygons are filled, and that if polygons cover the full 360-degree range around a pixel, then that pixel will be drawn once and only once—just what we need in order to be able to fit filled polygons together seamlessly.

This sort of non-overlapping polygon filling isn't ideal for all purposes. Polygons are skewed toward the top and left edges, which not only introduces drawing error relative to the ideal polygon but also means that a filled polygon won't match the same polygon drawn unfilled. Narrow wedges and one-pixel-wide polygons will show up spottily. All in all, the choice of polygon-filling approach depends entirely on the ways in which the filled polygons must be used.

For our purposes, nonoverlapping polygons are the way to go, so let's have at them.

Filling Non-Overlapping Convex Polygons

Without further ado, Listing 21.1 contains a function, **FillConvexPolygon**, that accepts a list of points that describe a convex polygon, with the last point assumed to connect to the first, and scans it into a list of lines to fill, then passes that list to the function **DrawHorizontalLineList** in Listing 21.2. Listing 21.3 is a sample program that calls **FillConvexPolygon** to draw polygons of various sorts, and Listing 21.4 is a header file included by the other listings. Here are the listings; we'll pick up discussion on the other side.

LISTING 21.1 L21-1.C

```
/* Color-fills a convex polygon. All vertices are offset by (XOffset,
   YOffset). "Convex" means that every horizontal line drawn through
   the polygon at any point would cross exactly two active edges
   (neither horizontal lines nor zero-length edges count as active
   edges; both are acceptable anywhere in the polygon), and that the
   right & left edges never cross. (It's OK for them to touch, though,
   so long as the right edge never crosses over to the left of the
   left edge.) Nonconvex polygons won't be drawn properly. Returns 1
   for success, 0 if memory allocation failed. */

#include <stdio.h>
#include <math.h>
```

```
#ifdef __TURBOC__
#include <alloc.h>
#else    /* MSC */
#include <malloc.h>
#endif
#include "polygon.h"

/* Advances the index by one vertex forward through the vertex list,
   wrapping at the end of the list */
#define INDEX_FORWARD(Index) \
   Index = (Index + 1) % VertexList->Length;

/* Advances the index by one vertex backward through the vertex list,
   wrapping at the start of the list */
#define INDEX_BACKWARD(Index) \
   Index = (Index - 1 + VertexList->Length) % VertexList->Length;

/* Advances the index by one vertex either forward or backward through
   the vertex list, wrapping at either end of the list */
#define INDEX_MOVE(Index,Direction)                                  \
   if (Direction > 0)                                                \
      Index = (Index + 1) % VertexList->Length;                      \
   else                                                              \
      Index = (Index - 1 + VertexList->Length) % VertexList->Length;

extern void DrawHorizontalLineList(struct HLineList *, int);
static void ScanEdge(int, int, int, int, int, int, struct HLine **);

int FillConvexPolygon(struct PointListHeader * VertexList, int Color,
      int XOffset, int YOffset)
{
   int i, MinIndexL, MaxIndex, MinIndexR, SkipFirst, Temp;
   int MinPoint_Y, MaxPoint_Y, TopIsFlat, LeftEdgeDir;
   int NextIndex, CurrentIndex, PreviousIndex;
   int DeltaXN, DeltaYN, DeltaXP, DeltaYP;
   struct HLineList WorkingHLineList;
   struct HLine *EdgePointPtr;
   struct Point *VertexPtr;

   /* Point to the vertex list */
   VertexPtr = VertexList->PointPtr;

   /* Scan the list to find the top and bottom of the polygon */
   if (VertexList->Length == 0)
      return(1);  /* reject null polygons */
   MaxPoint_Y = MinPoint_Y = VertexPtr[MinIndexL = MaxIndex = 0].Y;
   for (i = 1; i < VertexList->Length; i++) {
      if (VertexPtr[i].Y < MinPoint_Y)
         MinPoint_Y = VertexPtr[MinIndexL = i].Y; /* new top */
      else if (VertexPtr[i].Y > MaxPoint_Y)
         MaxPoint_Y = VertexPtr[MaxIndex = i].Y; /* new bottom */
   }
   if (MinPoint_Y == MaxPoint_Y)
      return(1);  /* polygon is 0-height; avoid infinite loop below */

   /* Scan in ascending order to find the last top-edge point */
   MinIndexR = MinIndexL;
   while (VertexPtr[MinIndexR].Y == MinPoint_Y)
      INDEX_FORWARD(MinIndexR);
   INDEX_BACKWARD(MinIndexR); /* back up to last top-edge point */
```

```
/* Now scan in descending order to find the first top-edge point */
while (VertexPtr[MinIndexL].Y == MinPoint_Y)
   INDEX_BACKWARD(MinIndexL);
INDEX_FORWARD(MinIndexL); /* back up to first top-edge point */

/* Figure out which direction through the vertex list from the top
   vertex is the left edge and which is the right */
LeftEdgeDir = -1; /* assume left edge runs down thru vertex list */
if ((TopIsFlat = (VertexPtr[MinIndexL].X !=
      VertexPtr[MinIndexR].X) ? 1 : 0) == 1) {
   /* If the top is flat, just see which of the ends is leftmost */
   if (VertexPtr[MinIndexL].X > VertexPtr[MinIndexR].X) {
      LeftEdgeDir = 1;  /* left edge runs up through vertex list */
      Temp = MinIndexL;       /* swap the indices so MinIndexL   */
      MinIndexL = MinIndexR;  /* points to the start of the left */
      MinIndexR = Temp;       /* edge, similarly for MinIndexR   */
   }
} else {
   /* Point to the downward end of the first line of each of the
      two edges down from the top */
   NextIndex = MinIndexR;
   INDEX_FORWARD(NextIndex);
   PreviousIndex = MinIndexL;
   INDEX_BACKWARD(PreviousIndex);
   /* Calculate X and Y lengths from the top vertex to the end of
      the first line down each edge; use those to compare slopes
      and see which line is leftmost */
   DeltaXN = VertexPtr[NextIndex].X - VertexPtr[MinIndexL].X;
   DeltaYN = VertexPtr[NextIndex].Y - VertexPtr[MinIndexL].Y;
   DeltaXP = VertexPtr[PreviousIndex].X - VertexPtr[MinIndexL].X;
   DeltaYP = VertexPtr[PreviousIndex].Y - VertexPtr[MinIndexL].Y;
   if (((long)DeltaXN * DeltaYP - (long)DeltaYN * DeltaXP) < 0L) {
      LeftEdgeDir = 1;  /* left edge runs up through vertex list */
      Temp = MinIndexL;       /* swap the indices so MinIndexL   */
      MinIndexL = MinIndexR;  /* points to the start of the left */
      MinIndexR = Temp;       /* edge, similarly for MinIndexR   */
   }
}

/* Set the # of scan lines in the polygon, skipping the bottom edge
   and also skipping the top vertex if the top isn't flat because
   in that case the top vertex has a right edge component, and set
   the top scan line to draw, which is likewise the second line of
   the polygon unless the top is flat */
if ((WorkingHLineList.Length =
      MaxPoint_Y - MinPoint_Y - 1 + TopIsFlat) <= 0)
   return(1);  /* there's nothing to draw, so we're done */
WorkingHLineList.YStart = YOffset + MinPoint_Y + 1 - TopIsFlat;

/* Get memory in which to store the line list we generate */
if ((WorkingHLineList.HLinePtr =
      (struct HLine *) (malloc(sizeof(struct HLine) *
      WorkingHLineList.Length))) == NULL)
   return(0);  /* couldn't get memory for the line list */

/* Scan the left edge and store the boundary points in the list */
/* Initial pointer for storing scan converted left-edge coords */
EdgePointPtr = WorkingHLineList.HLinePtr;
/* Start from the top of the left edge */
PreviousIndex = CurrentIndex = MinIndexL;
```

```
   /* Skip the first point of the first line unless the top is flat;
      if the top isn't flat, the top vertex is exactly on a right
      edge and isn't drawn */
   SkipFirst = TopIsFlat ? 0 : 1;
   /* Scan convert each line in the left edge from top to bottom */
   do {
      INDEX_MOVE(CurrentIndex,LeftEdgeDir);
      ScanEdge(VertexPtr[PreviousIndex].X + XOffset,
            VertexPtr[PreviousIndex].Y,
            VertexPtr[CurrentIndex].X + XOffset,
            VertexPtr[CurrentIndex].Y, 1, SkipFirst, &EdgePointPtr);
      PreviousIndex = CurrentIndex;
      SkipFirst = 0; /* scan convert the first point from now on */
   } while (CurrentIndex != MaxIndex);

   /* Scan the right edge and store the boundary points in the list */
   EdgePointPtr = WorkingHLineList.HLinePtr;
   PreviousIndex = CurrentIndex = MinIndexR;
   SkipFirst = TopIsFlat ? 0 : 1;
   /* Scan convert the right edge, top to bottom. X coordinates are
      adjusted 1 to the left, effectively causing scan conversion of
      the nearest points to the left of but not exactly on the edge */
   do {
      INDEX_MOVE(CurrentIndex,-LeftEdgeDir);
      ScanEdge(VertexPtr[PreviousIndex].X + XOffset - 1,
            VertexPtr[PreviousIndex].Y,
            VertexPtr[CurrentIndex].X + XOffset - 1,
            VertexPtr[CurrentIndex].Y, 0, SkipFirst, &EdgePointPtr);
      PreviousIndex = CurrentIndex;
      SkipFirst = 0; /* scan convert the first point from now on */
   } while (CurrentIndex != MaxIndex);

   /* Draw the line list representing the scan converted polygon */
   DrawHorizontalLineList(&WorkingHLineList, Color);

   /* Release the line list's memory and we're successfully done */
   free(WorkingHLineList.HLinePtr);
   return(1);
}

/* Scan converts an edge from (X1,Y1) to (X2,Y2), not including the
   point at (X2,Y2). This avoids overlapping the end of one line with
   the start of the next, and causes the bottom scan line of the
   polygon not to be drawn. If SkipFirst != 0, the point at (X1,Y1)
   isn't drawn. For each scan line, the pixel closest to the scanned
   line without being to the left of the scanned line is chosen. */
static void ScanEdge(int X1, int Y1, int X2, int Y2, int SetXStart,
      int SkipFirst, struct HLine **EdgePointPtr)
{
   int Y, DeltaX, DeltaY;
   double InverseSlope;
   struct HLine *WorkingEdgePointPtr;

   /* Calculate X and Y lengths of the line and the inverse slope */
   DeltaX = X2 - X1;
   if ((DeltaY = Y2 - Y1) <= 0)
      return;     /* guard against 0-length and horizontal edges */
   InverseSlope = (double)DeltaX / (double)DeltaY;

   /* Store the X coordinate of the pixel closest to but not to the
      left of the line for each Y coordinate between Y1 and Y2, not
      including Y2 and also not including Y1 if SkipFirst != 0 */
   WorkingEdgePointPtr = *EdgePointPtr; /* avoid double dereference */
   for (Y = Y1 + SkipFirst; Y < Y2; Y++, WorkingEdgePointPtr++) {
      /* Store the X coordinate in the appropriate edge list */
      if (SetXStart == 1)
         WorkingEdgePointPtr->XStart =
               X1 + (int)(ceil((Y-Y1) * InverseSlope));
      else
         WorkingEdgePointPtr->XEnd =
               X1 + (int)(ceil((Y-Y1) * InverseSlope));
   }
   *EdgePointPtr = WorkingEdgePointPtr;   /* advance caller's ptr */
}
```

LISTING 21.2 L21-2.C

```
/* Draws all pixels in the list of horizontal lines passed in, in
   mode 13h, the VGA's 320x200 256-color mode. Uses a slow pixel-by-
   pixel approach, which does have the virtue of being easily ported
   to any environment. */

#include <dos.h>
#include "polygon.h"

#define SCREEN_WIDTH    320
#define SCREEN_SEGMENT  0xA000

static void DrawPixel(int, int, int);

void DrawHorizontalLineList(struct HLineList * HLineListPtr,
      int Color)
{
   struct HLine *HLinePtr;
   int Y, X;

   /* Point to the XStart/XEnd descriptor for the first (top)
      horizontal line */
   HLinePtr = HLineListPtr->HLinePtr;
   /* Draw each horizontal line in turn, starting with the top one and
      advancing one line each time */
   for (Y = HLineListPtr->YStart; Y < (HLineListPtr->YStart +
         HLineListPtr->Length); Y++, HLinePtr++) {
      /* Draw each pixel in the current horizontal line in turn,
         starting with the leftmost one */
      for (X = HLinePtr->XStart; X <= HLinePtr->XEnd; X++)
         DrawPixel(X, Y, Color);
   }
}

/* Draws the pixel at (X, Y) in color Color in VGA mode 13h */
static void DrawPixel(int X, int Y, int Color) {
   unsigned char far *ScreenPtr;

#ifdef __TURBOC__
   ScreenPtr = MK_FP(SCREEN_SEGMENT, Y * SCREEN_WIDTH + X);
#else    /* MSC 5.0 */
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) = Y * SCREEN_WIDTH + X;
#endif
   *ScreenPtr = (unsigned char)Color;
}
```

LISTING 21.3 L21-3.C

```
/* Sample program to exercise the polygon-filling routines. This code
   and all polygon-filling code has been tested with Borland and
   Microsoft compilers. */

#include <conio.h>
#include <dos.h>
#include "polygon.h"

/* Draws the polygon described by the point list PointList in color
   Color with all vertices offset by (X,Y) */
#define DRAW_POLYGON(PointList,Color,X,Y)                   \
   Polygon.Length = sizeof(PointList)/sizeof(struct Point); \
   Polygon.PointPtr = PointList;                            \
   FillConvexPolygon(&Polygon, Color, X, Y);

void main(void);
extern int FillConvexPolygon(struct PointListHeader *, int, int, int);

void main() {
   int i, j;
   struct PointListHeader Polygon;
   static struct Point ScreenRectangle[] =
         {{0,0},{320,0},{320,200},{0,200}};
   static struct Point ConvexShape[] =
         {{0,0},{121,0},{320,0},{200,51},{301,51},{250,51},{319,143},
         {320,200},{22,200},{0,200},{50,180},{20,160},{50,140},
         {20,120},{50,100},{20,80},{50,60},{20,40},{50,20}};
   static struct Point Hexagon[] =
         {{90,-50},{0,-90},{-90,-50},{-90,50},{0,90},{90,50}};
   static struct Point Triangle1[] = {{30,0},{15,20},{0,0}};
   static struct Point Triangle2[] = {{30,20},{15,0},{0,20}};
   static struct Point Triangle3[] = {{0,20},{20,10},{0,0}};
   static struct Point Triangle4[] = {{20,20},{20,0},{0,10}};
   union REGS regset;

   /* Set the display to VGA mode 13h, 320x200 256-color mode */
   regset.x.ax = 0x0013;   /* AH = 0 selects mode set function,
                              AL = 0x13 selects mode 0x13
                              when set as parameters for INT 0x10 */
   int86(0x10, &regset, &regset);

   /* Clear the screen to cyan */
   DRAW_POLYGON(ScreenRectangle, 3, 0, 0);

   /* Draw an irregular shape that meets our definition of convex but
      is not convex by any normal description */
   DRAW_POLYGON(ConvexShape, 6, 0, 0);
   getch();    /* wait for a keypress */

   /* Draw adjacent triangles across the top half of the screen */
   for (j=0; j<=80; j+=20) {
      for (i=0; i<290; i += 30) {
         DRAW_POLYGON(Triangle1, 2, i, j);
         DRAW_POLYGON(Triangle2, 4, i+15, j);
      }
   }

   /* Draw adjacent triangles across the bottom half of the screen */
   for (j=100; j<=170; j+=20) {
      /* Do a row of pointing-right triangles */
      for (i=0; i<290; i += 20) {
         DRAW_POLYGON(Triangle3, 40, i, j);
      }
      /* Do a row of pointing-left triangles halfway between one row
         of pointing-right triangles and the next, to fit between */
      for (i=0; i<290; i += 20) {
         DRAW_POLYGON(Triangle4, 1, i, j+10);
      }
   }
   getch();    /* wait for a keypress */

   /* Finally, draw a series of concentric hexagons of approximately
      the same proportions in the center of the screen */
   for (i=0; i<16; i++) {
      DRAW_POLYGON(Hexagon, i, 160, 100);
      for (j=0; j<sizeof(Hexagon)/sizeof(struct Point); j++) {
         /* Advance each vertex toward the center */
         if (Hexagon[j].X != 0) {
            Hexagon[j].X -= Hexagon[j].X >= 0 ? 3 : -3;
            Hexagon[j].Y -= Hexagon[j].Y >= 0 ? 2 : -2;
         } else {
            Hexagon[j].Y -= Hexagon[j].Y >= 0 ? 3 : -3;
         }
      }
   }
   getch();    /* wait for a keypress */

   /* Return to text mode and exit */
   regset.x.ax = 0x0003;    /* AL = 3 selects 80x25 text mode */
   int86(0x10, &regset, &regset);
}
```

LISTING 21.4 POLYGON.H

```
/* POLYGON.H: Header file for polygon-filling code */

/* Describes a single point (used for a single vertex) */
struct Point {
   int X;   /* X coordinate */
   int Y;   /* Y coordinate */
};

/* Describes a series of points (used to store a list of vertices that
   describe a polygon; each vertex is assumed to connect to the two
   adjacent vertices, and the last vertex is assumed to connect to the
   first) */
struct PointListHeader {
   int Length;                /* # of points */
   struct Point * PointPtr;   /* pointer to list of points */
};

/* Describes the beginning and ending X coordinates of a single
   horizontal line */
struct HLine {
   int XStart; /* X coordinate of leftmost pixel in line */
   int XEnd;   /* X coordinate of rightmost pixel in line */
};
```

```
/* Describes a Length-long series of horizontal lines, all assumed to
   be on contiguous scan lines starting at YStart and proceeding
   downward (used to describe a scan-converted polygon to the
   low-level hardware-dependent drawing code) */
struct HLineList {
   int Length;                /* # of horizontal lines */
   int YStart;                /* Y coordinate of topmost line */
   struct HLine * HLinePtr;   /* pointer to list of horz lines */
};
```

Listing 21.2 isn't particularly interesting; it merely draws each horizontal line in the passed-in list in the simplest possible way, one pixel at a time. (No, that doesn't make the pixel the fundamental primitive; in the next chapter I'll replace Listing 21.2 with a much faster version that doesn't bother with individual pixels at all.)

Listing 21.1 is where the action is in this chapter. Our goal is to scan out the left and right edges of each polygon so that all points inside and no points outside the polygon are drawn, and so that all points located exactly on the boundary are drawn only if they are not on right or bottom edges. That's precisely what Listing 21.1 does. Here's how:

Listing 21.1 first finds the top and bottom of the polygon, then works out from the top point to find the two ends of the top edge. If the ends are at different locations, the top is flat, which has two implications. First, it's easy to find the starting vertices and directions through the vertex list for the left and right edges. (To scan-convert them properly, we must first determine which edge is which.) Second, the top scan line of the polygon should be drawn without the rightmost pixel, because only the rightmost pixel of the horizontal edge that makes up the top scan line is part of a right edge.

If, on the other hand, the ends of the top edge are at the same location, the top is pointed. In that case, the top scan line of the polygon isn't drawn; it's part of the right-edge line that starts at the top vertex. (It's part of a left-edge line, too, but the right edge overrides.) When the top isn't flat, it's more difficult to tell in which direction through the vertex list the right and left edges go, because both edges start at the top vertex. The solution is to compare the slopes from the top vertex to the ends of the two lines coming out of it in order to see which is leftmost. The calculations in Listing 21.1 involving the various deltas do this, using a rearranged form of the slope-based equation:

```
(DeltaYN/DeltaXN)>(DeltaYP/DeltaXP)
```

Once we know where the left edge starts in the vertex list, we can scan-convert it a line segment at a time until the bottom vertex is reached. Each point is stored as the starting X coordinate for the corresponding scan line in the list we'll pass to **DrawHorizontalLineList**. The nearest X coordinate on each scan line that's on or to the right of the left edge is selected. The last point of each line segment making up the left edge isn't scan-converted, producing two desirable effects. First, it avoids drawing each vertex twice; two lines come into every vertex, but we want to scan-convert each vertex only once. Second, not scan-converting the last point of each line causes the bottom scan line of the polygon not to be drawn, as required by our rules. The first scan line of the polygon is also skipped if the top isn't flat.

Now we need to scan-convert the right edge into the ending X coordinate fields of the line list. This is performed in the same manner as for the left edge, except that every line in the right edge is moved one pixel to the left before being scan-converted. Why? We want the nearest point to the left of but not on the right edge, so that the right edge itself isn't drawn. As it happens, drawing the nearest point on or to the right of a line moved one pixel to the left is exactly the same as drawing the nearest point to the left of but not on that line in its original location. Sketch it out and you'll see what I mean.

Once the two edges are scan-converted, the whole line list is passed to **DrawHorizontalLineList**, and the polygon is drawn.

Finis.

Oddball Cases

Listing 21.1 handles zero-length segments (multiple vertices at the same location) by ignoring them, which will be useful down the road because scaled-down polygons can end up with nearby vertices moved to the same location. Horizontal line segments are fine anywhere in a polygon, too. Basically, Listing 21.1 scan-converts between active edges (the edges that define the extent of the polygon on each scan line) and both horizontal and zero-length lines are non-active; neither advances to another scan line, so they don't affect the edges being scanned.

I've limited this chapter's code to merely demonstrating the principles of filling convex polygons, and the listings given are by no means fast. In the next chapter, we'll spice things up by eliminating the floating point calculations and pixel-at-a-time drawing and tossing a little assembly language into the mix.

Fast Convex Polygons

Chapter 22

Filling Polygons in a Hurry

In the previous chapter, we explored the surprisingly intricate process of filling convex polygons. Now we're going to fill them an order of magnitude or so faster.

Two thoughts may occur to some of you at this point: "Oh, no, he's not going to get into assembly language and device-dependent code, is he?" and, "Why bother with polygon filling—or, indeed, any drawing primitives—anyway? Isn't that what GUIs and third-party libraries are for?"

To which I answer, "Well, yes, I am," and, "If you have to ask, you've missed the magic of microcomputer programming." Actually, both questions ask the same thing, and that is: "Why should I, as a programmer, have any idea how my program actually works?"

Put that way, it sounds a little different, doesn't it?

GUIs, reusable code, portable code written entirely in high-level languages, and object-oriented programming are all the rage now, and promise to remain so for the foreseeable future. The thrust of this technology is to enhance the software development process by offloading as much responsibility as possible to other programmers, and by writing all remaining code in modular, generic form. This modular code then becomes a black box to be reused endlessly without another thought about what actually lies inside. GUIs also reduce development time by making many interface choices for you. That, in turn, makes it possible to create quickly and reliably programs that will be easy for new users to pick up, so software becomes easier to both produce and learn. This is, without question, a Good Thing.

The "black box" approach does not, however, necessarily cause the software itself to become faster, smaller, or more innovative; quite the opposite, I suspect. I'll reserve judgement on whether that is a good thing or not, but I'll make a prediction: In the short run, the aforementioned techniques will lead to noticeably larger, slower programs, as programmers understand less and less of what the key parts of their programs do and rely increasingly on general-purpose code written by other people. (In the long run, programs will be bigger and slower yet, but computers will be so fast and will have so much memory that no one will care.) Over time, PC programs will also come to be more similar to one another—and to programs running on other platforms, such as the Mac—as regards both user interface and performance.

Again, I am not saying that this is bad. It does, however, have major implications for the future nature of PC graphics programming, in ways that will directly affect the means by which many of you earn your livings. Not so very long from now, graphics programming—all programming, for that matter—will become mostly a matter of assembling in various ways components written by other people, and will cease to be the all-inclusively creative, mindbendingly complex pursuit it is today. (Using legally certified black boxes is, by the way, one direction in which the patent lawyers are leading us; legal considerations may be the final nail in the coffin of homegrown code.) For now, though, it's still within your power, as a PC programmer, to understand and even control every single thing that happens on a computer if you so desire, to realize any vision you may have. Take advantage of this unique window of opportunity to create some magic!

Neither does it hurt to understand what's involved in drawing, say, a filled polygon, even if you are using a GUI. You will better understand the performance implications of the available GUI functions, and you will be able to fill in any gaps in the functions provided. You may even find that you can outperform the GUI on occasion by doing your own drawing into a system memory bitmap, then copying the result to the screen; for instance, you can do this under Windows by using the WinG library available from Microsoft. You will also be able to understand why various quirks exist, and will be able to put them to good use. For example, the X Window System follows the polygon drawing rules described in the previous chapter (although it's not obvious from the X Window System documentation); if you understood the previous chapter's discussion, you're in good shape to use polygons under X.

In short, even though doing so runs counter to current trends, it helps to understand how things work, especially when they're very visible parts of the software you develop. That said, let's learn more about filling convex polygons.

Fast Convex Polygon Filling

In addressing the topic of filling convex polygons in the previous chapter, the implementation we came up with met all of our functional requirements. In particular, it met stringent rules that guaranteed that polygons would never overlap or have gaps at shared edges, an important consideration when building polygon-based images. Unfortunately, the implementation was also slow as molasses. In this chapter we'll work up polygon-filling code that's fast enough to be truly usable.

Our original polygon filling code involved three major tasks, each performed by a separate function:

- Tracing each polygon edge to generate a coordinate list (performed by the function **ScanEdge**);
- Drawing the scanned-out horizontal lines that constitute the filled polygon (**DrawHorizontalLineList**); and
- Characterizing the polygon and coordinating the tracing and drawing (**FillConvexPolygon**).

The amount of time that the previous chapter's sample program spent in each of these areas is shown in Table 22.1. As you can see, half the time was spent drawing and the other half was spent tracing the polygon edges (the time spent in **FillConvexPolygon** was relatively minuscule), so we have our choice of where to begin optimizing.

Fast Drawing

Let's start with drawing, which is easily sped up. The previous chapter's code used a double-nested loop that called a draw-pixel function to plot each pixel in the polygon individually. That's a ridiculous approach in a graphics mode that offers linearly mapped memory, as does VGA mode 13H, the mode in which we're working. At the very least, we could point a far pointer to the left edge of each polygon scan line, then draw each pixel in that scan line in quick succession, using something along the lines of ***ScrPtr++ = FillColor;** inside a loop.

However, it seems silly to use a loop when the x86 has an instruction, **REP STOS**, that's uniquely suited to filling linear memory buffers. There's no way to use **REP STOS** directly in C code, but it's a good bet that the **memset** library function uses **REP STOS**, so you could greatly enhance performance by using **memset** to draw each scan line of the polygon in a single shot. That, however, is easier said than done. The **memset** function linked in from the library is tied to the memory model in use; in small (which includes Tiny, Small, or Medium) data models **memset** accepts only near pointers, so it can't be used to access screen memory. Consequently, a large (which includes Compact, Large, or Huge) data model must be used to allow **memset** to draw to display memory—a clear case of the tail wagging the dog. This is an excellent example of why, although it is possible to use C to do virtually anything, it's sometimes much simpler just to use a little assembly code and be done with it.

At any rate, Listing 22.1 for this chapter shows a version of **DrawHorizontalLineList** that uses memset to draw each scan line of the polygon in a single call. When linked to Chapter 21's test program, Listing 22.1 shown below increases pure drawing speed (disregarding edge tracing and other nondrawing time) by more than an order of magnitude over Chapter 21's draw-pixel-based code, despite the fact that Listing 22.1 requires a large (in this case, the Compact) data model. Listing 22.1 works fine with

Table 22.1. Polygon Fill Performance

Implementation	Total Polygon Filling Time	DrawHorizontal LineList	ScanEdge	FillConvex Polygon
Drawing to display memory in mode 13h				
C floating point scan/ DrawPixel drawing code from Chapter 21, (small model)	11.69	5.80 seconds (50% of total)	5.86 (50%)	0.03 (<1%)
C floating point scan/ memset drawing (Listing 22.1, compact model)	6.64	0.49 (7%)	6.11 (92%)	0.04 (<1%)
C integer scan/ memset drawing (Listing 22.1 & Listing 22.2, compact model)	0.60	0.49 (82%)	0.07 (12%)	0.04 (7%)
C integer scan/ ASM drawing (Listing 22.2 & Listing 22.3, small model)	0.45	0.36 (80%)	0.06 (13%)	0.03 (7%)
ASM integer scan/ ASM drawing (Listing 23.3 & Listing 23.4, small model)	0.42	0.36 (86%)	0.03 (7%)	0.03 (7%)
Drawing to system memory				
C integer scan/ memset drawing (Listing 22.1 & Listing 22.2, compact model)	0.31	0.20 (65%)	0.07 (23%)	0.04 (13%)
ASM integer scan/ ASM drawing (Li sting 22.3 & Listing 22.4, small model)	0.13	0.07 (54%)	0.03 (23%)	0.03 (23%)

All times are in seconds, as measured with Turbo Profiler on a 20-MHz cached 386 with no math coprocessor installed. Note that time spent in **main()** is not included. C code was compiled with Borland C++ with maximum optimization (-G -O -Z -r -a); assembly language code was assembled with TASM. Percentages of combined times are rounded to the nearest percent, so the sum of the three percentages does not always equal 100.

Borland C++, but may not work with other compilers, for it relies on the aforementioned interaction between **memset** and the selected memory model.

LISTING 22.1 L22-1.C

```
/* Draws all pixels in the list of horizontal lines passed in, in
   mode 13h, the VGA's 320x200 256-color mode. Uses memset to fill
   each line, which is much faster than using DrawPixel but requires
   that a large data model (compact, large, or huge) be in use when
   running in real mode or 286 protected mode.
   All C code tested with Borland C++. */

#include <string.h>
#include <dos.h>
#include "polygon.h"

#define SCREEN_WIDTH    320
#define SCREEN_SEGMENT  0xA000

void DrawHorizontalLineList(struct HLineList * HLineListPtr,
      int Color)
{
   struct HLine *HLinePtr;
   int Length, Width;
   unsigned char far *ScreenPtr;

   /* Point to the start of the first scan line on which to draw */
   ScreenPtr = MK_FP(SCREEN_SEGMENT,
         HLineListPtr->YStart * SCREEN_WIDTH);

   /* Point to the XStart/XEnd descriptor for the first (top)
      horizontal line */
   HLinePtr = HLineListPtr->HLinePtr;
   /* Draw each horizontal line in turn, starting with the top one and
      advancing one line each time */
   Length = HLineListPtr->Length;
   while (Length-- > 0) {
      /* Draw the whole horizontal line if it has a positive width */
      if ((Width = HLinePtr->XEnd - HLinePtr->XStart + 1) > 0)
         memset(ScreenPtr + HLinePtr->XStart, Color, Width);
      HLinePtr++;                 /* point to next scan line X info */
      ScreenPtr += SCREEN_WIDTH; /* point to next scan line start */
   }
}
```

At this point, I'd like to mention that benchmarks are notoriously unreliable; the results in Table 22.1 are accurate *only* for the test program, and only when running on a particular system. Results could be vastly different if smaller, larger, or more complex polygons were drawn, or if a faster or slower computer/VGA combination were used. These factors notwithstanding, the test program does fill a variety of polygons of varying complexity sized from large to small and in between, and certainly the order of magnitude difference between Listing 22.1 and the old version of **DrawHorizontalLineList** is a clear indication of which code is superior.

Anyway, Listing 22.1 has the desired effect of vastly improving drawing time. There are cycles yet to be had in the drawing code, but as tracing polygon edges now takes 92 percent of the polygon filling time, it's logical to optimize the tracing code next.

Fast Edge Tracing

There's no secret as to why last chapter's **ScanEdge** was so slow: It used floating point calculations. One secret of fast graphics is using integer or fixed-point calculations, instead. (Sure, the floating point code would run faster if a math coprocessor were installed, but it would still be slower than the alternatives; besides, why require a math coprocessor when you don't have to?) Both integer and fixed-point calculations are fast. In many cases, fixed-point is faster, but integer calculations have one tremendous virtue: They're completely accurate. The tiny imprecision inherent in either fixed or floating-point calculations can result in occasional pixels being one position off from their proper location. This is no great tragedy, but after going to so much trouble to ensure that polygons don't overlap at common edges, why not get it exactly right?

In fact, when I tested out the integer edge tracing code by comparing an integer-based test image to one produced by floating-point calculations, two pixels out of the whole screen differed, leading me to suspect a bug in the integer code. It turned out, however, that's in those two cases, the floating point results were sufficiently imprecise to creep from just under an integer value to just over it, so that the **ceil** function returned a coordinate that was one too large.

Floating point is very accurate—but it is not precise. Integer calculations, properly performed, are.

Listing 22.2 shows a C implementation of integer edge tracing. Vertical and diagonal lines, which are trivial to trace, are special-cased. Other lines are broken into two categories: Y-major (closer to vertical) and X-major (closer to horizontal). The handlers for the Y-major and X-major cases operate on the principle of similar triangles: The number of X pixels advanced per scan line is the same as the ratio of the X delta of the edge to the Y delta. Listing 22.2 is more complex than the original floating point implementation, but not painfully so. In return for that complexity, Listing 22.2 is more than 80 times faster at scanning edges—and, as just mentioned, it's actually more accurate than the floating point code.

Ya gotta love that integer arithmetic.

LISTING 22.2 L22-2.C

```
/* Scan converts an edge from (X1,Y1) to (X2,Y2), not including the
   point at (X2,Y2). If SkipFirst == 1, the point at (X1,Y1) isn't
   drawn; if SkipFirst == 0, it is. For each scan line, the pixel
   closest to the scanned edge without being to the left of the
   scanned edge is chosen. Uses an all-integer approach for speed and
   precision. */

#include <math.h>
#include "polygon.h"

void ScanEdge(int X1, int Y1, int X2, int Y2, int SetXStart,
      int SkipFirst, struct HLine **EdgePointPtr)
{
   int Y, DeltaX, Height, Width, AdvanceAmt, ErrorTerm, i;
   int ErrorTermAdvance, XMajorAdvanceAmt;
   struct HLine *WorkingEdgePointPtr;

   WorkingEdgePointPtr = *EdgePointPtr; /* avoid double dereference */
   AdvanceAmt = ((DeltaX = X2 - X1) > 0) ? 1 : -1;
                            /* direction in which X moves (Y2 is
                               always > Y1, so Y always counts up) */

   if ((Height = Y2 - Y1) <= 0)  /* Y length of the edge */
      return;     /* guard against 0-length and horizontal edges */

   /* Figure out whether the edge is vertical, diagonal, X-major
      (mostly horizontal), or Y-major (mostly vertical) and handle
      appropriately */
   if ((Width = abs(DeltaX)) == 0) {
      /* The edge is vertical; special-case by just storing the same
         X coordinate for every scan line */
      /* Scan the edge for each scan line in turn */
      for (i = Height - SkipFirst; i-- > 0; WorkingEdgePointPtr++) {
         /* Store the X coordinate in the appropriate edge list */
         if (SetXStart == 1)
            WorkingEdgePointPtr->XStart = X1;
         else
            WorkingEdgePointPtr->XEnd = X1;
      }
   } else if (Width == Height) {
      /* The edge is diagonal; special-case by advancing the X
         coordinate 1 pixel for each scan line */
      if (SkipFirst) /* skip the first point if so indicated */
         X1 += AdvanceAmt; /* move 1 pixel to the left or right */
      /* Scan the edge for each scan line in turn */
      for (i = Height - SkipFirst; i-- > 0; WorkingEdgePointPtr++) {
         /* Store the X coordinate in the appropriate edge list */
         if (SetXStart == 1)
            WorkingEdgePointPtr->XStart = X1;
         else
            WorkingEdgePointPtr->XEnd = X1;
         X1 += AdvanceAmt; /* move 1 pixel to the left or right */
      }
   } else if (Height > Width) {
      /* Edge is closer to vertical than horizontal (Y-major) */
      if (DeltaX >= 0)
         ErrorTerm = 0; /* initial error term going left->right */
      else
         ErrorTerm = -Height + 1;   /* going right->left */
      if (SkipFirst) {   /* skip the first point if so indicated */
         /* Determine whether it's time for the X coord to advance */
         if ((ErrorTerm += Width) > 0) {
            X1 += AdvanceAmt; /* move 1 pixel to the left or right */
            ErrorTerm -= Height; /* advance ErrorTerm to next point */
         }
      }
      /* Scan the edge for each scan line in turn */
      for (i = Height - SkipFirst; i-- > 0; WorkingEdgePointPtr++) {
         /* Store the X coordinate in the appropriate edge list */
         if (SetXStart == 1)
            WorkingEdgePointPtr->XStart = X1;
         else
            WorkingEdgePointPtr->XEnd = X1;
         /* Determine whether it's time for the X coord to advance */
         if ((ErrorTerm += Width) > 0) {
            X1 += AdvanceAmt; /* move 1 pixel to the left or right */
            ErrorTerm -= Height; /* advance ErrorTerm to correspond */
         }
      }
   } else {
      /* Edge is closer to horizontal than vertical (X-major) */
      /* Minimum distance to advance X each time */
      XMajorAdvanceAmt = (Width / Height) * AdvanceAmt;
      /* Error term advance for deciding when to advance X 1 extra */
      ErrorTermAdvance = Width % Height;
      if (DeltaX >= 0)
         ErrorTerm = 0; /* initial error term going left->right */
      else
         ErrorTerm = -Height + 1;   /* going right->left */
      if (SkipFirst) {   /* skip the first point if so indicated */
         X1 += XMajorAdvanceAmt;    /* move X minimum distance */
         /* Determine whether it's time for X to advance one extra */
         if ((ErrorTerm += ErrorTermAdvance) > 0) {
            X1 += AdvanceAmt;       /* move X one more */
            ErrorTerm -= Height; /* advance ErrorTerm to correspond */
         }
      }
      /* Scan the edge for each scan line in turn */
      for (i = Height - SkipFirst; i-- > 0; WorkingEdgePointPtr++) {
         /* Store the X coordinate in the appropriate edge list */
         if (SetXStart == 1)
            WorkingEdgePointPtr->XStart = X1;
         else
            WorkingEdgePointPtr->XEnd = X1;
         X1 += XMajorAdvanceAmt;    /* move X minimum distance */
         /* Determine whether it's time for X to advance one extra */
         if ((ErrorTerm += ErrorTermAdvance) > 0) {
            X1 += AdvanceAmt;       /* move X one more */
            ErrorTerm -= Height; /* advance ErrorTerm to correspond */
         }
      }
   }

   *EdgePointPtr = WorkingEdgePointPtr;   /* advance caller's ptr */
}
```

The Finishing Touch: Assembly Language

The C implementation in Listing 22.2 is now nearly 20 times as fast as the original, which is good enough for most purposes. Still, it requires that one of the large data models be used (for **memset**), and it's certainly not the fastest possible code. The obvious next step is assembly language.

Listing 22.3 is an assembly language version of **DrawHorizontalLineList**. In actual use, it proved to be about 36 percent faster than Listing 22.1; better than a poke in the eye with a sharp stick, but just barely. There's more to these timing results than meets that eye, though. Display memory generally responds much more slowly than system memory, especially in 386 and 486 systems. That means that much of the time taken by Listing 22.3 is actually spent waiting for display memory accesses to complete, with the processor forced to idle by wait states. If, instead, Listing 22.3 drew to a local buffer in system memory or to a particularly fast VGA, the assembly implementation might well display a far more substantial advantage over the C code.

And indeed it does. When the test program is modified to draw to a local buffer, both the C and assembly language versions get 0.29 seconds faster, that being a measure of the time taken by display memory wait states. With those wait states factored out, the assembly language version of **DrawHorizontalLineList** becomes almost three times as fast as the C code.

There is a lesson here. An optimization has no fixed payoff; its value fluctuates according to the context in which it is used. There's relatively little benefit to further optimizing code that already spends half its time waiting for display memory; no matter how good your optimizations, you'll get only a two-times speedup at best, and generally much less than that. There is, on the other hand, potential for tremendous improvement when drawing to system memory, so if that's where most of your drawing will occur, optimizations such as Listing 22.3 are well worth the effort.

Know the environments in which your code will run, and know where the cycles go in those environments.

LISTING 22.3 L22-3.ASM

```
; Draws all pixels in the list of horizontal lines passed in, in
; mode 13h, the VGA's 320x200 256-color mode. Uses REP STOS to fill
; each line.
; C near-callable as:
;     void DrawHorizontalLineList(struct HLineList * HLineListPtr,
;          int Color);
; All assembly code tested with TASM and MASM
```

```
SCREEN_WIDTH     equ   320
SCREEN_SEGMENT   equ   0a000h

HLine struc
XStart           dw    ?           ;X coordinate of leftmost pixel in line
XEnd             dw    ?           ;X coordinate of rightmost pixel in line
HLine            ends

HLineList struc
Lngth            dw    ?           ;# of horizontal lines
YStart           dw    ?           ;Y coordinate of topmost line
HLinePtr         dw    ?           ;pointer to list of horz lines
HLineList        ends

Parms struc
                 dw    2 dup(?)    ;return address & pushed BP
HLineListPtr     dw    ?           ;pointer to HLineList structure
Color            dw    ?           ;color with which to fill
Parms            ends

        .model small
        .code
        public _DrawHorizontalLineList
        align   2
_DrawHorizontalLineList   proc
        push    bp                      ;preserve caller's stack frame
        mov     bp,sp                   ;point to our stack frame
        push    si                      ;preserve caller's register variables
        push    di
        cld                             ;make string instructions inc pointers

        mov     ax,SCREEN_SEGMENT
        mov     es,ax                   ;point ES to display memory for REP STOS

        mov     si,[bp+HLineListPtr]          ;point to the line list
        mov     ax,SCREEN_WIDTH         ;point to the start of the first scan
        mul     [si+YStart]             ; line in which to draw
        mov     dx,ax                   ;ES:DX points to first scan line to
                                        ; draw
        mov     bx,[si+HLinePtr]        ;point to the XStart/XEnd descriptor
                                        ; for the first (top) horizontal line
        mov     si,[si+Lngth]           ;# of scan lines to draw
        and     si,si                   ;are there any lines to draw?
        jz      FillDone                ;no, so we're done
        mov     al,byte ptr [bp+Color]        ;color with which to fill
        mov     ah,al                   ;duplicate color for STOSW
FillLoop:
        mov     di,[bx+XStart]          ;left edge of fill on this line
        mov     cx,[bx+XEnd]            ;right edge of fill
        sub     cx,di
        js      LineFillDone            ;skip if negative width
        inc     cx                      ;width of fill on this line
        add     di,dx                   ;offset of left edge of fill
        test    di,1                    ;does fill start at an odd address?
        jz      MainFill                ;no
        stosb                           ;yes, draw the odd leading byte to
                                        ; word-align the rest of the fill
        dec     cx                      ;count off the odd leading byte
        jz      LineFillDone            ;done if that was the only byte
MainFill:
        shr     cx,1                    ;# of words in fill
        rep     stosw                   ;fill as many words as possible
        adc     cx,cx                   ;1 if there's an odd trailing byte to
                                        ; do, 0 otherwise
        rep     stosb                   ;fill any odd trailing byte
LineFillDone:
        add     bx,size HLine           ;point to the next line descriptor
        add     dx,SCREEN_WIDTH         ;point to the next scan line
        dec     si                      ;count off lines to fill
        jnz     FillLoop
FillDone:
        pop     di                      ;restore caller's register variables
        pop     si
        pop     bp                      ;restore caller's stack frame
        ret
_DrawHorizontalLineList   endp
        end
```

Maximizing REP STOS

Listing 22.3 doesn't take the easy way out and use **REP STOSB** to fill each scan line; instead, it uses **REP STOSW** to fill as many pixel pairs as possible via word-sized accesses, using **STOSB** only to do odd bytes. Word accesses to odd addresses are always split by the processor into 2-byte accesses. Such word accesses take twice as long as word accesses to even addresses, so Listing 22.3 makes sure that all word accesses occur at even addresses, by performing a leading **STOSB** first if necessary.

Listing 22.3 is another case in which it's worth knowing the environment in which your code will run. Extra code is required to perform aligned word-at-a-time filling, resulting in extra overhead. For very small or narrow polygons, that overhead might overwhelm the advantage of drawing a word at a time, making plain old **REP STOSB** faster.

Faster Edge Tracing

Finally, Listing 22.4 is an assembly language version of **ScanEdge**. Listing 22.4 is a relatively straightforward translation from C to assembly, but is nonetheless about twice as fast as Listing 22.2.

The version of **ScanEdge** in Listing 22.4 could certainly be sped up still further by unrolling the loops. **FillConvexPolygon**, the overall coordination routine, hasn't even been converted to assembly language, so that could be sped up as well. I haven't bothered with these optimizations because all code other than **DrawHorizontalLineList** takes only 14 percent of the overall polygon filling time when drawing to display memory; the potential return on optimizing nondrawing code simply isn't great enough to justify the effort. Part of the value of a profiler is being able to tell when to stop optimizing; with Listings 22.3 and 22.4 in use, more than two-thirds of the time taken to draw polygons is spent waiting for display memory, so optimization is pretty much maxed out. However, further optimization might be worthwhile when drawing to system memory, where wait states are out of the picture and the nondrawing code takes a significant portion (46 percent) of the overall time.

Again, *know where the cycles go.*

By the way, note that all the versions of **ScanEdge** and **FillConvexPolygon** that we've looked at are adapter-independent, and that the C code is also machine-independent; all adapter-specific code is isolated in **DrawHorizontalLineList**. This makes it easy to add support for other graphics systems, such as the 8514/A, the XGA, or, for that matter, a completely non-PC system.

LISTING 22.4 L22-4.ASM

```
; Scan converts an edge from (X1,Y1) to (X2,Y2), not including the
; point at (X2,Y2). If SkipFirst == 1, the point at (X1,Y1) isn't
; drawn; if SkipFirst == 0, it is. For each scan line, the pixel
; closest to the scanned edge without being to the left of the scanned
; edge is chosen. Uses an all-integer approach for speed & precision.
; C near-callable as:
;    void ScanEdge(int X1, int Y1, int X2, int Y2, int SetXStart,
;     int SkipFirst, struct HLine **EdgePointPtr);
; Edges must not go bottom to top; that is, Y1 must be <= Y2.
; Updates the pointer pointed to by EdgePointPtr to point to the next
;  free entry in the array of HLine structures.

HLine   struc
XStart           dw    ?          ;X coordinate of leftmost pixel in scan line
XEnd             dw    ?          ;X coordinate of rightmost pixel in scan line
HLine   ends

Parms   struc
                 dw    2 dup(?)   ;return address & pushed BP
X1               dw    ?          ;X start coord of edge
Y1               dw    ?          ;Y start coord of edge
X2               dw    ?          ;X end coord of edge
Y2               dw    ?          ;Y end coord of edge
SetXStart        dw    ?          ;1 to set the XStart field of each
                                  ; HLine struc, 0 to set XEnd
SkipFirst        dw    ?          ;1 to skip scanning the first point
                                  ; of the edge, 0 to scan first point
EdgePointPtr     dw    ?          ;pointer to a pointer to the array of
                                  ; HLine structures in which to store
                                  ; the scanned X coordinates
Parms   ends

;Offsets from BP in stack frame of local variables.
AdvanceAmt      equ     -2
Height          equ     -4
LOCAL_SIZE      equ      4        ;total size of local variables

        .model small
        .code
        public _ScanEdge
        align  2
_ScanEdge        proc
        push     bp                 ;preserve caller's stack frame
        mov      bp,sp              ;point to our stack frame
        sub      sp,LOCAL_SIZE      ;allocate space for local variables
        push     si                 ;preserve caller's register variables
        push     di
        mov     di,[bp+EdgePointPtr]
        mov     di,[di]            ;point to the HLine array
        cmp     [bp+SetXStart],1   ;set the XStart field of each HLine
                                   ; struc?
        jz      HLinePtrSet        ;yes, DI points to the first XStart
        add     di,XEnd            ;no, point to the XEnd field of the
                                   ; first HLine struc
HLinePtrSet:
        mov     bx,[bp+Y2]
        sub     bx,[bp+Y1]         ;edge height
        jle     ToScanEdgeExit     ;guard against 0-length & horz edges
        mov     [bp+Height],bx     ;Height = Y2 - Y1
        sub     cx,cx              ;assume ErrorTerm starts at 0 (true if
                                   ; we're moving right as we draw)
        mov     dx,1               ;assume AdvanceAmt = 1 (move right)
        mov     ax,[bp+X2]
        sub     ax,[bp+X1]         ;DeltaX = X2 - X1
        jz      IsVertical         ;it's a vertical edge--special case it
        jns     SetAdvanceAmt      ;DeltaX >= 0
        mov     cx,1               ;DeltaX < 0 (move left as we draw)
        sub     cx,bx              ;ErrorTerm = -Height + 1
        neg     dx                 ;AdvanceAmt = -1 (move left)
        neg     ax                 ;Width = abs(DeltaX)
SetAdvanceAmt:
        mov     [bp+AdvanceAmt],dx
; Figure out whether the edge is diagonal, X-major (more horizontal),
; or Y-major (more vertical) and handle appropriately.
        cmp     ax,bx              ;if Width==Height, it's a diagonal edge
        jz      IsDiagonal         ;it's a diagonal edge--special case
        jb      YMajor             ;it's a Y-major (more vertical) edge
                                   ;it's an X-major (more horz) edge
        sub     dx,dx              ;prepare DX:AX (Width) for division
        div     bx                 ;Width/Height
                                   ;DX = error term advance per scan line
        mov     si,ax              ;SI = minimum # of pixels to advance X
                                   ; on each scan line
        test    [bp+AdvanceAmt],8000h ;move left or right?
        jz      XMajorAdvanceAmtSet ;right, already set
        neg     si                 ;left, negate the distance to advance
                                   ; on each scan line
XMajorAdvanceAmtSet:   ;
        mov     ax,[bp+X1]         ;starting X coordinate
                cmp   [bp+SkipFirst],1      ;skip the first point?
        jz      XMajorSkipEntry    ;yes
XMajorLoop:
        mov     [di],ax            ;store the current X value
        add     di,size HLine      ;point to the next HLine struc
XMajorSkipEntry:
        add     ax,si              ;set X for the next scan line
        add     cx,dx              ;advance error term
        jle     XMajorNoAdvance    ;not time for X coord to advance one
                                   ; extra
        add     ax,[bp+AdvanceAmt] ;advance X coord one extra
        sub     cx,[bp+Height]     ;adjust error term back
XMajorNoAdvance:
        dec     bx                 ;count off this scan line
        jnz     XMajorLoop
        jmp     ScanEdgeDone
        align   2
ToScanEdgeExit:
        jmp     ScanEdgeExit
        align   2
IsVertical:
        mov     ax,[bp+X1]          ;starting (and only) X coordinate
        sub     bx,[bp+SkipFirst]   ;loop count = Height - SkipFirst
        jz      ScanEdgeExit        ;no scan lines left after skipping 1st
VerticalLoop:
        mov     [di],ax             ;store the current X value
        add     di,size HLine       ;point to the next HLine struc
        dec     bx                  ;count off this scan line
        jnz     VerticalLoop
        jmp     ScanEdgeDone
        align   2
IsDiagonal:
        mov     ax,[bp+X1]          ;starting X coordinate
        cmp     [bp+SkipFirst],1    ;skip the first point?
        jz      DiagonalSkipEntry   ;yes
DiagonalLoop:
        mov     [di],ax             ;store the current X value
        add     di,size HLine       ;point to the next HLine struc
DiagonalSkipEntry:
        add     ax,dx               ;advance the X coordinate
        dec     bx                  ;count off this scan line
        jnz     DiagonalLoop
        jmp     ScanEdgeDone
        align   2
YMajor:
        push    bp                  ;preserve stack frame pointer
        mov     si,[bp+X1]          ;starting X coordinate
        cmp     [bp+SkipFirst],1    ;skip the first point?
        mov     bp,bx               ;put Height in BP for error term calcs
        jz      YMajorSkipEntry     ;yes, skip the first point
YMajorLoop:
        mov     [di],si             ;store the current X value
        add     di,size HLine       ;point to the next HLine struc
YMajorSkipEntry:
        add     cx,ax               ;advance the error term
        jle     YMajorNoAdvance     ;not time for X coord to advance
        add     si,dx               ;advance the X coordinate
        sub     cx,bp               ;adjust error term back
YMajorNoAdvance:
        dec     bx                  ;count off this scan line
        jnz     YMajorLoop
        pop     bp                  ;restore stack frame pointer
ScanEdgeDone:
        cmp     [bp+SetXStart],1    ;were we working with XStart field?
        jz      UpdateHLinePtr      ;yes, DI points to the next XStart
        sub     di,XEnd             ;no, point back to the XStart field
UpdateHLinePtr:
        mov     bx,[bp+EdgePointPtr]  ;point to pointer to HLine array
        mov     [bx],di             ;update caller's HLine array pointer
ScanEdgeExit:
        pop     di                  ;restore caller's register variables
        pop     si
        mov     sp,bp               ;deallocate local variables
        pop     bp                  ;restore caller's stack frame
        ret
_ScanEdge       endp
        end
```

Of Songs, Taxes, and the Simplicity of Complex Polygons

Chapter 23

Dealing with Irregular Polygonal Areas

Every so often, my daughter asks me to sing her to sleep. (If you've ever heard me sing, this may cause you concern about either her hearing or her judgement, but love knows no bounds.) As any parent is well aware, singing a young child to sleep can easily take several hours, or until sunrise, whichever comes last. One night, running low on children's songs, I switched to a Beatles medley, and at long last her breathing became slow and regular. At the end, I softly sang "A Hard Day's Night," then quietly stood up to leave. As I tiptoed out, she said, in a voice not even faintly tinged with sleep, "Dad, what do they mean, 'working like a dog'? Chasing a stick? That doesn't make sense; people don't chase sticks."

That led us into a discussion of idioms, which made about as much sense to her as an explanation of quantum mechanics. Finally, I fell back on my standard explanation of the Universe, which is that a lot of the time it simply doesn't make sense.

As a general principle, that explanation holds up remarkably well. (In fact, having just done my taxes, I think Earth is actually run by blob-creatures from the planet Mrxx, who are helplessly doubled over with laughter at the ridiculous things they can make us do. "Let's make them get Social Security numbers for their pets next year!" they're saying right now, gasping for breath.) Occasionally, however, one has the rare pleasure of finding a corner of the Universe that makes sense, where everything fits together as if preordained.

Filling arbitrary polygons is such a case.

Filling Arbitrary Polygons

In Chapter 21, I described three types of polygons: convex, nonconvex, and complex. *The RenderMan Companion,* a terrific book by Steve Upstill (Addison-Wesley, 1990) has an intuitive definition of *convex*: If a rubber band stretched around a polygon touches all vertices in the order they're defined, then the polygon is convex. If a polygon has intersecting edges, it's complex. If a polygon doesn't have intersecting edges but isn't convex, it's nonconvex. Nonconvex is a special case of complex, and convex is a special case of nonconvex. (Which, I'm well aware, makes nonconvex a lousy name—noncomplex would have been better—but I'm following X Window System nomenclature here.)

The reason for distinguishing between these three types of polygons is that the more specialized types can be filled with markedly faster approaches. Complex polygons require the slowest approach; however, that approach will serve to fill any polygon of any sort. Nonconvex polygons require less sorting, because edges never cross. Convex polygons can be filled fastest of all by simply scanning the two sides of the polygon, as we saw in Chapter 22.

Before we dive into complex polygon filling, I'd like to point out that the code in this chapter, like all polygon filling code I've ever seen, requires that the caller describe the type of the polygon to be filled. Often, however, the caller doesn't know what type of polygon it's passing, or specifies complex for simplicity, because that will work for all polygons; in such a case, the polygon filler will use the slow complex-fill code even if the polygon is, in fact, a convex polygon. In Chapter 24, I'll discuss one way to improve this situation.

Active Edges

The basic premise of filling a complex polygon is that for a given scan line, we determine all intersections between the polygon's edges and that scan line and then fill the spans between the intersections, as shown in Figure 23.1. (Section 3.6 of Foley and van Dam's *Computer Graphics,* Second Edition provides an overview of this and other aspects of polygon filling.) There are several rules that might be used to determine which spans are drawn and which aren't; we'll use the odd/even rule, which specifies that drawing turns on after odd-numbered intersections (first, third, and so on) and off after even-numbered intersections.

The question then becomes how can we most efficiently determine which edges cross each scan line and where? As it happens, there is a great deal of coherence from one scan line to the next in a polygon edge list, because each edge starts at a given Y coordinate and continues unbroken until it ends. In other words, edges don't leap about and stop and start randomly; the X coordinate of an edge at one scan line is a consistent delta from that edge's X coordinate at the last scan line, and that is consistent for the length of the line.

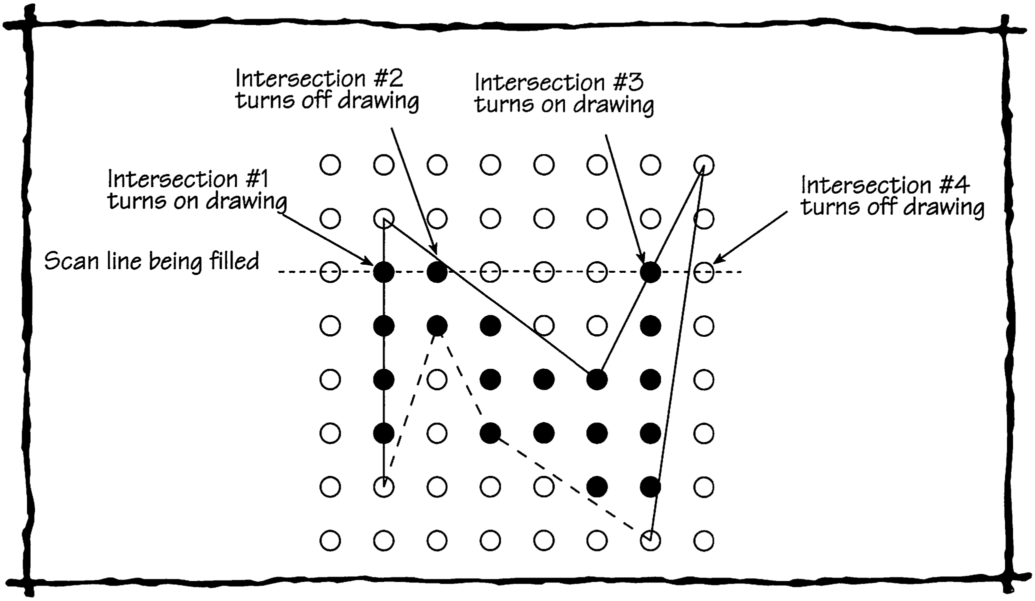


Figure 23.1 Filling One Scan Line by Finding Intersecting Edges

This allows us to reduce the number of edges that must be checked for intersection; on any given scan line, we only need to check for intersections with the currently active edges—edges that start on that scan line, plus all edges that start on earlier (above) scan lines and haven't ended yet—as shown in Figure 23.2. This suggests that we can proceed from the top scan line of the polygon to the bottom, keeping a running list of currently active edges—called the *active edge table* (AET)—with the edges sorted in

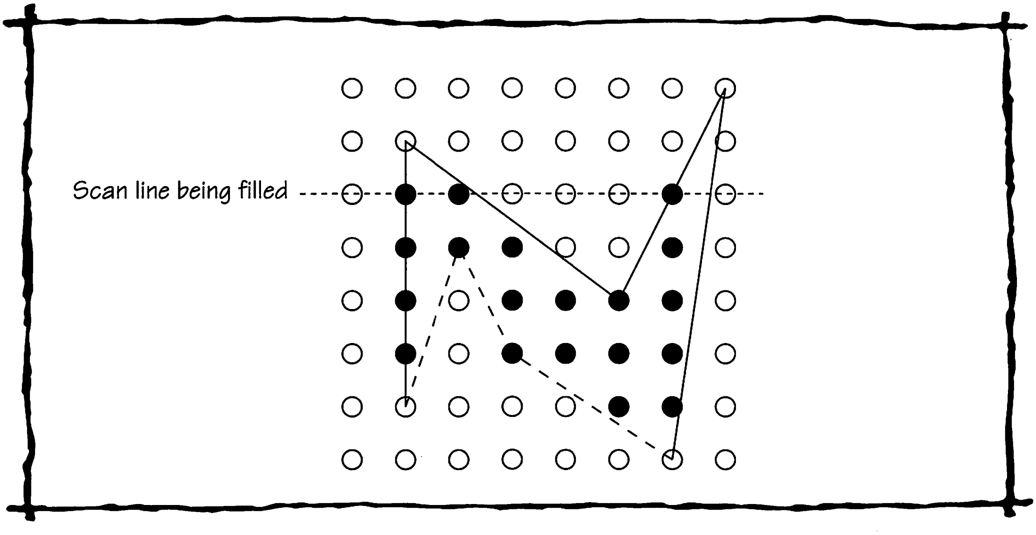


Figure 23.2 Checking Currently Active Edges (Solid Lines)

order of ascending X coordinate of intersection with the current scan line. Then, we can simply fill each scan line in turn according to the list of active edges at that line.

Maintaining the AET from one scan line to the next involves three steps: First, we must add to the AET any edges that start on the current scan line, making sure to keep the AET X-sorted for efficient odd/even scanning. Second, we must remove edges that end on the current scan line. Third, we must advance the X coordinates of active edges with the same sort of error term-based, Bresenham's-like approach we used for convex polygons, again ensuring that the AET is X-sorted after advancing the edges.

Advancing the X coordinates is easy. For each edge, we'll store the current X coordinate and all required error term information, and we'll use that to advance the edge one scan line at a time; then, we'll resort the AET by X coordinate as needed. Removing edges as they end is also easy; we'll just count down the length of each active edge on each scan line and remove an edge when its count reaches zero. Adding edges as their tops are encountered is a tad more complex. While there are a number of ways to do this, one particularly efficient approach is to start out by putting all the edges of the polygon, sorted by increasing Y coordinate, into a single list, called the *global edge table* (GET). Then, as each scan line is encountered, all edges at the start of the GET that begin on the current scan line are moved to the AET; because the GET is Y-sorted, there's no need to search the entire GET. For still greater efficiency, edges in the GET that share common Y coordinates can be sorted by increasing X coordinate; this ensures that no more than one pass through the AET per scan line is ever needed when adding new edges from the GET in such a way as to keep the AET sorted in ascending X order.

What form should the GET and AET take? Linked lists of edge structures, as shown in Figure 23.3. With linked lists, all that's required to move edges from the GET to the

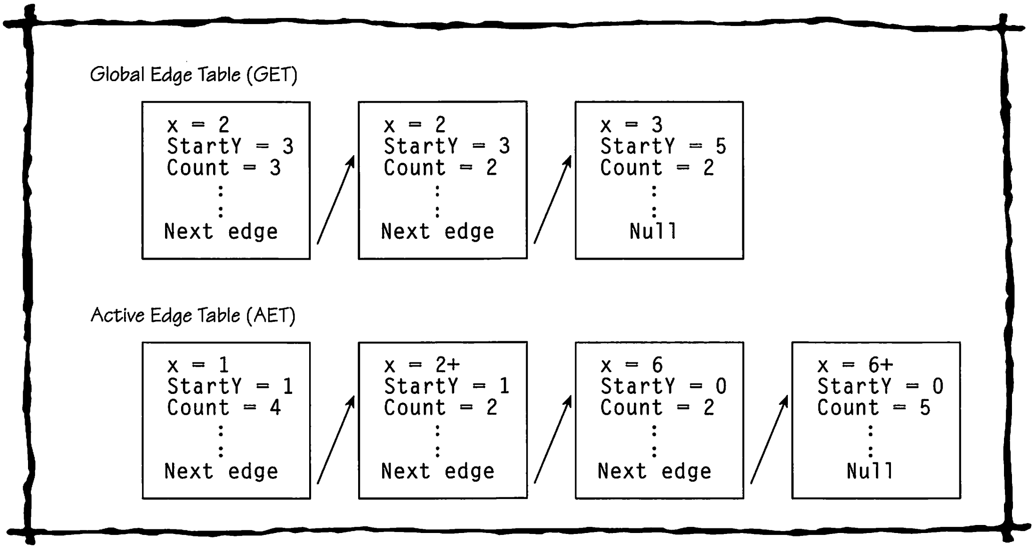


Figure 23.3 The Global and Active Edge Tables as Linked Lists

AET as they become active, sort the AET, and remove edges that have been fully drawn is the exchanging of a few pointers.

In summary, we'll initially store all the polygon edges in Y-primary/X-secondary sort order in the GET, complete with initial X and Y coordinates, error terms and error term adjustments, lengths, and directions of X movement for each edge. Once the GET is built, we'll do the following:

1. Set the current Y coordinate to the Y coordinate of the first edge in the GET.
2. Move all edges with the current Y coordinate from the GET to the AET, removing them from the GET and maintaining the X-sorted order of the AET.
3. Draw all odd-to-even spans in the AET at the current Y coordinate.
4. Count down the lengths of all edges in the AET, removing any edges that are done, and advancing the X coordinates of all remaining edges in the AET by one scan line.
5. Sort the AET in order of ascending X coordinate.
6. Advance the current Y coordinate by one scan line.
7. If either the AET or GET isn't empty, go to step 2.

That's really all there is to it. Compare Listing 23.1 below to the fast convex polygon filling code from Chapter 22, and you'll see that, contrary to expectation, complex polygon filling is indeed one of the more sane and sensible corners of the universe.

LISTING 23.1 L23-1.C

```
/* Color-fills an arbitrarily-shaped polygon described by VertexList.
   If the first and last points in VertexList are not the same, the path
   around the polygon is automatically closed. All vertices are offset
   by (XOffset, YOffset). Returns 1 for success, 0 if memory allocation
   failed. All C code tested with Borland C++.
   If the polygon shape is known in advance, speedier processing may be
   enabled by specifying the shape as follows: "convex" - a rubber band
   stretched around the polygon would touch every vertex in order;
   "nonconvex" - the polygon is not self-intersecting, but need not be
   convex; "complex" - the polygon may be self-intersecting, or, indeed,
   any sort of polygon at all. Complex will work for all polygons; convex
   is fastest. Undefined results will occur if convex is specified for a
   nonconvex or complex polygon.
   Define CONVEX_CODE_LINKED if the fast convex polygon filling code from
   Chapter 21 is linked in. Otherwise, convex polygons are
   handled by the complex polygon filling code.
   Nonconvex is handled as complex in this implementation. See text for a
   discussion of faster nonconvex handling. */

#include <stdio.h>
#include <math.h>
#ifdef __TURBOC__
#include <alloc.h>
#else   /* MSC */
#include <malloc.h>
#endif
#include "polygon.h"
```

```
#define SWAP(a,b) {temp = a; a = b; b = temp;}

struct EdgeState {
   struct EdgeState *NextEdge;
   int X;
   int StartY;
   int WholePixelXMove;
   int XDirection;
   int ErrorTerm;
   int ErrorTermAdjUp;
   int ErrorTermAdjDown;
   int Count;
};

extern void DrawHorizontalLineSeg(int, int, int, int);
extern int FillConvexPolygon(struct PointListHeader *, int, int, int);
static void BuildGET(struct PointListHeader *, struct EdgeState *, int, int);
static void MoveXSortedToAET(int);
static void ScanOutAET(int, int);
static void AdvanceAET(void);
static void XSortAET(void);

/* Pointers to global edge table (GET) and active edge table (AET) */
static struct EdgeState *GETPtr, *AETPtr;

int FillPolygon(struct PointListHeader * VertexList, int Color,
      int PolygonShape, int XOffset, int YOffset)
{
   struct EdgeState *EdgeTableBuffer;
   int CurrentY;

#ifdef CONVEX_CODE_LINKED
   /* Pass convex polygons through to fast convex polygon filler */
   if (PolygonShape == CONVEX)
      return(FillConvexPolygon(VertexList, Color, XOffset, YOffset));
#endif

   /* It takes a minimum of 3 vertices to cause any pixels to be
      drawn; reject polygons that are guaranteed to be invisible */
   if (VertexList->Length < 3)
      return(1);
   /* Get enough memory to store the entire edge table */
   if ((EdgeTableBuffer =
         (struct EdgeState *) (malloc(sizeof(struct EdgeState) *
         VertexList->Length))) == NULL)
      return(0);  /* couldn't get memory for the edge table */
   /* Build the global edge table */
   BuildGET(VertexList, EdgeTableBuffer, XOffset, YOffset);
   /* Scan down through the polygon edges, one scan line at a time,
      so long as at least one edge remains in either the GET or AET */
   AETPtr = NULL;    /* initialize the active edge table to empty */
   CurrentY = GETPtr->StartY; /* start at the top polygon vertex */
   while ((GETPtr != NULL) || (AETPtr != NULL)) {
      MoveXSortedToAET(CurrentY);  /* update AET for this scan line */
      ScanOutAET(CurrentY, Color); /* draw this scan line from AET */
      AdvanceAET();                /* advance AET edges 1 scan line */
      XSortAET();                  /* resort on X */
      CurrentY++;                  /* advance to the next scan line */
   }
   /* Release the memory we've allocated and we're done */
   free(EdgeTableBuffer);
   return(1);
}

/* Creates a GET in the buffer pointed to by NextFreeEdgeStruc from
   the vertex list. Edge endpoints are flipped, if necessary, to
   guarantee all edges go top to bottom. The GET is sorted primarily
   by ascending Y start coordinate, and secondarily by ascending X
   start coordinate within edges with common Y coordinates. */
static void BuildGET(struct PointListHeader * VertexList,
      struct EdgeState * NextFreeEdgeStruc, int XOffset, int YOffset)
{
   int i, StartX, StartY, EndX, EndY, DeltaY, DeltaX, Width, temp;
   struct EdgeState *NewEdgePtr;
   struct EdgeState *FollowingEdge, **FollowingEdgeLink;
   struct Point *VertexPtr;

   /* Scan through the vertex list and put all non-0-height edges into
      the GET, sorted by increasing Y start coordinate */
   VertexPtr = VertexList->PointPtr;   /* point to the vertex list */
   GETPtr = NULL;   /* initialize the global edge table to empty */
   for (i = 0; i < VertexList->Length; i++) {
      /* Calculate the edge height and width */
      StartX = VertexPtr[i].X + XOffset;
      StartY = VertexPtr[i].Y + YOffset;
      /* The edge runs from the current point to the previous one */
      if (i == 0) {
         /* Wrap back around to the end of the list */
         EndX = VertexPtr[VertexList->Length-1].X + XOffset;
         EndY = VertexPtr[VertexList->Length-1].Y + YOffset;
      } else {
         EndX = VertexPtr[i-1].X + XOffset;
         EndY = VertexPtr[i-1].Y + YOffset;
      }
      /* Make sure the edge runs top to bottom */
      if (StartY > EndY) {
         SWAP(StartX, EndX);
         SWAP(StartY, EndY);
      }
      /* Skip if this can't ever be an active edge (has 0 height) */
      if ((DeltaY = EndY - StartY) != 0) {
         /* Allocate space for this edge's info, and fill in the
            structure */
         NewEdgePtr = NextFreeEdgeStruc++;
         NewEdgePtr->XDirection =   /* direction in which X moves */
               ((DeltaX = EndX - StartX) > 0) ? 1 : -1;
         Width = abs(DeltaX);
         NewEdgePtr->X = StartX;
         NewEdgePtr->StartY = StartY;
         NewEdgePtr->Count = DeltaY;
         NewEdgePtr->ErrorTermAdjDown = DeltaY;
         if (DeltaX >= 0)  /* initial error term going L->R */
            NewEdgePtr->ErrorTerm = 0;
         else              /* initial error term going R->L */
            NewEdgePtr->ErrorTerm = -DeltaY + 1;
         if (DeltaY >= Width) {     /* Y-major edge */
            NewEdgePtr->WholePixelXMove = 0;
            NewEdgePtr->ErrorTermAdjUp = Width;
         } else {                   /* X-major edge */
            NewEdgePtr->WholePixelXMove =
                  (Width / DeltaY) * NewEdgePtr->XDirection;
            NewEdgePtr->ErrorTermAdjUp = Width % DeltaY;
         }
         /* Link the new edge into the GET so that the edge list is
            still sorted by Y coordinate, and by X coordinate for all
            edges with the same Y coordinate */
         FollowingEdgeLink = &GETPtr;
         for (;;) {
            FollowingEdge = *FollowingEdgeLink;
            if ((FollowingEdge == NULL) ||
                  (FollowingEdge->StartY > StartY) ||
                  ((FollowingEdge->StartY == StartY) &&
                  (FollowingEdge->X >= StartX))) {
               NewEdgePtr->NextEdge = FollowingEdge;
               *FollowingEdgeLink = NewEdgePtr;
               break;
            }
            FollowingEdgeLink = &FollowingEdge->NextEdge;
         }
      }
   }
}

/* Sorts all edges currently in the active edge table into ascending
   order of current X coordinates */
static void XSortAET() {
   struct EdgeState *CurrentEdge, **CurrentEdgePtr, *TempEdge;
   int SwapOccurred;

   /* Scan through the AET and swap any adjacent edges for which the
      second edge is at a lower current X coord than the first edge.
      Repeat until no further swapping is needed */
   if (AETPtr != NULL) {
      do {
         SwapOccurred = 0;
         CurrentEdgePtr = &AETPtr;
         while ((CurrentEdge = *CurrentEdgePtr)->NextEdge != NULL) {
            if (CurrentEdge->X > CurrentEdge->NextEdge->X) {
               /* The second edge has a lower X than the first;
                  swap them in the AET */
               TempEdge = CurrentEdge->NextEdge->NextEdge;
               *CurrentEdgePtr = CurrentEdge->NextEdge;
               CurrentEdge->NextEdge->NextEdge = CurrentEdge;
               CurrentEdge->NextEdge = TempEdge;
               SwapOccurred = 1;
            }
            CurrentEdgePtr = &(*CurrentEdgePtr)->NextEdge;
         }
      } while (SwapOccurred != 0);
   }
}

/* Advances each edge in the AET by one scan line.
   Removes edges that have been fully scanned. */
static void AdvanceAET() {
   struct EdgeState *CurrentEdge, **CurrentEdgePtr;

   /* Count down and remove or advance each edge in the AET */
   CurrentEdgePtr = &AETPtr;
   while ((CurrentEdge = *CurrentEdgePtr) != NULL) {
      /* Count off one scan line for this edge */
      if ((--(CurrentEdge->Count)) == 0) {
         /* This edge is finished, so remove it from the AET */
         *CurrentEdgePtr = CurrentEdge->NextEdge;
      } else {
         /* Advance the edge's X coordinate by minimum move */
         CurrentEdge->X += CurrentEdge->WholePixelXMove;
         /* Determine whether it's time for X to advance one extra */
         if ((CurrentEdge->ErrorTerm +=
               CurrentEdge->ErrorTermAdjUp) > 0) {
            CurrentEdge->X += CurrentEdge->XDirection;
            CurrentEdge->ErrorTerm -= CurrentEdge->ErrorTermAdjDown;
         }
         CurrentEdgePtr = &CurrentEdge->NextEdge;
      }
   }
}

/* Moves all edges that start at the specified Y coordinate from the
   GET to the AET, maintaining the X sorting of the AET. */
static void MoveXSortedToAET(int YToMove) {
   struct EdgeState *AETEdge, **AETEdgePtr, *TempEdge;
   int CurrentX;

   /* The GET is Y sorted. Any edges that start at the desired Y
      coordinate will be first in the GET, so we'll move edges from
      the GET to AET until the first edge left in the GET is no longer
      at the desired Y coordinate. Also, the GET is X sorted within
      each Y coordinate, so each successive edge we add to the AET is
      guaranteed to belong later in the AET than the one just added. */
   AETEdgePtr = &AETPtr;
   while ((GETPtr != NULL) && (GETPtr->StartY == YToMove)) {
      CurrentX = GETPtr->X;
      /* Link the new edge into the AET so that the AET is still
         sorted by X coordinate */
      for (;;) {
         AETEdge = *AETEdgePtr;
         if ((AETEdge == NULL) || (AETEdge->X >= CurrentX)) {
            TempEdge = GETPtr->NextEdge;
            *AETEdgePtr = GETPtr;  /* link the edge into the AET */
            GETPtr->NextEdge = AETEdge;
            AETEdgePtr = &GETPtr->NextEdge;
            GETPtr = TempEdge;   /* unlink the edge from the GET */
            break;
         } else {
            AETEdgePtr = &AETEdge->NextEdge;
         }
      }
   }
}

/* Fills the scan line described by the current AET at the specified Y
   coordinate in the specified color, using the odd/even fill rule */
static void ScanOutAET(int YToScan, int Color) {
   int LeftX;
   struct EdgeState *CurrentEdge;

   /* Scan through the AET, drawing line segments as each pair of edge
      crossings is encountered. The nearest pixel on or to the right
      of left edges is drawn, and the nearest pixel to the left of but
      not on right edges is drawn */
   CurrentEdge = AETPtr;
   while (CurrentEdge != NULL) {
      LeftX = CurrentEdge->X;
      CurrentEdge = CurrentEdge->NextEdge;
      DrawHorizontalLineSeg(YToScan, LeftX, CurrentEdge->X-1, Color);
      CurrentEdge = CurrentEdge->NextEdge;
   }
}
```

Complex Polygon Filling: An Implementation

Listing 23.1 just shown presents a function, **FillPolygon**(), that fills polygons of all shapes. If **CONVEX_FILL_LINKED** is defined, the fast convex fill code from Chapter 22 is linked in and used to draw convex polygons. Otherwise, convex polygons are handled as if they were complex. Nonconvex polygons are also handled as complex, although this is not necessary, as discussed shortly.

Listing 23.1 is a faithful implementation of the complex polygon filling approach just described, with separate functions corresponding to each of the tasks, such as building the GET and X-sorting the AET. Listing 23.2 provides the actual drawing code used to fill spans, built on a draw pixel routine that is the only hardware dependency anywhere in the C code. Listing 23.3 is the header file for the polygon filling code; note that it is an expanded version of the header file used by the fast convex polygon fill code from Chapter 22. (They may have the same name but are *not* the same file!) Listing 23.4 is a sample program that, when linked to Listings 23.1 and 23.2, demonstrates drawing polygons of various sorts.

LISTING 23.2 L23-2.C

```
/* Draws all pixels in the horizontal line segment passed in, from
   (LeftX,Y) to (RightX,Y), in the specified color in mode 13h, the
   VGA's 320x200 256-color mode. Both LeftX and RightX are drawn. No
   drawing will take place if LeftX > RightX. */

#include <dos.h>
#include "polygon.h"

#define SCREEN_WIDTH    320
#define SCREEN_SEGMENT  0xA000

static void DrawPixel(int, int, int);

void DrawHorizontalLineSeg(Y, LeftX, RightX, Color) {
   int X;

   /* Draw each pixel in the horizontal line segment, starting with
      the leftmost one */
   for (X = LeftX; X <= RightX; X++)
      DrawPixel(X, Y, Color);
}

/* Draws the pixel at (X, Y) in color Color in VGA mode 13h */
static void DrawPixel(int X, int Y, int Color) {
   unsigned char far *ScreenPtr;

#ifdef __TURBOC__
```

```
   ScreenPtr = MK_FP(SCREEN_SEGMENT, Y * SCREEN_WIDTH + X);
#else    /* MSC 5.0 */
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) = Y * SCREEN_WIDTH + X;
#endif
   *ScreenPtr = (unsigned char) Color;
}
```

LISTING 23.3 POLYGON.H

```
/* POLYGON.H: Header file for polygon-filling code */

#define CONVEX    0
#define NONCONVEX 1
#define COMPLEX   2

/* Describes a single point (used for a single vertex) */
struct Point {
   int X;   /* X coordinate */
   int Y;   /* Y coordinate */
};
/* Describes a series of points (used to store a list of vertices that
   describe a polygon; each vertex connects to the two adjacent
   vertices; the last vertex is assumed to connect to the first) */
struct PointListHeader {
   int Length;                /* # of points */
   struct Point * PointPtr;   /* pointer to list of points */
};
/* Describes the beginning and ending X coordinates of a single
   horizontal line (used only by fast polygon fill code) */
struct HLine {
   int XStart; /* X coordinate of leftmost pixel in line */
   int XEnd;   /* X coordinate of rightmost pixel in line */
};
/* Describes a Length-long series of horizontal lines, all assumed to
   be on contiguous scan lines starting at YStart and proceeding
   downward (used to describe a scan-converted polygon to the
   low-level hardware-dependent drawing code) (used only by fast
   polygon fill code). */
struct HLineList {
   int Length;                /* # of horizontal lines */
   int YStart;                /* Y coordinate of topmost line */
   struct HLine * HLinePtr;   /* pointer to list of horz lines */
};
```

LISTING 23.4 L23-4.C

```
/* Sample program to exercise the polygon-filling routines */

#include <conio.h>
#include <dos.h>
#include "polygon.h"

#define DRAW_POLYGON(PointList,Color,Shape,X,Y)             \
   Polygon.Length = sizeof(PointList)/sizeof(struct Point); \
   Polygon.PointPtr = PointList;                            \
   FillPolygon(&Polygon, Color, Shape, X, Y);
```

```
void main(void);
extern int FillPolygon(struct PointListHeader *, int, int, int, int);

void main() {
   int i, j;
   struct PointListHeader Polygon;
   static struct Point Polygon1[] =
         {{0,0},{100,150},{320,0},{0,200},{220,50},{320,200}};
   static struct Point Polygon2[] =
         {{0,0},{320,0},{320,200},{0,200},{0,0},{50,50},
          {270,50},{270,150},{50,150},{50,50}};
   static struct Point Polygon3[] =
         {{0,0},{10,0},{105,185},{260,30},{15,150},{5,150},{5,140},
          {260,5},{300,5},{300,15},{110,200},{100,200},{0,10}};
   static struct Point Polygon4[] =
         {{0,0},{30,-20},{30,0},{0,20},{-30,0},{-30,-20}};
   static struct Point Triangle1[] = {{30,0},{15,20},{0,0}};
   static struct Point Triangle2[] = {{30,20},{15,0},{0,20}};
   static struct Point Triangle3[] = {{0,20},{20,10},{0,0}};
   static struct Point Triangle4[] = {{20,20},{20,0},{0,10}};
   union REGS regset;

   /* Set the display to VGA mode 13h, 320x200 256-color mode */
   regset.x.ax = 0x0013;
   int86(0x10, &regset, &regset);

   /* Draw three complex polygons */
   DRAW_POLYGON(Polygon1, 15, COMPLEX, 0, 0);
   getch();    /* wait for a keypress */
   DRAW_POLYGON(Polygon2, 5, COMPLEX, 0, 0);
   getch();    /* wait for a keypress */
   DRAW_POLYGON(Polygon3, 3, COMPLEX, 0, 0);
   getch();    /* wait for a keypress */

   /* Draw some adjacent nonconvex polygons */
   for (i=0; i<5; i++) {
      for (j=0; j<8; j++) {
         DRAW_POLYGON(Polygon4, 16+i*8+j, NONCONVEX, 40+(i*60),
               30+(j*20));
      }
   }
   getch();    /* wait for a keypress */

   /* Draw adjacent triangles across the screen */
   for (j=0; j<=80; j+=20) {
      for (i=0; i<290; i += 30) {
         DRAW_POLYGON(Triangle1, 2, CONVEX, i, j);
         DRAW_POLYGON(Triangle2, 4, CONVEX, i+15, j);
      }
   }
   for (j=100; j<=170; j+=20) {
      /* Do a row of pointing-right triangles */
      for (i=0; i<290; i += 20) {
         DRAW_POLYGON(Triangle3, 40, CONVEX, i, j);
      }
      /* Do a row of pointing-left triangles halfway between one row
         of pointing-right triangles and the next, to fit between */
      for (i=0; i<290; i += 20) {
         DRAW_POLYGON(Triangle4, 1, CONVEX, i, j+10);
      }
   }
   getch();    /* wait for a keypress */
   /* Return to text mode and exit */
   regset.x.ax = 0x0003;
   int86(0x10, &regset, &regset);
}
```

Listing 23.4 illustrates several interesting aspects of polygon filling. The first and third polygons drawn illustrate the operation of the odd/even fill rule. The second polygon drawn illustrates how holes can be created in seemingly solid objects; an edge runs from the outside of the rectangle to the inside, the edges comprising the hole are defined, and then the same edge is used to move back to the outside; because the edges join seamlessly, the rectangle appears to form a solid boundary around the hole.

The set of V-shaped polygons drawn by Listing 23.4 demonstrate that polygons sharing common edges meet but do not overlap. This characteristic, which I discussed at length in Chapter 21, is not a trivial matter; it allows polygons to fit together without fear of overlapping or missed pixels. In general, Listing 23.1 guarantees that polygons are filled such that common boundaries and vertices are drawn once and only once. This has the side-effect for any individual polygon of not drawing pixels that lie exactly on the bottom or right boundaries or at vertices that terminate bottom or right boundaries.

By the way, I have not seen polygon boundary filling handled precisely this way elsewhere. The boundary filling approach in Foley and van Dam is similar, but seems to me to not draw all boundary and vertex pixels once and only once.

More on Active Edges

Edges of zero height—horizontal edges and edges defined by two vertices at the same location—never even make it into the GET in Listing 23.1. A polygon edge of zero height can never be an active edge, because it can never intersect a scan line; it can only run along the scan line, and the span it runs along is defined not by that edge but by the edges that connect to its endpoints.

Performance Considerations

How fast is Listing 23.1? When drawing triangles on a 20-MHz 386, it's less than one-fifth the speed of the fast convex polygon fill code. However, most of that time is spent drawing individual pixels; when Listing 23.2 is replaced with the fast assembly line segment drawing code in Listing 23.5, performance improves by two and one-half times, to about half as fast as the fast convex fill code. Even after conversion to assembly in Listing 23.5, **DrawHorizontalLineSeg** still takes more than half of the total execution time, and the remaining time is spread out fairly evenly over the various subroutines in Listing 23.1. Consequently, there's no single place in which it's possible to greatly improve performance, and the maximum additional improvement that's possible looks to be a good deal less than two times; for that reason, and because of space limitations, I'm not going to convert the rest of the code to assembly. However, when filling a polygon with a great many edges, and especially one with a great many active edges at one time, relatively more time would be spent traversing the linked lists. In such a case, conversion to assembly (which does a very good job with linked list processing) could pay off reasonably well.

LISTING 23.5 L23-5.ASM

```
; Draws all pixels in the horizontal line segment passed in, from
;  (LeftX,Y) to (RightX,Y), in the specified color in mode 13h, the
;  VGA's 320x200 256-color mode. No drawing will take place if
;  LeftX > RightX. Tested with TASM
; C near-callable as:
;       void DrawHorizontalLineSeg(Y, LeftX, RightX, Color);

SCREEN_WIDTH    equ     320
SCREEN_SEGMENT  equ     0a000h

Parms   struc
        dw      2 dup(?) ;return address & pushed BP
Y       dw      ?       ;Y coordinate of line segment to draw
LeftX   dw      ?       ;left endpoint of the line segment
RightX  dw      ?       ;right endpoint of the line segment
Color   dw      ?       ;color in which to draw the line segment
Parms   ends

        .model small
        .code
        public _DrawHorizontalLineSeg
        align   2
_DrawHorizontalLineSeg  proc
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to our stack frame
        push    di              ;preserve caller's register variable
        cld                     ;make string instructions inc pointers
        mov     ax,SCREEN_SEGMENT
        mov     es,ax           ;point ES to display memory
        mov     di,[bp+LeftX]
        mov     cx,[bp+RightX]
        sub     cx,di           ;width of line
        jl      DrawDone        ;RightX < LeftX; no drawing to do
        inc     cx              ;include both endpoints
        mov     ax,SCREEN_WIDTH
        mul     [bp+Y]          ;offset of scan line on which to draw
        add     di,ax           ;ES:DI points to start of line seg
        mov     al,byte ptr [bp+Color] ;color in which to draw
        mov     ah,al           ;put color in AH for STOSW
        shr     cx,1            ;# of words to fill
        rep     stosw           ;fill a word at a time
        adc     cx,cx
        rep     stosb           ;draw the odd byte, if any
DrawDone:
        pop     di              ;restore caller's register variable
        pop     bp              ;restore caller's stack frame
        ret
_DrawHorizontalLineSeg  endp
        end
```

The algorithm used to X-sort the AET is an interesting performance consideration. Listing 23.1 uses a bubble sort, usually a poor choice for performance. However, bubble sorts perform well when the data are already almost sorted, and because of the X coherence of edges from one scan line to the next, that's generally the case with the AET. An insertion sort might be somewhat faster, depending on the state of the AET when any particular sort occurs, but a bubble sort will generally do just fine.

An insertion sort that scans backward through the AET from the current edge rather than forward from the start of the AET could be quite a bit faster, because edges rarely move more than one or two positions through the AET. However, scanning backward requires a doubly linked list, rather than the singly linked list used in Listing 23.1. I've chosen to use a singly linked list partly to minimize memory requirements (double-linking requires an extra pointer field) and partly because supporting back links would complicate the code a good bit. The main reason, though, is that the potential rewards for the complications of back links and insertion sorting aren't great enough; profiling a variety of polygons reveals that less than ten percent of total time is spent sorting the AET.

The potential 1 to 5 percent speedup gained by optimizing AET sorting just isn't worth it in any but the most demanding application—a good example of the need to keep an overall perspective when comparing the theoretical characteristics of various approaches.

Nonconvex Polygons

Nonconvex polygons can be filled somewhat faster than complex polygons. Because edges never cross or switch positions with other edges once they're in the AET, the AET for a nonconvex polygon needs to be sorted only when new edges are added. In order for this to work, though, edges must be added to the AET in strict left-to-right order. Complications arise when dealing with two edges that start at the same point, because slopes must be compared to determine which edge is leftmost. This is certainly doable, but because of space limitations and limited performance returns, I haven't implemented this in Listing 23.1.

Details, Details

Every so often, a programming demon that I'd thought I'd forever laid to rest arises to haunt me once again. A minor example of this—an imp, if you will—is the use of " = " when I mean " == ," which I've done all too often in the past, and am sure I'll do again. That's minor deviltry, though, compared to the considerably greater evils of one of my personal scourges, of which I was recently reminded anew: too-close attention to detail. Not seeing the forest for the trees. Looking low when I should have looked high. Missing the big picture, if you catch my drift.

Thoreau said it best: "Our life is frittered away by detail....Simplify, simplify." That quote sprang to mind when I received a letter a while back from Anton Treuenfels of Fridley, Minnesota, thanking me for clarifying the principles of filling adjacent convex polygons in my ongoing writings on graphics programming. (You'll find this material in the previous two chapters.) Anton then went on to describe his own method for filling convex polygons.

Anton's approach had its virtues and drawbacks, foremost among the virtues being a simplicity Thoreau would have admired. For instance, in writing my polygon-filling code, I had spent quite some time trying to figure out the best way to identify which edge was the left edge and which the right, finally settling on comparing the slopes of the edges if the top of the polygon wasn't flat, and comparing the starting points of the edges if the top was flat. Anton simplified this tremendously by not bothering to figure out ahead of time which was the right edge of the polygon and which the left, instead scanning out the two edges in whatever order he found them and letting the low-level drawing code test, and if necessary swap, the endpoints of each horizontal line of the fill, so that filling started at the leftmost edge. This is a little slower than my approach (although the difference is almost surely negligible), but it also makes quite a bit of code go away.

What that example, and others like it in Anton's letter, did was kick my mind into a mode that it hadn't—but should have—been in when I wrote the code, a mode in which I began to wonder, "How else can I simplify this code?"; what you might call Occam's Razor mode. You see, I created the convex polygon-drawing code by first writing pseudocode, then writing C code, and finally writing assembly code, and once the pseudocode was finished, I stopped thinking about the interactions of the various portions of the program.

In other words, I became so absorbed in individual details that I forgot to consider the code as a whole. That was a mistake, and an embarrassing one for someone who constantly preaches that programmers should look at their code from a variety of perspectives; the next chapter shows just how much difference thinking about the big picture can make. May my embarrassment be your enlightenment.

The point is not whether, in the final analysis, my code or Anton's code is better; both have their advantages. The point is that I was programming with half a deck because I was so fixated on the details of a single type of implementation; I ended up with relatively hard-to-write, complex code, and missed out on many potentially useful optimizations by being so focused. It's a big world out there, and there are many subtle approaches to any problem, so relax and keep the big picture in mind as you implement your programs. Your code will likely be not only better, but also simpler. And whenever you see me walking across hot coals in this book or elsewhere when there's an easier way to go, please, let me know!

Thanks, Anton.

Those Way-Down Polygon Nomenclature Blues

Chapter 24

Names Do Matter when You Conceptualize a Data Structure

After I wrote the columns on polygons in *Dr. Dobb's Journal* that became Chapters 21-23, long-time reader Bill Huber wrote to take me to task—and a well-deserved kick in the fanny it was, I might add—for my use of non-standard polygon terminology in those columns. Unix's X-Window System (XWS) defines three categories of polygons: complex, nonconvex, and convex. These three categories, each a specialized subset of the preceding category, not-so-coincidentally map quite nicely to three increasingly fast polygon filling techniques. Therefore, I used the XWS names to describe the sorts of polygons that can be drawn with each of the polygon filling techniques.

The problem is that those names don't accurately describe all the sorts of polygons that the techniques are capable of drawing. Convex polygons are those for which no interior angle is greater than 180 degrees. The "convex" drawing approach described in the previous few chapters actually handles a number of polygons that are not convex; in fact, it can draw any polygon through which no horizontal line can be drawn that intersects the boundary more than twice. (In other words, the boundary reverses the Y direction exactly twice, disregarding polygons that have degenerated into horizontal lines, which I'm going to ignore.)

Bill was kind enough to send me the pages out of *Computational Geometry, An Introduction* (Springer-Verlag, 1988) that describe the correct terminology; such polygons are, in fact, "monotone with respect to a vertical line" (which unfortunately makes a rather long **#define** variable). Actually, to be a tad more precise, I'd call them "monotone with respect to a vertical line and simple," where "simple" means "not self-intersecting." Similarly, the polygon type I called "nonconvex" is actually "simple," and I suppose what I called "complex" should be referred to as "nonsimple," or maybe just "none of the above."

> *This may seem like nit-picking, but actually, it isn't; what it's really about is the tremendous importance of having a shared language. In one of his books, Richard Feynman describes having developed his own mathematical framework, complete with his own notation and terminology, in high school. When he got to college and started working with other people who were at his level, he suddenly understood that people can't share ideas effectively unless they speak the same language; otherwise, they waste a great deal of time on misunderstandings and explanation.*

Or, as Bill Huber put it, "You are free to adopt your own terminology when it suits your purposes well. But you risk losing or confusing those who could be among your most astute readers—those who already have been trained in the same or a related field." Ditto. Likewise. *D'accord.* And *mea culpa*; I shall endeavor to watch my language in the future.

Nomenclature in Action

Just to show you how much difference proper description and interchange of ideas can make, consider the case of identifying convex polygons. When I was writing about polygons in my column in *DDJ*, a nonfunctional method for identifying such polygons—checking for exactly two X direction changes and two Y direction changes around the perimeter of the polygon—crept into the column by accident. That method, as I noted in a later column, does not work. (That's why you won't find it in this book.) Still, a fast method of checking for convex polygons would be highly desirable, because such polygons can be drawn with the fast code from Chapter 22, rather than the relatively slow, general-purpose code from Chapter 23.

Now consider Bill's point that we're not limited to drawing convex polygons in our "convex fill" code, but can actually handle any simple polygon that's monotone with respect to a vertical line. Additionally, consider Anton Treuenfels's point, made back in Chapter 23, that life gets simpler if we stop worrying about which edge of a polygon is the left edge and which is the right, and instead just scan out each raster line starting at whichever edge is left-most. Now, what do we have?

What we have is an approach passed along by Jim Kent, of Autodesk Animator fame. If we modify the low-level code to check which edge is left-most on each scan line and start drawing there, as just described, then we can handle any polygon that's monotone with respect to a vertical line regardless of whether the edges cross. (I'll call

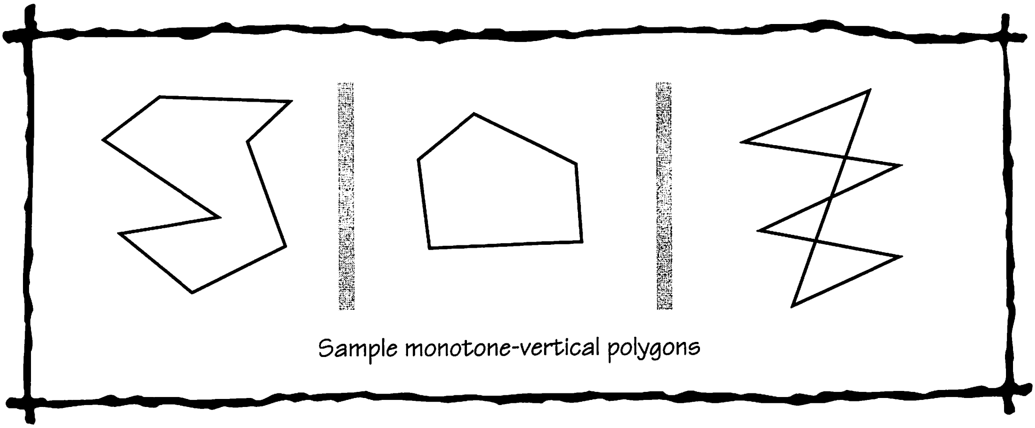


Figure 24.1 Monotone-Vertical Polygons

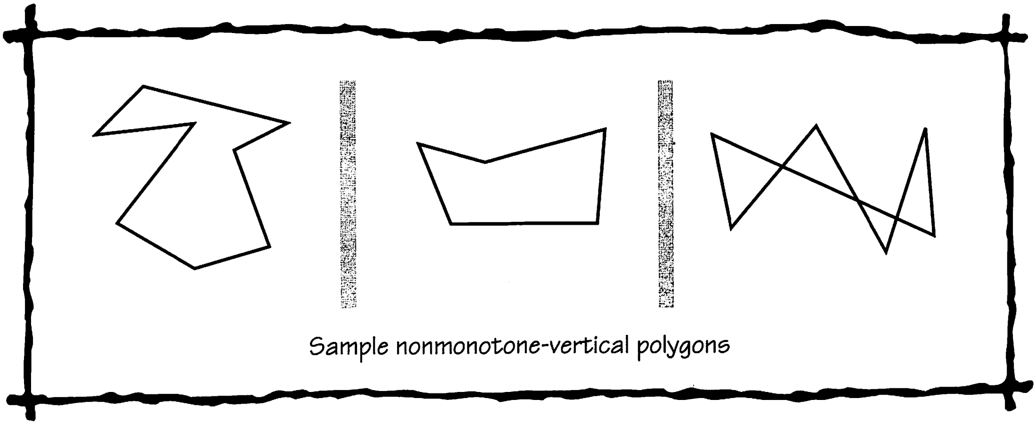


Figure 24.2 Non-Monotone-Vertical Polygons

this "monotone-vertical" from now on; if anyone wants to correct that terminology, jump right in.) In other words, we can then handle nonsimple polygons that are monotone-vertical; self-intersection is no longer a problem. We just scan around the polygon's perimeter looking for exactly two direction reversals along the Y axis only, and if that proves to be the case, we can handle the polygon at high speed. Figure 24.1 shows polygons that can be drawn by a monotone-vertical capable filler; Figure 24.2 shows some that cannot. Listing 24.1 shows code to test whether a polygon is appropriately monotone.

LISTING 24.1 L24-1.C

```
/* Returns 1 if polygon described by passed-in vertex list is monotone with
respect to a vertical line, 0 otherwise. Doesn't matter if polygon is simple
(non-self-intersecting) or not. Tested with Borland C++ in small model. */

#include "polygon.h"

#define SIGNUM(a) ((a>0)?1:((a<0)?-1:0))
```

```
int PolygonIsMonotoneVertical(struct PointListHeader * VertexList)
{
   int i, Length, DeltaYSign, PreviousDeltaYSign;
   int NumYReversals = 0;
   struct Point *VertexPtr = VertexList->PointPtr;

   /* Three or fewer points can't make a non-vertical-monotone polygon */
   if ((Length=VertexList->Length) < 4) return(1);

   /* Scan to the first non-horizontal edge */
   PreviousDeltaYSign = SIGNUM(VertexPtr[Length-1].Y - VertexPtr[0].Y);
   i = 0;
   while ((PreviousDeltaYSign == 0) && (i < (Length-1))) {
      PreviousDeltaYSign = SIGNUM(VertexPtr[i].Y - VertexPtr[i+1].Y);
      i++;
   }

   if (i == (Length-1)) return(1);  /* polygon is a flat line */

   /* Now count Y reversals. Might miss one reversal, at the last vertex, but
      because reversal counts must be even, being off by one isn't a problem */
   do {
      if ((DeltaYSign = SIGNUM(VertexPtr[i].Y - VertexPtr[i+1].Y))
            != 0) {
         if (DeltaYSign != PreviousDeltaYSign) {
            /* Switched Y direction; not vertical-monotone if
               reversed Y direction as many as three times */
            if (++NumYReversals > 2) return(0);
            PreviousDeltaYSign = DeltaYSign;
         }
      }
   } while (i++ < (Length-1));
   return(1);  /* it's a vertical-monotone polygon */
}
```

Listings 24.2 and 24.3 are variants of the fast convex polygon fill code from Chapter 22, modified to be able to handle all monotone-vertical polygons, including nonsimple ones; the edge-scanning code (Listing 22.4 from Chapter 22) remains the same, and so is not shown again here.

LISTING 24.2 L24-2.C

```
/* Color-fills a convex polygon. All vertices are offset by (XOffset, YOffset).
"Convex" means "monotone with respect to a vertical line"; that is, every
horizontal line drawn through the polygon at any point would cross exactly two
active edges (neither horizontal lines nor zero-length edges count as active
edges; both are acceptable anywhere in the polygon). Right & left edges may
cross (polygons may be nonsimple). Polygons that are not convex according to
this definition won't be drawn properly. (Yes, "convex" is a lousy name for
this type of polygon, but it's convenient; use "monotone-vertical" if it makes
you happier!).
*******************************************************************
NOTE: the low-level drawing routine, DrawHorizontalLineList, must be able to
reverse the edges, if necessary to make the correct edge left edge. It must
also expect right edge to be specified in +1 format (the X coordinate is 1 past
highest coordinate to draw). In both respects, this differs from low-level
drawing routines presented in earlier columns; changes are necessary to make it
possible to draw nonsimple monotone-vertical polygons; that in turn makes it
possible to use Jim Kent's test for monotone-vertical polygons.
*******************************************************************
Returns 1 for success, 0 if memory allocation failed */

#include <stdio.h>
#include <math.h>
#include <stdlib.h>
#include "polygon.h"

/* Advances the index by one vertex forward through the vertex list,
wrapping at the end of the list */
#define INDEX_FORWARD(Index) \
   Index = (Index + 1) % VertexList->Length;

/* Advances the index by one vertex backward through the vertex list,
wrapping at the start of the list */
#define INDEX_BACKWARD(Index) \
   Index = (Index - 1 + VertexList->Length) % VertexList->Length;

/* Advances the index by one vertex either forward or backward through
the vertex list, wrapping at either end of the list */
#define INDEX_MOVE(Index,Direction)                                    \
   if (Direction > 0)                                                  \
      Index = (Index + 1) % VertexList->Length;                        \
   else                                                                \
      Index = (Index - 1 + VertexList->Length) % VertexList->Length;

extern void ScanEdge(int, int, int, int, int, int, struct HLine **);
extern void DrawHorizontalLineList(struct HLineList *, int);

int FillMonotoneVerticalPolygon(struct PointListHeader * VertexList,
      int Color, int XOffset, int YOffset)
{
   int i, MinIndex, MaxIndex, MinPoint_Y, MaxPoint_Y;
   int NextIndex, CurrentIndex, PreviousIndex;
   struct HLineList WorkingHLineList;
   struct HLine *EdgePointPtr;
   struct Point *VertexPtr;

   /* Point to the vertex list */
   VertexPtr = VertexList->PointPtr;

   /* Scan the list to find the top and bottom of the polygon */
   if (VertexList->Length == 0)
      return(1);  /* reject null polygons */
   MaxPoint_Y = MinPoint_Y = VertexPtr[MinIndex = MaxIndex = 0].Y;
   for (i = 1; i < VertexList->Length; i++) {
      if (VertexPtr[i].Y < MinPoint_Y)
         MinPoint_Y = VertexPtr[MinIndex = i].Y; /* new top */
      else if (VertexPtr[i].Y > MaxPoint_Y)
         MaxPoint_Y = VertexPtr[MaxIndex = i].Y; /* new bottom */
   }

   /* Set the # of scan lines in the polygon, skipping the bottom edge */
   if ((WorkingHLineList.Length = MaxPoint_Y - MinPoint_Y) <= 0)
      return(1);  /* there's nothing to draw, so we're done */
   WorkingHLineList.YStart = YOffset + MinPoint_Y;

   /* Get memory in which to store the line list we generate */
   if ((WorkingHLineList.HLinePtr =
         (struct HLine *) (malloc(sizeof(struct HLine) *
         WorkingHLineList.Length))) == NULL)
      return(0);  /* couldn't get memory for the line list */

   /* Scan the first edge and store the boundary points in the list */
   /* Initial pointer for storing scan converted first-edge coords */
   EdgePointPtr = WorkingHLineList.HLinePtr;
   /* Start from the top of the first edge */
   PreviousIndex = CurrentIndex = MinIndex;
   /* Scan convert each line in the first edge from top to bottom */
   do {
      INDEX_BACKWARD(CurrentIndex);
      ScanEdge(VertexPtr[PreviousIndex].X + XOffset,
            VertexPtr[PreviousIndex].Y,
            VertexPtr[CurrentIndex].X + XOffset,
            VertexPtr[CurrentIndex].Y, 1, 0, &EdgePointPtr);
      PreviousIndex = CurrentIndex;
   } while (CurrentIndex != MaxIndex);

   /* Scan the second edge and store the boundary points in the list */
   EdgePointPtr = WorkingHLineList.HLinePtr;
   PreviousIndex = CurrentIndex = MinIndex;
   /* Scan convert the second edge, top to bottom */
   do {
      INDEX_FORWARD(CurrentIndex);
      ScanEdge(VertexPtr[PreviousIndex].X + XOffset,
            VertexPtr[PreviousIndex].Y,
            VertexPtr[CurrentIndex].X + XOffset,
            VertexPtr[CurrentIndex].Y, 0, 0, &EdgePointPtr);
      PreviousIndex = CurrentIndex;
   } while (CurrentIndex != MaxIndex);

   /* Draw the line list representing the scan converted polygon */
   DrawHorizontalLineList(&WorkingHLineList, Color);

   /* Release the line list's memory and we're successfully done */
   free(WorkingHLineList.HLinePtr);
   return(1);
}
```

LISTING 24.3 L24-3.ASM

```
; Draws all pixels in list of horizontal lines passed in, in mode 13h, VGA's
; 320x200 256-color mode. Uses REP STOS to fill each line.
; ******************************************************************
; NOTE: is able to reverse the X coords for a scan line, if necessary to make
; XStart < XEnd. Expects whichever edge is rightmost on any scan line to be in
; +1 format; that is, XEnd is 1 greater than rightmost pixel to draw. if
; XStart == XEnd, nothing is drawn on that scan line.
; ******************************************************************
; C near-callable as:
;     void DrawHorizontalLineList(struct HLineList * HLineListPtr, int Color);
; All assembly code tested with TASM and MASM

SCREEN_WIDTH    equ     320
SCREEN_SEGMENT  equ     0a000h

HLine   struc
XStart  dw      ?       ;X coordinate of leftmost pixel in line
XEnd    dw      ?       ;X coordinate of rightmost pixel in line
HLine   ends
```

```
HLineList struc
Lngth    dw      ?       ;# of horizontal lines
YStart   dw      ?       ;Y coordinate of topmost line
HLinePtr dw     ?        ;pointer to list of horz lines
HLineList ends

Parms   struc
                dw      2 dup(?) ;return address & pushed BP
HLineListPtr    dw      ?       ;pointer to HLineList structure
Color           dw      ?       ;color with which to fill
Parms   ends
        .model small
        .code
        public _DrawHorizontalLineList
        align   2
_DrawHorizontalLineList proc
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to our stack frame
        push    si              ;preserve caller's register variables
        push    di
        cld                     ;make string instructions inc pointers

        mov     ax,SCREEN_SEGMENT
        mov     es,ax   ;point ES to display memory for REP STOS

        mov     si,[bp+HLineListPtr] ;point to the line list
        mov     ax,SCREEN_WIDTH ;point to the start of the first scan
        mul     [si+YStart]     ; line in which to draw
        mov     dx,ax           ;ES:DX points to first scan line to draw
        mov     bx,[si+HLinePtr] ;point to the XStart/XEnd descriptor
                                ; for the first (top) horizontal line
        mov     si,[si+Lngth]   ;# of scan lines to draw
        and     si,si           ;are there any lines to draw?
        jz      FillDone        ;no, so we're done
        mov     al,byte ptr [bp+Color] ;color with which to fill
        mov     ah,al           ;duplicate color for STOSW
FillLoop:
        mov     di,[bx+XStart]  ;left edge of fill on this line
        mov     cx,[bx+XEnd]    ;right edge of fill
        cmp     di,cx           ;is XStart > XEnd?
        jle     NoSwap          ;no, we're all set
        xchg    di,cx           ;yes, so swap edges
NoSwap:
        sub     cx,di           ;width of fill on this line
        jz      LineFillDone    ;skip if zero width
        add     di,dx           ;offset of left edge of fill
        test    di,1            ;does fill start at an odd address?
        jz      MainFill        ;no
        stosb                   ;yes, draw the odd leading byte to
                                ; word-align the rest of the fill
        dec     cx              ;count off the odd leading byte
        jz      LineFillDone    ;done if that was the only byte
MainFill:
        shr     cx,1            ;# of words in fill
        rep     stosw           ;fill as many words as possible
        adc     cx,cx           ;1 if there's an odd trailing byte to
                                ; do, 0 otherwise
        rep     stosb           ;fill any odd trailing byte
LineFillDone:
        add     bx,size HLine   ;point to the next line descriptor
        add     dx,SCREEN_WIDTH ;point to the next scan line
        dec     si              ;count off lines to fill
        jnz     FillLoop
FillDone:
        pop     di              ;restore caller's register variables
        pop     si
        pop     bp              ;restore caller's stack frame
        ret
_DrawHorizontalLineList endp
        end
```

Listing 24.4 is almost identical to Listing 23.1 from Chapter 23. I've modified Listing 23.1 to employ the vertical-monotone detection test we've been talking about and use the fast vertical-monotone drawing code whenever possible; that's what Listing 24.4 is. Note well that Listing 23.5 from Chapter 23 is also required in order for this code to link. Listing 24.5 is an appropriately updated version of the POLYGON.H header file.

LISTING 24.4 L24-4.C

```
/* Color-fills an arbitrarily-shaped polygon described by VertexList.
If the first and last points in VertexList are not the same, the path
around the polygon is automatically closed. All vertices are offset
by (XOffset, YOffset). Returns 1 for success, 0 if memory allocation
failed. All C code tested with Borland C++.

If the polygon shape is known in advance, speedier processing may be
enabled by specifying the shape as follows: "convex" - a rubber band
stretched around the polygon would touch every vertex in order;
"nonconvex" - the polygon is not self-intersecting, but need not be
convex; "complex" - the polygon may be self-intersecting, or, indeed,
any sort of polygon at all. Complex will work for all polygons; convex
is fastest. Undefined results will occur if convex is specified for a
nonconvex or complex polygon.

Define CONVEX_CODE_LINKED if the fast convex polygon filling code from
the February 1991 column is linked in. Otherwise, convex polygons are
handled by the complex polygon filling code.
Nonconvex is handled as complex in this implementation. See text for a
discussion of faster nonconvex handling. */

#include <stdio.h>
#include <math.h>
#ifdef __TURBOC__
#include <alloc.h>
#else   /* MSC */
#include <malloc.h>
#endif
#include "polygon.h"

#define SWAP(a,b) {temp = a; a = b; b = temp;}

struct EdgeState {
   struct EdgeState *NextEdge;
   int X;
   int StartY;
   int WholePixelXMove;
   int XDirection;
   int ErrorTerm;
   int ErrorTermAdjUp;
   int ErrorTermAdjDown;
   int Count;
};

extern void DrawHorizontalLineSeg(int, int, int, int);
extern int FillMonotoneVerticalPolygon(struct PointListHeader *,
   int, int, int);
extern int PolygonIsMonotoneVertical(struct PointListHeader *);
static void BuildGET(struct PointListHeader *, struct EdgeState *,
   int, int);
static void MoveXSortedToAET(int);
static void ScanOutAET(int, int);
static void AdvanceAET(void);
static void XSortAET(void);

/* Pointers to global edge table (GET) and active edge table (AET) */
static struct EdgeState *GETPtr, *AETPtr;

int FillPolygon(struct PointListHeader * VertexList, int Color,
      int PolygonShape, int XOffset, int YOffset)
{
   struct EdgeState *EdgeTableBuffer;
   int CurrentY;


#ifdef CONVEX_CODE_LINKED
   /* Pass convex polygons through to fast convex polygon filler */
   if ((PolygonShape == CONVEX) ||
         PolygonIsMonotoneVertical(VertexList))
      return(FillMonotoneVerticalPolygon(VertexList, Color, XOffset,
            YOffset));
#endif

   /* It takes a minimum of 3 vertices to cause any pixels to be
      drawn; reject polygons that are guaranteed to be invisible */
   if (VertexList->Length < 3)
      return(1);
   /* Get enough memory to store the entire edge table */
   if ((EdgeTableBuffer =
         (struct EdgeState *) (malloc(sizeof(struct EdgeState) *
         VertexList->Length))) == NULL)
      return(0);  /* couldn't get memory for the edge table */
   /* Build the global edge table */
   BuildGET(VertexList, EdgeTableBuffer, XOffset, YOffset);
   /* Scan down through the polygon edges, one scan line at a time,
      so long as at least one edge remains in either the GET or AET */
   AETPtr = NULL;    /* initialize the active edge table to empty */
   CurrentY = GETPtr->StartY; /* start at the top polygon vertex */
   while ((GETPtr != NULL) || (AETPtr != NULL)) {
      MoveXSortedToAET(CurrentY);  /* update AET for this scan line */
      ScanOutAET(CurrentY, Color); /* draw this scan line from AET */
      AdvanceAET();                /* advance AET edges 1 scan line */
      XSortAET();                  /* resort on X */
      CurrentY++;                  /* advance to the next scan line */
   }
   /* Release the memory we've allocated and we're done */
   free(EdgeTableBuffer);
   return(1);
}
```

```
/* Creates a GET in the buffer pointed to by NextFreeEdgeStruc from
   the vertex list. Edge endpoints are flipped, if necessary, to
   guarantee all edges go top to bottom. The GET is sorted primarily
   by ascending Y start coordinate, and secondarily by ascending X
   start coordinate within edges with common Y coordinates. */
static void BuildGET(struct PointListHeader * VertexList,
      struct EdgeState * NextFreeEdgeStruc, int XOffset, int YOffset)
{
   int i, StartX, StartY, EndX, EndY, DeltaY, DeltaX, Width, temp;
   struct EdgeState *NewEdgePtr;
   struct EdgeState *FollowingEdge, **FollowingEdgeLink;
   struct Point *VertexPtr;

   /* Scan through the vertex list and put all non-0-height edges into
      the GET, sorted by increasing Y start coordinate */
   VertexPtr = VertexList->PointPtr;   /* point to the vertex list */
   GETPtr = NULL;    /* initialize the global edge table to empty */
   for (i = 0; i < VertexList->Length; i++) {
      /* Calculate the edge height and width */
      StartX = VertexPtr[i].X + XOffset;
      StartY = VertexPtr[i].Y + YOffset;
      /* The edge runs from the current point to the previous one */
      if (i == 0) {
         /* Wrap back around to the end of the list */
         EndX = VertexPtr[VertexList->Length-1].X + XOffset;
         EndY = VertexPtr[VertexList->Length-1].Y + YOffset;
      } else {
         EndX = VertexPtr[i-1].X + XOffset;
         EndY = VertexPtr[i-1].Y + YOffset;
      }
      /* Make sure the edge runs top to bottom */
      if (StartY > EndY) {
         SWAP(StartX, EndX);
         SWAP(StartY, EndY);
      }
      /* Skip if this can't ever be an active edge (has 0 height) */
      if ((DeltaY = EndY - StartY) != 0) {
         /* Allocate space for this edge's info, and fill in the
            structure */
         NewEdgePtr = NextFreeEdgeStruc++;
         NewEdgePtr->XDirection =   /* direction in which X moves */
               ((DeltaX = EndX - StartX) > 0) ? 1 : -1;
         Width = abs(DeltaX);
         NewEdgePtr->X = StartX;
         NewEdgePtr->StartY = StartY;
         NewEdgePtr->Count = DeltaY;
         NewEdgePtr->ErrorTermAdjDown = DeltaY;
         if (DeltaX >= 0)  /* initial error term going L->R */
            NewEdgePtr->ErrorTerm = 0;
         else              /* initial error term going R->L */
            NewEdgePtr->ErrorTerm = -DeltaY + 1;
         if (DeltaY >= Width) {     /* Y-major edge */
            NewEdgePtr->WholePixelXMove = 0;
            NewEdgePtr->ErrorTermAdjUp = Width;
         } else {                   /* X-major edge */
            NewEdgePtr->WholePixelXMove =
                  (Width / DeltaY) * NewEdgePtr->XDirection;
            NewEdgePtr->ErrorTermAdjUp = Width % DeltaY;
         }
         /* Link the new edge into the GET so that the edge list is
            still sorted by Y coordinate, and by X coordinate for all
            edges with the same Y coordinate */
         FollowingEdgeLink = &GETPtr;
         for (;;) {
            FollowingEdge = *FollowingEdgeLink;
            if ((FollowingEdge == NULL) ||
                  (FollowingEdge->StartY > StartY) ||
                  ((FollowingEdge->StartY == StartY) &&
                  (FollowingEdge->X >= StartX))) {
               NewEdgePtr->NextEdge = FollowingEdge;
               *FollowingEdgeLink = NewEdgePtr;
               break;
            }
            FollowingEdgeLink = &FollowingEdge->NextEdge;
         }
      }
   }
}

/* Sorts all edges currently in the active edge table into ascending
   order of current X coordinates */
static void XSortAET() {
   struct EdgeState *CurrentEdge, **CurrentEdgePtr, *TempEdge;
   int SwapOccurred;

   /* Scan through the AET and swap any adjacent edges for which the
      second edge is at a lower current X coord than the first edge.
      Repeat until no further swapping is needed */
   if (AETPtr != NULL) {
      do {
         SwapOccurred = 0;
         CurrentEdgePtr = &AETPtr;
         while ((CurrentEdge = *CurrentEdgePtr)->NextEdge != NULL) {
            if (CurrentEdge->X > CurrentEdge->NextEdge->X) {
               /* The second edge has a lower X than the first;
                  swap them in the AET */
               TempEdge = CurrentEdge->NextEdge->NextEdge;
               *CurrentEdgePtr = CurrentEdge->NextEdge;
               CurrentEdge->NextEdge->NextEdge = CurrentEdge;
               CurrentEdge->NextEdge = TempEdge;
               SwapOccurred = 1;
            }
            CurrentEdgePtr = &(*CurrentEdgePtr)->NextEdge;
         }
      } while (SwapOccurred != 0);
   }
}

/* Advances each edge in the AET by one scan line.
   Removes edges that have been fully scanned. */
static void AdvanceAET() {
   struct EdgeState *CurrentEdge, **CurrentEdgePtr;

   /* Count down and remove or advance each edge in the AET */
   CurrentEdgePtr = &AETPtr;
   while ((CurrentEdge = *CurrentEdgePtr) != NULL) {
      /* Count off one scan line for this edge */
      if ((--(CurrentEdge->Count)) == 0) {
         /* This edge is finished, so remove it from the AET */
         *CurrentEdgePtr = CurrentEdge->NextEdge;
      } else {
         /* Advance the edge's X coordinate by minimum move */
         CurrentEdge->X += CurrentEdge->WholePixelXMove;
         /* Determine whether it's time for X to advance one extra */
         if ((CurrentEdge->ErrorTerm +=
               CurrentEdge->ErrorTermAdjUp) > 0) {
            CurrentEdge->X += CurrentEdge->XDirection;
            CurrentEdge->ErrorTerm -= CurrentEdge->ErrorTermAdjDown;
         }
         CurrentEdgePtr = &CurrentEdge->NextEdge;
      }
   }
}

/* Moves all edges that start at the specified Y coordinate from the
   GET to the AET, maintaining the X sorting of the AET. */
static void MoveXSortedToAET(int YToMove) {
   struct EdgeState *AETEdge, **AETEdgePtr, *TempEdge;
   int CurrentX;

   /* The GET is Y sorted. Any edges that start at the desired Y
      coordinate will be first in the GET, so we'll move edges from
      the GET to AET until the first edge left in the GET is no longer
      at the desired Y coordinate. Also, the GET is X sorted within
      each Y coordinate, so each successive edge we add to the AET is
      guaranteed to belong later in the AET than the one just added. */
   AETEdgePtr = &AETPtr;
   while ((GETPtr != NULL) && (GETPtr->StartY == YToMove)) {
      CurrentX = GETPtr->X;
      /* Link the new edge into the AET so that the AET is still
         sorted by X coordinate */
      for (;;) {
         AETEdge = *AETEdgePtr;
         if ((AETEdge == NULL) || (AETEdge->X >= CurrentX)) {
            TempEdge = GETPtr->NextEdge;
            *AETEdgePtr = GETPtr;  /* link the edge into the AET */
            GETPtr->NextEdge = AETEdge;
            AETEdgePtr = &GETPtr->NextEdge;
            GETPtr = TempEdge;   /* unlink the edge from the GET */
            break;
         } else {
            AETEdgePtr = &AETEdge->NextEdge;
         }
      }
   }
}

/* Fills the scan line described by the current AET at the specified Y
   coordinate in the specified color, using the odd/even fill rule */
static void ScanOutAET(int YToScan, int Color) {
   int LeftX;
   struct EdgeState *CurrentEdge;

   /* Scan through the AET, drawing line segments as each pair of edge
      crossings is encountered. The nearest pixel on or to the right
      of left edges is drawn, and the nearest pixel to the left of but
      not on right edges is drawn */
   CurrentEdge = AETPtr;
   while (CurrentEdge != NULL) {
      LeftX = CurrentEdge->X;
      CurrentEdge = CurrentEdge->NextEdge;
      DrawHorizontalLineSeg(YToScan, LeftX, CurrentEdge->X-1, Color);
      CurrentEdge = CurrentEdge->NextEdge;
   }
}
```

LISTING 24.5 POLYGON.H

```
/* Header file for polygon-filling code */

#define CONVEX    0
#define NONCONVEX 1
#define COMPLEX   2

/* Describes a single point (used for a single vertex) */
struct Point {
   int X;   /* X coordinate */
   int Y;   /* Y coordinate */
};

/* Describes series of points (used to store a list of vertices that describe
a polygon; each vertex is assumed to connect to the two adjacent vertices, and
last vertex is assumed to connect to the first) */
struct PointListHeader {
   int Length;                /* # of points */
   struct Point * PointPtr;   /* pointer to list of points */
};

/* Describes beginning and ending X coordinates of a single horizontal line */
struct HLine {
   int XStart; /* X coordinate of leftmost pixel in line */
   int XEnd;   /* X coordinate of rightmost pixel in line */
};

/* Describes a Length-long series of horizontal lines, all assumed to be on
contiguous scan lines starting at YStart and proceeding downward (used to
describe scan-converted polygon to low-level hardware-dependent drawing code) */
struct HLineList {
   int Length;                /* # of horizontal lines */
   int YStart;                /* Y coordinate of topmost line */
   struct HLine * HLinePtr;   /* pointer to list of horz lines */
};

/* Describes a color as an RGB triple, plus one byte for other info */
struct RGB { unsigned char Red, Green, Blue, Spare; };
```

Is monotone-vertical polygon detection worth all this trouble? Under the right circumstances, you bet. In a situation where a great many polygons are being drawn, and the application either doesn't know whether they're monotone-vertical or has no way to tell the polygon filler that they are, performance can be increased considerably if most polygons are, in fact, monotone-vertical. This potential performance advantage is helped along by the surprising fact that Jim's test for monotone-vertical status is simpler and faster than my original, nonfunctional test for convexity.

See what accurate terminology and effective communication can do?

The VGA versus the Jaggies

Chapter 25

The Sierra Hicolor DAC as the Means to Antialiased Lines

Does anything evolve faster than PC hardware? Not so long ago, we thought that juicing up the crystal in an AT from 6 to 8 MHz was awesome. Now we take it for granted when Intel triples the internal speed of a 33MHz CPU, and with the Pentium's superscalar execution and 90 MHz clock speeds, the trend is, if anything, accelerating. An awful lot of the PC's evolution has involved graphics adapters, and the next couple of chapters are going to be about the first successful step away from the 256-color SuperVGAs of the late 1980s, toward the Holy Grail of 24 bits per pixel.

In computer graphics, two display characteristics are paramount: color and resolution. In 1991, SuperVGAs had taken resolution up to 1024×768, but were still stuck at the 256-color resolution that IBM had designed into the original VGA. The rule for graphics is simple—the more colors the better—and the PC world was primed for a color breakthrough. The only questions were how and when it would happen.

The first shot was fired by Edsun Laboratories, in the form of the Edsun Continuous Edge Graphics (CEG) digital to analog converter (DAC, the chip that converts pixel values from the VGA into analog signals for input to the monitor). The CEG DAC was an ingenious bridge between SuperVGAs and higher color that required no modification to VGA chips and no additional memory, yet achieved (with considerable software effort) stunning results. If you're curious about ancient history, have a look at my "Graphics Programming" column in *Dr. Dobb's Journal* for April and May 1991, where I discussed the CEG DAC in detail. If you do look up these columns, you'll also find that my record as a prophet has its blemishes—I thought the CEG DAC was going to take off, but, alas, the CEG DAC's programming model was more than difficult and (far worse) delivery schedules slipped. Only a few Edsun-equippped VGAs ever made it into the field, and the unique Edsun technology became a historical oddity, its potential unrealized.

Time and technology marched on, and later in 1991 the spotlight settled on another new device, the Sierra Semiconductor Hicolor DAC, whose mission was much the same as the CEG DAC, but with a more promising implementation. The Hicolor DAC was and is easy to program, a simple extension of the 256-color programming model; it's also affordable and a simple drop-in replacement for the standard VGA DAC. Best of all, it shipped in good order and worked as advertised right off the bat, and, consequently, met with good success.

A fairly typical high-end SuperVGA card in late 1991 and early 1992 was built around the Tseng Labs ET4000 VGA chip, 1 MB of RAM, and the Hicolor DAC, a combination that enabled support of the then-unprecedented 800×600 and 640×480, 32,768-color modes. Other technologies have appeared to crowd the Hicolor DAC off the cutting edge, but the chip is still used in low-end VGAs, and almost all new video adapters these days support high-color modes much like the ones that the Hicolor DAC pioneered. Besides, there are still lots of Hicolor DACs around in the installed base, and the Hicolor programming model is still used by most new adapters, so the Hicolor DAC is well worth understanding as one of the keys to the generation of graphics hardware that in the early 1990s swept far beyond the limits set by the original VGA.

Unreal Color

To those of us who remembered buying IBM EGAs for $1000, it was kind of unreal to see an 800×600 32K-color VGA for less than $200 back in 1991. Understand, now, that I'm not talking about clever bitmap encoding or color look-up tables or other tricky ways of boosting color here. This is the real, 15-bpp (bits per pixel), almost true-color McCoy, beautifully suited to imaging, antialiasing, and virtually any sort of high-color graphics you might imagine. The Hicolor DAC supports normal bitmaps that are just like 256-color bitmaps, except that each pixel is composed of 15 bits spread across 2 bytes. If you know how to program 800×600 256-color mode, you should have no trouble at all programming the 800×600 32K-color mode; for the most part, just double the horizontal byte counts. (Lower-resolution 32K-color modes, such as 640×480, are also available.) The 32K-color banking schemes are the same as in 256-color modes, except that there are half as many pixels in each bank. Even the complexities of the DAC's programmable palette go away in 32K-color mode, because there is no programmable palette.

And therein lies the strength of the Hicolor DAC: It's easy to program. Theoretically, the Edsun CEG DAC could produce more precise images, with higher color content, using less display memory than the Hicolor DAC, because with the CEG DAC color resolutions of 24-bpp and even higher were possible. Practically speaking, however, it was hard to write software—especially real-time software—that took full advantage of the Edsun CEG DAC's capabilities. On the other hand, it's very easy to extend existing 256-color SuperVGA code to support the Hicolor DAC, and although

32K colors (15-bpp) is not the same as true color (24-bpp), it's close enough for most purposes, and *astonishingly* better than 256 colors. Digitized and rendered images look terrific on the Hicolor DAC, just as they did on the Edsun CEG DAC—and it's a lot easier and much faster to generate such images for the Hicolor DAC.

The Gamma Correction Disadvantage

The Hicolor DAC has three disadvantages. First, it requires twice as much memory at a given resolution as does an equivalent 256-color mode. This is no longer a significant problem; memory is cheap, with 1 MB essentially standard on SuperVGAs and 2MB becoming common. (The 1024×768 32K color mode that was impossible on a 1 MB SuperVGA is easy on a board with 2MB.) Second, graphics operations can take considerably longer, simply because there are twice as many bytes of display memory to be dealt with; however, the latest generation of SuperVGAs provides for such fast memory access that 32K-color software runs faster than 256-color software did on the first generation of SuperVGAs. Finally, the Hicolor DAC neither performs gamma correction in hardware nor provides a built-in look-up table to allow programmable gamma correction.

To refresh your memory, gamma correction is the process of compensating for the nonlinear response of pixel brightness to input voltage. A pixel with a green value of 60 is much more than twice as bright as a pixel of value 30. The Hicolor DAC's lack of built-in gamma correction puts the burden on software to perform the correction so that antialiasing will work properly, and so that images such as digitized photographs will display with the proper brightness. Software gamma correction is possible, but it's a time-consuming nuisance; it also decreases the effective color resolution of the Hicolor DAC for bright colors because the bright colors supported by the Hicolor DAC are spaced relatively farther apart than the dim colors.

The lack of gamma correction is, however, a manageable annoyance. On balance, the Hicolor DAC is true to its heritage; a logical, inexpensive, and painless extension of SuperVGA. The obvious next steps are 1024×768 in 32K colors (now common enough, but very exotic in 1991), and 800×600 with 24 bpp; heck, 4 MB of display memory (eight 4-Megabit RAMS) would be enough for 1024×768 24-bpp with room to spare, and, as I write this, that's right around the corner. In short, the Hicolor DAC is squarely in the mainstream of VGA evolution. (Note that although most of the first generation of Hicolor boards were built around the Tseng ET4000, which quietly and for good reason became the preeminent SuperVGA chip of 1991 and 1992, the Hicolor DAC works with other VGA chips and can be found in SuperVGAs of all sorts.)

Polygon Antialiasing

To my mind, the best thing about the Hicolor DAC is that it makes fast, general antialiasing possible. You see, what I've been working toward in this book is real-time

3-D perspective drawing on a standard PC, without the assistance of any expensive hardware. The object model I'll be using is polygon-based; hence the fast polygon fill code I presented a few chapters back. With Mode X (320×240, 256 colors, undocumented by IBM but covered in this book in Part VIII), we now have a fast, square-pixel, page-flipped, 256-color mode, the best that standard VGA has to offer. In this mode, it's possible to do not only real-time, polygon-based perspective drawing and animation, but also relatively sophisticated effects such as lighting sources, smooth shading, and hidden surface removal. That's everything we need for real-time 3-D—but things could still be better.

Pixels are so large in Mode X that polygons have *very* visibly jagged edges. These jaggies are the result of *aliasing*; that is, distortion of the true image that results from undersampling at the low pixel rate of the screen. Jaggies are a serious problem; the whole point of real-time 3-D is to create the illusion of reality, but jaggies quickly destroy that illusion, particularly when they're crawling along the edges of moving objects. More frequent sampling (higher resolution) helps, but not as much as you'd think. What's really needed is the ability to blend colors arbitrarily within a single pixel, the better to reflect the nature of the true image in the neighborhood of that pixel—that is, *antialiasing*. The pixels are still as large as ever, but with the colors blended properly, the eye processes the screen as a continuous image, rather than as a collection of discrete pixels, and perceives the image at much higher resolution than the display actually supports.

There are many ways to antialias, some of them fast enough for real-time processing, and they can work wonders in improving image appearance—but they all require a high degree of freedom in choosing colors. For many sorts of graphics, 256 simultaneous colors is fine, but it's not enough for generally useful antialiasing (although we will shortly see an interesting sort of special-case antialiasing with 256 colors). Therefore, the one element lacking in standard SuperVGA for affordable real-time 3-D has been good antialiasing.

Sierra filled that gap. The Hicolor DAC provides plenty of colors (although I sure do wish the software didn't have to do gamma correction!) and makes them available in a way that allows for efficient programming. In the next chapter, I'll present antialiasing code for the Hicolor DAC.

256-Color Antialiasing

In the next chapter, I'll explain how the Hicolor DAC actually works—how to detect it, how to initialize it, the pixel format, banking, and so on—and then I'll demonstrate Hicolor antialiasing. For now, I'm going to demonstrate antialiasing on a standard

VGA, partly to introduce the uncomplicated but effective antialiasing technique that I'll use in the next chapter, partly so you can see the improvement that even quick and dirty antialiasing produces, and partly to show the sorts of interesting things that can be done with the palette in 256-color mode.

I'm going to draw a cube in perspective. For reference, Listing 25.1 draws the cube in mode 13H (320×200, 256 colors) using the standard polygon fill routine that I developed back in Chapters 21 and 22. No, the perspective calculations aren't performed in Listing 25.1; I just got the polygon vertices out of some 3-D software that I'm developing and hardwired them into Listing 25.1. Never fear, though; we'll get to true 3-D soon enough.

Some listings from previous chapters are required to build the executable files for this chapter (including the edge-scanning code in Listing 22.2 and POLYGON.H), but to lessen the confusion all of these are present in the Chapter 25 subdirectory on the listings diskette.

Listing 25.1 draws a serviceable cube, but the edges of the cube are very jagged. Imagine the cube spinning, and the jaggies rippling along its edges, and you'll see the full dimensions of the problem.

LISTING 25.1 L25-1.C

```
/* Demonstrates non-antialiased drawing in 256 color mode. Tested with
   Borland C++ in C mode in the small model. */

#include <conio.h>
#include <dos.h>
#include "polygon.h"

/* Draws the polygon described by the point list PointList in color
   Color with all vertices offset by (X,Y) */
#define DRAW_POLYGON(PointList,Color,X,Y)                   \
   Polygon.Length = sizeof(PointList)/sizeof(struct Point); \
   Polygon.PointPtr = PointList;                            \
   FillConvexPolygon(&Polygon, Color, X, Y);

void main(void);
extern int FillConvexPolygon(struct PointListHeader *, int, int, int);

/* Palette RGB settings to load the first four palette locations with
   black, pure blue, pure green, and pure red */
static char Palette[4*3] = {0, 0, 0,  0, 0, 63,  0, 63, 0,  63, 0, 0};

void main()
{
   struct PointListHeader Polygon;
   static struct Point Face0[] =
        {{198,138},{211,89},{169,44},{144,89}};
   static struct Point Face1[] =
        {{153,150},{198,138},{144,89},{105,113}};
   static struct Point Face2[] =
        {{169,44},{133,73},{105,113},{144,89}};
   union REGS regset;
   struct SREGS sregs;
   /* Set the display to VGA mode 13h, 320x200 256-color mode */
   regset.x.ax = 0x0013; int86(0x10, &regset, &regset);

   /* Set color 0 to black, color 1 to pure blue, color 2 to pure
      green, and color 3 to pure red */
   regset.x.ax = 0x1012;   /* load palette block BIOS function */
   regset.x.bx = 0;        /* start with palette register 0 */
   regset.x.cx = 4;        /* set four palette registers */
   regset.x.dx = (unsigned int) Palette;
   segread(&sregs);
   sregs.es = sregs.ds;       /* point ES:DX to Palette */
   int86x(0x10, &regset, &regset, &sregs);

   /* Draw the cube */
   DRAW_POLYGON(Face0, 3, 0, 0);
   DRAW_POLYGON(Face1, 2, 0, 0);
   DRAW_POLYGON(Face2, 1, 0, 0);
   getch();    /* wait for a keypress */

   /* Return to text mode and exit */
   regset.x.ax = 0x0003;   /* AL = 3 selects 80x25 text mode */
   int86(0x10, &regset, &regset);
}
```

Listings 25.2 and 25.3 together draw the same cube, but with simple, unweighted antialiasing. The results are much better than Listing 25.1; there's no question in my mind as to which cube I'd rather see in my graphics software.

LISTING 25.2 L25-2.C

```
/* Demonstrates unweighted antialiased drawing in 256 color mode.
   Tested with Borland C++ in C mode in the small model. */

#include <conio.h>
#include <dos.h>
#include <stdlib.h>
#include <string.h>
#include "polygon.h"

/* Draws the polygon described by the point list PointList in color
   Color, with all vertices offset by (X,Y), to ScanLineBuffer, at
   double horizontal and vertical resolution */
#define DRAW_POLYGON_DOUBLE_RES(PointList,Color,x,y)        \
   Polygon.Length = sizeof(PointList)/sizeof(struct Point); \
   Polygon.PointPtr = PointTemp;                            \
   /* Double all vertical & horizontal coordinates */       \
   for (k=0; k<sizeof(PointList)/sizeof(struct Point); k++) { \
      PointTemp[k].X = PointList[k].X * 2;                  \
      PointTemp[k].Y = PointList[k].Y * 2;                  \
   }                                                        \
   FillCnvxPolyDrvr(&Polygon, Color, x, y, DrawBandedList);

#define SCREEN_WIDTH 320
#define SCREEN_HEIGHT 200
#define SCREEN_SEGMENT 0xA000
#define SCAN_BAND_WIDTH (SCREEN_WIDTH*2)  /* # of double-res pixels
                                             across scan band */
```

```
#define BUFFER_SIZE  (SCREEN_WIDTH*2*2)   /* enough space for one scan
                                           line scanned out at double
                                           resolution horz and vert */
void main(void);
void DrawPixel(int, int, char);
int ColorComponent(int, int);
extern int FillCnvxPolyDrvr(struct PointListHeader *, int, int, int,
   void (*)());
extern void DrawBandedList(struct HLineList *, int);

/* Pointer to buffer in which double-res scanned data will reside */
unsigned char *ScanLineBuffer;
int ScanBandStart, ScanBandEnd;  /* top & bottom of each double-res
                                  band we'll draw to ScanLineBuffer */
int ScanBandWidth = SCAN_BAND_WIDTH;  /* # pixels across scan band */
static char Palette[256*3];

void main()
{
   int i, j, k;
   struct PointListHeader Polygon;
   struct Point PointTemp[4];
   static struct Point Face0[] =
         {{198,138},{211,89},{169,44},{144,89}};
   static struct Point Face1[] =
         {{153,150},{198,138},{144,89},{105,113}};
   static struct Point Face2[] =
         {{169,44},{133,73},{105,113},{144,89}};
   unsigned char Megapixel;
   union REGS regset;
   struct SREGS sregs;

   if ((ScanLineBuffer = malloc(BUFFER_SIZE)) == NULL) {
      printf("Couldn't get memory\n");
      exit(0);
   }

   /* Set the display to VGA mode 13h, 320x200 256-color mode */
   regset.x.ax = 0x0013; int86(0x10, &regset, &regset);

   /* Stack the palette for the desired megapixel effect, with each
      2-bit field representing 1 of 4 double-res pixels in one of four
      colors */
   for (i=0; i<256; i++) {
      Palette[i*3] = ColorComponent(i, 3);   /* red component */
      Palette[i*3+1] = ColorComponent(i, 2); /* green component */
      Palette[i*3+2] = ColorComponent(i, 1); /* blue component */
   }
   regset.x.ax = 0x1012;   /* load palette block BIOS function */
   regset.x.bx = 0;        /* start with palette register 0 */
   regset.x.cx = 256;      /* set all 256 palette registers */
   regset.x.dx = (unsigned int) Palette;
   segread(&sregs);
   sregs.es = sregs.ds;       /* point ES:DX to Palette */
   int86x(0x10, &regset, &regset, &sregs);

   /* Scan out the polygons at double resolution one screen scan line
      at a time (two double-res scan lines at a time) */
   for (i=0; i<SCREEN_HEIGHT; i++) {
      /* Set the band dimensions for this pass */
      ScanBandEnd = (ScanBandStart = i*2) + 1;
      /* Clear the drawing buffer */
      memset(ScanLineBuffer, 0, BUFFER_SIZE);
      /* Draw the current band of the cube to the scan line buffer */
      DRAW_POLYGON_DOUBLE_RES(Face0, 3, 0, 0);
      DRAW_POLYGON_DOUBLE_RES(Face1, 2, 0, 0);
      DRAW_POLYGON_DOUBLE_RES(Face2, 1, 0, 0);

      /* Coalesce the double-res pixels into normal screen pixels
         and draw them */
      for (j=0; j<SCREEN_WIDTH; j++) {
         Megapixel = (ScanLineBuffer[j*2] << 6) +
                     (ScanLineBuffer[j*2+1] << 4) +
                     (ScanLineBuffer[j*2+SCAN_BAND_WIDTH] << 2) +
                     (ScanLineBuffer[j*2+SCAN_BAND_WIDTH+1]);
         DrawPixel(j, i, Megapixel);
      }
   }

   getch();    /* wait for a keypress */

   /* Return to text mode and exit */
   regset.x.ax = 0x0003;   /* AL = 3 selects 80x25 text mode */
   int86(0x10, &regset, &regset);
}

/* Draws a pixel of color Color at (X,Y) in mode 13h */
void DrawPixel(int X, int Y, char Color)
{
   char far *ScreenPtr;

   ScreenPtr = (char far *)MK_FP(SCREEN_SEGMENT, Y*SCREEN_WIDTH+X);
   *ScreenPtr = Color;
}

/* Returns the gamma-corrected value representing the number of
   double-res pixels containing the specified color component in a
   megapixel with the specified value */
int ColorComponent(int Value, int Component)
{
   /* Palette settings for 0%, 25%, 50%, 75%, and 100% brightness,
      assuming a gamma value of 2.3 */
   static int GammaTable[] = {0, 34, 47, 56, 63};
   int i;

   /* Add up the number of double-res pixels of the specified color
      in a megapixel of this value */
   i = (((Value & 0x03) == Component) ? 1 : 0) +
       ((((Value >> 2) & 0x03) == Component) ? 1 : 0) +
       ((((Value >> 4) & 0x03) == Component) ? 1 : 0) +
       ((((Value >> 6) & 0x03) == Component) ? 1 : 0);
   /* Look up brightness of the specified color component in a
      megapixel of this value */
   return GammaTable[i];
}
```

LISTING 25.3 L25-3.C

```
/* Draws pixels from the list of horizontal lines passed in; drawing
   takes place only for scan lines between ScanBandStart and
   ScanBandEnd, inclusive; drawing goes to ScanLineBuffer, with
   the scan line at ScanBandStart mapping to the first scan line in
   ScanLineBuffer. Intended for use in unweighted antialiasing,
   whereby a polygon is scanned out into a buffer at a multiple of the
   screen's resolution, and then the scanned-out info in the buffer is
   grouped into megapixels that are mapped to the closest
   approximation the screen supports and drawn. Tested with Borland
   C++ in C mode in the small model */

#include <string.h>
#include <dos.h>
#include "polygon.h"

extern unsigned char *ScanLineBuffer;  /* drawing goes here */
extern int ScanBandStart, ScanBandEnd; /* limits of band to draw */
extern int ScanBandWidth;  /* # of pixels across scan band */

void DrawBandedList(struct HLineList * HLineListPtr, int Color)
{
   struct HLine *HLinePtr;
   int Length, Width, YStart = HLineListPtr->YStart;
   unsigned char *BufferPtr;

   /* Done if fully off the bottom or top of the band */
   if (YStart > ScanBandEnd) return;
   Length = HLineListPtr->Length;
   if ((YStart + Length) <= ScanBandStart) return;

   /* Point to the XStart/XEnd descriptor for the first (top)
      horizontal line */
   HLinePtr = HLineListPtr->HLinePtr;

   /* Confine drawing to the specified band */
   if (YStart < ScanBandStart) {
      /* Skip ahead to the start of the band */
      Length -= ScanBandStart - YStart;
      HLinePtr += ScanBandStart - YStart;
      YStart = ScanBandStart;
   }
   if (Length > (ScanBandEnd - YStart + 1))
      Length = ScanBandEnd - YStart + 1;

   /* Point to the start of the first scan line on which to draw */
   BufferPtr = ScanLineBuffer + (YStart - ScanBandStart) *
         ScanBandWidth;

   /* Draw each horizontal line within the band in turn, starting with
      the top one and advancing one line each time */
   while (Length-- > 0) {
      /* Draw the whole horizontal line if it has a positive width */
      if ((Width = HLinePtr->XEnd - HLinePtr->XStart + 1) > 0)
         memset(BufferPtr + HLinePtr->XStart, Color, Width);
      HLinePtr++;                /* point to next scan line X info */
      BufferPtr += ScanBandWidth; /* point to next scan line start */
   }
}
```

The antialiasing technique used in Listing 25.2 is straightforward. Each polygon is scanned out in the usual way, but at twice the screen's resolution both horizontally and vertically (which I'll call "double-resolution," although it produces four times as many pixels), with the double-resolution pixels drawn to a memory buffer, rather than directly to the screen.

Then, after all the polygons have been drawn to the memory buffer, a second pass is performed. This pass looks at the colors stored in each set of four double-resolution pixels, and draws to the screen a single pixel that reflects the colors and intensities of the four double-resolution pixels that make it up, as shown in Figure 25.1. In other words, Listing 25.2 temporarily draws the polygons at double resolution, then uses the extra information from the double-resolution bitmap to generate an image with an effective resolution considerably higher than the screen's actual 320×200 capabilities.

Two interesting tricks are employed in Listing 25.2. First, it would be best from the standpoint of speed if the entire screen could be drawn to the double-resolution intermediate buffer in a single pass. Unfortunately, a buffer capable of holding one full 640×400 screen would be 256K bytes in size—too much memory for most programs to spare. Consequently, Listing 25.2 instead scans out the image just two double-resolution scan lines (corresponding to one screen scan line) at a time. That is, the entire image is scanned once for every two double-resolution scan lines, and all information not concerning the two lines of current interest is thrown away. This banding is implemented in Listing 25.3, which accepts a full list of scan lines to draw, but actually draws only those lines within the current scan line band. Listing 25.3 also draws to the intermediate buffer, rather than to the screen.

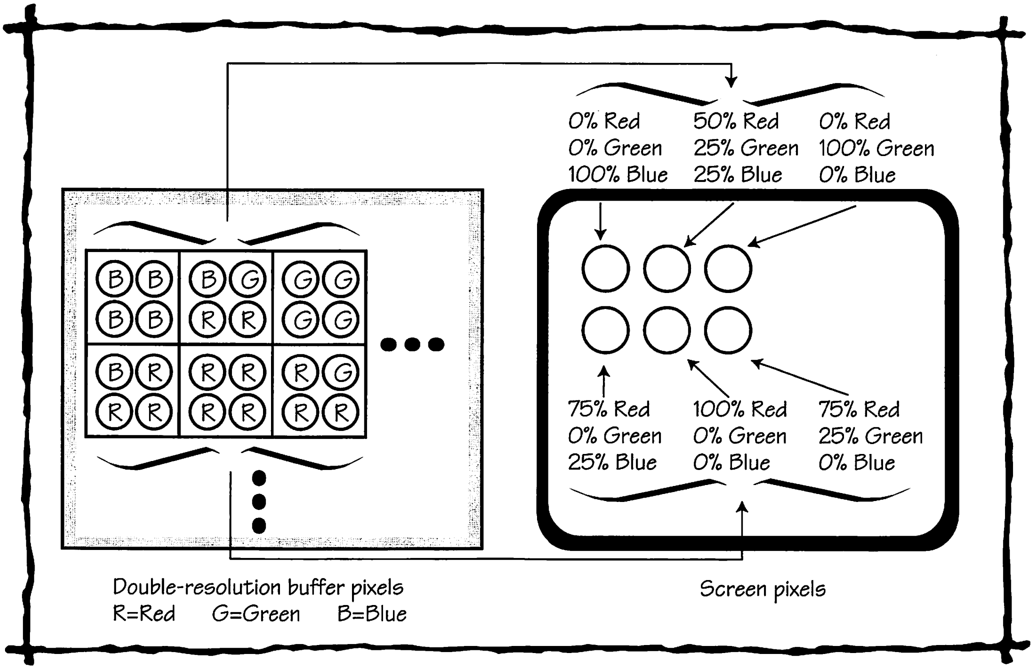


Figure 25.1 Mapping Double-Resolution Pixels to Single Screen Pixels

The polygon-scanning code from Chapter 21 was hard-wired to call the function **DrawHorizontalLineList**, which drew to the display; this is the polygon-drawing code called by Listing 25.1. That was fine so long as there was only one possible drawing target, but now we have two possible targets—the display (for nonantialiased drawing), and the intermediate buffer (for antialiased drawing). It's desirable to be able to mix the two, even within a single screen, because antialiased drawing looks better but nonantialiased is faster. Consequently, I have modified Listing 21.1 from Chapter 21—the function **FillConvexPolygon**—to create **FillCnvxPolyDrvr**, which is the same as **FillConvexPolygon**, except that it accepts as a parameter the name of the function to be used to draw the scanned-out polygon. The modified file is shown in its entirety in Listing 25.4.

LISTING 25.4 FILCNVX.C

```
/* Color-fills a convex polygon, using the passed-in driver to perform
   all drawing. All vertices are offset by (XOffset, YOffset).
   "Convex" means that every horizontal line drawn through the polygon
   at any point would cross exactly two active edges (neither
   horizontal lines nor zero-length edges count as active edges; both
   are acceptable anywhere in the polygon), and that the right & left
   edges never cross. (It's OK for them to touch, though, so long as
   the right edge never crosses over to the left of the left edge.)
   Nonconvex polygons won't be drawn properly. Returns 1 for success,
   0 if memory allocation failed. */

#include <stdio.h>
#include <math.h>
#ifdef __TURBOC__
#include <alloc.h>
#else    /* MSC */
#include <malloc.h>
#endif
#include "polygon.h"

/* Advances the index by one vertex forward through the vertex list,
   wrapping at the end of the list */
#define INDEX_FORWARD(Index) \
   Index = (Index + 1) % VertexList->Length;

/* Advances the index by one vertex backward through the vertex list,
   wrapping at the start of the list */
#define INDEX_BACKWARD(Index) \
   Index = (Index - 1 + VertexList->Length) % VertexList->Length;

/* Advances the index by one vertex either forward or backward through
   the vertex list, wrapping at either end of the list */
#define INDEX_MOVE(Index,Direction)                                  \
   if (Direction > 0)                                                \
      Index = (Index + 1) % VertexList->Length;                      \
   else                                                              \
      Index = (Index - 1 + VertexList->Length) % VertexList->Length;

void ScanEdge(int, int, int, int, int, int, struct HLine **);
```

```
int FillCnvxPolyDrvr(struct PointListHeader * VertexList, int Color,
      int XOffset, int YOffset, void (*DrawListFunc)())
{
   int i, MinIndexL, MaxIndex, MinIndexR, SkipFirst, Temp;
   int MinPoint_Y, MaxPoint_Y, TopIsFlat, LeftEdgeDir;
   int NextIndex, CurrentIndex, PreviousIndex;
   int DeltaXN, DeltaYN, DeltaXP, DeltaYP;
   struct HLineList WorkingHLineList;
   struct HLine *EdgePointPtr;
   struct Point *VertexPtr;

   /* Point to the vertex list */
   VertexPtr = VertexList->PointPtr;

   /* Scan the list to find the top and bottom of the polygon */
   if (VertexList->Length == 0)
      return(1);  /* reject null polygons */
   MaxPoint_Y = MinPoint_Y = VertexPtr[MinIndexL = MaxIndex = 0].Y;
   for (i = 1; i < VertexList->Length; i++) {
      if (VertexPtr[i].Y < MinPoint_Y)
         MinPoint_Y = VertexPtr[MinIndexL = i].Y; /* new top */
      else if (VertexPtr[i].Y > MaxPoint_Y)
         MaxPoint_Y = VertexPtr[MaxIndex = i].Y; /* new bottom */
   }
   if (MinPoint_Y == MaxPoint_Y)
      return(1);  /* polygon is 0-height; avoid infinite loop below */

   /* Scan in ascending order to find the last top-edge point */
   MinIndexR = MinIndexL;
   while (VertexPtr[MinIndexR].Y == MinPoint_Y)
      INDEX_FORWARD(MinIndexR);
   INDEX_BACKWARD(MinIndexR); /* back up to last top-edge point */

   /* Now scan in descending order to find the first top-edge point. */
   while (VertexPtr[MinIndexL].Y == MinPoint_Y)
      INDEX_BACKWARD(MinIndexL);
   INDEX_FORWARD(MinIndexL); /* back up to first top-edge point */

   /* Figure out which direction through the vertex list from the top
      vertex is the left edge and which is the right */
   LeftEdgeDir = -1; /* assume left edge runs down thru vertex list */
   if ((TopIsFlat = (VertexPtr[MinIndexL].X !=
         VertexPtr[MinIndexR].X) ? 1 : 0) == 1) {
      /* If the top is flat, just see which of the ends is leftmost */
      if (VertexPtr[MinIndexL].X > VertexPtr[MinIndexR].X) {
         LeftEdgeDir = 1;  /* left edge runs up through vertex list */
         Temp = MinIndexL;       /* swap the indices so MinIndexL   */
         MinIndexL = MinIndexR;  /* points to the start of the left */
         MinIndexR = Temp;       /* edge, similarly for MinIndexR   */
      }
   } else {
      /* Point to the downward end of the first line of each of the
         two edges down from the top */
      NextIndex = MinIndexR;
      INDEX_FORWARD(NextIndex);
      PreviousIndex = MinIndexL;
      INDEX_BACKWARD(PreviousIndex);
      /* Calculate X and Y lengths from the top vertex to the end of
         the first line down each edge; use those to compare slopes
         and see which line is leftmost */
      DeltaXN = VertexPtr[NextIndex].X - VertexPtr[MinIndexL].X;
   DeltaYN = VertexPtr[NextIndex].Y - VertexPtr[MinIndexL].Y;
   DeltaXP = VertexPtr[PreviousIndex].X - VertexPtr[MinIndexL].X;
   DeltaYP = VertexPtr[PreviousIndex].Y - VertexPtr[MinIndexL].Y;
   if (((long)DeltaXN * DeltaYP - (long)DeltaYN * DeltaXP) < 0L) {
      LeftEdgeDir = 1;  /* left edge runs up through vertex list */
      Temp = MinIndexL;       /* swap the indices so MinIndexL   */
      MinIndexL = MinIndexR;  /* points to the start of the left */
      MinIndexR = Temp;       /* edge, similarly for MinIndexR   */
   }
}

/* Set the # of scan lines in the polygon, skipping the bottom edge
   and also skipping the top vertex if the top isn't flat because
   in that case the top vertex has a right edge component, and set
   the top scan line to draw, which is likewise the second line of
   the polygon unless the top is flat. */
if ((WorkingHLineList.Length =
      MaxPoint_Y - MinPoint_Y - 1 + TopIsFlat) <= 0)
   return(1);  /* there's nothing to draw, so we're done */
WorkingHLineList.YStart = YOffset + MinPoint_Y + 1 - TopIsFlat;

/* Get memory in which to store the line list we generate */
if ((WorkingHLineList.HLinePtr =
      (struct HLine *) (malloc(sizeof(struct HLine) *
      WorkingHLineList.Length))) == NULL)
   return(0);  /* couldn't get memory for the line list */

/* Scan the left edge and store the boundary points in the list */
/* Initial pointer for storing scan converted left-edge coords */
EdgePointPtr = WorkingHLineList.HLinePtr;
/* Start from the top of the left edge */
PreviousIndex = CurrentIndex = MinIndexL;
/* Skip the first point of the first line unless the top is flat;
   if the top isn't flat, the top vertex is exactly on a right
   edge and isn't drawn */
SkipFirst = TopIsFlat ? 0 : 1;
/* Scan convert each line in the left edge from top to bottom */
do {
   INDEX_MOVE(CurrentIndex,LeftEdgeDir);
   ScanEdge(VertexPtr[PreviousIndex].X + XOffset,
         VertexPtr[PreviousIndex].Y,
         VertexPtr[CurrentIndex].X + XOffset,
         VertexPtr[CurrentIndex].Y, 1, SkipFirst, &EdgePointPtr);
   PreviousIndex = CurrentIndex;
   SkipFirst = 0; /* scan convert the first point from now on */
} while (CurrentIndex != MaxIndex);

/* Scan the right edge and store the boundary points in the list */
EdgePointPtr = WorkingHLineList.HLinePtr;
PreviousIndex = CurrentIndex = MinIndexR;
SkipFirst = TopIsFlat ? 0 : 1;
/* Scan convert the right edge, top to bottom. X coordinates are
   adjusted 1 to the left, effectively causing scan conversion of
   the nearest points to the left of but not exactly on the edge */
do {
   INDEX_MOVE(CurrentIndex,-LeftEdgeDir);
   ScanEdge(VertexPtr[PreviousIndex].X + XOffset - 1,
         VertexPtr[PreviousIndex].Y,
         VertexPtr[CurrentIndex].X + XOffset - 1,
         VertexPtr[CurrentIndex].Y, 0, SkipFirst, &EdgePointPtr);
   PreviousIndex = CurrentIndex;
```

```
      SkipFirst = 0; /* scan convert the first point from now on */
   } while (CurrentIndex != MaxIndex);

   /* Draw the line list representing the scan converted polygon */
   (*DrawListFunc)(&WorkingHLineList, Color);

   /* Release the line list's memory and we're successfully done */
   free(WorkingHLineList.HLinePtr);
   return(1);
}
```

The second interesting trick in Listing 25.2 is the way in which the palette is stacked to allow unweighted antialiasing. Listing 25.2 arranges the palette so that rather than 256 independent colors, we'll work with four-way combinations within each pixel of three independent colors (red, green, and blue), with each pixel accurately reflecting the intensities of each of the four color components (double-resolution pixels) that it contains. This allows fast and easy mapping from four double-resolution pixels to the single screen pixel to which they correspond. Figure 25.2 illustrates the mapping of subpixels (double-resolution pixels) through the palette to screen pixels. This palette organization converts mode 13H from a 256-color mode to a three-color antialiasing mode.

It's worth noting that many palette registers are set to identical values by Listing 25.2, because whereas the values of subpixels matter, arrangements of these values do not.

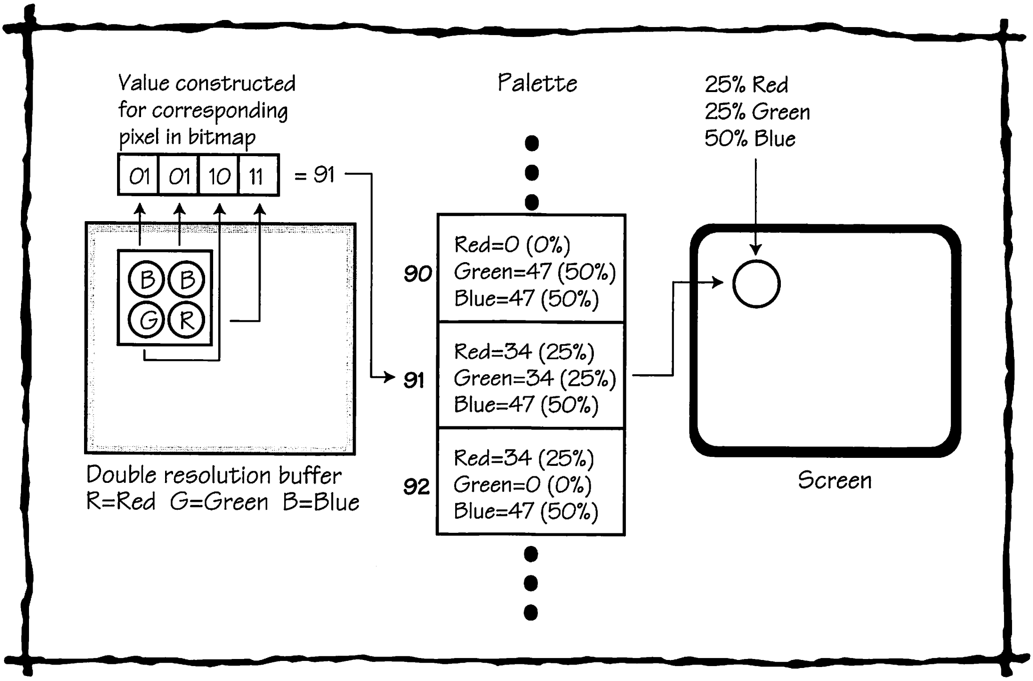


Figure 25.2 From the Double-Resolution Buffer to the Screen

For example, the pixel values 0x01, 0x04, 0x10, and 0x40 all map to 25 percent blue. By using a table look-up to map sets of four double-resolution pixels to screen pixel values, more than half the palette could be freed up for drawing with other colors.

Unweighted Antialiasing: How Good?

Is the antialiasing used in Listing 25.2 the finest possible antialiasing technique? It is not. It is an *unweighted* antialiasing technique, meaning that no accounting is made for how close to the center of a pixel a polygon edge might be. The edges are also biased a half-pixel or so in some cases, so registration with the underlying image isn't perfect. Nonetheless, the technique used in Listing 25.2 produces attractive results, which is what really matters; keep in mind that *all* screen displays are approximations, and unweighted antialiasing is certainly good enough for PC animation applications. Unweighted antialiasing can also support good performance, although this is not the case in Listings 25.2 and 25.3, where I have opted for clarity rather than performance. Increasing the number of lines drawn on each pass, or reducing the area processed to the smallest possible bounding rectangle, would help improve performance, as, of course, would the use of assembly language.

For further information on antialiasing, you might check out the standard reference: *Computer Graphics: Principles and Practice,* by Foley and Van Dam. Michael Covington's "Smooth Views," in the May, 1990 *Byte*, provides a short but meaty discussion of unweighted line antialiasing.

As relatively good as it looks, Listing 25.2 is still watered-down antialiasing, even of the unweighted variety. For all our clever palette stacking, we have only five levels of each primary color available; that's a far cry from the 32 levels of the Hicolor DAC, or the 256 levels of true color. The limitations of 256-color modes, even with the palette, are showing through.

In the next chapter, we'll take a look at how much better 15-bpp antialiasing can be.

Lines, Italian Style

Chapter 26

Using the Sierra Hicolor DAC to Make Errant Lines Look Good

There's an Italian saying, the gist of which is, "It need not be true, so long as it's well said." This strikes close to the essential truth of antialiasing: The image need not be accurate, so long as it *looks* like it is. You don't go to the trouble of antialiasing in order to get a mathematically precise representation of an image; you do it so the amazing human eye/brain integrating/pattern matching system will see what you want it to see.

This is a particularly relevant thought at the moment, for we're smack in the middle of discussing the Sierra Hicolor DAC, which makes classic, high-quality antialiasing, of the sort that Targa boards have offered for years, available at mass-market prices. To recap, the Hicolor DAC extends SuperVGA to provide selection among enough colors for serious rendering and antialiasing; 32,768 simultaneous colors, to be exact. The Hicolor DAC falls short of the 24-bpp true color standard, but you aren't likely to find a 24-bpp true color adapter priced anywhere close to what a Hicolor-based board is (although this is changing).

In the previous chapter, we looked at simple, unweighted antialiasing in the context of the VGA's standard 256-color mode, performing antialiasing between exactly three colors—red, green, and blue—with five semi-independent levels of each of the three primary colors available. In this chapter, we'll start off by discussing the basic Hicolor programming model, then we'll do the same sort of antialiasing as we did in the previous chapter—but this time with 32 fully independent levels of each primary color and resolutions up to 800×600, which makes quite a difference indeed.

A Brief Primer on the Sierra Hicolor DAC

The operation of the Hicolor DAC in 32K-color mode is remarkably simple. First, the VGA must be set to a 256-color mode with twice the desired horizontal resolution; for example, a 1600×600 256-color mode would be selected if 800×600 32K-color mode were desired. Then, the Hicolor DAC is set to high-color mode via the command register; in high-color mode, the Hicolor DAC takes each pair of 256-color pixels, joins them together into one 16-bit pixel, converts the red, green, and blue components (described shortly) directly to proportional analog values (no palette is involved), and sends them to the monitor.

There is a serious problem here, however: There is no standard way for an application to select a high-color mode. It's not enough to set up the Hicolor DAC; the VGA must also be set to the appropriate double-resolution 256-color mode, and the sequence for doing that—especially selecting high-speed clocks—varies from VGA to VGA. There is no VESA mode number for high-color modes; there is a VESA programming guideline for high-color modes, but it's certainly not as simple as a mode number. In any case, the VESA interface isn't always available.

Consequently, high-color mode selection is adapter-dependent. Fortunately, many of the Hicolor-based boards are built around the Tseng Labs ET4000 VGA chip, and Tseng provides a BIOS interface for high-color modes. (There's no guarantee that manufacturers using the ET4000 will follow the Tseng interface, but I suspect they will, as it's the closest thing to a standard at the moment.) Unfortunately, when I run the ET4000 BIOS function that reports whether a Hicolor DAC is present on my Toshiba portable without a Hicolor board installed, it hangs my system, so it's not a good idea to rely on the BIOS functions alone.

My solution, shown in Listing 26.1, is to first check for a Hicolor DAC and an ET4000 at the hardware level; if both are present, I call the BIOS (which is presumably at least not hostile to the Tseng BIOS high-color extensions at this point) to check for the availability of Hicolor modes, and finally, if all has gone well, to set the desired high-color mode. This is probably overkill, but at least this way you get three kinds of chip ID code to mix and match as you wish.

LISTING 26.1 L26-1.C

```
/* Looks for a Sierra Hicolor DAC; if one is present, puts the VGA into the
specified Hicolor (32K color) mode. Relies on the Tseng Labs ET4000 BIOS and
hardware; probably will not work on adapters built around other VGA chips.
Returns 1 for success, 0 for failure; failure can result from no Hicolor DAC,
too little display memory, or lack of an ET4000. Tested with Borland C++
in C mode in the small model. */

#include <dos.h>
#define DAC_MASK  0x3C6 /* DAC pixel mask reg address, also Sierra
                           command reg address when enabled */
#define DAC_WADDR 0x3C8  /* DAC write address reg address */
```

```
/* Mode selections: 0x2D=640x350; 0x2E=640x480; 0x2F=640x400; 0x30=800x600 */
int SetHCMode(int Mode) {
   int i, Temp1, Temp2, Temp3;
   union REGS regset;

   /* See if a Sierra SC1148X Hicolor DAC is present, by trying to
      program and then read back the DAC's command register. (Shouldn't be
      necessary when using the BIOS Get DAC Type function, but the BIOS function
      locks up some computers, so it's safer to check the hardware first). */
   inp(DAC_WADDR); /* reset the Sierra command reg enable sequence */
   for (i=0; i<4; i++) inp(DAC_MASK); /* enable command reg access */
   outp(DAC_MASK, 0x00); /* set command reg (if present) to 0x00, and
                            reset command reg enable sequence */
   outp(DAC_MASK, 0xFF); /* command reg access no longer enabled;
                            set pixel mask register to 0xFF */
   for (i=0; i<4; i++) inp(DAC_MASK); /* enable command reg access */
   /* If this is a Hicolor DAC, we should read back the 0 in the
      command reg; otherwise we get the 0xFF in the pixel mask reg */
   i = inp(DAC_MASK); inp(DAC_WADDR); /* reset enable sequence */
   if (i == 0xFF) return(0);

   /* Check for a Tseng Labs ET4000 by poking unique regs, (assumes
      VGA configured for color, w/CRTC addressing at 3D4/5) */
   outp(0x3BF, 3); outp(0x3D8, 0xA0);  /* unlock extended registers */
   /* Try toggling AC R16 bit 4 and seeing if it takes */
   inp(0x3DA); outp(0x3C0, 0x16 | 0x20);
   outp(0x3C0, ((Temp1 = inp(0x3C1)) | 0x10)); Temp2 = inp(0x3C1);
   outp(0x3C0, 0x16 | 0x20); outp(0x3C0, (inp(0x3C1) & ~0x10));
   Temp3 = inp(0x3C1); outp(0x3C0, 0x16 | 0x20);
   outp(0x3C0, Temp1);  /* restore original AC R16 setting */
   /* See if the bit toggled; if so, it's an ET3000 or ET4000 */
   if ((Temp3 & 0x10) || !(Temp2 & 0x10)) return(0);
   outp(0x3D4, 0x33); Temp1 = inp(0x3D5); /* get CRTC R33 setting */
   outp(0x3D5, 0x0A); Temp2 = inp(0x3D5); /* try writing to CRTC */
   outp(0x3D5, 0x05); Temp3 = inp(0x3D5); /*  R33 */
   outp(0x3D5, Temp1);  /* restore original CRTC R33 setting */
   /* If the register was writable, it's an ET4000 */
   if ((Temp3 != 0x05) || (Temp2 != 0x0A)) return(0);

   /* See if a Sierra SC1148X Hicolor DAC is present by querying the
      (presumably) ET4000-compatible BIOS. Not really necessary after
      the hardware check above, but generally more useful; in the
      future it will return information about other high-color DACs. */
   regset.x.ax = 0x10F1;   /* Get DAC Type BIOS function # */
   int86(0x10, &regset, &regset); /* ask BIOS for the DAC type */
   if (regset.x.ax != 0x0010) return(0); /* function not supported */
   switch (regset.h.bl) {
      case 0:  return(0);  /* normal DAC (non-Hicolor) */
      case 1:  break;      /* Sierra SC1148X 15-bpp Hicolor DAC */
      default: return(0);  /* other high-color DAC */
   }

   /* Set Hicolor mode */
   regset.x.ax = 0x10F0;   /* Set High-Color Mode BIOS function # */
   regset.h.bl = Mode;     /* desired resolution */
   int86(0x10, &regset, &regset); /* have BIOS enable Hicolor mode */
   return (regset.x.ax == 0x0010); /* 1 for success, 0 for failure */
}
```

Programming the Hicolor DAC

The pixel format of the Hicolor DAC is straightforward: Each pixel is stored in one word of display memory, with the lowest 5 bits forming the blue component, the next 5 bits forming the green component, the next 5 bits forming the red component, and bit 15 ignored, as shown in Figure 26.1. Pixels start at even addresses. The bits within a word are organized Intel style, with the byte at the even address containing bits 7–0 (blue and part of green), and the byte at the odd address containing bits 15–8 (red and the rest of green).

Pixels proceed linearly for the length of the bitmap; the organization is the same as 256-color mode, except that each pixel takes up one word, rather than one byte. As in SuperVGA 256-color modes, the bitmap is too long to be addressed in the 64K video memory window, so banking must be used; again, the banking is just like 256-color banking, except that each bank contains only half as many pixels; 32,768, to be exact.

On the ET4000, the Segment Select register at 3CDH controls banking, as shown in Figure 26.2. There are 16 banks, each spanning 64 Kbytes of the total 1-Mb bitmap. Banks can be selected separately for read and write to facilitate scrolling and screen-to-screen copies, although we won't need that in this chapter. Simple enough, but there's a catch: broken rasters.

Banks are 64K in length. If each Hicolor scan line is 1,600 bytes long, then 65,536/1,600=40 raster lines (lines 0–39) fit in bank 0—with 1,536 bytes of the next line (line 40), also in the first bank. The last 64 bytes of line 40 are in bank 1, as shown in Figure 26.3, so the line is split by the bank boundary; hence the term "broken raster." Broken

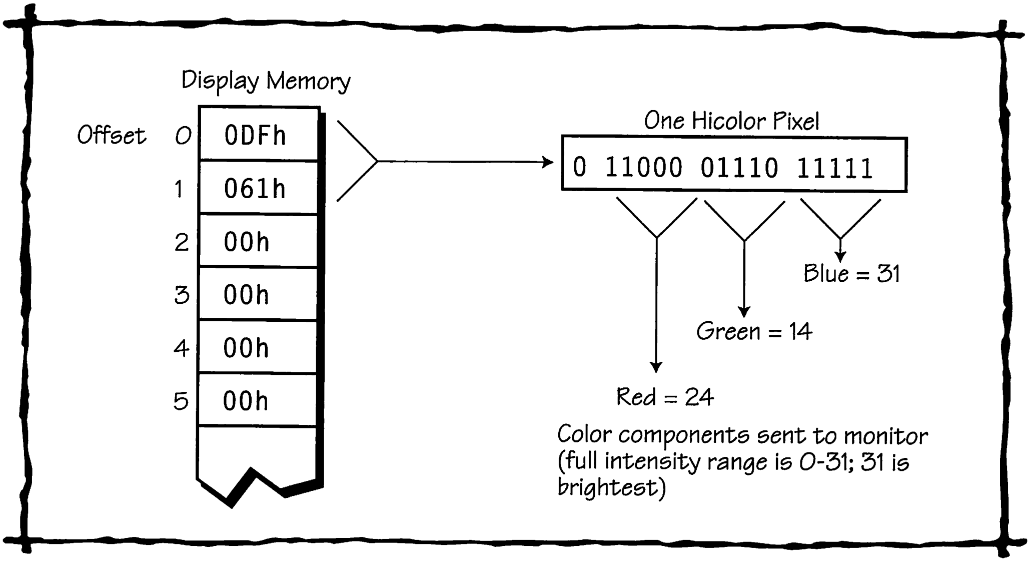


Figure 26.1 The Hicolor DAC 32K-Color Pixel Format

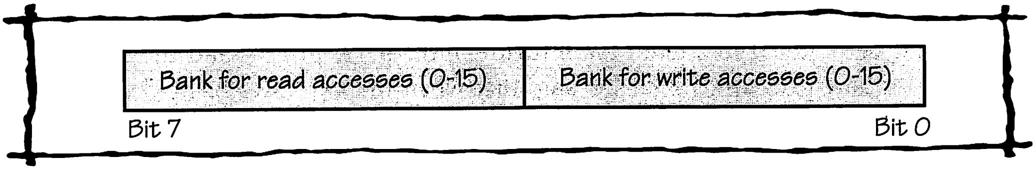


Figure 26.2 The ET4000 Segment Select Register (3CDH)

rasters crop up for other bank crossings as well, and make Hicolor programming somewhat slower (the extent of the slowdown depends heavily on the quality of the code) and considerably more complicated.

Broken rasters are not unique to Hicolor modes; 800×600 and 640×480 256-color modes also normally have broken rasters. However, there's a clever workaround for broken rasters in 256-color modes: Stretch the bitmap width to 1K pixels, via the Row Offset register, so that banks split between raster lines (although this works for 800×600 only if the VGA has 1 Mb or more of memory).

Sad to say, stretching the bitmap width to 1K pixels doesn't work in Hicolor mode. There's not enough memory on a 1MB SuperVGA to do it at 800×600, but that's not

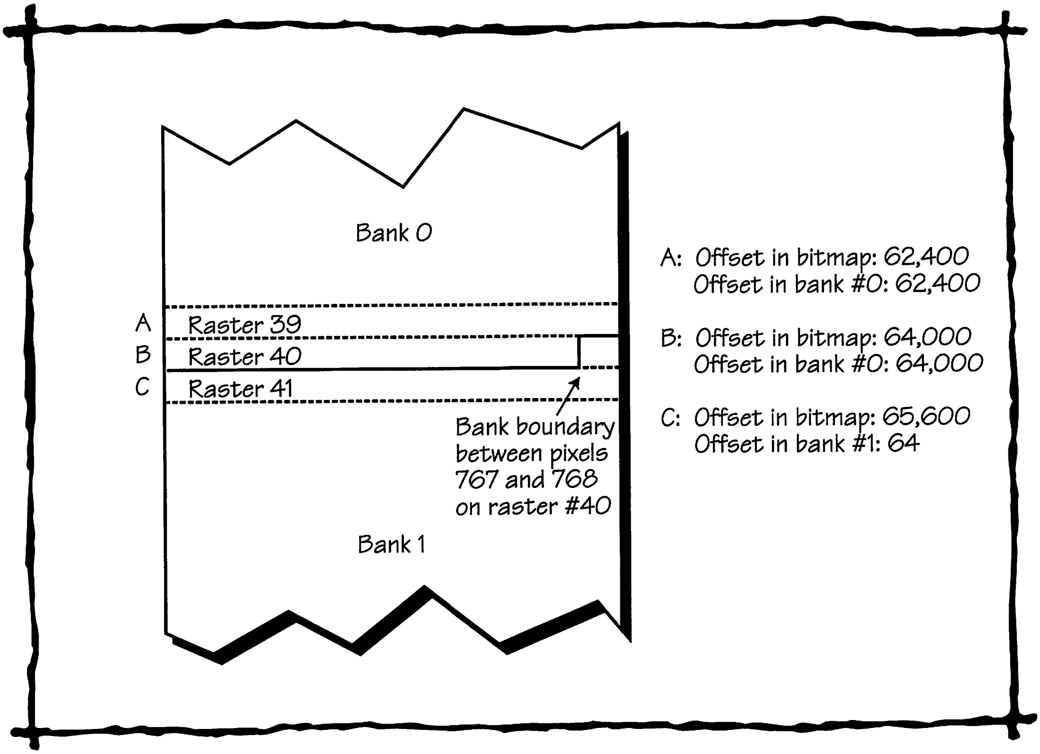

Bank 0
A
B
C
Raster 39
Raster 40
Raster 41
Bank boundary between pixels 767 and 768 on raster #40
Bank 1
A: Offset in bitmap: 62,400
Offset in bank #0: 62,400
B: Offset in bitmap: 64,000
Offset in bank #0: 64,000
C: Offset in bitmap: 65,600
Offset in bank #1: 64

Figure 26.3 A Broken Raster

the problem at 640×480. The problem is that a Row Offset register setting of 256 would be required to stretch the bitmap width to 1K pixels—and the Row Offset register only goes up to 255. I'm sure that when the VGA was being designed, 255 seemed like plenty, but then, 640K once seemed like pie in the sky.

The upshot is that Hicolor programming generally requires handling broken rasters. Generally—but not always. I learned of an exception from a a person I know only as "rfrederick" from M&T Online. He or she pointed out that setting the bitmap width—the offset from the start of one line to the start of the next—to 1,928 bytes in 640×480 Hicolor mode eliminates broken rasters (that is, displayed lines that span banks). A bitmap width of 1,928 is selected by setting the Row Offset register (CRTC register 13H) to 241, like so:

```
outpw(0x3d4, 0x13 | (241<<8));
```

Once the width is set, all you have to do is use 1,928 for the offset from one row to the next, rather than 1,280, and you're all set. Actually, the breaks are still there, but they can be ignored because they happen off to the right of the displayed portion of the bitmap. To get the Hicolor drawing code in this chapter to support 1,928-wide Hicolor bitmaps, just change **BitmapWidthInBytes** from 640*2 to 1,928. My online source credited this insight to the folks at Everex, to whom I am indebted.

Without the above workaround, or in 800×600 Hicolor mode, broken rasters are certainly a nuisance, but nonetheless a manageable one; next, we'll see polygon fill code that deals with broken rasters.

Non-Antialiased Hicolor Drawing

Listing 26.2 draws a perspective cube in 640×480 32K color mode, with help from the initialization code in Listing 26.1, the **DrawPixel**-based low-level polygon fill code in Listing 26.3, and the POLYGON.H header file in Listing 26.7. (FILCNVXD.C from the previous chapter and Listing 22.4 from Chapter 22 are also required; however, to make things less confusing for you, these will be in the Chapter 26 subdirectory on the listings diskette.) Not surprisingly, the cube drawn by Listing 26.2 looks a lot like the non-antialiased cube we drew in the previous chapter, but isn't as jagged because the resolution is now much higher. Nonetheless, jaggies are still quite prominent, and they remain clearly visible at 800×600. (I've used 640×480 mode so that the code will work on fixed-frequency monitors, but Listing 26.2 can be altered for 800×600 mode simply by changing the parameter passed to **SetHCMode** and the value of **BitmapWidthInBytes**.)

Listing 26.2 doesn't run very fast when linked to Listing 26.3; I suspect you'll like the low-level polygon fill code in Listing 26.4 much better. This code handles broken rasters reasonably efficiently, by checking for them at the beginning of each scan line, then splitting up the fill and banking appropriately whenever a bank crossing is detected.

LISTING 26.2 L26-2.C

```
/* Demonstrates non-antialiased drawing in 640x480 Hicolor (32K color) mode on
an ET4000-based SuperVGA with a Sierra Hicolor DAC installed. Tested with
Borland C++ in C mode in the small model. */

#include <conio.h>
#include <dos.h>
#include "polygon.h"
/* Draws the polygon described by the point list PointList in color
   Color, with all vertices offset by (x,y) */
#define DRAW_POLYGON(PointList,Color,x,y) {               \
   Polygon.Length = sizeof(PointList)/sizeof(struct Point); \
   Polygon.PointPtr = PointList;                           \
   FillCnvxPolyDrvr(&Polygon, Color, x, y, DrawHCLineList);}

void main(void);
extern int SetHCMode(int);
extern int FillCnvxPolyDrvr(struct PointListHeader *, int, int, int,
   void (*)());
extern void DrawHCLineList(struct HLineList *, int);
int BitmapWidthInBytes = 640*2; /* # of bytes per raster line */

void main()
{
   struct PointListHeader Polygon;
   static struct Point Face0[] = {{396,276},{422,178},{338,88},{288,178}};
   static struct Point Face1[] = {{306,300},{396,276},{288,178},{210,226}};
   static struct Point Face2[] = {{338,88},{266,146},{210,226},{288,178}};
   union REGS regset;

   /* Attempt to enable 640x480 Hicolor mode */
   if (SetHCMode(0x2E) == 0)
      { printf("No Hicolor DAC detected\n"); exit(0); };

   /* Draw the cube */
   DRAW_POLYGON(Face0, 0x1F, 0, 0);       /* full-intensity blue */
   DRAW_POLYGON(Face1, 0x1F << 5, 0, 0);  /* full-intensity green */
   DRAW_POLYGON(Face2, 0x1F << 10, 0, 0); /* full-intensity red */
   getch();    /* wait for a keypress */

   /* Return to text mode and exit */
   regset.x.ax = 0x0003;   /* AL = 3 selects 80x25 text mode */
   int86(0x10, &regset, &regset);
}
```

LISTING 26.3 L26-3.C

```
/* Draws all pixels in the list of horizontal lines passed in, in Hicolor
(32K color) mode on an ET4000-based SuperVGA. Uses a slow pixel-by-pixel
approach. Tested with Borland C++ in C mode in the small model. */

#include <dos.h>
#include "polygon.h"
#define SCREEN_SEGMENT     0xA000
#define GC_SEGMENT_SELECT  0x3CD

void DrawPixel(int, int, int);
extern int BitmapWidthInBytes; /* # of pixels per line */
```

```
void DrawHCLineList(struct HLineList * HLineListPtr,
      int Color)
{
   struct HLine *HLinePtr;
   int Y, X;

   /* Point to XStart/XEnd descriptor for the first (top) horizontal line */
   HLinePtr = HLineListPtr->HLinePtr;
   /* Draw each horizontal line in turn, starting with the top one and
      advancing one line each time */
   for (Y = HLineListPtr->YStart; Y < (HLineListPtr->YStart +
         HLineListPtr->Length); Y++, HLinePtr++) {
      /* Draw each pixel in the current horizontal line in turn,
         starting with the leftmost one */
      for (X = HLinePtr->XStart; X <= HLinePtr->XEnd; X++)
         DrawPixel(X, Y, Color);
   }
}

/* Draws the pixel at (X, Y) in color Color in Hicolor mode on an
   ET4000-based SuperVGA */
void DrawPixel(int X, int Y, int Color) {
   unsigned int far *ScreenPtr, Bank;
   unsigned long BitmapAddress;

   /* Full bitmap address of pixel, as measured from address 0 to
      address 0xFFFFF. (X << 1) because pixels are 2 bytes in size */
   BitmapAddress = (unsigned long) Y * BitmapWidthInBytes + (X << 1);
   /* Map in the proper bank. Bank # is upper word of bitmap addr */
   Bank = *(((unsigned int *)&BitmapAddress) + 1);
   /* Upper nibble is read bank #, lower nibble is write bank # */
   outp(GC_SEGMENT_SELECT, (Bank << 4) | Bank);
   /* Draw into the bank */
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) = *((unsigned int *)&BitmapAddress);
   *ScreenPtr = (unsigned int)Color;
}
```

LISTING 26.4 L26-4.ASM

```
; Draws all pixels in the list of horizontal lines passed in, in
; Hicolor (32K color) mode on an ET4000-based SuperVGA. Uses REP STOSW
; to fill each line. Tested with TASM. C near-callable as:
;     void DrawHCLineList(struct HLineList * HLineListPtr, int Color);

SCREEN_SEGMENT  equu     0a000h
GC_SEGMENT_SELECT equ   03cdh

HLine   struc
XStart  dw      ?       ;X coordinate of leftmost pixel in line
XEnd    dw      ?       ;X coordinate of rightmost pixel in line
HLine   ends

HLineList struc
Lngth   dw      ?       ;# of horizontal lines
YStart  dw      ?       ;Y coordinate of topmost line
HLinePtr  dw    ?      ;pointer to list of horz lines
HLineList ends
```

```
Parms   struc
                dw      2 dup(?) ;return address & pushed BP
HLineListPtr    dw      ?       ;pointer to HLineList structure
Color           dw      ?       ;color with which to fill
Parms   ends

; Advances both the read and write windows to the next 64K bank.
; Note: Theoretically, a delay between IN and OUT may be needed under
; some circumstances to avoid accessing the VGA chip too quickly, but
; in actual practice, I haven't found any delay to be required.
INCREMENT_BANK  macro
        push    ax              ;preserve fill color
        push    dx              ;preserve scan line start pointer
        mov     dx,GC_SEGMENT_SELECT
        in      al,dx           ;get the current segment select
        add     al,11h          ;increment both the read & write banks
        out     dx,al           ;set the new bank #
        pop     dx              ;restore scan line start pointer
        pop     ax              ;restore fill color
        endm

        .model small
        .data
        extrn   _BitmapWidthInBytes:word
        .code
        public _DrawHCLineList
        align   2
_DrawHCLineList proc    near
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to our stack frame
        push    si              ;preserve caller's register variables
        push    di
        cld                     ;make string instructions inc pointers
        mov     ax,SCREEN_SEGMENT
        mov     es,ax   ;point ES to display memory for REP STOS
        mov     si,[bp+HLineListPtr] ;point to the line list
        mov     ax,[_BitmapWidthInBytes] ;point to the start of the
        mul     [si+YStart]     ; first scan line on which to draw
        mov     di,ax           ;ES:DI points to first scan line to
        mov     al,dl           ; draw; AL is the initial bank #
                                ;upper nibble of AL is read bank #,
        mov     cl,4            ; lower nibble is write bank # (only
        shl     dl,cl           ; the write bank is really needed for
        or      al,dl           ; this module, but it's less confusing
                                ; to point both to the same place)
        mov     dx,GC_SEGMENT_SELECT
        out     dx,al           ;set the initial bank
        mov     dx,di           ;ES:DX points to first scan line
        mov     bx,[si+HLinePtr] ;point to the XStart/XEnd descriptor
                                ; for the first (top) horizontal line
        mov     si,[si+Lngth]   ;# of scan lines to draw
        and     si,si           ;are there any lines to draw?
        jz      FillDone        ;no, so we're done
        mov     ax,[bp+Color]   ;color with which to fill
        mov     bp,[_BitmapWidthInBytes] ;so we can keep everything
                                ; in registers inside the loop
                                ;***stack frame pointer destroyed!***
FillLoop:
        mov     di,[bx+XStart]  ;left edge of fill on this line
        mov     cx,[bx+XEnd]    ;right edge of fill
        sub     cx,di
        jl      LineFillDone    ;skip if negative width
        inc     cx              ;# of pixels to fill on this line
        add     di,di           ;*2 because pixels are 2 bytes in size
        add     dx,bp           ;do we cross a bank during this line?
        jnc     NormalFill      ;no
        jz      NormalFill      ;no
                                ;yes, there is a bank crossing on this
                                ; line; figure out where
        sub     dx,bp           ;point back to start of line
        add     di,dx           ;offset of left edge of fill
        jc      CrossBankBeforeFilling ;raster splits before the left
                                ; edge of fill
        add     cx,cx           ;fill width in bytes (pixels * 2)
        add     di,cx           ;do we split during the fill area?
        jnc     CrossBankAfterFilling ;raster splits after the right
        jz      CrossBankAfterFilling ; edge of fill
                                ;bank boundary falls within fill area;
                                ; draw in two parts, one in each bank
        sub     di,cx           ;point back to start of fill area
        neg     di              ;# of bytes left before split
        sub     cx,di           ;# of bytes to fill to the right of
                                ; the bank split
        push    cx              ;remember right-of-split fill width
        mov     cx,di           ;# of left-of-split bytes to fill
        shr     cx,1            ;# of left-of-split words to fill
        neg     di              ;offset at which to start filling
        rep     stosw           ;fill left-of-split portion of line
        pop     cx              ;get back right-of-split fill width
        shr     cx,1            ;# of right-of-split words to fill
                                ;advance to the next bank
        INCREMENT_BANK          ;point to the next bank (DI already
                                ; points to offset 0, as desired)
        rep     stosw           ;fill right-of-split portion of line
        add     dx,bp           ;point to the next scan line
        jmp     short CountDownLine ; (already advanced the bank)
;======================================================================
        align   2               ;fill area is entirely to the left of
CrossBankAfterFilling:          ; the bank boundary
        sub     di,cx           ;point back to start of fill area
        shr     cx,1            ;CX = fill width in pixels
        jmp     short FillAndAdvance ;doesn't split until after the
                                ; fill area, so handle normally
;======================================================================
        align   2               ;fill area is entirely to the right of
CrossBankBeforeFilling:         ; the bank boundary
        INCREMENT_BANK          ;first, point to the next bank, where
                                ; the fill area resides
        rep     stosw           ;fill this scan line
        add     dx,bp           ;point to the next scan line
        jmp     short CountDownLine ; (already advanced the bank)
;======================================================================
        align   2               ;no bank boundary problems; just fill
NormalFill:                     ; normally
        sub     dx,bp           ;point back to start of line
        add     di,dx           ;offset of left edge of fill
FillAndAdvance:
        rep     stosw           ;fill this scan line
LineFillDone:
        add     dx,bp           ;point to the next scan line
        jnc     CountDownLine   ;didn't cross a bank boundary
        INCREMENT_BANK          ;did cross, so point to the next bank
CountDownLine:
        add     bx,size HLine   ;point to the next line descriptor
        dec     si              ;count off lines to fill
        jnz     FillLoop
FillDone:
        pop     di              ;restore caller's register variables
        pop     si
        pop     bp              ;restore caller's stack frame
        ret
;=====================================================================
_DrawHCLineList endp
        end
```

Simple Unweighted Antialiasing

As the saying goes, you can never be too rich, too thin, or have too many colors available. Personally, I only buy one of those three assertions: You really can't have too many colors. Listings 26.5 and 26.6, together with Listings 26.1, 26.3, and 26.7, FILCNVXD.C from the previous chapter, and Listing 22.4 from Chapter 22, show why. This program draws the same cube, but this time employing the simple, unweighted antialiasing we used in the previous chapter—and taking advantage of the full color range of the Hicolor DAC. The results are excellent: On my venerable NEC MultiSync, at a viewing distance of one foot, all but two of the edges look absolutely smooth, with not the slightest hint of jaggies, and the two imperfect edges show only slight ripples. At two feet, the cube looks perfect. The difference between the non-antialiased and antialiased cubes is astounding, considering that we're working with the same resolution in both cases.

A quick review of the simple antialiasing used in this chapter and the previous one: The image is drawn to a memory buffer at a multiple of the resolution that the actual screen supports. Each pixel on the screen maps to a group of hi-res pixels (subpixels), arranged in a square in the memory buffer. The colors of the subpixels in each square are averaged, and the corresponding screen pixel is set to the average subpixel color.

There's not enough memory to scan out the entire image at high resolution (about 50K is required just to scan out one 800×600 raster line at 4× resolution!), so Listing 26.6 scans out just those pixels that lie in a specified band. (Each band corresponds to a single raster line in Listing 26.5.) Note that Listing 26.6 draws 32-bit pixels to the memory buffer; this is true color, plus an extra byte for flexibility. Consequently, Listing 26.6 is a general-purpose tool, and can be used with any sort of adapter, as long as the main program knows how to convert from true color to adapter-specific pixels. Listing 26.5 does this by calculating the average intensity in each subpixel group of each of the three primary colors, in the range 0–255, then looking up the gamma corrected equivalent color value for the Hicolor DAC, mapped into the range 0–31.

A quick look at the gamma-corrected color mapping table in Listing 26.5 shows why hardware gamma correction is sorely missed in the Hicolor DAC. The brightest half of the color range—from half intensity to full intensity—is spanned by only 9 of the Hicolor DAC's 32 color values. That means that for brighter colors, the Hicolor DAC effectively has only half the color resolution that you'd expect from 5 bits per color gun, and the resolution is even worse at the highest intensities.

I'd like to take a moment to emphasize that although Listing 26.5 works with only the three primary colors, it could just as easily work with the thousands of colors that can be produced as mixes of the three primaries; there are none of the limitations of 256-color mode, and no special tricks (such as biasing the palette according to color frequency) need be used. Inevitably, though, proportionately fewer intermediate blends are available and hence antialiasing becomes less precise when there is less contrast between colors; you're not going to be able to do much antialiasing between a pixel with a green true color value of 250 and another with a value of 255. This is where the lack of gamma correction and the difference between 15-bpp and true color become apparent.

LISTING 26.5 L26-5.C

```
/* Demonstrates unweighted antialiased drawing in 640x480 Hicolor (32K color)
   mode. Tested with Borland C++ in C mode in the small model. */

#include <conio.h>
#include <dos.h>
#include <stdlib.h>
#include <string.h>
#include "polygon.h"
/* Draws the polygon described by the point list PointList in the
   color specified by RED, GREEN, AND BLUE, with all vertices
   offset by (x,y), to ScanLineBuffer, at ResMul multiple of
   horizontal and vertical resolution. The address of ColorTemp is
   cast to an int to satisfy the prototype for FillCnvxPolyDrvr; this
   trick will work only in a small data model. */
#define DRAW_POLYGON_HIGH_RES(PointList,RED,GREEN,BLUE,x,y,ResMul) { \
   Polygon.Length = sizeof(PointList)/sizeof(struct Point);          \
   Polygon.PointPtr = PointTemp;                                     \
   /* Multiply all vertical & horizontal coordinates */              \
   for (k=0; k<sizeof(PointList)/sizeof(struct Point); k++) {        \
      PointTemp[k].X = PointList[k].X * ResMul;                      \
      PointTemp[k].Y = PointList[k].Y * ResMul;                      \
   }                                                                 \
   ColorTemp.Red=RED; ColorTemp.Green=GREEN; ColorTemp.Blue=BLUE;    \
   FillCnvxPolyDrvr(&Polygon, (int)&ColorTemp, x, y, DrawBandedList);}
#define SCREEN_WIDTH 640
#define SCREEN_SEGMENT 0xA000

void main(void);
extern void DrawPixel(int, int, char);
extern void DrawBandedList(struct HLineList *, struct RGB *);
extern int SetHCMode(int);
```

```
/* Table of gamma corrected mappings of linear color intensities in
   the range 0-255 to the nearest pixel values in the range 0-31,
   assuming a gamma of 2.3 */
static unsigned char ColorMappings[] = {
    0, 3, 4, 4, 5, 6, 6, 6, 7, 7, 8, 8, 8, 8, 9, 9, 9,10,10,10,
   10,10,11,11,11,11,11,12,12,12,12,12,13,13,13,13,13,13,14,14,
   14,14,14,14,14,15,15,15,15,15,15,15,16,16,16,16,16,16,16,16,
   17,17,17,17,17,17,17,17,17,18,18,18,18,18,18,18,18,18,19,19,
   19,19,19,19,19,19,19,19,20,20,20,20,20,20,20,20,20,20,20,21,
   21,21,21,21,21,21,21,21,21,21,22,22,22,22,22,22,22,22,22,22,
   22,22,22,23,23,23,23,23,23,23,23,23,23,23,23,24,24,24,24,24,
   24,24,24,24,24,24,24,24,24,25,25,25,25,25,25,25,25,25,25,25,
   25,25,25,26,26,26,26,26,26,26,26,26,26,26,26,26,26,26,27,27,
   27,27,27,27,27,27,27,27,27,27,27,27,27,27,28,28,28,28,28,28,
   28,28,28,28,28,28,28,28,28,28,28,29,29,29,29,29,29,29,29,29,
   29,29,29,29,29,29,29,29,30,30,30,30,30,30,30,30,30,30,30,30,
   30,30,30,30,30,30,31,31,31,31,31,31,31,31,31,31};
/* Pointer to buffer in which high-res scanned data will reside */
struct RGB *ScanLineBuffer;
int ScanBandStart, ScanBandEnd;  /* top & bottom of each high-res
                                  band we'll draw to ScanLineBuffer */
int ScanBandWidth;     /* # subpixels across each scan band */
int BitmapWidthInBytes = 640*2;  /* # of bytes per raster line in
                                   Hicolor VGA display memory */
void main()
{
   int i, j, k, m, Red, Green, Blue, jXRes, kXWidth;
   int SubpixelsPerMegapixel;
   unsigned int Megapixel, ResolutionMultiplier;
   long BufferSize;
   struct RGB ColorTemp;
   struct PointListHeader Polygon;
   struct Point PointTemp[4];
   static struct Point Face0[] =
         {{396,276},{422,178},{338,88},{288,178}};
   static struct Point Face1[] =
         {{306,300},{396,276},{288,178},{210,226}};
   static struct Point Face2[] =
         {{338,88},{266,146},{210,226},{288,178}};
   int LeftBound=210, RightBound=422, TopBound=88, BottomBound=300;
   union REGS regset;

   printf("Subpixel resolution multiplier:");
   scanf("%d", &ResolutionMultiplier);
   SubpixelsPerMegapixel = ResolutionMultiplier*ResolutionMultiplier;
   ScanBandWidth = SCREEN_WIDTH*ResolutionMultiplier;

   /* Get enough space for one scan line scanned out at high
      resolution horz and vert (each pixel is 4 bytes) */
   if ((BufferSize = (long)ScanBandWidth*4*ResolutionMultiplier) >
         0xFFFF) {
      printf("Band won't fit in one segment\n"); exit(0); }
   if ((ScanLineBuffer = malloc((int)BufferSize)) == NULL) {
      printf("Couldn't get memory\n"); exit(0); }

   /* Attempt to enable 640x480 Hicolor mode */
   if (SetHCMode(0x2E) == 0)
      { printf("No Hicolor DAC detected\n"); exit(0); };

   /* Scan out the polygons at high resolution one screen scan line at
      a time (ResolutionMultiplier high-res scan lines at a time) */
   for (i=TopBound; i<=BottomBound; i++) {
      /* Set the band dimensions for this pass */
      ScanBandEnd = (ScanBandStart = i*ResolutionMultiplier) +
            ResolutionMultiplier - 1;
      /* Clear the drawing buffer */
      memset(ScanLineBuffer, 0, BufferSize);
      /* Draw the current band of the cube to the scan line buffer */
      DRAW_POLYGON_HIGH_RES(Face0,0xFF,0,0,0,0,ResolutionMultiplier);
      DRAW_POLYGON_HIGH_RES(Face1,0,0xFF,0,0,0,ResolutionMultiplier);
      DRAW_POLYGON_HIGH_RES(Face2,0,0,0xFF,0,0,ResolutionMultiplier);

  /* Coalesce subpixels into normal screen pixels (megapixels) and draw them */
      for (j=LeftBound; j<=RightBound; j++) {
         jXRes = j*ResolutionMultiplier;
         /* For each screen pixel, sum all the corresponding
            subpixels, for each color component */
         for (k=Red=Green=Blue=0; k<ResolutionMultiplier; k++) {
            kXWidth = k*ScanBandWidth;
            for (m=0; m<ResolutionMultiplier; m++) {
               Red += ScanLineBuffer[jXRes+kXWidth+m].Red;
               Green += ScanLineBuffer[jXRes+kXWidth+m].Green;
               Blue += ScanLineBuffer[jXRes+kXWidth+m].Blue;
            }
         }
         /* Calc each color component's average brightness; convert
            that into a gamma corrected portion of a Hicolor pixel,
            then combine the colors into one Hicolor pixel */
         Red = ColorMappings[Red/SubpixelsPerMegapixel];
         Green = ColorMappings[Green/SubpixelsPerMegapixel];
         Blue = ColorMappings[Blue/SubpixelsPerMegapixel];
         Megapixel = (Red << 10) + (Green << 5) + Blue;
         DrawPixel(j, i, Megapixel);
      }
   }
   getch();    /* wait for a keypress */

   /* Return to text mode and exit */
   regset.x.ax = 0x0003;   /* AL = 3 selects 80x25 text mode */
   int86(0x10, &regset, &regset);
}
```

LISTING 26.6 L26-6.C

```
/* Draws pixels from the list of horizontal lines passed in, to a 32-bpp
buffer; drawing takes place only for scan lines between ScanBandStart and
ScanBandEnd, inclusive; drawing goes to ScanLineBuffer, with the scan line at
ScanBandStart mapping to the first scan line in ScanLineBuffer. Note that
Color here points to an RGB structure that maps directly to the buffer's pixel
format, rather than containing a 16-bit integer. Tested with Borland C++
in C mode in the small model. */

#include "polygon.h"

extern struct RGB *ScanLineBuffer;  /* drawing goes here */
extern int ScanBandStart, ScanBandEnd; /* limits of band to draw */
extern int ScanBandWidth;  /* # of subpixels across scan band */

void DrawBandedList(struct HLineList * HLineListPtr,
   struct RGB *Color)
{
   struct HLine *HLinePtr;
   int Length, Width, YStart = HLineListPtr->YStart, i;
   struct RGB *BufferPtr, *WorkingBufferPtr;

   /* Done if fully off the bottom or top of the band */
   if (YStart > ScanBandEnd) return;
   Length = HLineListPtr->Length;
   if ((YStart + Length) <= ScanBandStart) return;

   /* Point to XStart/XEnd descriptor for the first (top) horizontal line */
   HLinePtr = HLineListPtr->HLinePtr;

   /* Confine drawing to the specified band */
   if (YStart < ScanBandStart) {
      /* Skip ahead to the start of the band */
      Length -= ScanBandStart - YStart;
      HLinePtr += ScanBandStart - YStart;
      YStart = ScanBandStart;
   }
   if (Length > (ScanBandEnd - YStart + 1))
      Length = ScanBandEnd - YStart + 1;

   /* Point to the start of the first scan line on which to draw */
   BufferPtr = ScanLineBuffer + (YStart-ScanBandStart)*ScanBandWidth;

   /* Draw each horizontal line within the band in turn, starting with
      the top one and advancing one line each time */
   while (Length-- > 0) {
      /* Fill whole horiz line with Color if it has positive width */
      if ((Width = HLinePtr->XEnd - HLinePtr->XStart + 1) > 0) {
         WorkingBufferPtr = BufferPtr + HLinePtr->XStart;
         for (i = 0; i < Width; i++) *WorkingBufferPtr++ = *Color;
      }
      HLinePtr++;                /* point to next scan line X info */
      BufferPtr += ScanBandWidth; /* point to start of next line */
   }
}
```

LISTING 26.7 POLYGON.H

```
/* POLYGON.H: Header file for polygon-filling code */

/* Describes a single point (used for a single vertex) */
struct Point {
   int X;   /* X coordinate */
   int Y;   /* Y coordinate */
};

/* Describes a series of points (used to store a list of vertices that
describe a polygon; each vertex is assumed to connect to the two adjacent
vertices, and the last vertex is assumed to connect to the first) */
struct PointListHeader {
   int Length;                /* # of points */
   struct Point * PointPtr;   /* pointer to list of points */
};

/* Describes the beginning and ending X coordinates of a single
   horizontal line */
struct HLine {
   int XStart; /* X coordinate of leftmost pixel in line */
   int XEnd;   /* X coordinate of rightmost pixel in line */
};

/* Describes a Length-long series of horizontal lines, all assumed to be on
contiguous scan lines starting at YStart and proceeding downward (used to
describe scan-converted polygon to low-level hardware-dependent drawing code)*/
struct HLineList {
   int Length;              /* # of horizontal lines */
   int YStart;              /* Y coordinate of topmost line */
   struct HLine * HLinePtr; /* pointer to list of horz lines */
};

/* Describes a color as an RGB triple, plus one byte for other info */
struct RGB { unsigned char Red, Green, Blue, Spare; };
```

Notes on the Antialiasing Implementation

Listing 26.5 features user-selectable subpixel resolution, which is the multiple of the screen resolution at which the image should be drawn into the memory buffer. A subpixel resolution of two times normal along both axes (2×) looks much better than nonantialiased drawing, but still has visible jaggies. Subpixel resolution of 4× looks terrific, as mentioned earlier. Higher subpixel resolutions are, practically speaking, reserved for 386 protected mode, because they would require a buffer larger than 64K to hold the high-resolution equivalent of a single scan line.

On the downside, Listing 26.5 is very slow, even though the conversion process from true color pixels to Hicolor pixels is limited to the bounding rectangle for the cube being drawn, thereby saving the time that was wasted in the previous chapter drawing the empty space around the cube. It could easily be sped up by (say) an order of magnitude, in a number of ways. First, you could implement an ASM function that's the equivalent of **memset**, but stores longs (dwords) rather than chars (bytes). In the absence of any such C library function, Listing 26.6 uses a loop with a pointer to a long; hardly a recipe for high performance.

Listing 26.5 could also be sped up by doing the screen pixel construction from each square of subpixels in assembly language using pointers rather than array look-ups. It would also help to organize the screen pixel drawing more as a variant rectangle fill, instead of going through **DrawPixel** every time, so that the screen pointer doesn't have to be recalculated from scratch and the bank doesn't need to be calculated and set for every pixel. Clipping each polygon to the band before rather than after scanning it out would speed things up, as would building an edge list for the polygons once, ahead of time, then advancing it incrementally to scan out each band, rather than doing one complete scan of each polygon for each band. Bigger bands would help; drawing the whole image to the memory buffer in one burst, then converting the entire image to Hicolor pixels in a single operation, would be ideal, but would require a ridiculous amount of memory. (Would you believe, 31 MB for one full 800×600 Hicolor screen at 4× resolution?)

Finally, to alter Listing 26.5 for 800×600 Hicolor mode, change the parameter passed to **SetHCMode**, the value of **BitmapWidthInBytes**, and the value of **SCREEN_WIDTH**.

Further Thoughts on Antialiasing

The banded true color approach of Listings 26.5 and 26.6 is easily extended to other antialiasing approaches. For example, you could, if you wished, average together all the subpixels not within a square, but rather within a circle of radius **sqrt(2.0)*Resolution Multiplier /2** around each pixel center. This approach is a little more complicated, but it has one great virtue: An image will be antialiased identically, regardless of its rotation.

Why is the shape of the subpixel area that's collected into a screen pixel important when the maximum resolution we can actually draw with is the resolution of the screen? I'll quote William vanRyper, from the graphics.disp/vga conference on BIX:

"If you anti-alias an edge on the screen, and let the eye-brain pick the edge somewhere in the gradient between the object color and the background, you can adjust the placement of that perceptual edge by altering the ramp of the gradient. If the number of intermediate values you can choose among is greater than the number of gradient pixels you set (across the edge), you can adjust the position of the perceptual edge in increments of less than a pixel. This means you can locate the antialiased object to subpixel precision."

In other words, by using blends of color in a smooth, consistent gradient across a boundary, you can get the eye to pick out the boundary location with a precision that's greater than the resolution of the screen. This is, of course, part and parcel of the wonderful eye/ brain magic that allows color to substitute for resolution and makes antialiasing worthwhile.

Given that we can draw images with perceived resolution higher than the screen, consistency in subpixel placement is very important. Unfortunately, our simple square antialiasing does not produce the same results (a consistent color gradient) for an image rotated 45 degrees as it does for an unrotated image—but antialiasing based on a circular subpixel area does. So the shape of the subpixel area used for antialiasing matters because if it's not symmetric in all directions, boundaries will appear to wiggle as images rotate, destroying the image of reality that antialiased animation strives to create.

On the other hand, if you're drawing only static images, use a square subpixel area for antialiasing; it's fast, easy, and looks just fine in that context. As I said at the outset, we're not seeking mathematical perfection here, just a good-looking display for the purpose at hand. If it looks good, it *is* good.

Wu'ed in Haste; Fried, Stewed at Leisure

Chapter 27

Fast Antialiased Lines Using Wu's Algorithm

The thought first popped into my head as I unenthusiastically picked through the salad bar at a local "family" restaurant, trying to decide whether the meatballs, the fried clams, or the lasagna was likely to shorten my life the least. I decided on the chicken in mystery sauce.

The thought recurred when my daughter asked, "Dad, is that fried chicken?"

"I don't think so," I said. "I think it's stewed chicken."

"It looks like fried chicken."

"Maybe it's fried, stewed chicken," my wife volunteered hopefully. I took a bite. It was, indeed, fried, stewed chicken. I can now, unhesitatingly and without reservation, recommend that you avoid fried, stewed chicken at all costs.

The thought I had was as follows: *This is not good food.* Not a profound thought, but it raises an interesting question: Why was I eating in this restaurant? The answer, to borrow a phrase from E.F. Schumacher, is *appropriate technology.* For a family on a budget, with a small child, tired of staring at each other over the kitchen table, this was a perfect place to eat. It was cheap, it had greasy food and ice cream, no one cared if children dropped things or talked loudly or walked around, and, most important of all, it wasn't home. So what if the food was lousy? Good food was a luxury, a bonus; everything on the above list was necessary. A family restaurant was the appropriate dining-out technology, given the parameters within which we had to work.

When I read through SIGGRAPH proceedings and other state-of-the-art computer-graphics material, all too often I feel like I'm dining at a four-star restaurant with two-year-old triplets and an empty wallet. We're talking incredibly inappropriate technology for PC graphics here. Sure, I say to myself as I read about an antialiasing technique, that sounds wonderful—if I had 24-bpp color, and dedicated hardware to do the processing, and all day to wait to generate one image. Yes, I think, that is a good way to do hidden surface removal—in a system with hardware z-buffering. Most of the stuff in the journal *Computer Graphics* is riveting, but, alas, pretty much useless on PCs. When an x86 has to do all the work, speed becomes the overriding parameter, especially for real-time graphics.

Literature that's applicable to fast PC graphics is hard enough to find, but what we'd really like is above-average image quality combined with terrific speed, and there's almost no literature of that sort around. There is some, however, and you folks are right on top of it. For example, alert reader Michael Chaplin, of San Diego, wrote to suggest that I might enjoy the line-antialiasing algorithm presented in Xiaolin Wu's article, "An Efficient Antialiasing Technique," in the July 1991 issue of *Computer Graphics*. Michael was dead-on right. This is a great algorithm, combining excellent antialiased line quality with speed that's close to that of non-antialiased Bresenham's line drawing. This is the sort of algorithm that makes you want to go out and write a wire-frame animation program, just so you can see how good those smooth lines look in motion. Wu antialiasing is a wonderful example of what can be accomplished on inexpensive, mass-market hardware with the proper programming perspective. In short, it's a splendid example of appropriate technology for PCs.

Wu Antialiasing

Antialiasing, as we've been discussing for the past few chapters, is the process of smoothing lines and edges so that they appear less jagged. Antialiasing is partly an aesthetic issue, because it makes images more attractive. It's also partly an accuracy issue, because it makes it possible to position and draw images with effectively more precision than the resolution of the display. Finally, it's partly a flat-out necessity, to avoid the horrible, crawling, jagged edges of temporal aliasing when performing animation.

The basic premise of Wu antialiasing is almost ridiculously simple: As the algorithm steps one pixel unit at a time along the major (longer) axis of a line, it draws the two pixels bracketing the line along the minor axis at each point. Each of the two bracketing pixels is drawn with a weighted fraction of the full intensity of the drawing color, with the weighting for each pixel equal to one minus the pixel's distance along the minor axis from the ideal line. Yes, it's a mouthful, but Figure 27.1 illustrates the concept.

The intensities of the two pixels that bracket the line are selected so that they always sum to exactly 1; that is, to the intensity of one fully illuminated pixel of the drawing color. The presence of aggregate full-pixel intensity means that at each step, the line has the same brightness it would have if a single pixel were drawn at precisely the correct location. Moreover, thanks to the distribution of the intensity weighting, that brightness is centered at the ideal line. Not coincidentally, a line drawn with pixel pairs of aggregate single-pixel intensity, centered on the ideal line, is perceived by the eye not as a jagged collection of pixel pairs, but as a smooth line centered on the ideal line. Thus, by weighting the bracketing pixels properly at each step, we can readily produce what

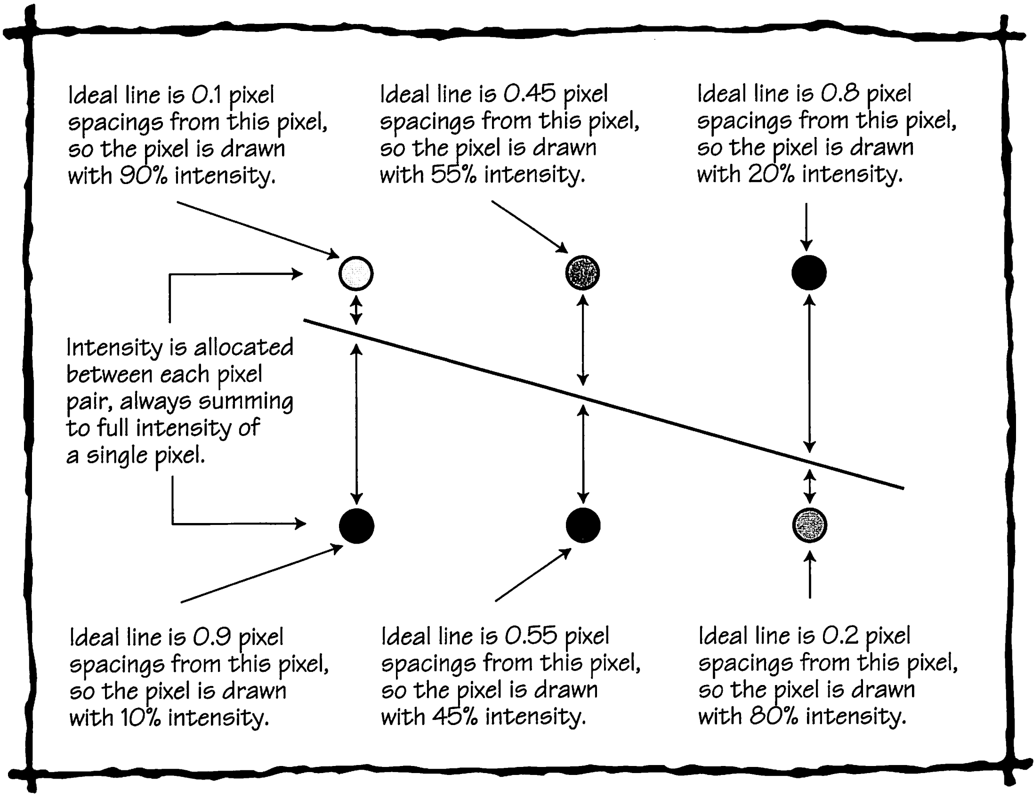

Ideal line is 0.1 pixel spacings from this pixel, so the pixel is drawn with 90% intensity.
Ideal line is 0.45 pixel spacings from this pixel, so the pixel is drawn with 55% intensity.
Ideal line is 0.8 pixel spacings from this pixel, so the pixel is drawn with 20% intensity.
Intensity is allocated between each pixel pair, always summing to full intensity of a single pixel.
Ideal line is 0.9 pixel spacings from this pixel, so the pixel is drawn with 10% intensity.
Ideal line is 0.55 pixel spacings from this pixel, so the pixel is drawn with 45% intensity.
Ideal line is 0.2 pixel spacings from this pixel, so the pixel is drawn with 80% intensity.

Figure 27.1 The Basic Concept of Wu Antialiasing

looks like a smooth line at precisely the right location, rather than the jagged pattern of line segments that non-antialiased line-drawing algorithms such as Bresenham's (see Part III) trace out.

You might expect that the implementation of Wu antialiasing would fall into two distinct areas: tracing out the line (that is, finding the appropriate pixel pairs to draw) and calculating the appropriate weightings for each pixel pair. Not so, however. The weighting calculations involve only a few shifts, XORs, and adds; for all practical purposes, tracing and weighting are rolled into one step—and a very fast step it is. How fast is it? On a 33-MHz 486 with a fast VGA, a good but not maxed-out assembly implementation of Wu antialiasing draws a more than respectable 5,000 150-pixel-long vectors per second. That's especially impressive considering that about 1,500,000 actual pixels are drawn per second, meaning that Wu antialiasing is drawing at around 50 percent of the maximum memory bandwidth—half the fastest theoretically possible drawing speed—of an AT-bus VGA. In short, Wu antialiasing is about as fast an antialiased line approach as you could ever hope to find for the VGA.

Tracing and Intensity in One

Horizontal, vertical, and diagonal lines do not require Wu antialiasing because they pass through the center of every pixel they meet; such lines can be drawn with fast, special-case code. For all other cases, Wu lines are traced out one step at a time along the major axis by means of a simple, fixed-point algorithm. The move along the minor axis with respect to a one-pixel move along the major axis (the line slope for lines with slopes less than 1, 1/slope for lines with slopes greater than 1) is calculated with a single integer divide. This value, called the "error adjust," is stored as a fixed-point fraction, in 0.16 format (that is, all bits are fractional, and the decimal point is just to the left of bit 15). An error accumulator, also in 0.16 format, is initialized to 0. Then the first pixel is drawn; no weighting is needed, because the line intersects its endpoints exactly.

Now the error adjust is added to the error accumulator. The error accumulator indicates how far between pixels the line has progressed along the minor axis at any given step; when the error accumulator turns over, it's time to advance one pixel along the minor axis. At each step along the line, the major-axis coordinate advances by one pixel. The two bracketing pixels to draw are simply the two pixels nearest the line along the minor axis. For instance, if X is the current major-axis coordinate and Y is the current minor-axis coordinate, the two pixels to be drawn are (X,Y) and (X,Y+1). In short, the derivation of the pixels at which to draw involves nothing more complicated than advancing one pixel along the major axis, adding the error adjust to the error accumulator, and advancing one pixel along the minor axis when the error accumulator turns over.

So far, nothing special; but now we come to the true wonder of Wu antialiasing. We know which pair of pixels to draw at each step along the line, but we also need to generate the two proper intensities, which must be inversely proportional to distance from the ideal line and sum to 1, and that's a potentially time-consuming operation. Let's assume, however, that the number of possible intensity levels to be used for weighting is the value NumLevels = 2^n for some integer n, with the minimum weighting (0 percent intensity) being the value 2^n-1, and the maximum weighting (100 percent intensity) being the value 0. Given that, lo and behold, the most significant n bits of the error accumulator select the proper intensity value for one element of the pixel pair, as shown in Figure 27.2. Better yet, 2^n-1 minus the intensity of the first pixel selects the intensity of the other pixel in the pair, because the intensities of the two pixels must sum to 1; as it happens, this result can be obtained simply by flipping the n least-significant bits of the first pixel's value. All this works because what the error accumulator accumulates is precisely the ideal line's current distance between the two bracketing pixels.

The intensity calculations take longer to describe than they do to perform. All that's involved is a shift of the error accumulator to right-justify the desired intensity weighting bits, and then an XOR to flip the least-significant n bits of the first pixel's value in

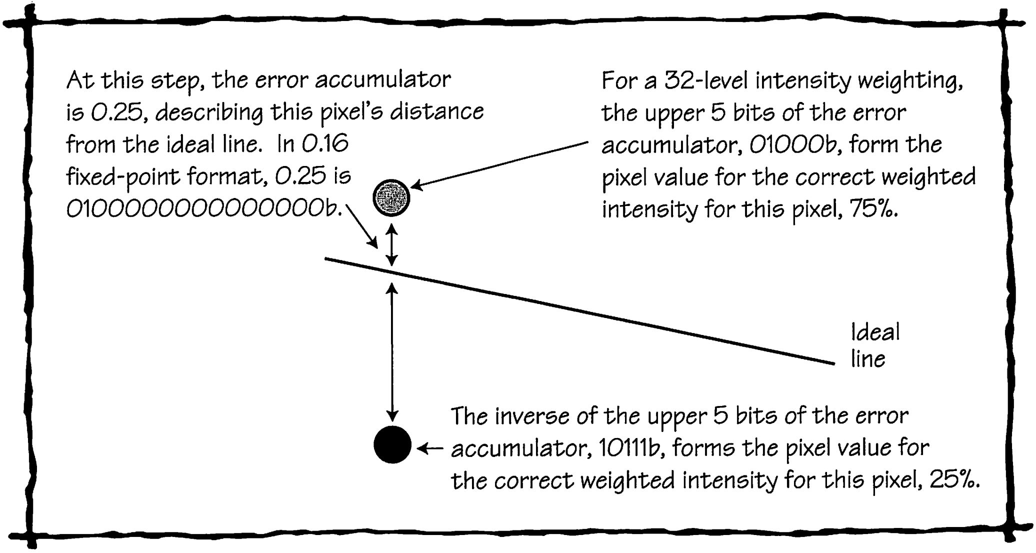

At this step, the error accumulator is 0.25, describing this pixel's distance from the ideal line. In 0.16 fixed-point format, 0.25 is 0100000000000000b.
For a 32-level intensity weighting, the upper 5 bits of the error accumulator, 01000b, form the pixel value for the correct weighted intensity for this pixel, 75%.
Ideal line
The inverse of the upper 5 bits of the error accumulator, 10111b, forms the pixel value for the correct weighted intensity for this pixel, 25%.

Figure 27.2 Wu Intensity Calculations

order to generate the second pixel's value. Listing 27.1 illustrates just how efficient Wu antialiasing is; the intensity calculations take only three statements, and the entire Wu line-drawing loop is only nine statements long. Of course, a single C statement can hide a great deal of complexity, but Listing 27.6, an assembly implementation, shows that only 15 instructions are required per step along the major axis—and the number of instructions could be reduced to ten by special-casing and loop unrolling. Make no mistake about it, Wu antialiasing is fast.

LISTING 27.1 L27-1.C

```
/* Function to draw an antialiased line from (X0,Y0) to (X1,Y1), using an
 * antialiasing approach published by Xiaolin Wu in the July 1991 issue of
 * Computer Graphics. Requires that the palette be set up so that there
 * are NumLevels intensity levels of the desired drawing color, starting at
 * color BaseColor (100% intensity) and followed by (NumLevels-1) levels of
 * evenly decreasing intensity, with color (BaseColor+NumLevels-1) being 0%
 * intensity of the desired drawing color (black). This code is suitable for
 * use at screen resolutions, with lines typically no more than 1K long; for
 * longer lines, 32-bit error arithmetic must be used to avoid problems with
 * fixed-point inaccuracy. No clipping is performed in DrawWuLine; it must be
 * performed either at a higher level or in the DrawPixel function.
 * Tested with Borland C++ in C compilation mode and the small model.
 */
extern void DrawPixel(int, int, int);

/* Wu antialiased line drawer.
 * (X0,Y0),(X1,Y1) = line to draw
 * BaseColor = color # of first color in block used for antialiasing, the
 *          100% intensity version of the drawing color
 * NumLevels = size of color block, with BaseColor+NumLevels-1 being the
 *          0% intensity version of the drawing color
 * IntensityBits = log base 2 of NumLevels; the # of bits used to describe
 *          the intensity of the drawing color. 2**IntensityBits==NumLevels
 */
void DrawWuLine(int X0, int Y0, int X1, int Y1, int BaseColor, int NumLevels,
   unsigned int IntensityBits)
{
   unsigned int IntensityShift, ErrorAdj, ErrorAcc;
   unsigned int ErrorAccTemp, Weighting, WeightingComplementMask;
   int DeltaX, DeltaY, Temp, XDir;

   /* Make sure the line runs top to bottom */
   if (Y0 > Y1) {
      Temp = Y0; Y0 = Y1; Y1 = Temp;
      Temp = X0; X0 = X1; X1 = Temp;
   }
   /* Draw the initial pixel, which is always exactly intersected by
      the line and so needs no weighting */
   DrawPixel(X0, Y0, BaseColor);

   if ((DeltaX = X1 - X0) >= 0) {
      XDir = 1;
   } else {
      XDir = -1;
      DeltaX = -DeltaX; /* make DeltaX positive */
   }
   /* Special-case horizontal, vertical, and diagonal lines, which
      require no weighting because they go right through the center of
      every pixel */
   if ((DeltaY = Y1 - Y0) == 0) {
      /* Horizontal line */
      while (DeltaX-- != 0) {
         X0 += XDir;
         DrawPixel(X0, Y0, BaseColor);
      }
      return;
   }
   if (DeltaX == 0) {
      /* Vertical line */
      do {
         Y0++;
         DrawPixel(X0, Y0, BaseColor);
      } while (--DeltaY != 0);
      return;
   }
   if (DeltaX == DeltaY) {
      /* Diagonal line */
      do {
         X0 += XDir;
         Y0++;
         DrawPixel(X0, Y0, BaseColor);
      } while (--DeltaY != 0);
      return;
   }
   /* line is not horizontal, diagonal, or vertical */
   ErrorAcc = 0;  /* initialize the line error accumulator to 0 */
   /* # of bits by which to shift ErrorAcc to get intensity level */
   IntensityShift = 16 - IntensityBits;
   /* Mask used to flip all bits in an intensity weighting, producing the
      result (1 - intensity weighting) */
   WeightingComplementMask = NumLevels - 1;
   /* Is this an X-major or Y-major line? */
   if (DeltaY > DeltaX) {
      /* Y-major line; calculate 16-bit fixed-point fractional part of a
         pixel that X advances each time Y advances 1 pixel, truncating the
         result so that we won't overrun the endpoint along the X axis */
      ErrorAdj = ((unsigned long) DeltaX << 16) / (unsigned long) DeltaY;
      /* Draw all pixels other than the first and last */
      while (--DeltaY) {
         ErrorAccTemp = ErrorAcc;   /* remember currrent accumulated error */
         ErrorAcc += ErrorAdj;      /* calculate error for next pixel */
         if (ErrorAcc <= ErrorAccTemp) {
            /* The error accumulator turned over, so advance the X coord */
            X0 += XDir;
         }
         Y0++; /* Y-major, so always advance Y */
         /* The IntensityBits most significant bits of ErrorAcc give us the
            intensity weighting for this pixel, and the complement of the
            weighting for the paired pixel */
         Weighting = ErrorAcc >> IntensityShift;
         DrawPixel(X0, Y0, BaseColor + Weighting);
         DrawPixel(X0 + XDir, Y0,
               BaseColor + (Weighting ^ WeightingComplementMask));
      }
      /* Draw the final pixel, which is always exactly intersected by the line
         and so needs no weighting */
      DrawPixel(X1, Y1, BaseColor);
      return;
   }
   /* It's an X-major line; calculate 16-bit fixed-point fractional part of a
      pixel that Y advances each time X advances 1 pixel, truncating the
      result to avoid overrunning the endpoint along the X axis */
   ErrorAdj = ((unsigned long) DeltaY << 16) / (unsigned long) DeltaX;
   /* Draw all pixels other than the first and last */
   while (--DeltaX) {
      ErrorAccTemp = ErrorAcc;   /* remember currrent accumulated error */
      ErrorAcc += ErrorAdj;      /* calculate error for next pixel */
      if (ErrorAcc <= ErrorAccTemp) {
         /* The error accumulator turned over, so advance the Y coord */
         Y0++;
      }
      X0 += XDir; /* X-major, so always advance X */
      /* The IntensityBits most significant bits of ErrorAcc give us the
         intensity weighting for this pixel, and the complement of the
         weighting for the paired pixel */
      Weighting = ErrorAcc >> IntensityShift;
      DrawPixel(X0, Y0, BaseColor + Weighting);
      DrawPixel(X0, Y0 + 1,
            BaseColor + (Weighting ^ WeightingComplementMask));
   }
   /* Draw the final pixel, which is always exactly intersected by the line
      and so needs no weighting */
   DrawPixel(X1, Y1, BaseColor);
}
```

Sample Wu Antialiasing

The true test of any antialiasing technique is how good it looks, so let's have a look at Wu antialiasing in action. Listing 27.1 shown just above is a C implementation of Wu antialiasing. Listing 27.2 is a sample program that draws a variety of Wu-antialiased lines, followed by non-antialiased lines, for comparison. Listing 27.3 contains **DrawPixel()** and **SetMode()** functions for mode 13H, the VGA's 320×200 256-color mode. Finally, Listing 27.4 is a simple, non-antialiased line-drawing routine. Link these four listings together and run the resulting program to see both Wu-antialiased and non-antialiased lines.

LISTING 27.2 L27-2.C

```
/* Sample line-drawing program to demonstrate Wu antialiasing. Also draws
 * non-antialiased lines for comparison.
 * Tested with Borland C++ in C compilation mode and the small model.
 */
#include <dos.h>
#include <conio.h>

void SetPalette(struct WuColor *);
extern void DrawWuLine(int, int, int, int, int, int, unsigned int);
extern void DrawLine(int, int, int, int, int);
extern void SetMode(void);
extern int ScreenWidthInPixels;  /* screen dimension globals */
extern int ScreenHeightInPixels;

#define NUM_WU_COLORS 2 /* # of colors we'll do antialiased drawing with */
struct WuColor {        /* describes one color used for antialiasing */
   int BaseColor;       /* # of start of palette intensity block in DAC */
   int NumLevels;       /* # of intensity levels */
   int IntensityBits;   /* IntensityBits == log2 NumLevels */
   int MaxRed;          /* red component of color at full intensity */
   int MaxGreen;        /* green component of color at full intensity */
   int MaxBlue;         /* blue component of color at full intensity */
};
enum {WU_BLUE=0, WU_WHITE=1};            /* drawing colors */
struct WuColor WuColors[NUM_WU_COLORS] =  /* blue and white */
    {{192, 32, 5, 0, 0, 0x3F}, {224, 32, 5, 0x3F, 0x3F, 0x3F}};

void main()
{
   int CurrentColor, i;
   union REGS regset;

   /* Draw Wu-antialiased lines in all directions */
   SetMode();
   SetPalette(WuColors);
   for (i=5; i<ScreenWidthInPixels; i += 10) {
      DrawWuLine(ScreenWidthInPixels/2-ScreenWidthInPixels/10+i/5,
            ScreenHeightInPixels/5, i, ScreenHeightInPixels-1,
            WuColors[WU_BLUE].BaseColor, WuColors[WU_BLUE].NumLevels,
            WuColors[WU_BLUE].IntensityBits);
   }
   for (i=0; i<ScreenHeightInPixels; i += 10) {
      DrawWuLine(ScreenWidthInPixels/2-ScreenWidthInPixels/10, i/5, 0, i,
            WuColors[WU_BLUE].BaseColor, WuColors[WU_BLUE].NumLevels,
            WuColors[WU_BLUE].IntensityBits);
   }
   for (i=0; i<ScreenHeightInPixels; i += 10) {
      DrawWuLine(ScreenWidthInPixels/2+ScreenWidthInPixels/10, i/5,
            ScreenWidthInPixels-1, i, WuColors[WU_BLUE].BaseColor,
            WuColors[WU_BLUE].NumLevels, WuColors[WU_BLUE].IntensityBits);
   }
   for (i=0; i<ScreenWidthInPixels; i += 10) {
      DrawWuLine(ScreenWidthInPixels/2-ScreenWidthInPixels/10+i/5,
            ScreenHeightInPixels, i, 0, WuColors[WU_WHITE].BaseColor,
            WuColors[WU_WHITE].NumLevels,
            WuColors[WU_WHITE].IntensityBits);
   }
   getch();                /* wait for a key press */

   /* Now clear the screen and draw non-antialiased lines */
   SetMode();
   SetPalette(WuColors);
   for (i=0; i<ScreenWidthInPixels; i += 10) {
      DrawLine(ScreenWidthInPixels/2-ScreenWidthInPixels/10+i/5,
            ScreenHeightInPixels/5, i, ScreenHeightInPixels-1,
            WuColors[WU_BLUE].BaseColor);
   }
   for (i=0; i<ScreenHeightInPixels; i += 10) {
      DrawLine(ScreenWidthInPixels/2-ScreenWidthInPixels/10, i/5, 0, i,
            WuColors[WU_BLUE].BaseColor);
   }
   for (i=0; i<ScreenHeightInPixels; i += 10) {
      DrawLine(ScreenWidthInPixels/2+ScreenWidthInPixels/10, i/5,
            ScreenWidthInPixels-1, i, WuColors[WU_BLUE].BaseColor);
   }
   for (i=0; i<ScreenWidthInPixels; i += 10) {
      DrawLine(ScreenWidthInPixels/2-ScreenWidthInPixels/10+i/5,
            ScreenHeightInPixels, i, 0, WuColors[WU_WHITE].BaseColor);
   }
   getch();                /* wait for a key press */

   regset.x.ax = 0x0003;   /* AL = 3 selects 80x25 text mode */
   int86(0x10, &regset, &regset);   /* return to text mode */
}

/* Sets up the palette for antialiasing with the specified colors.
 * Intensity steps for each color are scaled from the full desired intensity
 * of the red, green, and blue components for that color down to 0%
 * intensity; each step is rounded to the nearest integer. Colors are
 * corrected for a gamma of 2.3. The values that the palette is programmed
 * with are hardwired for the VGA's 6 bit per color DAC.
 */
void SetPalette(struct WuColor * WColors)
{
   int i, j;
   union REGS regset;
   struct SREGS sregset;
   static unsigned char PaletteBlock[256][3];   /* 256 RGB entries */
   /* Gamma-corrected DAC color components for 64 linear levels from 0% to
      100% intensity */
   static unsigned char GammaTable[] = {
      0, 10, 14, 17, 19, 21, 23, 24, 26, 27, 28, 29, 31, 32, 33, 34,
      35, 36, 37, 37, 38, 39, 40, 41, 41, 42, 43, 44, 44, 45, 46, 46,
      47, 48, 48, 49, 49, 50, 51, 51, 52, 52, 53, 53, 54, 54, 55, 55,
      56, 56, 57, 57, 58, 58, 59, 59, 60, 60, 61, 61, 62, 62, 63, 63};

   for (i=0; i<NUM_WU_COLORS; i++) {
      for (j=0; j<WColors[i].NumLevels; j++) {
         PaletteBlock[j][0] = GammaTable[((double)WColors[i].MaxRed * (1.0 -
               (double)j / (double)(WColors[i].NumLevels - 1))) + 0.5];
         PaletteBlock[j][1] = GammaTable[((double)WColors[i].MaxGreen * (1.0 -
               (double)j / (double)(WColors[i].NumLevels - 1))) + 0.5];
         PaletteBlock[j][2] = GammaTable[((double)WColors[i].MaxBlue * (1.0 -
               (double)j / (double)(WColors[i].NumLevels - 1))) + 0.5];
      }
      /* Now set up the palette to do Wu antialiasing for this color */
      regset.x.ax = 0x1012;   /* set block of DAC registers function */
      regset.x.bx = WColors[i].BaseColor;   /* first DAC location to load */
      regset.x.cx = WColors[i].NumLevels;   /* # of DAC locations to load */
      regset.x.dx = (unsigned int)PaletteBlock; /* offset of array from which
                                                   to load RGB settings */
      sregset.es = _DS; /* segment of array from which to load settings */
      int86x(0x10, &regset, &regset, &sregset); /* load the palette block */
   }
}
```

LISTING 27.3 L27-3.C

```
/* VGA mode 13h pixel-drawing and mode set functions.
 * Tested with Borland C++ in C compilation mode and the small model.
 */
#include <dos.h>

/* Screen dimension globals, used in main program to scale. */
int ScreenWidthInPixels = 320;
int ScreenHeightInPixels = 200;

/* Mode 13h draw pixel function. */
void DrawPixel(int X, int Y, int Color)
{
#define SCREEN_SEGMENT  0xA000
   unsigned char far *ScreenPtr;

   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) = (unsigned int) Y * ScreenWidthInPixels + X;
   *ScreenPtr = Color;
}

/* Mode 13h mode-set function. */
void SetMode()
{
   union REGS regset;

   /* Set to 320x200 256-color graphics mode */
   regset.x.ax = 0x0013;
   int86(0x10, &regset, &regset);
}
```

LISTING 27.4 L27-4.C

```
/* Function to draw a non-antialiased line from (X0,Y0) to (X1,Y1), using a
 * simple fixed-point error accumulation approach.
 * Tested with Borland C++ in C compilation mode and the small model.
 */
extern void DrawPixel(int, int, int);

/* Non-antialiased line drawer.
 * (X0,Y0),(X1,Y1) = line to draw, Color = color in which to draw
 */
void DrawLine(int X0, int Y0, int X1, int Y1, int Color)
{
   unsigned long ErrorAcc, ErrorAdj;
   int DeltaX, DeltaY, XDir, Temp;

   /* Make sure the line runs top to bottom */
   if (Y0 > Y1) {
      Temp = Y0; Y0 = Y1; Y1 = Temp;
      Temp = X0; X0 = X1; X1 = Temp;
   }
   DrawPixel(X0, Y0, Color);  /* draw the initial pixel */
   if ((DeltaX = X1 - X0) >= 0) {
      XDir = 1;
   } else {
      XDir = -1;
      DeltaX = -DeltaX; /* make DeltaX positive */
   }
   if ((DeltaY = Y1 - Y0) == 0)  /* done if only one point in the line */
      if (DeltaX == 0) return;

   ErrorAcc = 0x8000;   /* initialize line error accumulator to .5, so we can
                           advance when we get halfway to the next pixel */
   /* Is this an X-major or Y-major line? */
   if (DeltaY > DeltaX) {
      /* Y-major line; calculate 16-bit fixed-point fractional part of a
         pixel that X advances each time Y advances 1 pixel */
      ErrorAdj = ((((unsigned long)DeltaX << 17) / (unsigned long)DeltaY) +
            1) >> 1;
      /* Draw all pixels between the first and last */
      do {
         ErrorAcc += ErrorAdj;      /* calculate error for this pixel */
         if (ErrorAcc & ~0xFFFFL) {
            /* The error accumulator turned over, so advance the X coord */
            X0 += XDir;
            ErrorAcc &= 0xFFFFL;    /* clear integer part of result */
         }
         Y0++;                      /* Y-major, so always advance Y */
         DrawPixel(X0, Y0, Color);
      } while (--DeltaY);
      return;
   }
   /* It's an X-major line; calculate 16-bit fixed-point fractional part of a
      pixel that Y advances each time X advances 1 pixel */
   ErrorAdj = ((((unsigned long)DeltaY << 17) / (unsigned long)DeltaX) +
         1) >> 1;
   /* Draw all remaining pixels */
   do {
      ErrorAcc += ErrorAdj;      /* calculate error for this pixel */
      if (ErrorAcc & ~0xFFFFL) {
         /* The error accumulator turned over, so advance the Y coord */
         Y0++;
         ErrorAcc &= 0xFFFFL;    /* clear integer part of result */
      }
      X0 += XDir;                /* X-major, so always advance X */
      DrawPixel(X0, Y0, Color);
   } while (--DeltaX);
}
```

Listing 27.1 isn't particularly fast, because it calls **DrawPixel()** for each pixel. On the other hand, **DrawPixel()** makes it easy to try out Wu antialiasing in a variety of modes; just adapt the code in Listing 27.3 for the 256-color mode you want to support. For example, Listing 27.5 shows code to draw Wu-antialiased lines in 640×480 256-color mode on SuperVGAs built around the Tseng Labs ET4000 chip with at least 512K of display memory installed. It's well worth checking out Wu antialiasing at 640×480. Although antialiased lines look much smoother than normal lines at 320×200 resolution, they're far from perfect, because the pixels are so big that the eye can't blend them properly. At 640×480, however, Wu-antialiased lines look fabulous; from a couple of feet away, they look as straight and smooth as if they were drawn with a ruler.

LISTING 27.5 L27-5.C

```
/* Mode set and pixel-drawing functions for the 640x480 256-color mode of
 * Tseng Labs ET4000-based SuperVGAs.
 * Tested with Borland C++ in C compilation mode and the small model.
 */
#include <dos.h>

/* Screen dimension globals, used in main program to scale */
int ScreenWidthInPixels = 640;
int ScreenHeightInPixels = 480;

/* ET4000 640x480 256-color draw pixel function. */
void DrawPixel(int X, int Y, int Color)
{
#define SCREEN_SEGMENT       0xA000
#define GC_SEGMENT_SELECT    0x3CD /* ET4000 segment (bank) select reg */
   unsigned char far *ScreenPtr;
   unsigned int Bank;
   unsigned long BitmapAddress;

   /* full bitmap address of pixel, as measured from address 0 to 0xFFFFF */
   BitmapAddress = (unsigned long) Y * ScreenWidthInPixels + X;
   /* Bank # is upper word of bitmap addr */
   Bank = BitmapAddress >> 16;
   /* Upper nibble is read bank #, lower nibble is write bank # */
   outp(GC_SEGMENT_SELECT, (Bank << 4) | Bank);
   /* Draw into the bank */
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) = (unsigned int) BitmapAddress;
   *ScreenPtr = Color;
}

/* ET4000 640x480 256-color mode-set function. */
void SetMode()
{
   union REGS regset;

   /* Set to 640x480 256-color graphics mode */
   regset.x.ax = 0x002E;
   int86(0x10, &regset, &regset);
}
```

Listing 27.1 requires that the DAC palette be set up so that a **NumLevel**-long block of palette entries contains linearly decreasing intensities of the drawing color. The size of the block is programmable, but must be a power of two. The more intensity levels, the better. Wu says that 32 intensities is enough; on my system, eight and even four levels looked pretty good. I found that gamma correction, which gives linearly spaced intensity steps, improved antialiasing quality significantly. Fortunately, we can program the palette with gamma-corrected values, so our drawing code doesn't have to do any extra work.

Listing 27.1 isn't very fast, so I implemented Wu antialiasing in assembly, hard-coded for mode 13H. The implementation is shown in full in Listing 27.6. High-speed graphics code and fast VGAs go together like peanut butter and jelly, which is to say very well indeed; the assembly implementation ran more than twice as fast as the C code on my 486. Enough said!

LISTING 27.6 L27-6.ASM

```
; C near-callable function to draw an antialiased line from
; (X0,Y0) to (X1,Y1), in mode 13h, the VGA's standard 320x200 256-color
; mode. Uses an antialiasing approach published by Xiaolin Wu in the July
; 1991 issue of Computer Graphics. Requires that the palette be set up so
; that there are NumLevels intensity levels of the desired drawing color,
; starting at color BaseColor (100% intensity) and followed by (NumLevels-1)
; levels of evenly decreasing intensity, with color (BaseColor+NumLevels-1)
; being 0% intensity of the desired drawing color (black). No clipping is
; performed in DrawWuLine. Handles a maximum of 256 intensity levels per
; antialiased color. This code is suitable for use at screen resolutions,
; with lines typically no more than 1K long; for longer lines, 32-bit error
; arithmetic must be used to avoid problems with fixed-point inaccuracy.
; Tested with TASM.
;
; C near-callable as:
;   void DrawWuLine(int X0, int Y0, int X1, int Y1, int BaseColor,
;      int NumLevels, unsigned int IntensityBits);

SCREEN_WIDTH_IN_BYTES equ 320     ;# of bytes from the start of one scan line
                                  ; to the start of the next
SCREEN_SEGMENT   equ   0a000h     ;segment in which screen memory resides

; Parameters passed in stack frame.
parms   struc
        dw      2 dup (?)   ;pushed BP and return address
X0      dw      ?           ;X coordinate of line start point
Y0      dw      ?           ;Y coordinate of line start point
X1      dw      ?           ;X coordinate of line end point
Y1      dw      ?           ;Y coordinate of line end point
BaseColor dw    ?           ;color # of first color in block used for
                            ;antialiasing, the 100% intensity version of the
                            ;drawing color
NumLevels dw    ?           ;size of color block, with BaseColor+NumLevels-1
                            ; being the 0% intensity version of the drawing color
                            ; (maximum NumLevels = 256)
IntensityBits dw ?          ;log base 2 of NumLevels; the # of bits used to
                            ; describe the intensity of the drawing color.
                            ; 2**IntensityBits==NumLevels
                            ; (maximum IntensityBits = 8)
parms   ends

.model  small
.code
; Screen dimension globals, used in main program to scale.
```

```
_ScreenWidthInPixels    dw      320
_ScreenHeightInPixels   dw      200

        .code
        public  _DrawWuLine
_DrawWuLine proc near
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to local stack frame
        push    si              ;preserve C's register variables
        push    di
        push    ds              ;preserve C's default data segment
        cld                     ;make string instructions increment their pointers

; Make sure the line runs top to bottom.
        mov     si,[bp].X0
        mov     ax,[bp].Y0
        cmp     ax,[bp].Y1 ;swap endpoints if necessary to ensure that
        jna     NoSwap     ; Y0 <= Y1
        xchg    [bp].Y1,ax
        mov     [bp].Y0,ax
        xchg    [bp].X1,si
        mov     [bp].X0,si
NoSwap:

; Draw the initial pixel, which is always exactly intersected by the line
; and so needs no weighting.
        mov     dx,SCREEN_SEGMENT
        mov     ds,dx           ;point DS to the screen segment
        mov     dx,SCREEN_WIDTH_IN_BYTES
        mul     dx              ;Y0 * SCREEN_WIDTH_IN_BYTES yields the offset
                                ; of the start of the row start the initial
                                ; pixel is on
        add     si,ax           ;point DS:SI to the initial pixel
        mov     al,byte ptr [bp].BaseColor  ;color with which to draw
        mov     [si],al         ;draw the initial pixel

        mov     bx,1            ;XDir = 1; assume DeltaX >= 0
        mov     cx,[bp].X1
        sub     cx,[bp].X0      ;DeltaX; is it >= 1?
        jns     DeltaXSet       ;yes, move left->right, all set
                                ;no, move right->left
        neg     cx              ;make DeltaX positive
        neg     bx              ;XDir = -1
DeltaXSet:

; Special-case horizontal, vertical, and diagonal lines, which require no
; weighting because they go right through the center of every pixel.
        mov     dx,[bp].Y1
        sub     dx,[bp].Y0      ;DeltaY; is it 0?
        jnz     NotHorz         ;no, not horizontal
                                ;yes, is horizontal, special case
        and     bx,bx           ;draw from left->right?
        jns     DoHorz          ;yes, all set
        std                     ;no, draw right->left
DoHorz:
        lea     di,[bx+si]      ;point DI to next pixel to draw
        mov     ax,ds
        mov     es,ax           ;point ES:DI to next pixel to draw
        mov     al,byte ptr [bp].BaseColor ;color with which to draw
                                ;CX = DeltaX at this point
        rep     stosb           ;draw the rest of the horizontal line
        cld                                 ;restore default direction flag
        jmp     Done                        ;and we're done

        align   2
NotHorz:
        and     cx,cx                       ;is DeltaX 0?
        jnz     NotVert                     ;no, not a vertical line
                                            ;yes, is vertical, special case
        mov     al,byte ptr [bp].BaseColor  ;color with which to draw
VertLoop:
        add     si,SCREEN_WIDTH_IN_BYTES    ;point to next pixel to draw
        mov     [si],al                     ;draw the next pixel
        dec     dx                          ;--DeltaY
        jnz     VertLoop
        jmp     Done                        ;and we're done

        align   2
NotVert:
        cmp     cx,dx                       ;DeltaX == DeltaY?
        jnz     NotDiag                     ;no, not diagonal
                                            ;yes, is diagonal, special case
        mov     al,byte ptr [bp].BaseColor  ;color with which to draw
DiagLoop:
        lea     si,[si+SCREEN_WIDTH_IN_BYTES+bx]
                                            ;advance to next pixel to draw by
                                            ; incrementing Y and adding XDir to X
        mov     [si],al                     ;draw the next pixel
        dec     dx                          ;--DeltaY
        jnz     DiagLoop
        jmp     Done                        ;and we're done

; Line is not horizontal, diagonal, or vertical.
        align   2
NotDiag:
; Is this an X-major or Y-major line?
        cmp     dx,cx
        jb      XMajor                      ;it's X-major

; It's a Y-major line. Calculate the 16-bit fixed-point fractional part of a
; pixel that X advances each time Y advances 1 pixel, truncating the result
; to avoid overrunning the endpoint along the X axis.
        xchg    dx,cx           ;DX = DeltaX, CX = DeltaY
        sub     ax,ax           ;make DeltaX 16.16 fixed-point value in DX:AX
        div     cx              ;AX = (DeltaX << 16) / DeltaY. Won't overflow
                                ; because DeltaX < DeltaY
        mov     di,cx           ;DI = DeltaY (loop count)
        sub     si,bx           ;back up the start X by 1, as explained below
        mov     dx,-1           ;initialize the line error accumulator to -1,
                                ; so that it will turn over immediately and
                                ; advance X to the start X. This is necessary
                                ; properly to bias error sums of 0 to mean
                                ; "advance next time" rather than "advance
                                ; this time," so that the final error sum can
                                ; never cause drawing to overrun the final X
                                ; coordinate (works in conjunction with
                                ; truncating ErrorAdj, to make sure X can't
                                ; overrun)
        mov     cx,8                        ;CL = # of bits by which to shift
        sub     cx,[bp].IntensityBits       ; ErrorAcc to get intensity level (8
                                            ; instead of 16 because we work only
                                            ; with the high byte of ErrorAcc)
        mov     ch,byte ptr [bp].NumLevels   ;mask used to flip all bits in an
        dec     ch                           ; intensity weighting, producing
                                             ; result (1 - intensity weighting)
        mov     bp,BaseColor[bp]             ;***stack frame not available***
                                             ;***from now on               ***
        xchg    bp,ax                        ;BP = ErrorAdj, AL = BaseColor,
                                             ; AH = scratch register

; Draw all remaining pixels.
YMajorLoop:
        add     dx,bp                        ;calculate error for next pixel
        jnc     NoXAdvance                   ;not time to step in X yet
                                             ;the error accumulator turned over,
                                             ;so advance the X coord
        add     si,bx                        ;add XDir to the pixel pointer
NoXAdvance:
        add     si,SCREEN_WIDTH_IN_BYTES     ;Y-major, so always advance Y

; The IntensityBits most significant bits of ErrorAcc give us the intensity
; weighting for this pixel, and the complement of the weighting for the
; paired pixel.
        mov     ah,dh               ;msb of ErrorAcc
        shr     ah,cl               ;Weighting = ErrorAcc >> IntensityShift;
        add     ah,al               ;BaseColor + Weighting
        mov     [si],ah             ;DrawPixel(X, Y, BaseColor + Weighting);
        mov     ah,dh               ;msb of ErrorAcc
        shr     ah,cl               ;Weighting = ErrorAcc >> IntensityShift;
        xor     ah,ch               ;Weighting ^ WeightingComplementMask
        add     ah,al               ;BaseColor + (Weighting ^
WeightingComplementMask)
        mov     [si+bx],ah          ;DrawPixel(X+XDir, Y,
; BaseColor + (Weighting ^ WeightingComplementMask));
        dec     di                  ;--DeltaY
        jnz     YMajorLoop
        jmp     Done                ;we're done with this line

; It's an X-major line.
        align   2
XMajor:
; Calculate the 16-bit fixed-point fractional part of a pixel that Y advances
; each time X advances 1 pixel, truncating the result to avoid overrunning
; the endpoint along the X axis.
        sub     ax,ax               ;make DeltaY 16.16 fixed-point value in DX:AX
        div     cx                  ;AX = (DeltaY << 16) / Deltax. Won't overflow
                                    ; because DeltaY < DeltaX
        mov     di,cx               ;DI = DeltaX (loop count)
        sub     si,SCREEN_WIDTH_IN_BYTES    ;back up the start X by 1, as
                                    ; explained below
        mov     dx,-1               ;initialize the line error accumulator to -1,
                                    ; so that it will turn over immediately and
                                    ; advance Y to the start Y. This is necessary
                                    ; properly to bias error sums of 0 to mean
                                    ; "advance next time" rather than "advance
                                    ; this time," so that the final error sum can
                                    ; never cause drawing to overrun the final Y
                                    ; coordinate (works in conjunction with
                                    ; truncating ErrorAdj, to make sure Y can't
                                    ; overrun)
        mov     cx,8                   ;CL = # of bits by which to shift
        sub     cx,[bp].IntensityBits  ; ErrorAcc to get intensity level (8
                                       ; instead of 16 because we work only
                                       ; with the high byte of ErrorAcc)
        mov     ch,byte ptr [bp].NumLevels  ;mask used to flip all bits in an
        dec     ch                  ; intensity weighting, producing
                                    ; result (1 - intensity weighting)
        mov     bp,BaseColor[bp]    ;***stack frame not available***
                                    ;***from now on              ***
        xchg    bp,ax               ;BP = ErrorAdj, AL = BaseColor,
                                    ; AH = scratch register
; Draw all remaining pixels.
XMajorLoop:
        add     dx,bp               ;calculate error for next pixel
        jnc     NoYAdvance          ;not time to step in Y yet
                                    ;the error accumulator turned over,
                                    ; so advance the Y coord
        add     si,SCREEN_WIDTH_IN_BYTES    ;advance Y
NoYAdvance:
        add     si,bx               ;X-major, so add XDir to the pixel pointer

; The IntensityBits most significant bits of ErrorAcc give us the intensity
; weighting for this pixel, and the complement of the weighting for the
; paired pixel.
        mov     ah,dh               ;msb of ErrorAcc
        shr     ah,cl               ;Weighting = ErrorAcc >> IntensityShift;
        add     ah,al               ;BaseColor + Weighting
        mov     [si],ah             ;DrawPixel(X, Y, BaseColor + Weighting);
        mov     ah,dh               ;msb of ErrorAcc
        shr     ah,cl               ;Weighting = ErrorAcc >> IntensityShift;
        xor     ah,ch               ;Weighting ^ WeightingComplementMask
        add     ah,al               ;BaseColor + (Weighting ^
WeightingComplementMask)
        mov     [si+SCREEN_WIDTH_IN_BYTES],ah
 ;DrawPixel(X, Y+SCREEN_WIDTH_IN_BYTES,
 ; BaseColor + (Weighting ^ WeightingComplementMask));
        dec     di                  ;--DeltaX
        jnz     XMajorLoop

Done:                               ;we're done with this line
        pop     ds                  ;restore C's default data segment
        pop     di                  ;restore C's register variables
        pop     si
        pop     bp                  ;restore caller's stack frame
        ret                         ;done
_DrawWuLine endp
        end
```

Notes on Wu Antialiasing

Wu antialiasing can be applied to any curve for which it's possible to calculate at each step the positions and intensities of two bracketing pixels, although the implementation will generally be nowhere near as efficient as it is for lines. However, Wu's article in *Computer Graphics* does describe an efficient algorithm for drawing antialiased circles. Wu also describes a technique for antialiasing solids, such as filled circles and polygons. Wu's approach biases the edges of filled objects outward. Although this is no good for adjacent polygons of the sort used in rendering, it's certainly possible to design a more accurate polygon-antialiasing approach around Wu's basic weighting technique. The results would not be quite so good as more sophisticated antialiasing techniques, but they would be much faster.

In general, the results obtained by Wu antialiasing are only so-so, by theoretical measures. Wu antialiasing amounts to a simple box filter placed over a fixed-point step approximation of a line, and that process introduces a good deal of deviation from the ideal. On the other hand, Wu notes that even a 10 percent error in intensity doesn't lead to noticeable loss of image quality, and for Wu-antialiased lines up to 1K pixels in length, the error is under 10 percent. If it looks good, it is good—and it looks good.

With a 16-bit error accumulator, fixed-point inaccuracy becomes a problem for Wu-antialiased lines longer than 1K. For such lines, you should switch to using 32-bit error values, which would let you handle lines of any practical length.

In the listings, I have chosen to truncate, rather than round, the error-adjust value. This increases the intensity error of the line but guarantees that fixed-point inaccuracy won't cause the minor axis to advance past the endpoint. Overrunning the endpoint would result in the drawing of pixels outside the line's bounding box, and potentially even in an attempt to access pixels off the edge of the bitmap.

Finally, I should mention that, as published, Wu's algorithm draws lines symmetrically, from both ends at once. I haven't done this for a number of reasons, not least of which is that symmetric drawing is an inefficient way to draw lines that span banks on banked Super-VGAs. Banking aside, however, symmetric drawing is potentially faster, because it eliminates half of all calculations; in so doing, it cuts cumulative error in half, as well.

With or without symmetrical processing, Wu antialiasing beats fried, stewed chicken hands-down. Trust me on this one.

Bit-Plane Animation

Chapter 28

A Simple and Extremely Fast Animation Method for Limited Color

When it comes to computers, my first love is animation. There's nothing quite like the satisfaction of fooling the eye and creating a miniature reality simply by rearranging a few bytes of display memory. What makes animation particularly interesting is that it has to happen fast (as measured in human time), and without blinking and flickering, or else you risk destroying the illusion of motion and solidity. Those constraints make animation the toughest graphics challenge—and also the most rewarding.

It pains me to hear industry pundits rag on the PC when it comes to animation. Okay, I'll grant you that the PC isn't a Silicon Graphics workstation and never will be, but then neither is anything else on the market. The VGA offers good resolution and color, and while the hardware wasn't *designed* for animation, that doesn't mean we can't put it to work in that capacity. One lesson that any good PC graphics or assembly programmer learns quickly is that it's what the PC's hardware *can* do—not what it was intended to do—that's important. (By the way, if I were to pick one aspect of the PC to dump on, it would be sound, not animation. The PC's sound circuity really is lousy, and it's hard to understand why that should be, given that a cheap sound chip—which even the almost-forgotten PC*jr* had—would have changed everything. I guess IBM figured "serious" computer users would be put off by a computer that could make fun noises.)

Anyway, my point is that the PC's animation capabilities are pretty good. There's a trick, though: You can only push the VGA to its animation limits by stretching your mind a bit and using some unorthodox approaches to animation. In fact, stretching your mind is the key to producing good code for *any* task on the PC—that's the topic of my book *Zen of Code Optimization*, also published by Coriolis Group Books. For most software, however, it's not fatal if your code isn't excellent—there's slow but functional software all over the place. When it comes to VGA animation, though, you won't get to first base without a clever approach.

So, what clever approaches do I have in mind? All sorts. The resources of the VGA (or even its now-ancient predecessor, the EGA) are many and varied, and can be applied and combined in hundreds of ways to produce effective animation. For example, refer back to Chapter 1 for an example of page flipping. Or look at the July 1986 issue of *PC Tech Journal*, which describes the basic block-move animation technique, or the August 1987 issue of *PC Tech Journal*, which shows a software-sprite scheme built around the EGA's vertical interrupt and the AND-OR image drawing technique. Or look over the rest of this book, which contains dozens of tips and tricks that can be applied to animation, including Mode X-based techniques starting in Chapter 32 that are the basis for many commercial games.

This chapter adds yet another sort of animation to the list. We're going to take advantage of the bit-plane architecture and color palette of the VGA to develop an animation architecture that can handle several overlapping images with terrific speed and with virtually perfect visual quality. This technique produces no overlap effects or flicker and allows us to use the fastest possible method to draw images—the **REP MOVS** instruction. It has its limitations, but unlike Mode X and some other animation techniques, the techniques I'll show you in this chapter will also work on the EGA, which may be important in some applications.

As with any technique on the PC, there are tradeoffs involved with bit-plane animation. While bit-plane animation is extremely attractive as far as performance and visual quality are concerned, it is somewhat limited. Bit-plane animation supports only four colors plus the background color at any one time, each image must consist of only one of the four colors, and it's preferable that images of the same color not intersect.

It doesn't much matter if bit-plane animation isn't perfect for all applications, though. The real point of showing you bit-plane animation is to bring home the reality that the VGA is a complex adapter with many resources, and that you can do remarkable things if you understand those resources and come up with creative ways to put them to work at specific tasks.

Bit-Planes: The Basics

The underlying principle of bit-plane animation is extremely simple. The VGA has four separate bit planes in modes 0DH, 0EH, 10H, and 12H. Plane 0 normally contains data for the blue component of pixel color, plane 1 normally contains green pixel data, plane 2 red pixel data, and plane 3 intensity pixel data—but we're going to mix that up a bit in a moment, so we'll simply refer to them as planes 0, 1, 2, and 3 from now on.

Each bit plane can be written to independently. The contents of the four bit planes are used to generate pixels, with the four bits that control the color of each pixel coming from the four planes. However, the bits from the planes go through a look-up stage on the way to becoming pixels—they're used to look up a 6-bit color from one of the sixteen palette registers. Figure 28.1 shows how the bits from the four planes feed into the palette registers to select the color of each pixel. (On the VGA specifically, the output of the palette registers goes to the DAC for an additional look-up stage, as described in Chapters 11, 12, and 13.)

Take a good look at Figure 28.1. Any light bulbs going on over your head yet? If not, consider this. The general problem with VGA animation is that it's complex and time-consuming to manipulate images that span the four planes (as most do), and that it's hard to avoid interference problems when images intersect, since those images share the same bits in display memory. Since the four bit planes can be written to and read from independently, it should be apparent that if we could come up with a way to display images from each plane independently of whatever images are stored in the other planes, we would have four sets of images that we could manipulate very easily. There would be no interference effects between images in different planes, because images in one plane wouldn't share bits with images in another plane. What's more, since all the bits for a given image would reside in a single plane, we could do away

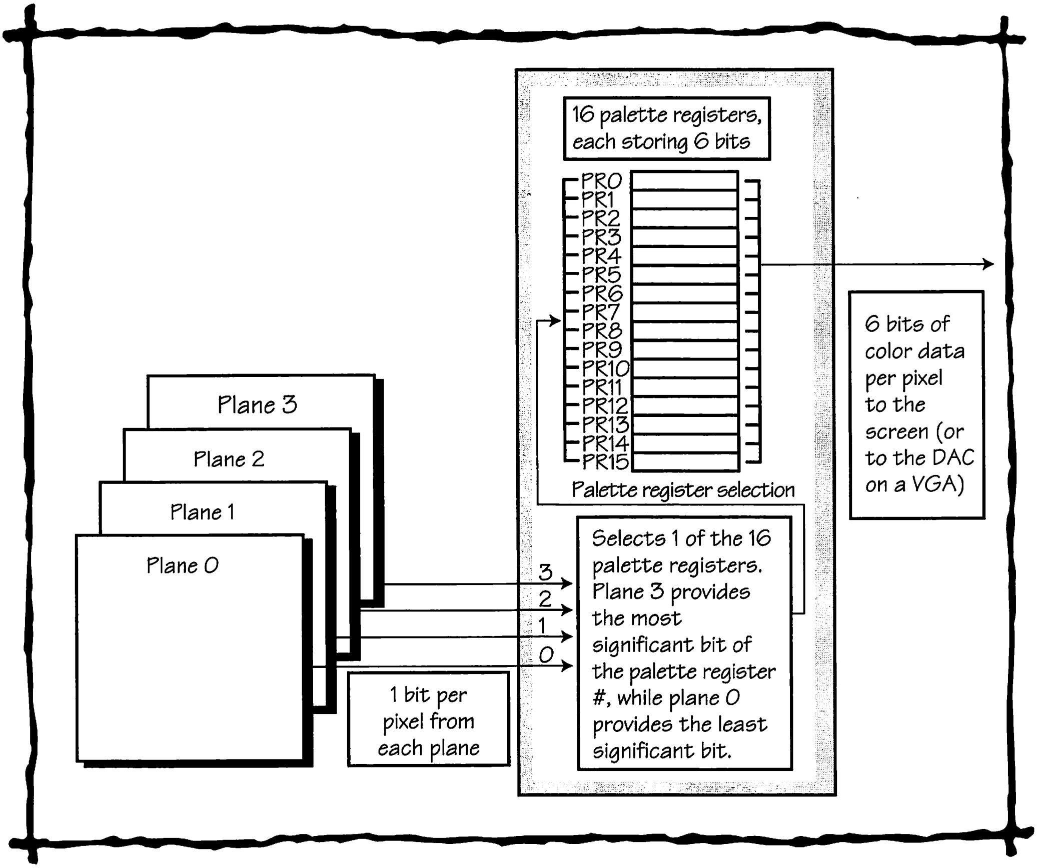

16 palette registers, each storing 6 bits
PR0
PR1
PR2
PR3
PR4
PR5
PR6
PR7
PR8
PR9
PR10
PR11
PR12
PR13
PR14
PR15
Palette register selection
6 bits of color data per pixel to the screen (or to the DAC on a VGA)
Plane 3
Plane 2
Plane 1
Plane 0
3
2
1
0
1 bit per pixel from each plane
Selects 1 of the 16 palette registers. Plane 3 provides the most significant bit of the palette register #, while plane 0 provides the least significant bit.

Figure 28.1 How 4 Bits of Video Data Become 6 Bits of Color

with the cumbersome programming of the VGA's complex hardware that is needed to manipulate images that span multiple planes.

All in all, it would be a good deal if we could store each image in a single plane, as shown in Figure 28.2. However, a problem arises when images in different planes overlap, as shown in Figure 28.3. The combined bits from overlapping images generate new colors, so the overlapping parts of the images don't look like they belong to either of the two images. What we really want, of course, is for one of the images to appear to be in front of the other. It would be better yet if the rearward image showed through any transparent (that is, background-colored) parts of the forward image. Can we do that?

You bet.

Stacking the Palette Registers

Suppose that instead of viewing the four bits per pixel coming out of display memory as selecting one of sixteen colors,we view those bits as selecting one of *four* colors. If the bit from plane 0 is 1, that would select color 0 (say, red). The bit from plane 1 would select color 1 (say, green), the bit from plane 2 would select color 2 (say, blue), and the bit from plane 3 would select color 3 (say, white). Whenever more than 1 bit is 1, the 1 bit from the lowest-numbered plane would determine the color, and 1 bits from all

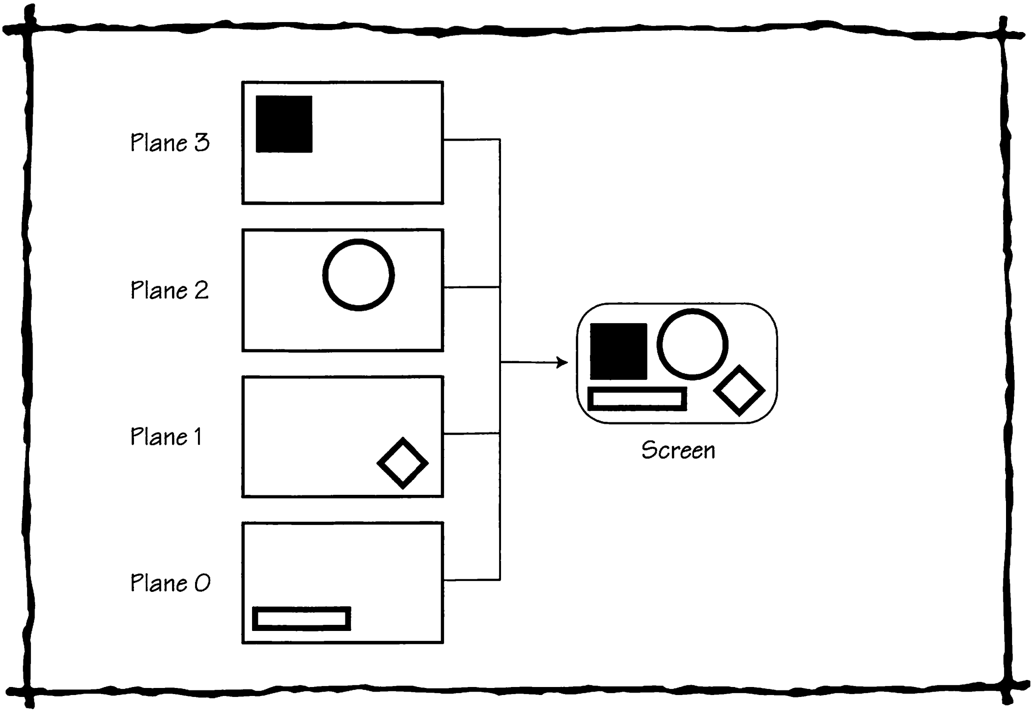


Figure 28.2 Storing Images in Separate Planes

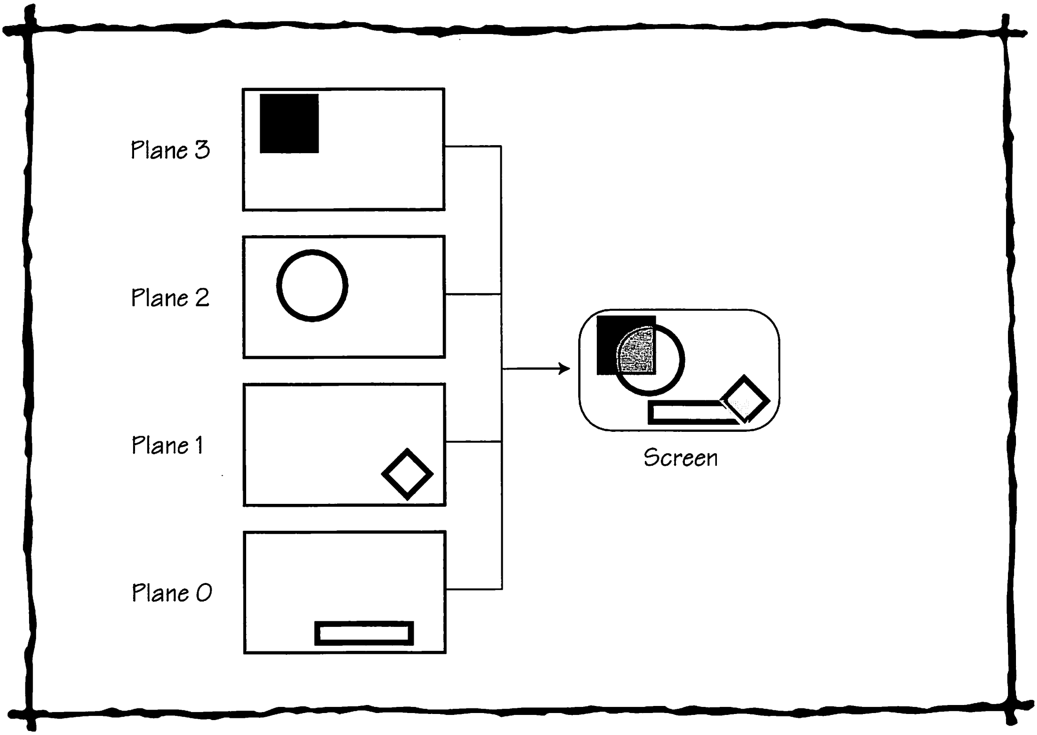


Figure 28.3 The Problem of Overlapping Colors

other planes would be ignored. Finally, the absence of any 1 bits at all would select the background color (say, black).

That would give us four colors and the background color. It would also give us nifty image precedence, with images in plane 0 appearing to be in front of images from the other planes, images in plane 1 appearing to be in front of images from planes 2 and 3, and so on. It would even give us transparency, where rearward images would show through holes within and around the edges of images in forward planes. Finally, and most importantly, it would meet all the criteria needed to allow us to store each image in a single plane, letting us manipulate the images very quickly and with no reprogramming of the VGA's hardware other than the few **OUT** instructions required to select the plane we want to write to.

Which leaves only one question: How do we get this magical pixel-precedence scheme to work? As it turns out, all we need to do is reprogram the palette registers so that the 1 bit from the plane with the highest precedence determines the color. The palette RAM settings for the colors described above are summarized in Table 28.1.

Remember that the 4-bit values coming from display memory select which palette register provides the actual pixel color. Given that, it's easy to see that the rightmost 1-bit of the four bits coming from display memory in Table 28.1 selects the pixel color. If the bit from plane 0 is 1, then the color is red, no matter what the other bits are, as

Table 28.1 Palette RAM Settings for Bit-Plane Animation

Bit Value For Plane 3 2 1 0	Palette Register	Register setting
0 0 0 0	0	00H (black)
0 0 0 1	1	3CH (red)
0 0 1 0	2	3AH (green)
0 0 1 1	3	3CH (red)
0 1 0 0	4	39H (blue)
0 1 0 1	5	3CH (red)
0 1 1 0	6	3AH (green)
0 1 1 1	7	3CH (red)
1 0 0 0	8	3FH (white)
1 0 0 1	9	3CH (red)
1 0 1 0	10	3AH (green)
1 0 1 1	11	3CH (red)
1 1 0 0	12	39H (blue)
1 1 0 1	13	3CH (red)
1 1 1 0	14	3AH (green)
1 1 1 1	15	3CH (red)

shown in Figure 28.4. If the bit from plane 0 is 0, then if the bit from plane 1 is 1 the color is green, and so on for planes 2 and 3. In other words, with the above palette register settings we instantly have exactly what we want, which is an approach that keeps images in one plane from interfering with images in other planes while providing precedence and transparency.

Seems almost too easy, doesn't it? Nonetheless, it works beautifully, as we'll see very shortly. First, though, I'd like to point out that there's nothing sacred about plane 0 having precedence. We could rearrange the palette register settings so that any plane had the highest precedence, followed by the other planes in any order. I've chosen to make plane 0 the highest precedence only because it seems simplest to think of plane 0 as appearing in front of plane 1, which is in front of plane 2, which is in front of plane 3.

Bit-Plane Animation in Action

Without further ado, Listing 28.1 shows bit-plane animation in action. Listing 28.1 animates 13 rather large images (each 32 pixels on a side) over a complex background at a good clip *even on a primordial 8088-based PC.* Five of the images move very quickly, while the other 8 bounce back and forth at a steady pace.

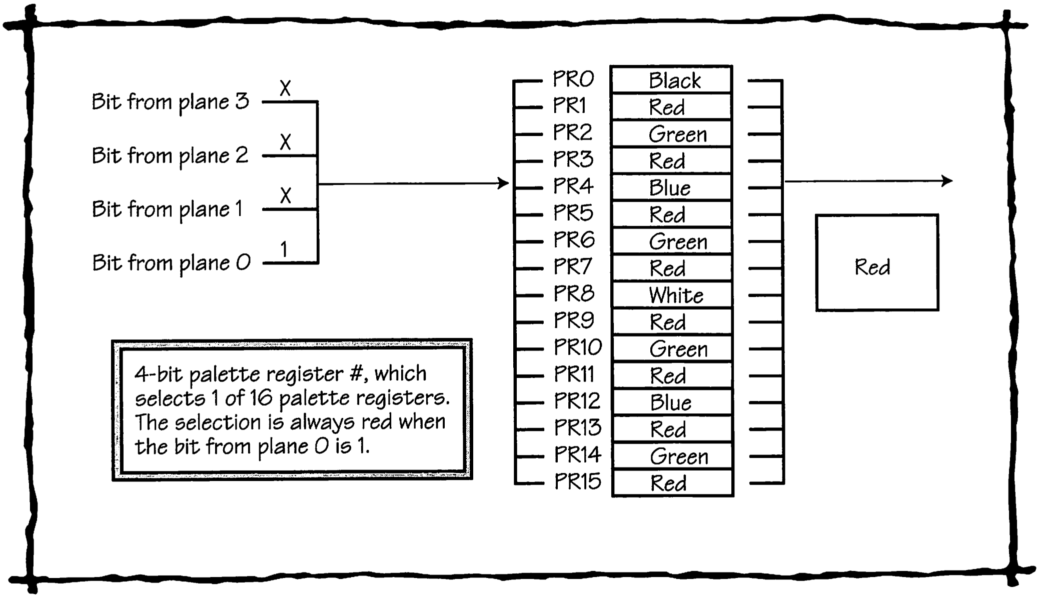


Figure 28.4 How Pixel Precedence Works

LISTING 28.1 L28-1.ASM

```
; Program to demonstrate bit-plane animation. Performs
; flicker-free animation with image transparency and
; image precedence across four distinct planes, with
; 13 32x32 images kept in motion at once.
;
;
; Set to higher values to slow down on faster computers.
; 0 is fine for a PC. 500 is a reasonable setting for an AT.
; Slowing animation further allows a good look at
; transparency and the lack of flicker and color effects
; when images cross.
;
SLOWDOWN   equ   10000
;
; Plane selects for the four colors we're using.
;
RED   equ   01h
GREEN equ   02h
BLUE  equ   04h
WHITE equ   08h
;
VGA_SEGMENT      equ   0a000h     ;mode 10h display memory
                                  ; segment
SC_INDEX         equ   3c4h       ;Sequence Controller Index
                                  ; register
MAP_MASK         equ   2          ;Map Mask register index in
                                  ; Sequence Controller
SCREEN_WIDTH     equ   80         ;# of bytes across screen
SCREEN_HEIGHT    equ   350        ;# of scan lines on screen
```

```
WORD_OUTS_OK     equ  1     ;set to 0 to assemble for
                            ; computers that can't
                            ; handle word outs to
                            ; indexed VGA regs
;
stack segment para stack 'STACK'
      db      512 dup (?)
stack ends
;
; Complete info about one object that we're animating.
;
ObjectStructure  struc
Delay            dw   ?     ;used to delay for n passes
                            ; throught the loop to
                            ; control animation speed
BaseDelay        dw   ?     ;reset value for Delay
Image            dw   ?     ;pointer to drawing info
                            ; for object
XCoord           dw   ?     ;object X location in pixels
XInc             dw   ?     ;# of pixels to increment
                            ; location by in the X
                            ; direction on each move
XLeftLimit       dw   ?     ;left limit of X motion
XRightLimit      dw   ?     ;right limit of X motion
YCoord           dw   ?     ;object Y location in pixels
YInc             dw   ?     ;# of pixels to increment
                            ; location by in the Y
                            ; direction on each move
YTopLimit        dw   ?     ;top limit of Y motion
YBottomLimit     dw   ?     ;bottom limit of Y motion
PlaneSelect      db   ?     ;mask to select plane to
                            ; which object is drawn
                 db   ?     ;to make an even # of words
                            ; long, for better 286
                            ; performance (keeps the
                            ; following structure
                            ; word-aligned)
ObjectStructure  ends
;
Data  segment    word 'DATA'
;
; Palette settings to give plane 0 precedence, followed by
; planes 1, 2, and 3. Plane 3 has the lowest precedence (is
; obscured by any other plane), while plane 0 has the
; highest precedence (displays in front of any other plane).
;
Colors     db    000h       ;background color=black
           db    03ch       ;plane 0 only=red
           db    03ah       ;plane 1 only=green
           db    03ch       ;planes 0&1=red (plane 0 priority)
           db    039h       ;plane 2 only=blue
           db    03ch       ;planes 0&2=red (plane 0 priority)
           db    03ah       ;planes 1&2=green (plane 1 priority)
           db    03ch       ;planes 0&1&2=red (plane 0 priority)
           db    03fh       ;plane 3 only=white
           db    03ch       ;planes 0&3=red (plane 0 priority)
           db    03ah       ;planes 1&3=green (plane 1 priority)
           db    03ch       ;planes 0&1&3=red (plane 0 priority)
           db    039h       ;planes 2&3=blue (plane 2 priority)
           db    03ch       ;planes 0&2&3=red (plane 0 priority)
           db    03ah       ;planes 1&2&3=green (plane 1 priority)
```

```
          db    03ch        ;planes 0&1&2&3=red (plane 0 priority)
          db    000h        ;border color=black
;
; Image of a hollow square.
; There's an 8-pixel-wide blank border around all edges
; so that the image erases the old version of itself as
; it's moved and redrawn.
;
Square      label byte
      dw    48,6  ;height in pixels, width in bytes
      rept  8
      db    0,0,0,0,0,0;top blank border
      endm
      .radix      2
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,00000000,00000000,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      db    0,11111111,11111111,11111111,11111111,0
      .radix      10
      rept  8
      db    0,0,0,0,0,0;bottom blank border
      endm
;
; Image of a hollow diamond with a smaller diamond in the
; middle.
; There's an 8-pixel-wide blank border around all edges
; so that the image erases the old version of itself as
; it's moved and redrawn.
;
Diamond     label byte
      dw    48,6  ;height in pixels, width in bytes
      rept  8
      db    0,0,0,0,0,0;top blank border
      endm
      .radix     2
      db    0,00000000,00000001,10000000,00000000,0
      db    0,00000000,00000011,11000000,00000000,0
      db    0,00000000,00000111,11100000,00000000,0
      db    0,00000000,00001111,11110000,00000000,0
      db    0,00000000,00011111,11111000,00000000,0
      db    0,00000000,00111110,01111100,00000000,0
      db    0,00000000,01111100,00111110,00000000,0
      db    0,00000000,11111000,00011111,00000000,0
      db    0,00000001,11110000,00001111,10000000,0
      db    0,00000011,11100000,00000111,11000000,0
      db    0,00000111,11000000,00000011,11100000,0
      db    0,00001111,10000001,10000001,11110000,0
      db    0,00011111,00000011,11000000,11111000,0
      db    0,00111110,00000111,11100000,01111100,0
      db    0,01111100,00001111,11110000,00111110,0
      db    0,11111000,00011111,11111000,00011111,0
      db    0,11111000,00011111,11111000,00011111,0
      db    0,01111100,00001111,11110000,00111110,0
      db    0,00111110,00000111,11100000,01111100,0
      db    0,00011111,00000011,11000000,11111000,0
      db    0,00001111,10000001,10000001,11110000,0
      db    0,00000111,11000000,00000011,11100000,0
      db    0,00000011,11100000,00000111,11000000,0
      db    0,00000001,11110000,00001111,10000000,0
      db    0,00000000,11111000,00011111,00000000,0
      db    0,00000000,01111100,00111110,00000000,0
      db    0,00000000,00111110,01111100,00000000,0
      db    0,00000000,00011111,11111000,00000000,0
      db    0,00000000,00001111,11110000,00000000,0
      db    0,00000000,00000111,11100000,00000000,0
      db    0,00000000,00000011,11000000,00000000,0
      db    0,00000000,00000001,10000000,00000000,0
      .radix     10
      rept  8
      db    0,0,0,0,0,0;bottom blank border
      endm
;
; List of objects to animate.
;
      even  ;word-align for better 286 performance
;
ObjectList label ObjectStructure
 ObjectStructure <1,21,Diamond,88,8,80,512,16,0,0,350,RED>
 ObjectStructure <1,15,Square,296,8,112,480,144,0,0,350,RED>
 ObjectStructure <1,23,Diamond,88,8,80,512,256,0,0,350,RED>
 ObjectStructure <1,13,Square,120,0,0,640,144,4,0,280,BLUE>
 ObjectStructure <1,11,Diamond,208,0,0,640,144,4,0,280,BLUE>
 ObjectStructure <1,8,Square,296,0,0,640,144,4,0,288,BLUE>
 ObjectStructure <1,9,Diamond,384,0,0,640,144,4,0,288,BLUE>
 ObjectStructure <1,14,Square,472,0,0,640,144,4,0,280,BLUE>
 ObjectStructure <1,8,Diamond,200,8,0,576,48,6,0,280,GREEN>
 ObjectStructure <1,8,Square,248,8,0,576,96,6,0,280,GREEN>
 ObjectStructure <1,8,Diamond,296,8,0,576,144,6,0,280,GREEN>
 ObjectStructure <1,8,Square,344,8,0,576,192,6,0,280,GREEN>
 ObjectStructure <1,8,Diamond,392,8,0,576,240,6,0,280,GREEN>
ObjectListEnd    label ObjectStructure
;
Data  ends
;
```

```
; Macro to output a word value to a port.
;
OUT_WORD   macro
if WORD_OUTS_OK
     out  dx,ax
else
     out  dx,al
     inc  dx
     xchg ah,al
     out  dx,al
     dec  dx
     xchg ah,al
endif
     endm
;
; Macro to output a constant value to an indexed VGA
; register.
;
CONSTANT_TO_INDEXED_REGISTER      macro ADDRESS, INDEX, VALUE
     mov  dx,ADDRESS
     mov  ax,(VALUE shl 8) + INDEX
     OUT_WORD
     endm
;
Code  segment
     assume     cs:Code, ds:Data
Start proc  near
     cld
     mov  ax,Data
     mov  ds,ax
;
; Set 640x350 16-color mode.
;
     mov  ax,0010h    ;AH=0 means select mode
                      ;AL=10h means select
                      ; mode 10h
     int  10h         ;BIOS video interrupt
;
; Set the palette up to provide bit-plane precedence. If
; planes 0 & 1 overlap, the plane 0 color will be shown;
; if planes 1 & 2 overlap, the plane 1 color will be
; shown; and so on.
;
     mov  ax,(10h shl 8) + 2     ;AH = 10h means
                                 ; set palette
                                 ; registers fn
                                 ;AL = 2 means set
                                 ; all palette
                                 ; registers
     push ds                     ;ES:DX points to
     pop  es                     ; the palette
     mov  dx,offset Colors       ; settings
     int  10h                    ;call the BIOS to
                                 ; set the palette
;
; Draw the static backdrop in plane 3. All the moving images
; will appear to be in front of this backdrop, since plane 3
; has the lowest precedence the way the palette is set up.
;
     CONSTANT_TO_INDEXED_REGISTER SC_INDEX, MAP_MASK, 08h
                                 ;allow data to go to
                                 ; plane 3 only
```

```
;
; Point ES to display memory for the rest of the program.
;
     mov   ax,VGA_SEGMENT
     mov   es,ax
;
     sub   di,di
     mov   bp,SCREEN_HEIGHT/16   ;fill in the screen
                                 ; 16 lines at a time
BackdropBlockLoop:
     call  DrawGridCross         ;draw a cross piece
     call  DrawGridVert          ;draw the rest of a
                                 ; 15-high block
     dec   bp
     jnz   BackdropBlockLoop
     call  DrawGridCross         ;bottom line of grid
;
; Start animating!
;
AnimationLoop:
     mov   bx,offset ObjectList  ;point to the first
                                 ; object in the list
;
; For each object, see if it's time to move and draw that
; object.
;
ObjectLoop:
;
; See if it's time to move this object.
;
     dec   [bx+Delay]            ;count down delay
     jnz   DoNextObject          ;still delaying-don't move
     mov   ax,[bx+BaseDelay]
     mov   [bx+Delay],ax         ;reset delay for next time
;
; Select the plane that this object will be drawn in.
;
     mov   dx,SC_INDEX
     mov   ah,[bx+PlaneSelect]
     mov   al,MAP_MASK
     OUT_WORD
;
; Advance the X coordinate, reversing direction if either
; of the X margins has been reached.
;
     mov   cx,[bx+XCoord]        ;current X location
     cmp   cx,[bx+XLeftLimit]    ;at left limit?
     ja    CheckXRightLimit      ;no
     neg   [bx+XInc]             ;yes-reverse
CheckXRightLimit:
     cmp   cx,[bx+XRightLimit]   ;at right limit?
     jb    SetNewX               ;no
     neg   [bx+XInc]             ;yes-reverse
SetNewX:
     add   cx,[bx+XInc]          ;move the X coord
     mov   [bx+XCoord],cx        ; & save it
;
; Advance the Y coordinate, reversing direction if either
; of the Y margins has been reached.
;
```

```
      mov   dx,[bx+YCoord]        ;current Y location
      cmp   dx,[bx+YTopLimit]     ;at top limit?
      ja    CheckYBottomLimit     ;no
      neg   [bx+YInc]             ;yes-reverse
CheckYBottomLimit:
      cmp   dx,[bx+YBottomLimit]  ;at bottom limit?
      jb    SetNewY               ;no
      neg   [bx+YInc]             ;yes-reverse
SetNewY:
      add   dx,[bx+YInc]          ;move the Y coord
      mov   [bx+YCoord],dx        ; & save it
;
; Draw at the new location. Because of the plane select
; above, only one plane will be affected.
;
      mov   si,[bx+Image]         ;point to the
                                  ; object's image
                                  ; info
      call  DrawObject
;
; Point to the next object in the list until we run out of
; objects.
;
DoNextObject:
      add   bx,size ObjectStructure
      cmp   bx,offset ObjectListEnd
      jb    ObjectLoop
;
; Delay as specified to slow things down.
;
if SLOWDOWN
      mov   cx,SLOWDOWN
DelayLoop:
      loop  DelayLoop
endif
;
; If a key's been pressed, we're done, otherwise animate
; again.
;
CheckKey:
      mov   ah,1
      int   16h                   ;is a key waiting?
      jz    AnimationLoop         ;no
      sub   ah,ah
      int   16h                   ;yes-clear the key & done
;
; Back to text mode.
;
      mov   ax,0003h              ;AL=03h means select
                                  ; mode 03h
      int   10h
;
; Back to DOS.
;
      mov   ah,4ch                ;DOS terminate function
      int   21h                   ;done
;
Start endp
;
; Draws a single grid cross-element at the display memory
; location pointed to by ES:DI. 1 horizontal line is drawn
; across the screen.
```

```
;
; Input: ES:DI points to the address at which to draw
;
; Output: ES:DI points to the address following the
;          line drawn
;
; Registers altered: AX, CX, DI
;
DrawGridCross    proc  near
     mov   ax,0ffffh               ;draw a solid line
     mov   cx,SCREEN_WIDTH/2-1
     rep   stosw                   ;draw all but the rightmost
                                   ; edge
     mov   ax,0080h
     stosw                         ;draw the right edge of the
                                   ; grid
     ret
DrawGridCross    endp
;
; Draws the non-cross part of the grid at the display memory
; location pointed to by ES:DI. 15 scan lines are filled.
;
; Input: ES:DI points to the address at which to draw
;
; Output: ES:DI points to the address following the
;          part of the grid drawn
;
; Registers altered: AX, CX, DX, DI
;
DrawGridVert     proc  near
     mov   ax,0080h                ;pattern for a vertical line
     mov   dx,15                   ;draw 15 scan lines (all of
                                   ; a grid block except the
                                   ; solid cross line)
BackdropRowLoop:
     mov   cx,SCREEN_WIDTH/2
     rep   stosw                   ;draw this scan line's bit
                                   ; of all the vertical lines
                                   ; on the screen
     dec   dx
     jnz   BackdropRowLoop
     ret
DrawGridVert     endp
;
; Draw the specified image at the specified location.
; Images are drawn on byte boundaries horizontally, pixel
; boundaries vertically.
; The Map Mask register must already have been set to enable
; access to the desired plane.
;
; Input:
;     CX - X coordinate of upper left corner
;     DX - Y coordinate of upper left corner
;     DS:SI - pointer to draw info for image
;     ES - display memory segment
;
; Output: none
;
; Registers altered: AX, CX, DX, SI, DI, BP
;
```

```
DrawObject proc  near
      mov  ax,SCREEN_WIDTH
      mul  dx                     ;calculate the start offset in
                                  ; display memory of the row the
                                  ; image will be drawn at
      shr  cx,1
      shr  cx,1
      shr  cx,1                   ;divide the X coordinate in pixels
                                  ; by 8 to get the X coordinate in
                                  ; bytes
      add  ax,cx                  ;destination offset in display
                                  ; memory for the image
      mov  di,ax                  ;point ES:DI to the address to
                                  ; which the image will be copied
                                  ; in display memory
      lodsw
      mov  dx,ax                  ;# of lines in the image
      lodsw                       ;# of bytes across the image
      mov  bp,SCREEN_WIDTH
      sub  bp,ax                  ;# of bytes to add to the display
                                  ; memory offset after copying a line
                                  ; of the image to display memory in
                                  ; order to point to the address
                                  ; where the next line of the image
                                  ; will go in display memory
DrawLoop:
      mov  cx,ax                  ;width of the image
      rep  movsb                  ;copy the next line of the image
                                  ; into display memory
      add  di,bp                  ;point to the address at which the
                                  ; next line will go in display
                                  ; memory
      dec  dx                     ;count down the lines of the image
      jnz  DrawLoop
      ret
DrawObject endp
;
Code  ends
      end  Start
```

For those of you who haven't experienced the frustrations of animation programming on a PC, there's a *whole* lot of animation going on in Listing 28.1. What's more, the animation is virtually flicker-free, partly thanks to bit-plane animation and partly because images are never really erased but rather are simply overwritten. (The principle behind the animation is that of redrawing each image with a blank fringe around it when it moves, so that the blank fringe erases the part of the old image that the new image doesn't overwrite. For details on this sort of animation, see the above-mentioned *PC Tech Journal* July 1986 article.) Better yet, the red images take precedence over the green images, which take precedence over the blue images, which take precedence over the white backdrop, and all obscured images show through holes in and around the edges of images in front of them.

In short, Listing 28.1 accomplishes everything we wished for earlier in an animation technique.

If you possibly can, run Listing 28.1. The animation may be a revelation to those of you who are used to weak, slow animation on PCs with EGA or VGA adapters. Bit-plane animation makes the PC look an awful lot like—dare I say it?—a games machine.

Listing 28.1 was designed to run at the absolute fastest speed, and as I mentioned it puts in a pretty amazing performance on the slowest PCs of all. Assuming you'll be running Listing 28.1 on an faster computer, you'll have to crank up the **DELAY** equate at the start of Listing 28.1 to slow things down to a reasonable pace. (It's not a very good game where all the pieces are a continual blur!) Even on something as modest as a 286-based AT, Listing 28.1 runs much too fast without a substantial delay (although it does look rather interesting at warp speed). We should all have such problems, eh? In fact, we could easily increase the number of animated images past 20 on that old AT, and well into the hundreds on a cutting-edge local-bus 486 or Pentium.

I'm not going to discuss Listing 28.1 in detail; the code is very thoroughly commented and should speak for itself, and most of the individual components of Listing 28.1—the Map Mask register, mode sets, word versus byte **OUT** instructions to the VGA—have been covered in earlier chapters. Do notice, however, that Listing 28.1 sets the palette exactly as I described earlier. This is accomplished by passing a pointer to a 17-byte array (1 byte for each of the 16 palette registers, and 1 byte for the border color) to the BIOS video interrupt (**INT** 10H), function 10H, subfunction 2.

Bit-plane animation does have inherent limitations, which we'll get to in a second. One limitation that is *not* inherent to bit-plane animation but simply a shortcoming of Listing 28.1 is somewhat choppy horizontal motion. In the interests of both clarity and keeping Listing 28.1 to a reasonable length, I decided to byte-align all images horizontally. This saved the many tables needed to define the 7 non-byte-aligned rotations of the images, as well as the code needed to support rotation. Unfortunately, it also meant that the smallest possible horizontal movement was 8 pixels (1 byte of display memory), which is far enough to be noticeable at certain speeds. The situation is, however, easily correctable with the additional rotations and code. We'll see an implementation of fully rotated images (in this case for Mode X, but the principles generalize nicely) in Chapter 34. Vertically, where there is no byte-alignment issue, the images move 4 or 6 pixels at a times, resulting in considerably smoother animation.

The addition of code to support rotated images would also open the door to support for internal animation, where the appearance of a given image changes over time to suggest that the image is an active entity. For example, propellers could whirl, jaws could snap, and jets could flare. Bit-plane animation with bit-aligned images and internal animation can look truly spectacular. It's a sight worth seeing, particularly for those who doubt the PC's worth when it comes to animation.

Limitations of Bit-Plane Animation

As I've said, bit-plane animation is not perfect. For starters, bit-plane animation can only be used in the VGA's planar modes, modes 0DH, 0EH, 10H, and 12H. Also, the reprogramming of the palette registers that provides image precedence also reduces the available color set from the normal 16 colors to just 5 (one color per plane plus the background color). Worse still, each image must consist entirely of only one of the four colors. Mixing colors within an image is not allowed, since the bits for each image are limited to a single plane and can therefore select only one color. Finally, all images of the same precedence must be the same color.

It is possible to work around the color limitations to some extent by using only one or two planes for bit-plane animation, while reserving the other planes for multi-color drawing. For example, you could use plane 3 for bit-plane animation while using planes 0-2 for normal 8-color drawing. The images in plane 3 would then appear to be in front of the 8-color images. If we wanted the plane 3 images to be yellow, we could set up the palette registers as shown in Table 28.2.

As you can see, the color yellow is displayed whenever a pixel's bit from plane 3 is 1. This gives the images from plane 3 precedence, while leaving us with the 8 normal low-intensity colors for images drawn across the other 3 planes, as shown in Figure 28.5. Of course, this approach provides only 1 rather than 3 high-precedence planes, but that might be a good tradeoff for being able to draw multi-colored images as a backdrop to the high-precedence images. For the right application, high-speed flicker-free plane 3 images moving in front of an 8-color backdrop could be a potent combination indeed.

Table 28.2 Palette RAM Settings for Two-Plane Animation

Palette Register	Register Setting
0	00H (black)
1	01H (blue)
2	02H (green)
3	03H (cyan)
4	04H (red)
5	05H (magenta)
6	14H (brown)
7	07H (light gray)
8	3EH (yellow)
9	3EH (yellow)
10	3EH (yellow)
11	3EH (yellow)
12	3EH (yellow)
13	3EH (yellow)
14	3EH (yellow)
15	3EH (yellow)

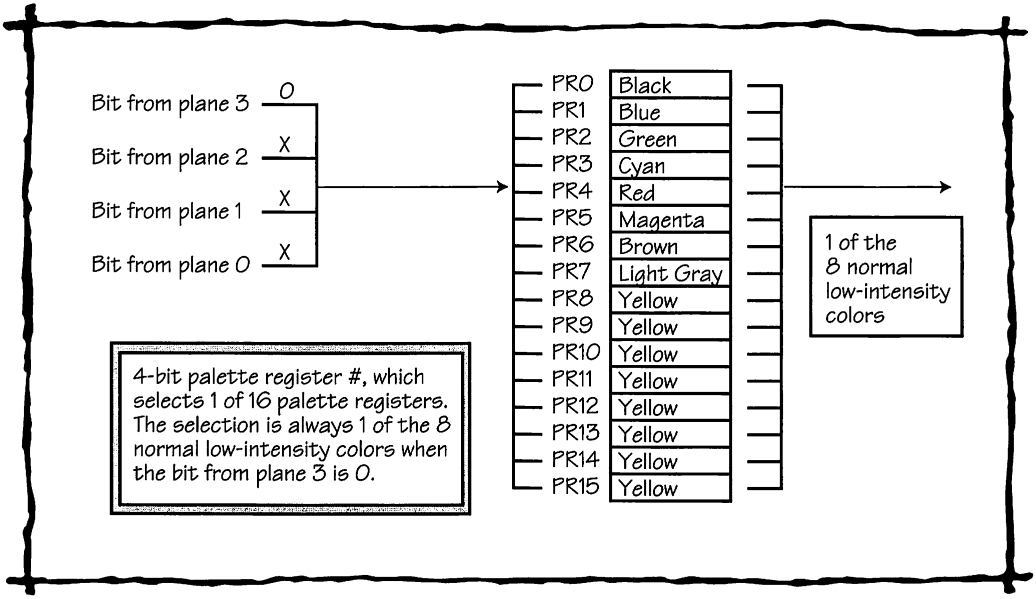


Figure 28.5 Pixel Precedence for Plane 3 Only

Another limitation of bit-plane animation is that it's best if images stored in the same plane never cross each other. Why? Because when images do cross, the blank fringe around each image can temporarily erase the overlapped parts of the other image or images, resulting in momentary flicker. While that's not fatal, it certainly detracts from the rock-solid animation effect of bit-plane animation.

Not allowing images in the same plane to overlap is actually less of a limitation than it seems. Run Listing 28.1 again. Unless you were looking for it, you'd never notice that images of the same color almost never overlap—there's plenty of action to distract the eye, and the trajectories of images of the same color are arranged so that they have a full range of motion without running into each other. The only exception is the chain of green images, which occasionally doubles back on itself when it bounces directly into a corner and reverses direction. Here, however, the images are moving so quickly that the brief moment during which one image's fringe blanks a portion of another image is noticeable only upon close inspection, and not particularly unaesthetic even then.

When a technique has such tremendous visual and performance advantages as does bit-plane animation, it behooves you to design your animation software so that the limitations of the animation technique don't get in the way. For example, you might design a shooting gallery game with all the images in a given plane marching along in step in a continuous band. The images could never overlap, so bit-plane animation would produce very high image quality.

Shearing and Page Flipping

As Listing 28.1 runs, you may occasionally see an image shear, with the top and bottom parts of the image briefly offset. This is a consequence of drawing an image directly into memory as that memory is being scanned for video data. Occasionally the CRT controller scans a given area of display memory for pixel data just as the program is changing that same memory. If the CRT controller scans memory faster than the CPU can modify that memory, then the CRT controller can scan out the bytes of display memory that have been already been changed, pass the point in the image that the CPU is currently drawing, and start scanning out bytes that haven't yet been changed. The result: Mismatched upper and lower portions of the image.

If the CRT controller scans more slowly than the CPU can modify memory (likely with a 386, a fast VGA, and narrow images), then the CPU can rip right past the CRT controller, with the same net result of mismatched top and bottom parts of the image, as the CRT controller scans out first unchanged bytes and then changed bytes. Basically, shear will occasionally occur unless the CPU and CRT proceed at exactly the same rate, which is most unlikely. Shear is more noticeable when there are fewer but larger images, since it's more apparent when a larger screen area is sheared, and because it's easier to spot one out of three large images momentarily shearing than one out of twenty small images.

Image shear isn't terrible—I've written and sold several games in which images occasionally shear, and I've never heard anyone complain—but neither is it ideal. One solution is page flipping, in which drawing is done to a non-displayed page of display memory while another page of display memory is shown on the screen. (We saw page flipping back in Chapter 1, we'll see it again in the next chapter, and we'll use it heavily starting in Chapter 32.) When the drawing is finished, the newly-drawn part of display memory is made the displayed page, so that the new screen becomes visible all at once, with no shearing or flicker. The other page is then drawn to, and when the drawing is complete the display is switched back to that page.

Page flipping can be used in conjunction with bit-plane animation, although page flipping does diminish some of the unique advantages of bit-plane animation. Page flipping produces animation of the highest visual quality whether bit-plane animation is used or not. There are a few drawbacks to page flipping, however.

Page flipping requires two display memory buffers, one to draw in and one to display at any given time. Unfortunately, in mode 12H there just isn't enough memory for two buffers, so page flipping is not an option in that mode.

Also, page flipping requires that you keep the contents of both buffers up to date, which can require a good deal of extra drawing.

Finally, page flipping requires that you wait until you're sure the page has flipped before you start drawing to the other page. Otherwise, you could end up modifying a page while it's still being displayed, defeating the whole purpose of page flipping. Waiting for pages to flip takes time and can slow overall performance significantly. What's more, it's sometimes difficult to be sure when the page has flipped, since not all VGA clones implement the display adapter status bits and page flip timing identically.

To sum up, bit-plane animation by itself is very fast and looks good. In conjunction with page flipping, bit-plane animation looks a little better but is slower, and the overall animation scheme is more difficult to implement and perhaps a bit less reliable on some computers.

Beating the Odds in the Jaw-Dropping Contest

Bit-plane animation is neat stuff. Heck, good animation of *any* sort is fun, and the PC is as good a place as any (well, almost any) to make people's jaws drop. (Certainly it's the place to go if you want to make a *lot* of jaws drop.) Don't let anyone tell you that you can't do good animation on the PC. You can—*if* you stretch your mind to find ways to bring the full power of the VGA to bear on your applications. Bit-plane animation isn't for every task; neither are page flipping, exclusive-ORing, pixel panning, or any of the many other animation techniques you have available. One or more tricks from that grab-bag should give you what you need, though, and the bigger your grab-bag, the better your programs.

Split Screens Save the Page-Flipped Day

Chapter 29

640x480 Page Flipped Animation in 64K...Almost

Almost doesn't count, they say—at least in horseshoes and maybe a few other things. This is especially true in digital circles, where if you need 12 MB of hard disk to install something and you only have ten MB left (a situation that seems to be some sort of eternal law) you're stuck.

And that's only infuriating until you dredge up the gumption to go in there and free up some space. How would you feel if you were up against an "almost-but-not-quite" kind of a wall that couldn't be breached by freeing up something elsewhere? Suppose you were within a few KB of implementing a wonderful VGA animation scheme that provided lots of screen space, square pixels, smooth motion and more than adequate speed—but all the memory you have is all there is? What would you do?

Scream a little. Or throw something that won't break easily. Then you sit down and let your right brain do what it was designed to do. Sure enough, there's a way, and in this chapter I'll explain how a little VGA secret called *page splitting* can save the day for page flipped animation in 640×480 mode. But to do that, I have to lay a little groundwork first. Or maybe a lot of groundwork.

No horseshoes here.

A Plethora of Challenges

In its simplest terms, computer animation consists of rapidly redrawing similar images at slightly differing locations, so that the eye interprets the successive images as a single object in motion over time. The fact that the world is an analog realm and the images displayed on a computer screen consist of discrete pixels updated at a maximum rate of about 70 Hz is irrelevant; your eye can interpret both real-world images and pixel patterns on the screen as objects in motion, and that's that.

One of the key problems of computer animation is that it takes time to redraw a screen, time during which the bitmap controlling the screen is in an intermediate state, with, quite possibly, many objects erased and others half-drawn. Even when only briefly displayed, a partially-updated screen can cause flicker at best, and at worst can destroy the illusion of motion entirely.

Another problem of animation is that the screen must update often enough so that motion appears continuous. A moving object that moves just once every second, shifting by hundreds of pixels each time it does move, will appear to jump, not to move smoothly. Therefore, there are two overriding requirements for smooth animation: 1) the bitmap must be updated quickly (once per frame—60 to 70 Hz—is ideal, although 30 Hz will do fine), and, 2) the process of redrawing the screen must be invisible to the user; only the end result should ever be seen. Both of these requirements are met by the program presented in Listings 29.1 and 29.2.

A Page Flipping Animation Demonstration

The listings taken together form a sample animation program, in which a single object bounces endlessly off other objects, with instructions and a count of bounces displayed at the bottom of the screen. I'll discuss various aspects of Listings 29.1 and 29.2 during the balance of this article. The listings are too complex and involve too much VGA and animation knowledge for for me to discuss it all in exhaustive detail (and I've covered a lot of this stuff earlier in the book); instead, I'll cover the major elements, leaving it to you to explore the finer points—and, I hope, to experiment with and expand on the code I'll provide.

LISTING 29.1 L29-1.C

```
/* Split screen VGA animation program. Performs page flipping in the
top portion of the screen while displaying non-page flipped
information in the split screen at the bottom of the screen.
Compiled with Borland C++ in C compilation mode. */

#include <stdio.h>
#include <conio.h>
#include <dos.h>
#include <math.h>

#define SCREEN_SEG         0xA000
#define SCREEN_PIXWIDTH    640   /* in pixels */
#define SCREEN_WIDTH       80    /* in bytes */
#define SPLIT_START_LINE   339
#define SPLIT_LINES        141
#define NONSPLIT_LINES     339
#define SPLIT_START_OFFSET 0
#define PAGE0_START_OFFSET (SPLIT_LINES*SCREEN_WIDTH)
#define PAGE1_START_OFFSET ((SPLIT_LINES+NONSPLIT_LINES)*SCREEN_WIDTH)
#define CRTC_INDEX   0x3D4 /* CRT Controller Index register */
```

```
#define CRTC_DATA    0x3D5 /* CRT Controller Data register */
#define OVERFLOW     0x07  /* index of CRTC reg holding bit 8 of the
                              line the split screen starts after */
#define MAX_SCAN     0x09  /* index of CRTC reg holding bit 9 of the
                              line the split screen starts after */
#define LINE_COMPARE 0x18  /* index of CRTC reg holding lower 8 bits
                              of line split screen starts after */
#define NUM_BUMPERS  (sizeof(Bumpers)/sizeof(bumper))
#define BOUNCER_COLOR 15
#define BACK_COLOR   1     /* playfield background color */

typedef struct {  /* one solid bumper to be bounced off of */
   int LeftX,TopY,RightX,BottomY;
   int Color;
} bumper;

typedef struct {     /* one bit pattern to be used for drawing */
   int WidthInBytes;
   int Height;
   unsigned char *BitPattern;
} image;

typedef struct {  /* one bouncing object to move around the screen */
   int LeftX,TopY;         /* location */
   int Width,Height;       /* size in pixels */
   int DirX,DirY;          /* motion vectors */
   int CurrentX[2],CurrentY[2]; /* current location in each page */
   int Color;              /* color in which to be drawn */
   image *Rotation0;       /* rotations for handling the 8 possible */
   image *Rotation1;       /* intrabyte start address at which the */
   image *Rotation2;       /* left edge can be */
   image *Rotation3;
   image *Rotation4;
   image *Rotation5;
   image *Rotation6;
   image *Rotation7;
} bouncer;

void main(void);
void DrawBumperList(bumper *, int, unsigned int);
void DrawSplitScreen(void);
void EnableSplitScreen(void);
void MoveBouncer(bouncer *, bumper *, int);
extern void DrawRect(int,int,int,int,int,unsigned int,unsigned int);
extern void ShowPage(unsigned int);
extern void DrawImage(int,int,image **,int,unsigned int,unsigned int);
extern void ShowBounceCount(void);
extern void TextUp(char *,int,int,unsigned int,unsigned int);
extern void SetBIOS8x8Font(void);

/* All bumpers in the playfield */
bumper Bumpers[] = {
   {0,0,19,339,2}, {0,0,639,19,2}, {620,0,639,339,2},
   {0,320,639,339,2}, {60,48,79,67,12}, {60,108,79,127,12},
   {60,168,79,187,12}, {60,228,79,247,12}, {120,68,131,131,13},
   {120,188,131,271,13}, {240,128,259,147,14}, {240,192,259,211,14},
   {208,160,227,179,14}, {272,160,291,179,14}, {228,272,231,319,11},
   {192,52,211,55,11}, {302,80,351,99,12}, {320,260,379,267,13},
   {380,120,387,267,13}, {420,60,579,63,11}, {428,110,571,113,11},
   {420,160,579,163,11}, {428,210,571,213,11}, {420,260,579,263,11} };
```

```
/* Image for bouncing object when left edge is aligned with bit 7 */
unsigned char _BouncerRotation0[] = {
   0xFF,0x0F,0xF0, 0xFE,0x07,0xF0, 0xFC,0x03,0xF0, 0xFC,0x03,0xF0,
   0xFE,0x07,0xF0, 0xFF,0xFF,0xF0, 0xCF,0xFF,0x30, 0x87,0xFE,0x10,
   0x07,0x0E,0x00, 0x07,0x0E,0x00, 0x07,0x0E,0x00, 0x07,0x0E,0x00,
   0x87,0xFE,0x10, 0xCF,0xFF,0x30, 0xFF,0xFF,0xF0, 0xFE,0x07,0xF0,
   0xFC,0x03,0xF0, 0xFC,0x03,0xF0, 0xFE,0x07,0xF0, 0xFF,0x0F,0xF0};
image BouncerRotation0 = {3, 20, _BouncerRotation0};

/* Image for bouncing object when left edge is aligned with bit 3 */
unsigned char _BouncerRotation4[] = {
   0x0F,0xF0,0xFF, 0x0F,0xE0,0x7F, 0x0F,0xC0,0x3F, 0x0F,0xC0,0x3F,
   0x0F,0xE0,0x7F, 0x0F,0xFF,0xFF, 0x0C,0xFF,0xF3, 0x08,0x7F,0xE1,
   0x00,0x70,0xE0, 0x00,0x70,0xE0, 0x00,0x70,0xE0, 0x00,0x70,0xE0,
   0x08,0x7F,0xE1, 0x0C,0xFF,0xF3, 0x0F,0xFF,0xFF, 0x0F,0xE0,0x7F,
   0x0F,0xC0,0x3F, 0x0F,0xC0,0x3F, 0x0F,0xE0,0x7F, 0x0F,0xF0,0xFF};
image BouncerRotation4 = {3, 20, _BouncerRotation4};

/* Initial settings for bouncing object. Only 2 rotations are needed
   because the object moves 4 pixels horizontally at a time */
bouncer Bouncer = {156,60,20,20,4,4,156,156,60,60,BOUNCER_COLOR,
   &BouncerRotation0,NULL,NULL,NULL,&BouncerRotation4,NULL,NULL,NULL};
unsigned int PageStartOffsets[2] =
   {PAGE0_START_OFFSET,PAGE1_START_OFFSET};
unsigned int BounceCount;

void main() {
   int DisplayedPage, NonDisplayedPage, Done, i;
   union REGS regset;

   regset.x.ax = 0x0012; /* set display to 640x480 16-color mode */
   int86(0x10, &regset, &regset);
   SetBIOS8x8Font();    /* set the pointer to the BIOS 8x8 font */
   EnableSplitScreen(); /* turn on the split screen */

   /* Display page 0 above the split screen */
   ShowPage(PageStartOffsets[DisplayedPage = 0]);

   /* Clear both pages to background and draw bumpers in each page */
   for (i=0; i<2; i++) {
      DrawRect(0,0,SCREEN_PIXWIDTH-1,NONSPLIT_LINES-1,BACK_COLOR,
            PageStartOffsets[i],SCREEN_SEG);
      DrawBumperList(Bumpers,NUM_BUMPERS,PageStartOffsets[i]);
   }

   DrawSplitScreen();   /* draw the static split screen info */
   BounceCount = 0;
   ShowBounceCount();    /* put up the initial zero count */

   /* Draw the bouncing object at its initial location */
   DrawImage(Bouncer.LeftX,Bouncer.TopY,&Bouncer.Rotation0,
         Bouncer.Color,PageStartOffsets[DisplayedPage],SCREEN_SEG);

   /* Move the object, draw it in the nondisplayed page, and flip the
      page until Esc is pressed */
   Done = 0;
   do {
      NonDisplayedPage = DisplayedPage ^ 1;
      /* Erase at current location in the nondisplayed page */
      DrawRect(Bouncer.CurrentX[NonDisplayedPage],
            Bouncer.CurrentY[NonDisplayedPage],
            Bouncer.CurrentX[NonDisplayedPage]+Bouncer.Width-1,
            Bouncer.CurrentY[NonDisplayedPage]+Bouncer.Height-1,
            BACK_COLOR,PageStartOffsets[NonDisplayedPage],SCREEN_SEG);
      /* Move the bouncer */
      MoveBouncer(&Bouncer, Bumpers, NUM_BUMPERS);
      /* Draw at the new location in the nondisplayed page */
      DrawImage(Bouncer.LeftX,Bouncer.TopY,&Bouncer.Rotation0,
            Bouncer.Color,PageStartOffsets[NonDisplayedPage],
            SCREEN_SEG);
      /* Remember where the bouncer is in the nondisplayed page */
      Bouncer.CurrentX[NonDisplayedPage] = Bouncer.LeftX;
      Bouncer.CurrentY[NonDisplayedPage] = Bouncer.TopY;
      /* Flip to the page we just drew into */
      ShowPage(PageStartOffsets[DisplayedPage = NonDisplayedPage]);
      /* Respond to any keystroke */
      if (kbhit()) {
         switch (getch()) {
            case 0x1B:           /* Esc to end */
               Done = 1; break;
            case 0:              /* branch on the extended code */
               switch (getch()) {
                  case 0x48:  /* nudge up */
                     Bouncer.DirY = -abs(Bouncer.DirY); break;
                  case 0x4B:  /* nudge left */
                     Bouncer.DirX = -abs(Bouncer.DirX); break;
                  case 0x4D:  /* nudge right */
                     Bouncer.DirX = abs(Bouncer.DirX); break;
                  case 0x50:  /* nudge down */
                     Bouncer.DirY = abs(Bouncer.DirY); break;
               }
               break;
            default:
               break;
         }
      }
   } while (!Done);

   /* Restore text mode and done */
   regset.x.ax = 0x0003;
   int86(0x10, &regset, &regset);
}

/* Draws the specified list of bumpers into the specified page */
void DrawBumperList(bumper * Bumpers, int NumBumpers,
      unsigned int PageStartOffset)
{
   int i;

   for (i=0; i<NumBumpers; i++,Bumpers++) {
      DrawRect(Bumpers->LeftX,Bumpers->TopY,Bumpers->RightX,
            Bumpers->BottomY,Bumpers->Color,PageStartOffset,
            SCREEN_SEG);
   }
}

/* Displays the current bounce count */
void ShowBounceCount() {
   char CountASCII[7];

   itoa(BounceCount,CountASCII,10); /* convert the count to ASCII */
   TextUp(CountASCII,344,64,SPLIT_START_OFFSET,SCREEN_SEG);
}
```

```
/* Frames the split screen and fills it with various text */
void DrawSplitScreen() {
   DrawRect(0,0,SCREEN_PIXWIDTH-1,SPLIT_LINES-1,0,SPLIT_START_OFFSET,
         SCREEN_SEG);
   DrawRect(0,1,SCREEN_PIXWIDTH-1,4,15,SPLIT_START_OFFSET,
         SCREEN_SEG);
   DrawRect(0,SPLIT_LINES-4,SCREEN_PIXWIDTH-1,SPLIT_LINES-1,15,
         SPLIT_START_OFFSET,SCREEN_SEG);
   DrawRect(0,1,3,SPLIT_LINES-1,15,SPLIT_START_OFFSET,SCREEN_SEG);
   DrawRect(SCREEN_PIXWIDTH-4,1,SCREEN_PIXWIDTH-1,SPLIT_LINES-1,15,
         SPLIT_START_OFFSET,SCREEN_SEG);
   TextUp("This is the split screen area...",8,8,SPLIT_START_OFFSET,
         SCREEN_SEG);
   TextUp("Bounces: ",272,64,SPLIT_START_OFFSET,SCREEN_SEG);
   TextUp("\033: nudge left",520,78,SPLIT_START_OFFSET,SCREEN_SEG);
   TextUp("\032: nudge right",520,90,SPLIT_START_OFFSET,SCREEN_SEG);
   TextUp("\031: nudge down",520,102,SPLIT_START_OFFSET,SCREEN_SEG);
   TextUp("\030: nudge up",520,114,SPLIT_START_OFFSET,SCREEN_SEG);
   TextUp("Esc to end",520,126,SPLIT_START_OFFSET,SCREEN_SEG);
}

/* Turn on the split screen at the desired line (minus 1 because the
   split screen starts *after* the line specified by the LINE_COMPARE
   register) (bit 8 of the split screen start line is stored in the
   Overflow register, and bit 9 is in the Maximum Scan Line reg) */
void EnableSplitScreen() {
   outp(CRTC_INDEX, LINE_COMPARE);
   outp(CRTC_DATA, (SPLIT_START_LINE - 1) & 0xFF);
   outp(CRTC_INDEX, OVERFLOW);
   outp(CRTC_DATA, (((((SPLIT_START_LINE - 1) & 0x100) >> 8) << 4) |
         (inp(CRTC_DATA) & ~0x10)));
   outp(CRTC_INDEX, MAX_SCAN);
   outp(CRTC_DATA, (((((SPLIT_START_LINE - 1) & 0x200) >> 9) << 6) |
         (inp(CRTC_DATA) & ~0x40)));
}

/* Moves the bouncer, bouncing if bumpers are hit */
void MoveBouncer(bouncer *Bouncer, bumper *BumperPtr, int NumBumpers) {
   int NewLeftX, NewTopY, NewRightX, NewBottomY, i;

   /* Move to new location, bouncing if necessary */
   NewLeftX = Bouncer->LeftX + Bouncer->DirX;   /* new coords */
   NewTopY = Bouncer->TopY + Bouncer->DirY;
   NewRightX = NewLeftX + Bouncer->Width - 1;
   NewBottomY = NewTopY + Bouncer->Height - 1;
   /* Compare the new location to all bumpers, checking for bounce */
   for (i=0; i<NumBumpers; i++,BumperPtr++) {
      /* If moving puts the bouncer inside this bumper, bounce */
      if (  (NewLeftX <= BumperPtr->RightX) &&
            (NewRightX >= BumperPtr->LeftX) &&
            (NewTopY <= BumperPtr->BottomY) &&
            (NewBottomY >= BumperPtr->TopY) ) {
         /* The bouncer has tried to move into this bumper; figure
            out which edge(s) it crossed, and bounce accordingly */
         if (((Bouncer->LeftX > BumperPtr->RightX) &&
               (NewLeftX <= BumperPtr->RightX)) ||
               (((Bouncer->LeftX + Bouncer->Width - 1) <
               BumperPtr->LeftX) &&
               (NewRightX >= BumperPtr->LeftX))) {
            Bouncer->DirX = -Bouncer->DirX;  /* bounce horizontally */
            NewLeftX = Bouncer->LeftX + Bouncer->DirX;
         }
         if (((Bouncer->TopY > BumperPtr->BottomY) &&
               (NewTopY <= BumperPtr->BottomY)) ||
               (((Bouncer->TopY + Bouncer->Height - 1) <
               BumperPtr->TopY) &&
               (NewBottomY >= BumperPtr->TopY))) {
            Bouncer->DirY = -Bouncer->DirY; /* bounce vertically */
            NewTopY = Bouncer->TopY + Bouncer->DirY;
         }
         /* Update the bounce count display; turn over at 10000 */
         if (++BounceCount >= 10000) {
            TextUp("0    ",344,64,SPLIT_START_OFFSET,SCREEN_SEG);
            BounceCount = 0;
         } else {
            ShowBounceCount();
         }
      }
   }
   Bouncer->LeftX = NewLeftX; /* set the final new coordinates */
   Bouncer->TopY = NewTopY;
}
```

LISTING 29.2 L29-2.ASM

```
; Low-level animation routines.
; Tested with TASM

SCREEN_WIDTH          equ     80      ;screen width in bytes
INPUT_STATUS_1        equ     03dah   ;Input Status 1 register
CRTC_INDEX            equ     03d4h   ;CRT Controller Index reg
START_ADDRESS_HIGH    equ     0ch     ;bitmap start address high byte
START_ADDRESS_LOW     equ     0dh     ;bitmap start address low byte
GC_INDEX              equ     03ceh   ;Graphics Controller Index reg
SET_RESET             equ     0       ;GC index of Set/Reset reg
G_MODE                equ     5       ;GC index of Mode register

        .model  small
        .data
BIOS8x8Ptr dd   ?       ;points to BIOS 8x8 font
; Tables used to look up left and right clip masks.
LeftMask db     0ffh, 07fh, 03fh, 01fh, 00fh, 007h, 003h, 001h
RightMask db    080h, 0c0h, 0e0h, 0f0h, 0f8h, 0fch, 0feh, 0ffh

        .code
; Draws the specified filled rectangle in the specified color.
; Assumes the display is in mode 12h. Does not clip and assumes
; rectangle coordinates are valid.
;
; C near-callable as: void DrawRect(int LeftX, int TopY, int RightX,
;       int BottomY, int Color, unsigned int ScrnOffset,
;       unsigned int ScrnSegment);

DrawRectParms   struc
           dw      2 dup (?)     ;pushed BP and return address
LeftX      dw      ?             ;X coordinate of left side of rectangle
TopY       dw      ?             ;Y coordinate of top side of rectangle
RightX     dw      ?             ;X coordinate of right side of rectangle
BottomY    dw      ?             ;Y coordinate of bottom side of rectangle
Color      dw      ?             ;color in which to draw rectangle (only the
                                 ; lower 4 bits matter)
```

```
ScrnOffset       dw   ?           ;offset of base of bitmap in which to draw
ScrnSegment      dw   ?           ;segment of base of bitmap in which to draw
DrawRectParms   ends

        public  _DrawRect
_DrawRect       proc    near
        push    bp                ;preserve caller's stack frame
        mov     bp,sp             ;point to local stack frame
        push    si                ;preserve caller's register variables
        push    di

        cld
        mov     dx,GC_INDEX
        mov     al,SET_RESET
        mov     ah,byte ptr Color[bp]
        out     dx,ax             ;set the color in which to draw
        mov     ax,G_MODE + (0300h)
        out     dx,ax             ;set to write mode 3
        les     di,dword ptr ScrnOffset[bp] ;point to bitmap start
        mov     ax,SCREEN_WIDTH
        mul     TopY[bp]          ;point to the start of the top scan
        add     di,ax             ; line to fill
        mov     ax,LeftX[bp]
        mov     bx,ax
        shr     ax,1              ;/8 = byte offset from left of screen
        shr     ax,1
        shr     ax,1
        add     di,ax             ;point to the upper left corner of fill area
        and     bx,7              ;isolate intrapixel address
        mov     dl,LeftMask[bx]   ;set the left-edge clip mask
        mov     bx,RightX[bp]
        mov     si,bx
        and     bx,7              ;isolate intrapixel address of right edge
        mov     dh,RightMask[bx]  ;set the right-edge clip mask
        mov     bx,LeftX[bp]
        and     bx,NOT 7          ;intrapixel address of left edge
        sub     si,bx
        shr     si,1
        shr     si,1
        shr     si,1              ;# of bytes across spanned by rectangle - 1
        jnz     MasksSet          ;if there's only one byte across,
        and     dl,dh             ; combine the masks
MasksSet:
        mov     bx,BottomY[bp]
        sub     bx,TopY[bp]       ;# of scan lines to fill - 1
FillLoop:
        push    di                ;remember line start offset
        mov     al,dl             ;left edge clip mask
        xchg    es:[di],al        ;draw the left edge
        inc     di                ;point to the next byte
        mov     cx,si             ;# of bytes left to do
        dec     cx                ;# of bytes left to do - 1
        js      LineDone          ;that's it if there's only 1 byte across
        jz      DrawRightEdge     ;no middle bytes if only 2 bytes across
        mov     al,0ffh           ;non-edge bytes are solid
        rep     stosb             ;draw the solid bytes across the middle
DrawRightEdge:
        mov     al,dh             ;right edge clip mask
        xchg    es:[di],al        ;draw the right edge
LineDone:
        pop     di                ;retrieve line start offset
        add     di,SCREEN_WIDTH   ;point to the next line
        dec     bx                ;count off scan lines
        jns     FillLoop

        pop     di                ;restore caller's register variables
        pop     si
        pop     bp                ;restore caller's stack frame
        ret
_DrawRect       endp

; Shows the page at the specified offset in the bitmap. Page is
; displayed when this routine returns.
;
; C near-callable as: void ShowPage(unsigned int StartOffset);

ShowPageParms   struc
        dw      2 dup (?)         ;pushed BP and return address
StartOffset dw  ?                 ;offset in bitmap of page to display
ShowPageParms   ends

        public  _ShowPage
_ShowPage       proc    near
        push    bp                ;preserve caller's stack frame
        mov     bp,sp             ;point to local stack frame
; Wait for display enable to be active (status is active low), to be
; sure both halves of the start address will take in the same frame.
        mov     bl,START_ADDRESS_LOW          ;preload for fastest
        mov     bh,byte ptr StartOffset[bp]   ; flipping once display
        mov     cl,START_ADDRESS_HIGH         ; enable is detected
        mov     ch,byte ptr StartOffset+1[bp]
        mov     dx,INPUT_STATUS_1
WaitDE:
        in      al,dx
        test    al,01h
        jnz     WaitDE            ;display enable is active low (0 = active)
; Set the start offset in display memory of the page to display.
        mov     dx,CRTC_INDEX
        mov     ax,bx
        out     dx,ax             ;start address low
        mov     ax,cx
        out     dx,ax             ;start address high
; Now wait for vertical sync, so the other page will be invisible when
; we start drawing to it.
        mov     dx,INPUT_STATUS_1
WaitVS:
        in      al,dx
        test    al,08h
        jz      WaitVS            ;vertical sync is active high (1 = active)
        pop     bp                ;restore caller's stack frame
        ret
_ShowPage       endp

; Displays the specified image at the specified location in the
; specified bitmap, in the desired color.
;
; C near-callable as: void DrawImage(int LeftX, int TopY,
;       image **RotationTable, int Color, unsigned int ScrnOffset,
;       unsigned int ScrnSegment);

DrawImageParms  struc
        dw      2 dup (?)         ;pushed BP and return address
```

```
DILeftX          dw   ?          ;X coordinate of left side of image
DITopY           dw   ?          ;Y coordinate of top side of image
RotationTable    dw   ?          ;pointer to table of pointers to image
                                 ; rotations
DIColor          dw   ?          ;color in which to draw image (only the
                                 ; lower 4 bits matter)
DIScrnOffset     dw   ?          ;offset of base of bitmap in which to draw
DIScrnSegment    dw   ?          ;segment of base of bitmap in which to draw
DrawImageParms  ends

image struc
WidthInBytes    dw      ?
Height          dw      ?
BitPattern      dw      ?
image ends

        public  _DrawImage
_DrawImage      proc    near
        push    bp               ;preserve caller's stack frame
        mov     bp,sp            ;point to local stack frame
        push    si               ;preserve caller's register variables
        push    di

        cld
        mov     dx,GC_INDEX
        mov     al,SET_RESET
        mov     ah,byte ptr DIColor[bp]
        out     dx,ax            ;set the color in which to draw
        mov     ax,G_MODE + (0300h)
        out     dx,ax            ;set to write mode 3
        les     di,dword ptr DIScrnOffset[bp] ;point to bitmap start
        mov     ax,SCREEN_WIDTH
        mul     DITopY[bp]       ;point to the start of the top scan
        add     di,ax            ; line on which to draw
        mov     ax,DILeftX[bp]
        mov     bx,ax
        shr     ax,1             ;/8 = byte offset from left of screen
        shr     ax,1
        shr     ax,1
        add     di,ax            ;point to the upper left corner of draw area
        and     bx,7             ;isolate intrapixel address
        shl     bx,1             ;*2 for word look-up
        add     bx,RotationTable[bp] ;point to the image structure for
        mov     bx,[bx]              ; the intrabyte rotation
        mov     dx,[bx].WidthInBytes ;image width
        mov     si,[bx].BitPattern   ;pointer to image pattern bytes
        mov     bx,[bx].Height       ;image height
DrawImageLoop:
        push    di               ;remember line start offset
        mov     cx,dx            ;# of bytes across
DrawImageLineLoop:
        lodsb                    ;get the next image byte
        xchg    es:[di],al       ;draw the next image byte
        inc     di               ;point to the following screen byte
        loop    DrawImageLineLoop
        pop     di               ;retrieve line start offset
        add     di,SCREEN_WIDTH  ;point to the next line
        dec     bx               ;count off scan lines
        jnz     DrawImageLoop

        pop     di               ;restore caller's register variables
        pop     si
        pop     bp                      ;restore caller's stack frame
        ret
_DrawImage      endp

; Draws a 0-terminated text string at the specified location in the
; specified bitmap in white, using the 8x8 BIOS font. Must be at an X
; coordinate that's a multiple of 8.
;
; C near-callable as: void TextUp(char *Text, int LeftX, int TopY,
;       unsigned int ScrnOffset, unsigned int ScrnSegment);

TextUpParms     struc
                dw      2 dup (?)       ;pushed BP and return address
Text            dw      ?               ;pointer to text to draw
TULeftX         dw      ?               ;X coordinate of left side of rectangle
                                        ; (must be a multiple of 8)
TUTopY          dw      ?               ;Y coordinate of top side of rectangle
TUScrnOffset    dw      ?               ;offset of base of bitmap in which to draw
TUScrnSegment   dw      ?               ;segment of base of bitmap in which to draw
TextUpParms     ends

        public  _TextUp
_TextUp proc    near
        push    bp                      ;preserve caller's stack frame
        mov     bp,sp                   ;point to local stack frame
        push    si                      ;preserve caller's register variables
        push    di

        cld
        mov     dx,GC_INDEX
        mov     ax,G_MODE + (0000h)
        out     dx,ax                   ;set to write mode 0
        les     di,dword ptr TUScrnOffset[bp] ;point to bitmap start
        mov     ax,SCREEN_WIDTH
        mul     TUTopY[bp]              ;point to the start of the top scan
        add     di,ax                   ; line the text starts on
        mov     ax,TULeftX[bp]
        mov     bx,ax
        shr     ax,1                    ;/8 = byte offset from left of screen
        shr     ax,1
        shr     ax,1
        add     di,ax                   ;point to the upper left corner of first char
        mov     si,Text[bp]             ;point to text to draw
TextUpLoop:
        lodsb                           ;get the next character to draw
        and     al,al
        jz      TextUpDone              ;done if null byte
        push    si                      ;preserve text string pointer
        push    di                      ;preserve character's screen offset
        push    ds                      ;preserve default data segment
        call    CharUp                  ;draw this character
        pop     ds                      ;restore default data segment
        pop     di                      ;retrieve character's screen offset
        pop     si                      ;retrieve text string pointer
        inc     di                      ;point to next character's start location
        jmp     TextUpLoop

TextUpDone:
        pop     di                      ;restore caller's register variables
        pop     si
        pop     bp                      ;restore caller's stack frame
        ret

CharUp:                                 ;draws the character in AL at ES:DI
        lds     si,[BIOS8x8Ptr]         ;point to the 8x8 font start
        mov     bl,al
        sub     bh,bh
        shl     bx,1
        shl     bx,1
        shl     bx,1                    ;*8 to look up character offset in font
        add     si,bx                   ;point DS:SI to character data in font
        mov     cx,8                    ;characters are 8 high
CharUpLoop:
        movsb                           ;copy the next character pattern byte
        add     di,SCREEN_WIDTH-1       ;point to the next dest byte
        loop    CharUpLoop
        ret
_TextUp endp

; Sets the pointer to the BIOS 8x8 font.
;
; C near-callable as: extern void SetBIOS8x8Font(void);

        public  _SetBIOS8x8Font
_SetBIOS8x8Font proc    near
        push    bp                      ;preserve caller's stack frame
        push    si                      ;preserve caller's register variables
        push    di                      ; and data segment (don't assume BIOS
        push    ds                      ; preserves anything)
        mov     ah,11h                  ;BIOS character generator function
        mov     al,30h                  ;BIOS information subfunction
        mov     bh,3                    ;request 8x8 font pointer
        int     10h                     ;invoke BIOS video services
        mov     word ptr [BIOS8x8Ptr],bp ;store the pointer
        mov     word ptr [BIOS8x8Ptr+2],es
        pop     ds
        pop     di                      ;restore caller's register variables
        pop     si
        pop     bp                      ;restore caller's stack frame
        ret
_SetBIOS8x8Font endp
        end
```

Listing 29.1 is written in C. It could equally well have been written in assembly language, and would then have been somewhat faster. However, I wanted to make the point (as I've made again and again) that assembly language, and, indeed, optimization in general, is needed only in the most critical portions of any program, and then only when the program would otherwise be too slow. Only in a highly performance-sensitive situation would the performance boost resulting from converting Listing 29.1 to assembly justify the time spent in coding and the bugs that would likely creep in—and the sample program already updates the screen at the maximum possible rate of once per frame even on a 1985-vintage 8-MHz AT. In this case, faster performance would result only in a longer wait for the page to flip.

Write Mode 3

It's possible to update the bitmap very efficiently on the VGA, because the VGA can draw up to 8 pixels at once, and because the VGA provides a number of hardware features to speed up drawing. This article makes considerable use of one particularly unusual hardware feature, write mode 3. We discussed write mode 3 back in Chapter 4, but we've covered a lot of ground since then—so I'm going to run through a quick refresher on write mode 3.

Some background: In the standard VGA's high-resolution mode, mode 12H (640x480 with 16 colors, the mode in which this chapter's sample program runs), each byte of display memory controls 8 adjacent pixels on the screen. (The color of each pixel is, in turn, controlled by 4 bits spread across the four VGA memory planes, but we need not concern ourselves with that here.) Now, there will often be times when we want to change some but not all of the pixels controlled by a particular byte of display memory. This is not easily done, for there is no way to write half a byte, or two bits, or such to memory; it's the whole byte or none of it at all.

You might think that using AND and OR to manipulate individual bits could solve the problem. Alas, not so. ANDing and ORing would work if the VGA had only one plane of memory (like the original monochrome Hercules Graphics Adapter) but the VGA has four planes, and ANDing and ORing would work only if we selected and manipulated each plane separately, a process that would be hideously slow. No, with the VGA you must use the hardware assist features, or you might as well forget about real-time screen updates altogether. Write mode 3 will do the trick for our present needs.

Write mode 3 is useful when you want to set some but not all of the pixels in a single byte of display memory *to the same color*. That is, if you want to draw a number of pixels within a byte in a single color, write mode 3 is a good way to do it.

Write mode 3 works like this. First, set the Graphics Controller Mode register to write mode 3. (Look at Listing 29.2 for code that does everything described here.) Next, set the Set/Reset register to the color with which you wish to draw, in the range 0-15. (It is not necessary to explicitly enable set/reset via the Enable Set/Reset register; write mode 3 does that automatically.) Then, to draw individual pixels within a single byte, simply read display memory, and then write a byte to display memory with 1-bits where you want the color to be drawn and 0-bits where you want the current bitmap contents to be preserved. (Note well that *the data actually read by the CPU doesn't matter*; the read operation latches all four planes' data, as described way back in Chapter 2.) So, for example, if write mode 3 is enabled and the Set/Reset register is set to 1 (blue), then the following sequence of operations:

```
mov   dx,0a000h
mov   es,dx
mov   al,es:[0]
mov   byte ptr es:[0],0f0h
```

will change the first 4 pixels on the screen (the left nibble of the byte at offset 0 in display memory) to blue, and will leave the next 4 pixels (the right nibble of the byte at offset 0) unchanged.

Using one **MOV** to read from display memory and another to write to display memory is not particularly efficient on some processors. In Listing 29.2, I instead use **XCHG**, which reads and then writes a memory location in a single operation, as in:

```
mov   dx,0a000h
mov   es,dx
mov   al,0f0h
xchg  es:[0],al
```

Again, the actual value that's read is irrelevant. In general, the **XCHG** approach is more compact than two **MOV**s, and is faster on 386 and earlier processors, but slower on 486s and Pentiums.

If all pixels in a byte of display memory are to be drawn in a single color, it's not necessary to read before writing, because none of the information in display memory at that byte needs to be preserved; a simple write of 0FFH (to draw all bits) will set all 8 pixels to the set/reset color:

```
mov   dx,0a000h
mov   es,dx
mov   byte ptr es:[di],0ffh
```

*If you're familiar with VGA programming, you're no doubt aware that everything that can be done with write mode 3 can also be accomplished in write mode 0 or write mode 2 by using the Bit Mask register. However, setting the Bit Mask register requires at least one **OUT** per byte written, in addition to the read and write of display memory, and **OUT**s are often slower than display memory accesses, especially on 386s and 486s. One of the great virtues of write mode 3 is that it requires virtually no **OUT**s and is therefore substantially faster for masking than the other write modes.*

In short, write mode 3 is a good choice for single-color drawing that modifies individual pixels within display memory bytes. Not coincidentally, the sample application draws only single-color objects within the animation area; this allows write mode 3 to be used for all drawing, in keeping with our desire for speedy screen updates.

Drawing Text

We'll need text in the sample application; is that also a good use for write mode 3? Sometimes it is, but not in this particular case.

Each character in a font is represented by a pattern of bits, with 1-bits representing character pixels and 0-bits representing background pixels. Since we'll be using the 8x8 font stored in the BIOS ROM (a pointer to which can be obtained by calling a BIOS service, as illustrated by Listing 29.2), each character is exactly 8 bits, or 1 byte wide. We'll further insist that characters be placed on byte boundaries (that is, with their left edges only at pixels with X coordinates that are multiples of 8); this means that the character bytes in the font are automatically aligned with display memory, and no rotation or clipping of characters is needed. Finally, we'll draw all text in white.

Given the above assumptions, drawing text is easy; we simply copy each byte of each character to the appropriate location in display memory, and *voila*, we're done. Text copying is done in write mode 0, in which the byte written to display memory is copied to all four planes at once; hence, 1-bits turn into white (color value 0FH, with 1-bits in all four planes), and 0-bits turn into black (color value 0). This is faster than using write mode 3 because write mode 3 requires a read/write of display memory (or at least preloading the latches with the background color), while the write mode 0 approach requires only a write to display memory.

Is write mode 0 always the best way to do text? Not at all. The write mode 0 approach described above draws both foreground and background pixels within the character box, forcing the background pixels to black at the same time that it forces the foreground pixels to white. If you want to draw transparent text (that is, draw only the character pixels, not the surrounding background box), write mode 3 is ideal. Also, matters get far more complicated if characters that aren't 8 pixels wide are drawn, or if characters are drawn starting at arbitrary pixel locations, without the multiple-of-8 column restriction, so that rotation and masking are required. Lastly, the Map Mask register can be used to draw text in colors other than white—but only if the background is black. Otherwise, the data remaining in the planes protected by the Map Mask will remain and can interfere with the colors of the text being drawn.

I'm not going to delve any deeper into the considerable issues of drawing VGA text; I just want to sensitize you to the existence of approaches other than the ones used in Listings 29.1 and 29.2. On the VGA, the rule is: If there's something you want to do, there probably are ten ways to do it, each with unique strengths and weaknesses. Your mission, should you decide to accept it, is to figure out which one is best for your particular application.

Page Flipping

Now that we know how to update the screen reasonably quickly, it's time to get on to the fun stuff. Page flipping answers the second requirement for animation, by keeping bitmap changes off the screen until they're complete. In other words, page flipping guarantees that partially updated bitmaps are never seen.

How is it possible to update a bitmap without seeing the changes as they're made? Easy—with page flipping, there are *two* bitmaps; the program shows you one bitmap while it updates the other. Conceptually, it's that simple. In practice, unfortunately, it's not so simple, because of the design of the VGA. To understand why that is, we must look at how the VGA turns bytes in display memory into pixels on the screen.

The VGA bitmap is a linear 64 KB block of memory. (True, most adapters nowadays are SuperVGAs with more than 256K of display memory, but every make of SuperVGA has its own way of letting you access that extra memory, so going beyond standard VGA is a daunting and difficult task. Also, it's hard to manipulate the large frame buffers of SuperVGA modes fast enough for real-time animation.) Normally, the VGA picks up the first byte of memory (the byte at offset 0) and displays the corresponding 8 pixels on the screen, then picks up the byte at offset 1 and displays the next 8 pixels, and so on to the end of the screen. However, the offset of the first byte of display memory picked up during each frame is not fixed at 0, but is rather programmable by way of the Start Address High and Low registers, which together store the 16-bit offset in display memory at which the bitmap to be displayed during the next frame starts. So, for example, in mode 10H (640×350, 16 colors), a large enough bitmap to store a complete screen of information can be stored at display memory offsets 0 through 27,999, and *another* full bitmap could be stored at offsets 28,000 through 55,999, as shown in Figure 29.1. (I'm discussing 640×350 mode at the moment for good reason; we'll get to 640×480 shortly.) When the Start Address registers are set to 0, the first bitmap (or page) is displayed; when they are set to 28,000, the second bitmap is displayed. Page-flipped animation can be performed by displaying page 0 and drawing to page 1, then setting the start address to page 1 to display that page and drawing to page 0, and so on *ad infinitum.*

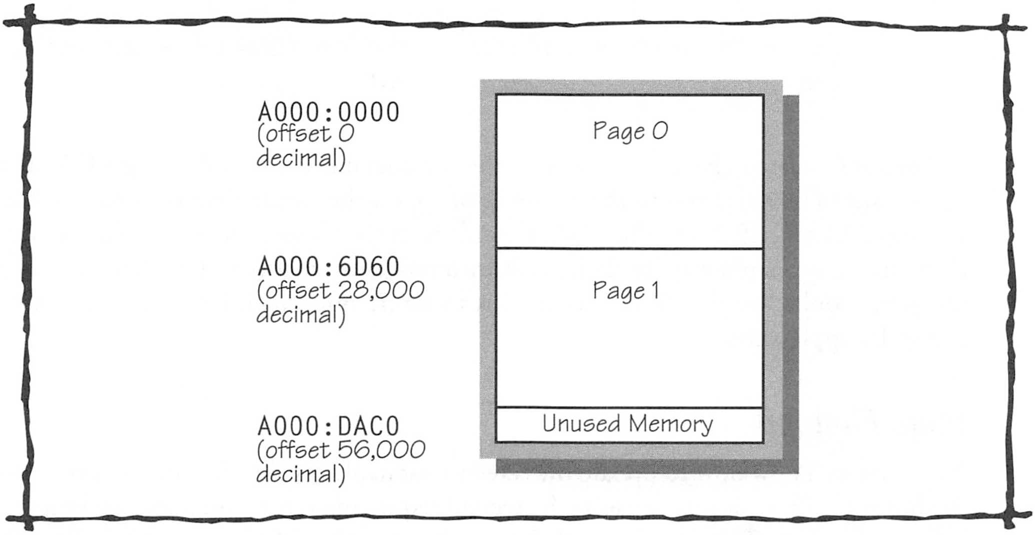


Figure 29.1 Memory Allocation for Mode 10H Page Flipping

Knowing when to Flip

There's a hitch, though, and that hitch is knowing exactly when it is that the page has flipped. The page doesn't flip the instant that you set the Start Address registers. The VGA loads the starting offset from the Start Address registers once before starting each frame, then pays those registers no nevermind until the next frame comes around. This means that you can set the Start Address registers whenever you want—but the page actually being displayed doesn't change until after the VGA loads that new offset in preparation for the next frame.

The potential problem should be obvious. Suppose that page 1 is being displayed, and you're updating page 0. You finish drawing to page 0, set the Start Address registers to 0 to switch to displaying page 0, and start updating page 1, which is no longer displayed. Or is it? If the VGA was in the middle of the current frame, displaying page 1, when you set the Start Address registers, then page 1 is going to be displayed for the rest of the frame, no matter what you do with the Start Address registers. If you start updating page 1 right away, any changes you make may well show up on the screen, because page 0 hasn't yet flipped to being displayed in place of page 1—and that defeats the whole purpose of page flipping.

To avoid this problem, it is mandatory that you wait until you're sure the page has flipped. The Start Address registers are, according to my tests, loaded at the start of the Vertical Sync signal, although that may not be the case with all VGA clones. The Vertical Sync status is provided as bit 3 of the Input Status 1 register, so it would seem that all you need to do to flip a page is set the new Start Address registers, wait for the start of the Vertical Sync pulse that indicates that the page has flipped, and be on your merry way.

Almost—but not quite. (Do I hear teeth gnashing in the background?) The problem is this: Suppose that, by coincidence, you set one of the Start Address registers just before the start of Vertical Sync, and the other right after the start of Vertical Sync. Why, then, for one frame the Start Address High value for one page would be mixed with the Start Address Low value for the other page, and, depending on the start address values, the whole screen could appear to shift any number of pixels for a single, horrible frame. *This must never happen!*The solution is to set the Start Address registers when you're certain Vertical Sync is not about to start. The easiest way to know that is to check for the Display Enable status (bit 0 of the Input Status 1 register) being active; that means that bitmap-controlled pixels are being scanned onto the screen, and, since Vertical Sync happens in the middle of the vertical non-display portion of the frame, Vertical Sync can never be anywhere nearby if Display Enable is active. (Note that one good alternative is to set up both pages with a start address that's a multiple of 256, and just change the Start Address High register and wait for Vertical Sync, with no Display Enable wait required.)

So, to flip pages, you must complete all drawing to the non-displayed page, wait for Display Enable to be active, set the new start address, and wait for Vertical Sync to be active. At that point, you can be fully confident that the page that you just flipped off the screen is not displayed and can safely (invisibly) be updated. A side benefit of page flipping is that your program will automatically have a constant time base, with the rate at which new screens are drawn synchronized to the frame rate of the display (typically 60 or 70 Hz). However, complex updates may take more than one frame to complete, especially on slower processors; this can be compensated for by maintaining a count of new screens drawn and cross-referencing that to the BIOS timer count periodically, accelerating the overall pace of the animation (moving farther each time and the like) if updates are happening too slowly.

Enter the Split Screen

So far, I've discussed page flipping in 640×350 mode. There's a reason for that: 640×350 is the highest-resolution standard mode in which there's enough display memory for two full pages on a standard VGA. It's possible to program the VGA to a non-standard 640×400 mode and still have two full pages, but that's pretty much the limit. One 640×480 page takes 38,400 bytes of display memory, and clearly there isn't enough room in 64 Kb of display memory for two of *those* monster pages.

And yet, 640×480 is a wonderful mode in many ways. It offers a 1:1 aspect ratio (square pixels), and it provides by far the best resolution of any 16-color mode. Surely there's *some* way to bring the visual appeal of page flipping to this mode?

Surely there is—but it's an odd solution indeed. The VGA has a feature, known as the *split screen*, that allows you to force the offset from which the VGA fetches video data back to 0 after any desired scan line. For example, you can program the VGA to scan through display memory as usual until it finishes scan line number 338, and then get the first byte of information for scan line number 339 from offset 0 in display memory.

That, in turn, allows us to divvy up display memory into three areas, as shown in Figure 29.2. The area from 0 to 11,279 is reserved for the split screen, the area from 11,280 to 38,399 is used for page 0, and the area from 38,400 to 65,519 is used for page 1. This allows page flipping to be performed in the top 339 scan lines (about 70 percent) of the screen, and leaves the bottom 141 scan lines for non-animation purposes, such as showing scores, instructions, statuses, and suchlike. (Note that the allocation of display memory and number of scan lines are dictated by the desire to have as many page-flipped scan lines as possible; you may, if you wish, have fewer page-flipped lines and reserve part of the bitmap for other uses, such as off-screen storage for images.)

The sample program for this chapter uses the split screen and page flipping exactly as described above. The playfield through which the object bounces is the page-flipped portion of the screen, and the rectangle at the bottom containing the bounce count and the instructions is the split (that is, not animatable) portion of the screen. Of course, to the user it all looks like one screen. There are no visible boundaries between the two unless you choose to create them.

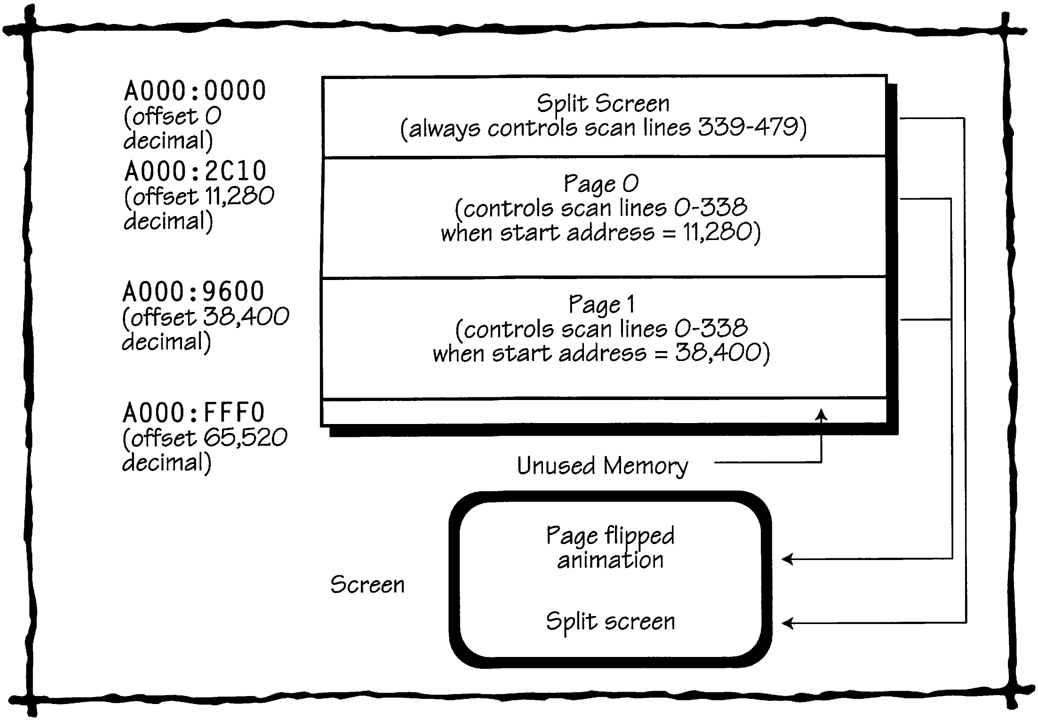


Figure 29.2 Memory Allocation for Mode 12H Page Flipping

Very few animation applications use the entire screen for animation. If you can get by with 339 scan lines of animation, split-screen page flipping gives you the best combination of square pixels and high resolution possible on a standard VGA.

So. Is VGA animation worth all the fuss? *Mais oui.* Run the sample program; if you've never seen aggressive VGA animation before, you'll be amazed at how smooth it can be. Not every square millimeter of every animated screen must be in constant motion. Most graphics screens need a little quiet space to display scores, coordinates, file names, or (if all else fails) company logos. If you don't tell the user they're only getting 339 scan lines of animation, they'll probably never know.

Dog Hair and Dirty Rectangles

Chapter 30

Different Angles on Animation

We brought our pets with us when we moved to Seattle. At about the same time, our Golden Retriever, Sam, observed his third birthday. Sam is relatively intelligent, in the sense that he is clearly smarter than a banana slug, although if he were in the same room with Jeff Duntemann's dog Mr. Byte, there's a reasonable chance that he would mistake Mr. Byte for something edible (a category that includes rocks, socks, and a surprising number of things too disgusting to mention), and Jeff would have to find a new source of things to write about.

But that's not important now. What is important is that—and I am not making this up—this morning I managed to find the one pair of socks Sam hadn't chewed holes in. And what's even more important is that after we moved and Sam turned three, he calmed down amazingly. We had been waiting for this magic transformation since Sam turned one, the age at which most puppies turn into normal dogs who lie around a lot, waking up to eat their Science Diet (motto, "The dog food that costs more than the average neurosurgeon makes in a year") before licking themselves in embarrassing places and going back to sleep. When Sam turned one and remained hopelessly out of control we said, "Goldens take two years to calm down," as if we had a clue. When he turned two and remained undeniably Sam we said, "Any day now." By the time he turned three, we were reduced to figuring that it was only about seven more years until he expired, at which point we might be able to take all the fur he had shed in his lifetime and weave ourselves some clothes without holes in them, or quite possibly a house.

But miracle of miracles, we moved, and Sam instantly turned into the dog we thought we'd gotten when we forked over $500—calm, sweet, and obedient. Weeks went by, and Sam was, if anything, better than ever. Clearly, the change was permanent.

And then we took Sam to the vet for his annual check-up and found that he had an ear infection. Thanks to the wonders of modern animal medicine, a $5 bottle of liquid restored his health in just two days. And with his health, we got, as a bonus, the old Sam. You see, Sam hadn't changed. He was just tired from being sick. Now he once again joyously knocks down any stranger who makes the mistake of glancing in his direction, and will, quite possibly, be booked any day now on suspicion of homicide by licking.

Plus ça Change

Okay, you give up. What exactly does this have to do with graphics? I'm glad you asked. The lesson to be learned from Sam, The Dog With A Brain The Size Of A Walnut, is that while things may *look* like they've changed, in fact they often haven't. Take VGA performance. If you buy a 486 with a SuperVGA, you'll get performance that knocks your socks off, especially if you run Windows. Things are liable to be so fast that you'll figure the SuperVGA has to deserve some of the credit. Well, maybe it does if it's a local-bus VGA. But maybe it doesn't, even if it is local bus—and it certainly doesn't if it's an ISA bus VGA, because no ISA bus VGA can run faster than about 300 nanoseconds per access, and VGAs capable of that speed have been common for at least a couple of years now.

Your 486 VGA system is fast almost entirely because it has a 486 in it. (486 systems with graphics accelerators such as the ATI Ultra or Diamond Stealth are another story altogether.) Underneath it all, the VGA is still painfully slow—and if you have an old VGA or IBM's original PS/2 motherboard VGA, it's incredibly slow. The fastest ISA-bus VGA around is two to twenty times slower than system memory, and the slowest VGA around is as much as 100 times slower. In the old days, the rule was, "Display memory is slow, and should be avoided." Nowadays, the rule is, "Display memory is not quite so slow, but should still be avoided."

So, as I say, sometimes things don't change. Of course, sometimes they do change. For example, in just 49 dog years, I fully expect to own at least one pair of underwear without a single hole in it. Which brings us, deus ex machina and the creek don't rise, to yet another animation method: dirty-rectangle animation.

VGA Access Times

Actually, before we get to dirty rectangles, I'd like to take you through a quick refresher on VGA memory and I/O access times. I want to do this partly because the slow access times of the VGA make dirty-rectangle animation particularly attractive, and partly as a public service, because even I was shocked by the results of some I/O performance tests I recently ran.

Table 30.1 shows the results of the aforementioned I/O performance tests, as run on two 486/33 SuperVGA systems under the Phar Lap 386|DOS-Extender. (The systems and VGAs are unnamed because this is a not-very-scientific spot test, and I don't want to unfairly malign, say, a VGA whose only sin is being plugged into a lousy motherboard,

Table 30.1 Results of I/O Performance Tests Run under the Phar Lap 386lDOS-Extender

		OUT Time in Microseconds and Cycles	
OUT Instruction	Official Time	486 #1/16-bit VGA#1	486 #2/16-bit VGA #2
OUT DX,AL repeated 1,000 times nonstop (maximum byte access)	0.300 s 10 cycles	2.546 s 84 cycles	0.813 s 27 cycles
OUT DX,AX repeated 1,000 times nonstop (maximum word access)	0.300 s 10 cycles	3.820 s 126 cycles	1.066 s 35 cycles
OUT DX,AL repeated 1,000 times, but interspersed with MULs (random byte access)	0.300 s 10 cycles	1.610 s 53 cycles	0.780 s 26 cycles
OUT DX,AX repeated 1,000 times, but interspersed with MULs (random word access)	0.300 s 10 cycles	2.830 s 93 cycles	1.010 s 33 cycles

or vice versa). Under Phar Lap, 32-bit protected-mode apps run with full I/O privileges, meaning that the **OUT** instructions I measured had the best official cycle times possible on the 486: 10 cycles. **OUT** officially takes 16 cycles in real mode on a 486, and officially takes a mind-boggling 30 cycles in protected mode if running *without* full I/O privileges (as is normally the case for protected-mode applications). Basically, I/O is just plain slow on a 486.

As slow as 30 or even 10 cycles is for an **OUT**, one could only wish that VGA I/O were actually that fast. The fastest measured **OUT** to a VGA in Table 30.1 is 26 cycles, and the slowest is 126—this for an operation that's *supposed* to take 10 cycles. To put this in context, **MUL** takes only 13 to 42 cycles, and a normal **MOV** to or from system memory takes exactly one cycle on the 486. In short, **OUT**s to VGAs are as much as 100 times slower than normal memory accesses, and are generally two to four times slower than even display memory accesses, although there are exceptions.

Of course, VGA display memory has its own performance problems. The fastest ISA bus VGA can, at best, support sustained write times of about 10 cycles per word-sized write on a 486/33; 15 or 20 cycles is more common, even for relatively fast SuperVGAs; the worst case I've seen is 65 cycles per byte. However, intermittent writes, mixed with a lot of register and cache-only code, can effectively execute in one cycle, thanks to the caching design of many VGAs and the 486's 4-deep write buffer, which stores pending writes while the CPU continues executing instructions. Display memory reads tend to take longer, because coprocessing isn't possible—one microsecond is a reasonable rule of thumb for VGA reads, although there's considerable variation. So VGA memory tends not to be as bad as VGA I/O, but lord knows it isn't *good.*

__OUTs__, in general, are lousy on the 486 (and to think they only took three cycles on the 286!). __OUTs__ to VGAs are particularly lousy. Display memory performance is pretty poor, especially for reads. The conclusions are obvious, I would hope. Structure your graphics code, and, in general, all 486 code, to avoid __OUTs__.

For graphics, this especially means using write mode 3 rather than the bit-mask register. When you must use the bit mask, arrange drawing so that you can set the bit mask once, then do a lot of drawing with that mask. For example, draw a whole edge at once, then the middle, then the other edge, rather than setting the bit mask several times on each scan line to draw the edge and middle bytes together. Don't read from display memory if you don't have to. Write each pixel once and only once.

It is indeed a strange concept: The key to fast graphics is staying away from the graphics adapter as much as possible.

Dirty-Rectangle Animation

The relative slowness of VGA hardware is part of the appeal of the technique that I call "dirty-rectangle" animation, in which a complete copy of the contents of display memory is maintained in offscreen system (nondisplay) memory. All drawing is done to this system buffer. As offscreen drawing is done, a list is maintained of the bounding rectangles for the drawn-to areas; these are the *dirty rectangles*, "dirty" in the sense that that have been altered and no longer match the contents of the screen. After all drawing for a frame is completed, all the dirty rectangles for that frame are copied to the screen in a burst, and then the cycle of off-screen drawing begins again.

Why, exactly, would we want to go through all this complication, rather than simply drawing to the screen in the first place? The reason is visual quality. If we were to do all our drawing directly to the screen, there'd be a lot of flicker as objects were erased and then redrawn. Similarly, overlapped drawing done with the painter's algorithm (in which farther objects are drawn first, so that nearer objects obscure them) would flicker as farther objects were visible for short periods. With dirty-rectangle animation, only the finished pixels for any given frame ever appear on the screen; intermediate results are never visible. Figure 30.1 illustrates the visual problems associated with drawing directly to the screen; Figure 30.2 shows how dirty-rectangle animation solves these problems.

So Why Not Use Page Flipping?

Well, then, if we want good visual quality, why not use page flipping? For one thing, not all adapters and all modes support page flipping. The CGA and MCGA don't, and neither do the VGA's 640×480 16-color or 320×200 256-color modes, or many

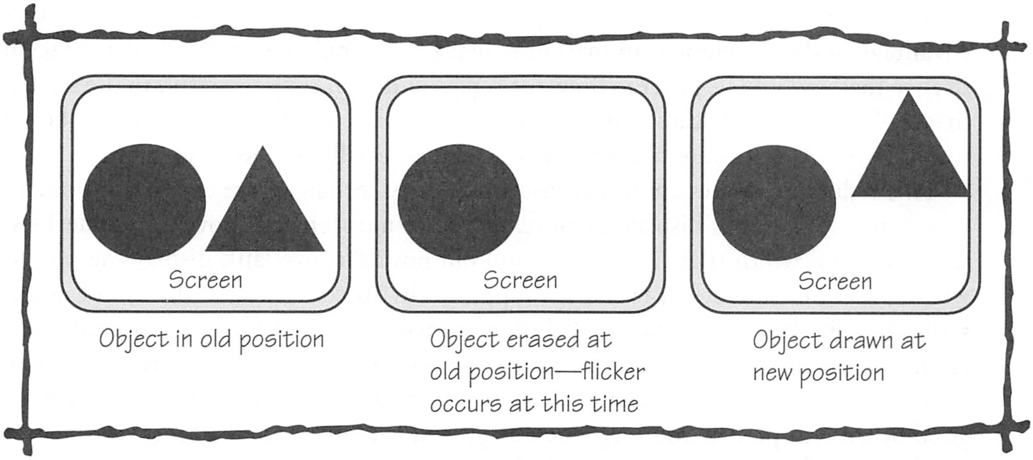

Screen
Object in old position
Screen
Object erased at old position—flicker occurs at this time
Screen
Object drawn at new position

Figure 30.1 Drawing Directly to the Screen

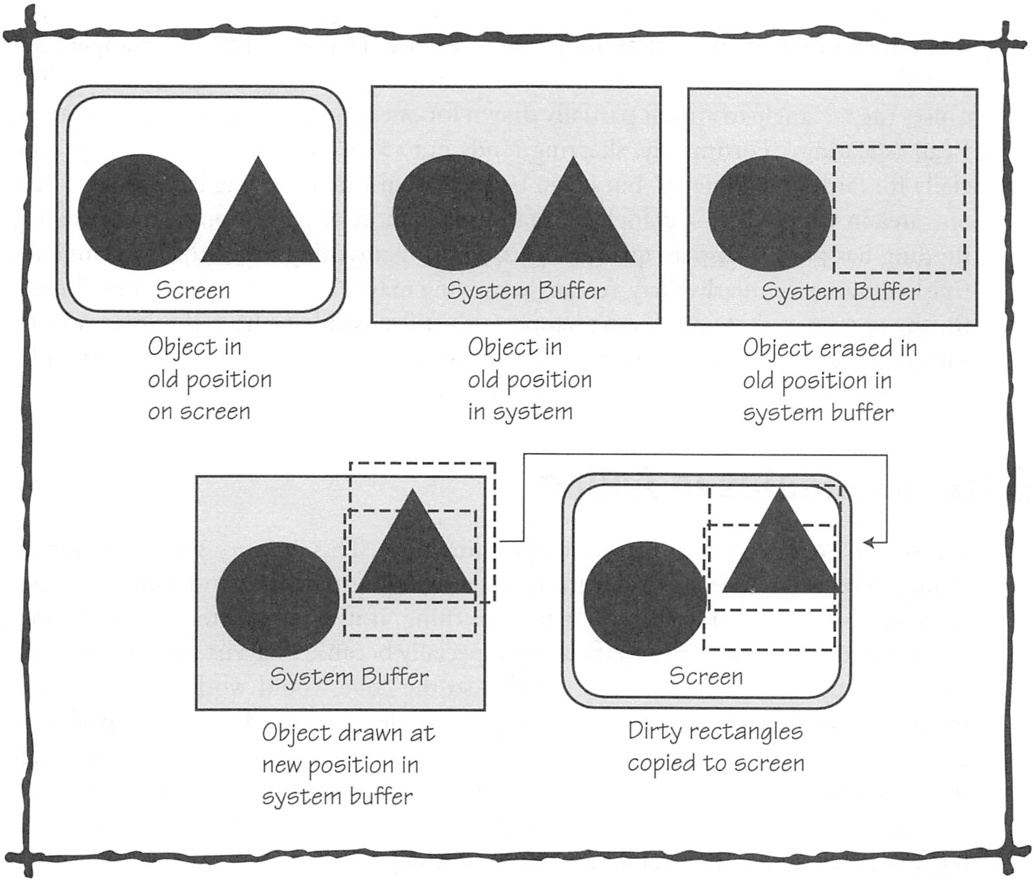

Screen
Object in old position on screen
System Buffer
Object in old position in system
System Buffer
Object erased in old position in system buffer
System Buffer
Object drawn at new position in system buffer
Screen
Dirty rectangles copied to screen

Figure 30.2 Dirty Rectangle Animation

SuperVGA modes. In contrast, *all* adapters support dirty-rectangle animation. Another advantage of dirty-rectangle animation is that it's generally faster. While it may seem strange that it would be faster to draw off-screen and then copy the result to the screen, that is often the case, because dirty-rectangle animation usually reduces the number of times the VGA's hardware needs to be touched, especially in 256-color modes.

This reduction comes about because when dirty rectangles are erased, it's done in system memory, not in display memory, and since most objects move a good deal less than their full width (that is, the new and old positions overlap), display memory is written to fewer times than with page flipping. (In 16-color modes, this is not necessarily the case, because of the parallelism obtained from the VGA's planar hardware.) Also, read/modify/write operations are performed in fast system memory rather than slow display memory, so display memory rarely needs to be read. This is particularly good because display memory is generally even slower for reads than for writes.

Also, page flipping wastes a good deal of time waiting for the page to flip at the end of the frame. Dirty-rectangle animation never needs to wait for anything because partially drawn images are never present in display memory. Actually, in one sense, partially drawn images are sometimes present because it's possible for a rectangle to be partially drawn when the scanning raster beam reaches that part of the screen. This causes the rectangle to appear partially drawn for one frame, producing a phenomenon I call "shearing." Fortunately, shearing tends not to be particularly distracting, especially for fairly small images, but it can be a problem when copying large areas. This is one area in which dirty-rectangle animation falls short of page flipping, because page flipping has perfect display quality, never showing anything other than a completely finished frame. Similarly, dirty-rectangle copying may take two or more frame times to finish, so even if shearing doesn't happen, it's still possible to have the images in the various dirty rectangles show up non-simultaneously. In my experience, this latter phenomenon is not a serious problem, but do be aware of it.

Dirty Rectangles in Action

Listing 30.1 demonstrates dirty-rectangle animation. This is a very simple implementation, in several respects. For one thing, it's written entirely in C, and animation fairly cries out for assembly language. For another thing, it uses far pointers, which C often handles with less than optimal efficiency, especially because I haven't used library functions to copy and fill memory. (I did this so the code would work in any memory model.) Also, Listing 30.1 doesn't attempt to coalesce rectangles so as to perform a minimum number of display-memory accesses; instead, it copies each dirty rectangle to the screen, even if it overlaps with another rectangle, so some pixels are copied multiple times. Listing 30.1 runs pretty well, considering all of its failings; on my 486/33, ten 11×11 images animate at a very respectable clip.

LISTING 30.1 L30-1.C

```
/* Sample simple dirty-rectangle animation program. Doesn't attempt to coalesce
   rectangles to minimize display memory accesses. Not even vaguely optimized!
   Tested with Borland C++ in the small model. */

#include <stdlib.h>
#include <conio.h>
#include <alloc.h>
#include <memory.h>
#include <dos.h>

#define SCREEN_WIDTH  320
#define SCREEN_HEIGHT 200
#define SCREEN_SEGMENT 0xA000

/* Describes a rectangle */
typedef struct {
   int Top;
   int Left;
   int Right;
   int Bottom;
} Rectangle;

/* Describes an animated object */
typedef struct {
   int X;            /* upper left corner in virtual bitmap */
   int Y;
   int XDirection;   /* direction and distance of movement */
   int YDirection;
} Entity;

/* Storage used for dirty rectangles */
#define MAX_DIRTY_RECTANGLES  100
int NumDirtyRectangles;
Rectangle DirtyRectangles[MAX_DIRTY_RECTANGLES];

/* If set to 1, ignore dirty rectangle list and copy the whole screen. */
int DrawWholeScreen = 0;

/* Pixels for image we'll animate */
#define IMAGE_WIDTH  11
#define IMAGE_HEIGHT 11
char ImagePixels[] = {
  15,15,15, 9, 9, 9, 9, 9,15,15,15,
  15,15, 9, 9, 9, 9, 9, 9, 9,15,15,
  15, 9, 9,14,14,14,14,14, 9, 9,15,
   9, 9,14,14,14,14,14,14,14, 9, 9,
   9, 9,14,14,14,14,14,14,14, 9, 9,
   9, 9,14,14,14,14,14,14,14, 9, 9,
   9, 9,14,14,14,14,14,14,14, 9, 9,
   9, 9,14,14,14,14,14,14,14, 9, 9,
  15, 9, 9,14,14,14,14,14, 9, 9,15,
  15,15, 9, 9, 9, 9, 9, 9, 9,15,15,
  15,15,15, 9, 9, 9, 9, 9,15,15,15,
};
/* animated entities */
#define NUM_ENTITIES 10
Entity Entities[NUM_ENTITIES];
```

```
/* pointer to system buffer into which we'll draw */
char far *SystemBufferPtr;

/* pointer to screen */
char far *ScreenPtr;

void EraseEntities(void);
void CopyDirtyRectanglesToScreen(void);
void DrawEntities(void);

void main()
{
   int i, XTemp, YTemp;
   unsigned int TempCount;
   char far *TempPtr;
   union REGS regs;
   /* Allocate memory for the system buffer into which we'll draw */
   if (!(SystemBufferPtr = farmalloc((unsigned int)SCREEN_WIDTH*
         SCREEN_HEIGHT))) {
      printf("Couldn't get memory\n");
      exit(1);
   }
   /* Clear the system buffer */
   TempPtr = SystemBufferPtr;
   for (TempCount = ((unsigned)SCREEN_WIDTH*SCREEN_HEIGHT); TempCount--; ) {
      *TempPtr++ = 0;
   }
   /* Point to the screen */
   ScreenPtr = MK_FP(SCREEN_SEGMENT, 0);

   /* Set up the entities we'll animate, at random locations */
   randomize();
   for (i = 0; i < NUM_ENTITIES; i++) {
      Entities[i].X = random(SCREEN_WIDTH - IMAGE_WIDTH);
      Entities[i].Y = random(SCREEN_HEIGHT - IMAGE_HEIGHT);
      Entities[i].XDirection = 1;
      Entities[i].YDirection = -1;
   }
   /* Set 320x200 256-color graphics mode */
   regs.x.ax = 0x0013;
   int86(0x10, &regs, &regs);

   /* Loop and draw until a key is pressed */
   do {
      /* Draw the entities to the system buffer at their current locations,
         updating the dirty rectangle list */
      DrawEntities();

      /* Draw the dirty rectangles, or the whole system buffer if
         appropriate */
      CopyDirtyRectanglesToScreen();

      /* Reset the dirty rectangle list to empty */
      NumDirtyRectangles = 0;

      /* Erase the entities in the system buffer at their old locations,
         updating the dirty rectangle list */
      EraseEntities();

      /* Move the entities, bouncing off the edges of the screen */
      for (i = 0; i < NUM_ENTITIES; i++) {
         XTemp = Entities[i].X + Entities[i].XDirection;
         YTemp = Entities[i].Y + Entities[i].YDirection;
         if ((XTemp < 0) || ((XTemp + IMAGE_WIDTH) > SCREEN_WIDTH)) {
            Entities[i].XDirection = -Entities[i].XDirection;
            XTemp = Entities[i].X + Entities[i].XDirection;
         }
         if ((YTemp < 0) || ((YTemp + IMAGE_HEIGHT) > SCREEN_HEIGHT)) {
            Entities[i].YDirection = -Entities[i].YDirection;
            YTemp = Entities[i].Y + Entities[i].YDirection;
         }
         Entities[i].X = XTemp;
         Entities[i].Y = YTemp;
      }

   } while (!kbhit());
   getch();    /* clear the keypress */
   /* Back to text mode */
   regs.x.ax = 0x0003;
   int86(0x10, &regs, &regs);
}
/* Draw entities at current locations, updating dirty rectangle list. */
void DrawEntities()
{
   int i, j, k;
   char far *RowPtrBuffer;
   char far *TempPtrBuffer;
   char far *TempPtrImage;
   for (i = 0; i < NUM_ENTITIES; i++) {
      /* Remember the dirty rectangle info for this entity */
      if (NumDirtyRectangles >= MAX_DIRTY_RECTANGLES) {
         /* Too many dirty rectangles; just redraw the whole screen */
         DrawWholeScreen = 1;
      } else {
         /* Remember this dirty rectangle */
         DirtyRectangles[NumDirtyRectangles].Left = Entities[i].X;
         DirtyRectangles[NumDirtyRectangles].Top = Entities[i].Y;
         DirtyRectangles[NumDirtyRectangles].Right =
               Entities[i].X + IMAGE_WIDTH;
         DirtyRectangles[NumDirtyRectangles++].Bottom =
               Entities[i].Y + IMAGE_HEIGHT;
      }
      /* Point to the destination in the system buffer */
      RowPtrBuffer = SystemBufferPtr + (Entities[i].Y * SCREEN_WIDTH) +
            Entities[i].X;
      /* Point to the image to draw */
      TempPtrImage = ImagePixels;
      /* Copy the image to the system buffer */
      for (j = 0; j < IMAGE_HEIGHT; j++) {
         /* Copy a row */
         for (k = 0, TempPtrBuffer = RowPtrBuffer; k < IMAGE_WIDTH; k++) {
            *TempPtrBuffer++ = *TempPtrImage++;
         }
         /* Point to the next system buffer row */
         RowPtrBuffer += SCREEN_WIDTH;
      }
   }
}
/* Copy the dirty rectangles, or the whole system buffer if appropriate,
   to the screen. */
void CopyDirtyRectanglesToScreen()
{
   int i, j, k, RectWidth, RectHeight;
   unsigned int TempCount;
   unsigned int Offset;
   char far *TempPtrScreen;
   char far *TempPtrBuffer;

   if (DrawWholeScreen) {
      /* Just copy the whole buffer to the screen */
      DrawWholeScreen = 0;
      TempPtrScreen = ScreenPtr;
      TempPtrBuffer = SystemBufferPtr;
      for (TempCount = ((unsigned)SCREEN_WIDTH*SCREEN_HEIGHT); TempCount--; ) {
         *TempPtrScreen++ = *TempPtrBuffer++;
      }
   } else {
      /* Copy only the dirty rectangles */
      for (i = 0; i < NumDirtyRectangles; i++) {
         /* Offset in both system buffer and screen of image */
         Offset = (unsigned int) (DirtyRectangles[i].Top * SCREEN_WIDTH) +
               DirtyRectangles[i].Left;
         /* Dimensions of dirty rectangle */
         RectWidth = DirtyRectangles[i].Right - DirtyRectangles[i].Left;
         RectHeight = DirtyRectangles[i].Bottom - DirtyRectangles[i].Top;
         /* Copy a dirty rectangle */
         for (j = 0; j < RectHeight; j++) {

            /* Point to the start of row on screen */
            TempPtrScreen = ScreenPtr + Offset;

            /* Point to the start of row in system buffer */
            TempPtrBuffer = SystemBufferPtr + Offset;

            /* Copy a row */
            for (k = 0; k < RectWidth; k++) {
               *TempPtrScreen++ = *TempPtrBuffer++;
            }
            /* Point to the next row */
            Offset += SCREEN_WIDTH;
         }
      }
   }
}
/* Erase the entities in the system buffer at their current locations,
   updating the dirty rectangle list. */
void EraseEntities()
{
   int i, j, k;
   char far *RowPtr;
   char far *TempPtr;

   for (i = 0; i < NUM_ENTITIES; i++) {
      /* Remember the dirty rectangle info for this entity */
      if (NumDirtyRectangles >= MAX_DIRTY_RECTANGLES) {
         /* Too many dirty rectangles; just redraw the whole screen */
         DrawWholeScreen = 1;
      } else {
         /* Remember this dirty rectangle */
         DirtyRectangles[NumDirtyRectangles].Left = Entities[i].X;
         DirtyRectangles[NumDirtyRectangles].Top = Entities[i].Y;
         DirtyRectangles[NumDirtyRectangles].Right =
               Entities[i].X + IMAGE_WIDTH;
         DirtyRectangles[NumDirtyRectangles++].Bottom =
               Entities[i].Y + IMAGE_HEIGHT;
      }
      /* Point to the destination in the system buffer */
      RowPtr = SystemBufferPtr + (Entities[i].Y*SCREEN_WIDTH) + Entities[i].X;

      /* Clear the entity's rectangle */
      for (j = 0; j < IMAGE_HEIGHT; j++) {
         /* Clear a row */
         for (k = 0, TempPtr = RowPtr; k < IMAGE_WIDTH; k++) {
            *TempPtr++ = 0;
         }
         /* Point to the next row */
         RowPtr += SCREEN_WIDTH;
      }
   }
}
```

One point I'd like to make is that although the system-memory buffer in Listing 30.1 has exactly the same dimensions as the screen bitmap, that's not a requirement, and there are some good reasons not to make the two the same size. For example, if the system buffer is bigger than the area displayed on the screen, it's possible to pan the visible area around the system buffer. Or, alternatively, the system buffer can be just the size of a desired window, representing a window into a larger, virtual buffer. We could then draw the desired portion of the virtual bitmap into the system-memory buffer, then copy the buffer to the screen, and the effect will be of having panned the window to the new location.

Another argument in favor of a small viewing window is that it restricts the amount of display memory actually drawn to. Restricting the display memory used for animation reduces the total number of display-memory accesses, which in turn boosts overall performance; it also improves the performance and appearance of panning, in which the whole window has to be redrawn or copied.

If you keep a close watch, you'll notice that many high-performance animation games similarly restrict their full-featured animation area to a relatively small region. Often, it's hard to tell that this is the case, because the animation region is surrounded by flashy digitized graphics and by items such as scoreboards and status screens, but look closely and see if the animation region in your favorite game isn't smaller than you thought.

Hi-Res VGA Page Flipping

On a standard VGA, hi-res mode is mode 12H, which offers 640×480 resolution with 16 colors. That's a nice mode, with plenty of pixels, and square ones at that, but it lacks one thing—page flipping. The problem is that the mode 12H bitmap is 150 Kbytes in size, and the standard VGA has only 256 Kbytes total, too little memory for two of those monster mode 12H pages. With only one page, flipping is obviously out of the question, and without page flipping, top-flight, hi-res animation can't be implemented. The standard fallback is to use the EGA's hi-res mode, mode 10H (640×350, 16 colors) for page flipping, but this mode is less than ideal for a couple of reasons: It offers sharply lower vertical resolution, and it's lousy for handling scaled-up CGA graphics, because the vertical resolution is a fractional multiple—1.75 times, to be exact—of that of the CGA. CGA resolution may not seem important these days, but many images were originally created for the CGA, as were many graphics packages and games, and it's at least convenient to be able to handle CGA graphics easily. Then, too, 640×350 is also a poor multiple of the 200 scan lines of the popular 320×200 256-color mode 13H of the VGA.

There are a couple of interesting, if imperfect, solutions to the problem of hi-res page flipping. One is to use the split screen to enable page flipping only in the top two-thirds of the screen; see the previous chapter for details, and for details on the mechanics of page flipping generally. This doesn't address the CGA problem, but it does yield square pixels and a full 640×480 screen resolution, although not all those pixels are flippable and thus animatable.

A second solution is to program the screen to a 640×400 mode. Such a mode uses almost every byte of display memory (64,000 bytes, actually; you could add another few lines, if you really wanted to), and thereby provides the highest resolution possible on the VGA for a fully page-flipped display. It maps well to CGA and mode 13H resolutions, being either identical or double in both dimensions. As an added benefit, it offers an easy-on-the-eyes 70-Hz frame rate, as opposed to the 60 Hz that is the best that mode 12H can offer, due to the design of standard VGA monitors. Best of all, perhaps, is that 640×400 16-color mode is easy to set up.

The key to 640×400 mode is understanding that on a VGA, mode 10H (640×350) is, at heart, a 400-scan-line mode. What I mean by that is that in mode 10H, the Vertical Total register, which controls the total number of scan lines, both displayed and nondisplayed, is set to 447, exactly the same as in the VGA's text modes, which do in fact support 400 scan lines. A properly sized and centered display is achieved in mode 10H by setting the polarity of the sync pulses to tell the monitor to scan vertically at a faster rate (to make fewer lines fill the screen), by starting the overscan after 350 lines, and by setting the vertical sync and blanking pulses appropriately for the faster vertical scanning rate. Changing those settings is all that's required to turn mode 10H into a 640×400 mode, and that's easy to do, as illustrated by Listing 30.2, which provides mode set code for 640×400 mode.

LISTING 30.2 L30-2.C

```
/* Mode set routine for VGA 640x400 16-color mode. Tested with
   Borland C++ in C compilation mode. */

#include <dos.h>
```

```
void Set640x400()
{
   union REGS regset;

   /* First, set to standard 640x350 mode (mode 10h) */
   regset.x.ax = 0x0010;
   int86(0x10, &regset, &regset);

   /* Modify the sync polarity bits (bits 7 & 6) of the
      Miscellaneous Output register (readable at 0x3CC, writable at
      0x3C2) to select the 400-scan-line vertical scanning rate */
   outp(0x3C2, ((inp(0x3CC) & 0x3F) | 0x40));

   /* Now, tweak the registers needed to convert the vertical
      timings from 350 to 400 scan lines */
   outpw(0x3D4, 0x9C10);   /* adjust the Vertical Sync Start register
                              for 400 scan lines */
   outpw(0x3D4, 0x8E11);   /* adjust the Vertical Sync End register
                              for 400 scan lines */
   outpw(0x3D4, 0x8F12);   /* adjust the Vertical Display End
                              register for 400 scan lines */
   outpw(0x3D4, 0x9615);   /* adjust the Vertical Blank Start
                              register for 400 scan lines */
   outpw(0x3D4, 0xB916);   /* adjust the Vertical Blank End register
                              for 400 scan lines */
}
```

In 640×400, 16-color mode, page 0 runs from offset 0 to offset 31,999 (7CFFH), and page 1 runs from offset 32,000 (7D00H) to 63,999 (0F9FFH). Page 1 is selected by programming the Start Address registers (CRTC registers 0CH, the high 8 bits, and 0DH, the low 8 bits) to 7D00H. Actually, because the low byte of the start address is 0 for both pages, you can page flip simply by writing 0 or 7DH to the Start Address High register (CRTC register 0CH); this has the benefit of eliminating a nasty class of potential synchronization bugs that can arise when both registers must be set. Listing 30.3 illustrates simple 640×400 page flipping.

LISTING 30.3 L30-3.C

```
/* Sample program to exercise VGA 640x400 16-color mode page flipping, by
   drawing a horizontal line at the top of page 0 and another at bottom of page 1,
   then flipping between them once every 30 frames. Tested with Borland C++,
   in C compilation mode. */

#include <dos.h>
#include <conio.h>

#define SCREEN_SEGMENT  0xA000
#define SCREEN_HEIGHT   400
#define SCREEN_WIDTH_IN_BYTES 80
#define INPUT_STATUS_1  0x3DA /* color-mode address of Input Status 1
                                 register */
/* The page start addresses must be even multiples of 256, because page
   flipping is performed by changing only the upper start address byte */
#define PAGE_0_START 0
#define PAGE_1_START (400*SCREEN_WIDTH_IN_BYTES)
```

```
void main(void);
void Wait30Frames(void);
extern void Set640x400(void);

void main()
{
   int i;
   unsigned int far *ScreenPtr;
   union REGS regset;

   Set640x400();  /* set to 640x400 16-color mode */

   /* Point to first line of page 0 and draw a horizontal line across screen */
   FP_SEG(ScreenPtr) = SCREEN_SEGMENT;
   FP_OFF(ScreenPtr) = PAGE_0_START;
   for (i=0; i<(SCREEN_WIDTH_IN_BYTES/2); i++) *ScreenPtr++ = 0xFFFF;

   /* Point to last line of page 1 and draw a horizontal line across screen */
   FP_OFF(ScreenPtr) =
         PAGE_1_START + ((SCREEN_HEIGHT-1)*SCREEN_WIDTH_IN_BYTES);
   for (i=0; i<(SCREEN_WIDTH_IN_BYTES/2); i++) *ScreenPtr++ = 0xFFFF;

   /* Now flip pages once every 30 frames until a key is pressed */
   do {
      Wait30Frames();

      /* Flip to page 1 */
      outpw(0x3D4, 0x0C | ((PAGE_1_START >> 8) << 8));

      Wait30Frames();

      /* Flip to page 0 */
      outpw(0x3D4, 0x0C | ((PAGE_0_START >> 8) << 8));
   } while (kbhit() == 0);

   getch(); /* clear the key press */

   /* Return to text mode and exit */
   regset.x.ax = 0x0003;   /* AL = 3 selects 80x25 text mode */
   int86(0x10, &regset, &regset);
}

void Wait30Frames()
{
   int i;

   for (i=0; i<30; i++) {
      /* Wait until we're not in vertical sync, so we can catch leading edge */
      while ((inp(INPUT_STATUS_1) & 0x08) != 0) ;
      /* Wait until we are in vertical sync */
      while ((inp(INPUT_STATUS_1) & 0x08) == 0) ;
   }
}
```

After I described 640×400 mode in a magazine article, Bill Lindley, of Mesa, Arizona, wrote me to suggest that when programming the VGA to a nonstandard mode of this sort, it's a good idea to tell the BIOS about the new screen size, for a couple of reasons. For one thing, pop-up utilities often use the BIOS variables; Bill's memory-resident screen printer, EGAD Screen Print, determines the number of scan lines to print by multiplying the BIOS "number of text rows" variable times the "character height" variable. For another, the BIOS itself may do a poor job of displaying text if not given proper information; the active text area may not match the screen dimensions, or an inappropriate graphics font may be used. (Of course, the BIOS isn't going to be able to display text anyway in highly nonstandard modes such as Mode X, but it will do fine in slightly nonstandard modes such as 640×400 16-color mode.) In the case of the 640×400 16-color model described a little earlier, Bill suggests that the code in Listing 30.4 be called immediately after putting the VGA into that mode to tell the BIOS that we're working with 25 rows of 16-pixel-high text. I think this is an excellent suggestion; it can't hurt, and may save you from getting aggravating tech support calls down the road.

LISTING 30.4 L30-4.C

```
/* Function to tell the BIOS to set up properly sized characters for 25 rows of
   16 pixel high text in 640x400 graphics mode. Call immediately after mode set.
   Based on a contribution by Bill Lindley. */

#include <dos.h>

void Set640x400()
{
   union REGS regs;

   regs.h.ah = 0x11;            /* character generator function */
   regs.h.al = 0x24;            /* use ROM 8x16 character set for graphics */
   regs.h.bl = 2;               /* 25 rows */
   int86(0x10, &regs, &regs);   /* invoke the BIOS video interrupt
                                   to set up the text */
}
```

The 640×400 mode I've described here isn't exactly earthshaking, but it can come in handy for page flipping and CGA emulation, and I'm sure that some of you will find it useful at one time or another.

Another Interesting Twist on Page Flipping

I've spent a fair amount of time exploring various ways to do animation. I thought I had pegged all the possible ways to do animation: exclusive-ORing; simply drawing and erasing objects; drawing objects with a blank fringe to erase them at their old locations as they're drawn; page flipping; and, finally, drawing to local memory and copying the dirty (modified) rectangles to the screen, as I've discussed in this chapter.

To my surprise, someone threw me an interesting and useful twist on animation not long ago, which turned out to be a cross between page flipping and dirty-rectangle animation. That someone was Serge Mathieu of Concepteva Inc., in Rosemere, Quebec, who informed me that he designs everything "from a game *point de vue.*"

In normal page flipping, you display one page while you update the other page. Then you display the new page while you update the other. This works fine, but the need to keep two pages current can make for a lot of bookkeeping and possibly extra drawing, especially in applications where only some of the objects are redrawn each time.

Serge didn't care to do all that bookkeeping in his animation applications, so he came up with the following approach, which I've reworded, amplified, and slightly modified in the summary here:

1. Set the start address to display page 0.
2. Draw to page 1.
3. Set the start address to display page 1 (the newly drawn page), then wait for the leading edge of vertical sync, at which point the page has flipped and it's safe to modify page 0.
4. Copy, via the latches, from page 1 to page 0 the areas that changed from the previous screen to the current one.
5. Set the start address to display page 0, which is now identical to page 1, then wait for the leading edge of vertical sync, at which point the page has flipped and it's safe to modify page 1.
6. Go to step 2.

The great benefit of Serge's approach is that the only page that is ever actually drawn to (as opposed to being block-copied to) is page 1. Only one page needs to be maintained, and the complications of maintaining two separate pages vanish entirely. The performance of Serge's approach may be better or worse than standard page flipping, depending on whether a lot of extra work is required to maintain two pages or not. My guess is that Serge's approach will usually be slower, owing to the considerable amount of display-memory copying involved, and also to the double page-flip per frame. There's no doubt, however, that Serge's approach is simpler, and the resultant display quality is every bit as good as standard page flipping. Given page flipping's fair degree of complication, this approach is a valuable tool, especially for less-experienced animation programmers.

An interesting variation on Serge's approach doesn't page flip nor wait for vertical sync:

1. Set the start address to display page 0.
2. Draw to page 1.
3. Copy, via the latches, the areas that changed from the last screen to the current one from page 1 to page 0.
4. Go to step 2.

This approach totally eliminates page flipping, which can consume a great deal of time. The downside is that images may shear for one frame if they're only partially copied when the raster beam reaches them. This approach is basically a standard dirty-rectangle approach, except that the drawing buffer is stored in display memory, rather than in system memory. Whether this technique is faster than drawing to system memory depends on whether the benefit you get from the VGA's hardware, such as the Bit Mask, the ALUs, and especially the latches (for copying the dirty rectangles) is sufficient to outweigh the extra display-memory accesses involved in drawing and copying, since display memory is notoriously slow.

Finally, I'd like to point out that in any scheme that involves changing the display-memory start address, a clever trick can potentially reduce the time spent waiting for pages to flip. Normally, it's necessary to wait for display enable to be active, then set the two start address registers, and finally wait for vertical sync to be active, so that you know the new start address has taken effect. The start-address registers must never be set around the time vertical sync is active (the new start address is accepted at either the start or end of vertical sync on the EGAs and VGAs I'm familiar with), because it would then be possible to load a half-changed start address (one register loaded, the other not yet loaded), and the screen would jump for a frame. Avoiding this condition is the motivation for waiting for display enable, because display enable is active only when vertical sync is not active and will not become active for a long while.

Suppose, however, that you arrange your page start addresses so that they both have a low-byte value of 0 (page 0 starts at 0000H, and page 1 starts at 8000H, for example). Page flipping can then be done simply by setting the new high byte of the start address, then waiting for the leading edge of vertical sync. This eliminates the need to wait for display enable (the two bytes of the start address can never be mismatched); page flipping will often involve less waiting, because display enable becomes inactive long before vertical sync becomes active. Using the above approach reclaims all the time between the end of display enable and the start of vertical sync for doing useful work. (The steps I've given for Serge's animation approach assume that the single-byte approach is in use; that's why display enable is never waited for.)

In the next chapter, I'll return to the original dirty-rectangle algorithm presented in this chapter, and goose it a little with some assembly, so that we can see what dirty rectangle animation is really made of. (Probably not dog hair...)

Who Was that Masked Image?

Chapter 31

Optimizing Dirty-Rectangle Animation

Programming is, by and large, a linear process. One statement or instruction follows another, in predictable sequences, with tiny building blocks strung together to make a custom state machine. As programmers, we grow adept at this sort of idealized linear thinking, which is, of course, A Good Thing. Still, it's important to keep in mind that there's a large chunk of the human mind that doesn't work in a linear fashion.

I've written elsewhere about the virtues of nonlinear/right-brain/lateral/what-have-you thinking in solving tough programming problems, such as debugging or optimization, but it bears repeating. The mind can be an awesome pattern-matching and extrapolation tool, if you let it. For example, the other day I was grinding my way through a particularly difficult bit of debugging. The code had been written by someone else, and, to my mind, there's nothing worse than debugging someone else's code; there's always the nasty feeling that you don't quite know what's going on. The overall operation of this code wouldn't come clear in my head, no matter how long I stared at it, leaving me with a rising sense of frustration and a determination not to quit until I got this bug.

In the midst of this, a coworker poked his head through the door and told me he had something I had to listen to. Reluctantly, I went to his office, whereupon he played a tape of what is surely one of the most bizarre 911 calls in history. No doubt some of you have heard this tape, which I will briefly describe as involving a deer destroying the interior of a car and biting a man in the neck. Perhaps you found it funny, perhaps not—but as for me, it hit me exactly right. I started laughing helplessly, tears rolling down my face. When I went back to work—presto!—the pieces of the debugging puzzle had come together in my head, and the work went quickly and easily.

Obviously, my mind needed a break from linear, left-brain, push-it-out thinking, so it could do the sort of integrating work it does so well—but that it's rarely willing to do under conscious control. It was exactly this sort of thinking I had in mind when I titled my 1989 optimization book *Zen of Assembly Language.* (Although I must admit that few people seem to have gotten the connection, and I've had to field a lot of questions about whether I'm a Zen disciple. I'm not—actually, I'm more of a Dave Barry disciple. If you don't know who Dave Barry is, you should; he's good for your right brain.) Give your mind a break once in a while, and I'll bet you'll find you're more productive.

We're strange thinking machines, but we're the best ones yet invented, and it's worth learning how to tap our full potential. And with that, it's back to dirty-rectangle animation.

Dirty-Rectangle Animation, Continued

In the last chapter, I introduced the idea of dirty-rectangle animation. This technique is an alternative to page flipping that's capable of producing animation of very high visual quality, without any help at all from video hardware, and without the need for any extra, nondisplayed video memory. This makes dirty-rectangle animation more widely usable than page flipping, because many adapters don't support page flipping. Dirty-rectangle animation also tends to be simpler to implement than page flipping, because there's only one bitmap to keep track of. A final advantage of dirty-rectangle animation is that it's potentially somewhat faster than page flipping, because display-memory accesses can theoretically be reduced to exactly one access for each pixel that changes from one frame to the next.

The speed advantage of dirty-rectangle animation was entirely theoretical in the previous chapter, because the implementation was completely in C, and because no attempt was made to minimize display memory accesses. The visual quality of Chapter 30's animation was also less than ideal, for reasons we'll explore shortly. The code in Listings 31.1 and 31.2 addresses the shortcomings of Chapter 30's code.

Listing 31.2 implements the low-level drawing routines in assembly language, which boosts performance a good deal. For maximum performance, it would be worthwhile to convert more of Listing 31.1 into assembly, so a call isn't required for each animated image, and overall performance could be improved by streamlining the C code, but Listing 31.2 goes a long way toward boosting animation speed. This program now supports snappy animation of 15 images (as opposed to 10 for the software presented in the last chapter), and the images are now two pixels wider. That level of performance is all the more impressive considering that for this chapter I've converted the code from using rectangular images to using masked images.

LISTING 31.1 L31-1.C

```
/* Sample simple dirty-rectangle animation program, partially optimized and
   featuring internal animation, masked images (sprites), and nonoverlapping dirty
   rectangle copying. Tested with Borland C++ in the small model. */

#include <stdlib.h>
#include <conio.h>
```

```
#include <alloc.h>
#include <memory.h>
#include <dos.h>

/* Comment out to disable overlap elimination in the dirty rectangle list. */
#define CHECK_OVERLAP 1
#define SCREEN_WIDTH  320
#define SCREEN_HEIGHT 200
#define SCREEN_SEGMENT 0xA000

/* Describes a dirty rectangle */
typedef struct {
   void *Next;    /* pointer to next node in linked dirty rect list */
   int Top;
   int Left;
   int Right;
   int Bottom;
} DirtyRectangle;
/* Describes an animated object */
typedef struct {
   int X;           /* upper left corner in virtual bitmap */
   int Y;
   int XDirection;  /* direction and distance of movement */
   int YDirection;
   int InternalAnimateCount; /* tracking internal animation state */
   int InternalAnimateMax;   /* maximum internal animation state */
} Entity;
/* storage used for dirty rectangles */
#define MAX_DIRTY_RECTANGLES  100
int NumDirtyRectangles;
DirtyRectangle DirtyRectangles[MAX_DIRTY_RECTANGLES];
/* head/tail of dirty rectangle list */
DirtyRectangle DirtyHead;
/* If set to 1, ignore dirty rectangle list and copy the whole screen. */
int DrawWholeScreen = 0;
/* pixels and masks for the two internally animated versions of the image
   we'll animate */
#define IMAGE_WIDTH  13
#define IMAGE_HEIGHT 11
char ImagePixels0[] = {
   0, 0, 0, 9, 9, 9, 9, 9, 0, 0, 0, 0, 0,
   0, 0, 9, 9, 9, 9, 9, 9, 9, 0, 0, 0, 0,
   0, 9, 9, 0, 0,14,14,14, 9, 9, 0, 0, 0,
   9, 9, 0, 0, 0, 0,14,14,14, 9, 9, 0, 0,
   9, 9, 0, 0, 0, 0,14,14,14, 9, 9, 0, 0,
   9, 9,14, 0, 0,14,14,14,14, 9, 9, 0, 0,
   9, 9,14,14,14,14,14,14,14, 9, 9, 0, 0,
   9, 9,14,14,14,14,14,14,14, 9, 9, 0, 0,
   0, 9, 9,14,14,14,14,14, 9, 9, 0, 0, 0,
   0, 0, 9, 9, 9, 9, 9, 9, 9, 0, 0, 0, 0,
   0, 0, 0, 9, 9, 9, 9, 9, 0, 0, 0, 0, 0,
};
char ImageMask0[] = {
   0, 0, 0, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0,
   0, 0, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0,
   0, 1, 1, 0, 0, 1, 1, 1, 1, 1, 0, 0, 0,
   1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 0, 0,
   1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 0, 0,
   1, 1, 1, 0, 0, 1, 1, 1, 1, 1, 1, 0, 0,
   1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0,
   1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0,
   0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0,
   0, 0, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0,
   0, 0, 0, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0,
};
char ImagePixels1[] = {
   0, 0, 0, 9, 9, 9, 9, 9, 0, 0, 0, 0, 9,
   0, 0, 9, 9, 9, 9, 9, 9, 9, 0, 9, 9, 9,
   0, 9, 9, 0, 0,14,14,14, 9, 9, 9, 9, 0,
   9, 9, 0, 0, 0, 0,14,14,14, 0, 0, 0, 0,
   9, 9, 0, 0, 0, 0,14,14, 0, 0, 0, 0, 0,
   9, 9,14, 0, 0,14,14,14, 0, 0, 0, 0, 0,
   9, 9,14,14,14,14,14,14, 0, 0, 0, 0, 0,
   9, 9,14,14,14,14,14,14,14, 0, 0, 0, 0,
   0, 9, 9,14,14,14,14,14, 9, 9, 9, 9, 0,
   0, 0, 9, 9, 9, 9, 9, 9, 9, 0, 9, 9, 9,
   0, 0, 0, 9, 9, 9, 9, 9, 0, 0, 0, 9, 9,
};
char ImageMask1[] = {
   0, 0, 0, 1, 1, 1, 1, 1, 0, 0, 0, 0, 1,
   0, 0, 1, 1, 1, 1, 1, 1, 1, 0, 1, 1, 1,
   0, 1, 1, 0, 0, 1, 1, 1, 1, 1, 1, 1, 0,
   1, 1, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 0,
   1, 1, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0,
   1, 1, 1, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0,
   1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0,
   1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0,
   0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0,
   0, 0, 1, 1, 1, 1, 1, 1, 1, 0, 1, 1, 1,
   0, 0, 0, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1,
};
/* Pointers to pixel and mask data for various internally animated
   versions of our animated image. */
char * ImagePixelArray[] = {ImagePixels0, ImagePixels1};
char * ImageMaskArray[] = {ImageMask0, ImageMask1};
/* Animated entities */
#define NUM_ENTITIES 15
Entity Entities[NUM_ENTITIES];
/* pointer to system buffer into which we'll draw */
char far *SystemBufferPtr;
/* pointer to screen */
char far *ScreenPtr;
void EraseEntities(void);
void CopyDirtyRectanglesToScreen(void);
void DrawEntities(void);
void AddDirtyRect(Entity *, int, int);
void DrawMasked(char far *, char *, char *, int, int, int);
void FillRect(char far *, int, int, int, int);
void CopyRect(char far *, char far *, int, int, int, int);

void main()
{
   int i, XTemp, YTemp;
   unsigned int TempCount;
   char far *TempPtr;
   union REGS regs;
   /* Allocate memory for the system buffer into which we'll draw */
   if (!(SystemBufferPtr = farmalloc((unsigned int)SCREEN_WIDTH*
         SCREEN_HEIGHT))) {
      printf("Couldn't get memory\n");
      exit(1);
   }
   /* Clear the system buffer */
   TempPtr = SystemBufferPtr;
   for (TempCount = ((unsigned)SCREEN_WIDTH*SCREEN_HEIGHT); TempCount--; ) {
      *TempPtr++ = 0;
   }
   /* Point to the screen */
   ScreenPtr = MK_FP(SCREEN_SEGMENT, 0);
   /* Set up the entities we'll animate, at random locations */
   randomize();
   for (i = 0; i < NUM_ENTITIES; i++) {
      Entities[i].X = random(SCREEN_WIDTH - IMAGE_WIDTH);
      Entities[i].Y = random(SCREEN_HEIGHT - IMAGE_HEIGHT);
      Entities[i].XDirection = 1;
      Entities[i].YDirection = -1;
      Entities[i].InternalAnimateCount = i & 1;
      Entities[i].InternalAnimateMax = 2;
   }
   /* Set the dirty rectangle list to empty, and set up the head/tail node
      as a sentinel */
   NumDirtyRectangles = 0;
   DirtyHead.Next = &DirtyHead;
   DirtyHead.Top = 0x7FFF;
   DirtyHead.Left= 0x7FFF;
   DirtyHead.Bottom = 0x7FFF;
   DirtyHead.Right = 0x7FFF;
   /* Set 320x200 256-color graphics mode */
   regs.x.ax = 0x0013;
   int86(0x10, &regs, &regs);
   /* Loop and draw until a key is pressed */
   do {
      /* Draw the entities to the system buffer at their current locations,
         updating the dirty rectangle list */
      DrawEntities();
      /* Draw the dirty rectangles, or the whole system buffer if
         appropriate */
      CopyDirtyRectanglesToScreen();
      /* Reset the dirty rectangle list to empty */
      NumDirtyRectangles = 0;
      DirtyHead.Next = &DirtyHead;
      /* Erase the entities in the system buffer at their old locations,
         updating the dirty rectangle list */
      EraseEntities();
      /* Move the entities, bouncing off the edges of the screen */
      for (i = 0; i < NUM_ENTITIES; i++) {
         XTemp = Entities[i].X + Entities[i].XDirection;
         YTemp = Entities[i].Y + Entities[i].YDirection;
         if ((XTemp < 0) || ((XTemp + IMAGE_WIDTH) > SCREEN_WIDTH)) {
            Entities[i].XDirection = -Entities[i].XDirection;
            XTemp = Entities[i].X + Entities[i].XDirection;
         }
         if ((YTemp < 0) || ((YTemp + IMAGE_HEIGHT) > SCREEN_HEIGHT)) {
            Entities[i].YDirection = -Entities[i].YDirection;
            YTemp = Entities[i].Y + Entities[i].YDirection;
         }
         Entities[i].X = XTemp;
         Entities[i].Y = YTemp;
      }
   } while (!kbhit());
   getch();    /* clear the keypress */

   /* Return back to text mode */
   regs.x.ax = 0x0003;
   int86(0x10, &regs, &regs);
}
```

```
/* Draw entities at their current locations, updating dirty rectangle list. */
void DrawEntities()
{
   int i;
   char far *RowPtrBuffer;
   char *TempPtrImage;
   char *TempPtrMask;
   Entity *EntityPtr;

   for (i = 0, EntityPtr = Entities; i < NUM_ENTITIES; i++, EntityPtr++) {
      /* Remember the dirty rectangle info for this entity */
      AddDirtyRect(EntityPtr, IMAGE_HEIGHT, IMAGE_WIDTH);
      /* Point to the destination in the system buffer */
      RowPtrBuffer = SystemBufferPtr + (EntityPtr->Y * SCREEN_WIDTH) +
            EntityPtr->X;
      /* Advance the image animation pointer */
      if (++EntityPtr->InternalAnimateCount >=
            EntityPtr->InternalAnimateMax) {
         EntityPtr->InternalAnimateCount = 0;
      }
      /* Point to the image and mask to draw */
      TempPtrImage = ImagePixelArray[EntityPtr->InternalAnimateCount];
      TempPtrMask = ImageMaskArray[EntityPtr->InternalAnimateCount];
      DrawMasked(RowPtrBuffer, TempPtrImage, TempPtrMask, IMAGE_HEIGHT,
               IMAGE_WIDTH, SCREEN_WIDTH);
   }
}
/* Copy the dirty rectangles, or the whole system buffer if appropriate,
   to the screen. */
void CopyDirtyRectanglesToScreen()
{
   int i, RectWidth, RectHeight;
   unsigned int Offset;
   DirtyRectangle * DirtyPtr;
   if (DrawWholeScreen) {
      /* Just copy the whole buffer to the screen */
      DrawWholeScreen = 0;
      CopyRect(ScreenPtr, SystemBufferPtr, SCREEN_HEIGHT, SCREEN_WIDTH,
               SCREEN_WIDTH, SCREEN_WIDTH);
   } else {
      /* Copy only the dirty rectangles, in the YX-sorted order in which
         they're linked */
      DirtyPtr = DirtyHead.Next;
      for (i = 0; i < NumDirtyRectangles; i++) {
         /* Offset in both system buffer and screen of image */
         Offset = (unsigned int) (DirtyPtr->Top * SCREEN_WIDTH) +
               DirtyPtr->Left;
         /* Dimensions of dirty rectangle */
         RectWidth = DirtyPtr->Right - DirtyPtr->Left;
         RectHeight = DirtyPtr->Bottom - DirtyPtr->Top;
         /* Copy a dirty rectangle */
         CopyRect(ScreenPtr + Offset, SystemBufferPtr + Offset,
               RectHeight, RectWidth, SCREEN_WIDTH, SCREEN_WIDTH);
         /* Point to the next dirty rectangle */
         DirtyPtr = DirtyPtr->Next;
      }
   }
}
/* Erase the entities in the system buffer at their current locations,
   updating the dirty rectangle list. */
void EraseEntities()
```

```
{
   int i;
   char far *RowPtr;

   for (i = 0; i < NUM_ENTITIES; i++) {
      /* Remember the dirty rectangle info for this entity */
      AddDirtyRect(&Entities[i], IMAGE_HEIGHT, IMAGE_WIDTH);
      /* Point to the destination in the system buffer */
      RowPtr = SystemBufferPtr + (Entities[i].Y * SCREEN_WIDTH) +
            Entities[i].X;
      /* Clear the rectangle */
      FillRect(RowPtr, IMAGE_HEIGHT, IMAGE_WIDTH, SCREEN_WIDTH, 0);
   }
}
/* Add a dirty rectangle to the list. The list is maintained in top-to-bottom,
   left-to-right (YX sorted) order, with no pixel ever included twice, to minimize
   the number of display memory accesses and to avoid screen artifacts resulting
   from a large time interval between erasure and redraw for a given object or for
   adjacent objects. The technique used is to check for overlap between the
   rectangle and all rectangles already in the list. If no overlap is found, the
   rectangle is added to the list. If overlap is found, the rectangle is broken
   into nonoverlapping pieces, and the pieces are added to the list by recursive
   calls to this function. */
   void AddDirtyRect(Entity * pEntity, int ImageHeight, int ImageWidth)
{
   DirtyRectangle * DirtyPtr;
   DirtyRectangle * TempPtr;
   Entity TempEntity;
   int i;
   if (NumDirtyRectangles >= MAX_DIRTY_RECTANGLES) {
      /* Too many dirty rectangles; just redraw the whole screen */
      DrawWholeScreen = 1;
      return;
   }
   /* Remember this dirty rectangle. Break up if necessary to avoid
      overlap with rectangles already in the list, then add whatever
      rectangles are left, in YX sorted order */
#ifdef CHECK_OVERLAP
   /* Check for overlap with existing rectangles */
   TempPtr = DirtyHead.Next;
   for (i = 0; i < NumDirtyRectangles; i++, TempPtr = TempPtr->Next) {
      if ((TempPtr->Left < (pEntity->X + ImageWidth)) &&
         (TempPtr->Right > pEntity->X) &&
         (TempPtr->Top < (pEntity->Y + ImageHeight)) &&
          (TempPtr->Bottom > pEntity->Y)) {

         /* We've found an overlapping rectangle. Calculate the
            rectangles, if any, remaining after subtracting out the
            overlapped areas, and add them to the dirty list */
         /* Check for a nonoverlapped left portion */
         if (TempPtr->Left > pEntity->X) {
            /* There's definitely a nonoverlapped portion at the left; add
               it, but only to at most the top and bottom of the overlapping
               rect; top and bottom strips are taken care of below */
            TempEntity.X = pEntity->X;
            TempEntity.Y = max(pEntity->Y, TempPtr->Top);
            AddDirtyRect(&TempEntity,
                  min(pEntity->Y + ImageHeight, TempPtr->Bottom) -
                  TempEntity.Y,
                        TempPtr->Left - pEntity->X);
         }
         /* Check for a nonoverlapped right portion */
         if (TempPtr->Right < (pEntity->X + ImageWidth)) {
            /* There's definitely a nonoverlapped portion at the right; add
               it, but only to at most the top and bottom of the overlapping
               rect; top and bottom strips are taken care of below */
            TempEntity.X = TempPtr->Right;
            TempEntity.Y = max(pEntity->Y, TempPtr->Top);
            AddDirtyRect(&TempEntity,
                  min(pEntity->Y + ImageHeight, TempPtr->Bottom) -
                  TempEntity.Y,
                  (pEntity->X + ImageWidth) - TempPtr->Right);
         }
         /* Check for a nonoverlapped top portion */
         if (TempPtr->Top > pEntity->Y) {
            /* There's a top portion that's not overlapped */
            TempEntity.X = pEntity->X;
            TempEntity.Y = pEntity->Y;
            AddDirtyRect(&TempEntity, TempPtr->Top - pEntity->Y, ImageWidth);
         }
         /* Check for a nonoverlapped bottom portion */
         if (TempPtr->Bottom < (pEntity->Y + ImageHeight)) {
            /* There's a bottom portion that's not overlapped */
            TempEntity.X = pEntity->X;
            TempEntity.Y = TempPtr->Bottom;
            AddDirtyRect(&TempEntity,
                  (pEntity->Y + ImageHeight) - TempPtr->Bottom, ImageWidth);
         }
         /* We've added all non-overlapped portions to the dirty list */
         return;
      }
   }
#endif /* CHECK_OVERLAP */
   /* There's no overlap with any existing rectangle, so we can just
      add this rectangle as-is */
   /* Find the YX-sorted insertion point. Searches will always terminate,
      because the head/tail rectangle is set to the maximum values */
   TempPtr = &DirtyHead;
   while (((DirtyRectangle *)TempPtr->Next)->Top < pEntity->Y) {
      TempPtr = TempPtr->Next;
   }
   while ((((DirtyRectangle *)TempPtr->Next)->Top == pEntity->Y) &&
           (((DirtyRectangle *)TempPtr->Next)->Left < pEntity->X)) {
      TempPtr = TempPtr->Next;
   }
   /* Set the rectangle and actually add it to the dirty list */
   DirtyPtr = &DirtyRectangles[NumDirtyRectangles++];
   DirtyPtr->Left = pEntity->X;
   DirtyPtr->Top = pEntity->Y;
   DirtyPtr->Right = pEntity->X + ImageWidth;
   DirtyPtr->Bottom = pEntity->Y + ImageHeight;
   DirtyPtr->Next = TempPtr->Next;
   TempPtr->Next = DirtyPtr;
}
```

LISTING 31.2 L31-2.ASM

```
; Assembly language helper routines for dirty rectangle animation. Tested with
; TASM.
; Fills a rectangle in the specified buffer.
; C-callable as:
;  void FillRect(char far * BufferPtr, int RectHeight, int RectWidth,
;                   int BufferWidth, int Color);
;
        .model  small
        .code
parms   struc
                dw      ?       ;pushed BP
                dw      ?       ;pushed return address
BufferPtr       dd      ?       ;far pointer to buffer in which to fill
RectHeight      dw      ?       ;height of rectangle to fill
RectWidth       dw      ?       ;width of rectangle to fill
BufferWidth     dw      ?       ;width of buffer in which to fill
Color           dw      ?       ;color with which to fill
parms   ends
        public  _FillRect
_FillRect        proc    near
        cld
        push    bp
        mov     bp,sp
        push    di

        les     di,[bp+BufferPtr]
        mov     dx,[bp+RectHeight]
        mov     bx,[bp+BufferWidth]
        sub     bx,[bp+RectWidth]       ;distance from end of one dest scan
                                        ; to start of next
        mov     al,byte ptr [bp+Color]
        mov     ah,al                   ;double the color for REP STOSW
RowLoop:
        mov     cx,[bp+RectWidth]
        shr     cx,1
        rep     stosw
        adc     cx,cx
        rep     stosb
        add     di,bx                   ;point to next scan to fill
        dec     dx                      ;count down rows to fill
        jnz     RowLoop

        pop     di
        pop     bp
        ret
_FillRect   endp

; Draws a masked image (a sprite) to the specified buffer. C-callable as:
;     void DrawMasked(char far * BufferPtr, char * Pixels, char * Mask,
;                   int ImageHeight, int ImageWidth, int BufferWidth);
parms2  struc
                dw      ?       ;pushed BP
                dw      ?       ;pushed return address
BufferPtr2      dd      ?       ;far pointer to buffer in which to draw
Pixels          dw      ?       ;pointer to image pixels
Mask            dw      ?       ;pointer to image mask
ImageHeight     dw      ?       ;height of image to draw
ImageWidth      dw      ?       ;width of image to draw
BufferWidth2    dw      ?       ;width of buffer in which to draw
parms2  ends
        public  _DrawMasked
_DrawMasked     proc    near
        cld
        push    bp
        mov     bp,sp
        push    si
        push    di
        les     di,[bp+BufferPtr2]
        mov     si,[bp+Mask]
        mov     bx,[bp+Pixels]
        mov     dx,[bp+ImageHeight]
        mov     ax,[bp+BufferWidth2]
        sub     ax,[bp+ImageWidth]      ;distance from end of one dest scan
        mov     [bp+BufferWidth2],ax    ; to start of next
RowLoop2:
        mov     cx,[bp+ImageWidth]
ColumnLoop:
        lodsb                           ;get the next mask byte
        and     al,al                   ;draw this pixel?
        jz      SkipPixel               ;no
        mov     al,[bx]                 ;yes, draw the pixel
        mov     es:[di],al
SkipPixel:
        inc     bx                      ;point to next source pixel
        inc     di                      ;point to next dest pixel
        dec     cx
        jnz     ColumnLoop
        add     di,[bp+BufferWidth2]    ;point to next scan to fill
        dec     dx                      ;count down rows to fill
        jnz     RowLoop2

        pop     di
        pop     si
        pop     bp
        ret
_DrawMasked     endp

; Copies a rectangle from one buffer to another. C-callable as:
;     void CopyRect(DestBufferPtr, SrcBufferPtr, CopyHeight, CopyWidth,
;                   DestBufferWidth, SrcBufferWidth);

parms3  struc
                dw      ?       ;pushed BP
                dw      ?       ;pushed return address
DestBufferPtr   dd      ?       ;far pointer to buffer to which to copy
SrcBufferPtr    dd      ?       ;far pointer to buffer from which to copy
CopyHeight      dw      ?       ;height of rect to copy
CopyWidth       dw      ?       ;width of rect to copy
DestBufferWidth dw      ?       ;width of buffer to which to copy
SrcBufferWidth  dw      ?       ;width of buffer from which to copy
parms3  ends
        public  _CopyRect
_CopyRect       proc    near
        cld
        push    bp
        mov     bp,sp
        push    si
        push    di
        push    ds

        les     di,[bp+DestBufferPtr]
        lds     si,[bp+SrcBufferPtr]
        mov     dx,[bp+CopyHeight]
        mov     bx,[bp+DestBufferWidth] ;distance from end of one dest scan
        sub     bx,[bp+CopyWidth]       ; of copy to the next
        mov     ax,[bp+SrcBufferWidth]  ;distance from end of one source scan
        sub     ax,[bp+CopyWidth]       ; of copy to the next
```

```
RowLoop3:
        mov     cx,[bp+CopyWidth]       ;# of bytes to copy
        shr     cx,1
        rep     movsw                   ;copy as many words as possible
        adc     cx,cx
        rep     movsb                   ;copy odd byte, if any
        add     si,ax                   ;point to next source scan line
        add     di,bx                   ;point to next dest scan line
        dec     dx                      ;count down rows to fill
        jnz     RowLoop3

        pop     ds
        pop     di
        pop     si
        pop     bp
        ret
_CopyRect       endp
        end
```

Masked Images

Masked images are rendered by drawing an object's pixels through a mask; pixels are actually drawn only where the mask specifies that drawing is allowed. This makes it possible to draw nonrectangular objects that don't improperly interfere with one another when they overlap. Masked images also make it possible to have transparent areas (windows) within objects. Masked images produce far more realistic animation than do rectangular images, and therefore are more desirable. Unfortunately, masked images are also considerably slower to draw—however, a good assembly language implementation can go a long way toward making masked images draw rapidly enough, as illustrated by this chapter's code. (Masked images are also known as *sprites*; some video hardware supports sprites directly, but on the PC it's necessary to handle sprites in software.)

Masked images make it possible to render scenes so that a given image convincingly appears to be in front of or behind other images; that is, so images are displayed in *z-order* (by distance). By consistently drawing images that are supposed to be farther away before drawing nearer images, the nearer images will appear in front of the other images, and because masked images draw only precisely the correct pixels (as opposed to blank pixels in the bounding rectangle), there's no interference between overlapping images to destroy the illusion.

In this chapter, I've used the approach of having separate, paired masks and images. Another, quite different approach to masking is to specify a transparent color for copying, and copy only those pixels that are not the transparent color. This has the advantage of not requiring separate mask data, so it's more compact, and the code to implement this is a little less complex than the full masking I've implemented. On the other hand, the transparent color approach is less flexible because it makes one color undrawable. Also, with a transparent color, it's not possible to keep the same base image but use different masks, because the mask information is embedded in the image data.

Internal Animation

I've added another feature essential to producing convincing animation: *internal animation*, which is the process of changing the appearance of a given object over time, as distinguished from changing only the *location* of a given object. Internal animation makes images look active and alive. I've implemented the simplest possible form of internal animation in Listing 31.1—alternation between two images—but even this level of internal animation greatly improves the feel of the overall animation. You could easily increase the number of images cycled through, simply by increasing the value of **InternalAnimateMax** for a given entity. You could also implement more complex image-selection logic to produce more interesting and less predictable internal-animation effects, such as jumping, ducking, running, and the like.

Dirty-Rectangle Management

As mentioned above, dirty-rectangle animation makes it possible to access display memory a minimum number of times. The previous chapter's code didn't do any of that; instead, it copied all portions of every dirty rectangle to the screen, regardless of overlap between rectangles. The code I've presented in this chapter goes to the other extreme, taking great pains never to draw overlapped portions of rectangles more than once. This is accomplished by checking for overlap whenever a rectangle is to be added to the dirty list. When overlap with an existing rectangle is detected, the new rectangle is reduced to between zero and four nonoverlapping rectangles. Those rectangles are then again considered for addition to the dirty list, and may again be reduced, if additional overlap is detected.

A good deal of code is required to generate a fully nonoverlapped dirty list. Is it worth it? It certainly can be, but in the case of Listing 31.1, probably not. For one thing, you'd need larger, heavily overlapped objects for this approach to pay off big. Besides, this program is mostly in C, and spends a lot of time doing things other than actually accessing display memory. It also takes a fair amount of time just to generate the nonoverlapped list; the overhead of all the looping, intersecting, and calling required to generate the list eats up a lot of the benefits of accessing display memory less often. Nonetheless, fully nonoverlapped drawing can be useful under the right circumstances, and I've implemented it in Listing 31.1 so you'll have something to refer to should you decide to go this route.

There are a couple of additional techniques you might try if you want to wring maximum performance out of dirty-rectangle animation. You could try coalescing rectangles as you generate the dirty-rectangle list. That is, you could detect pairs of rectangles that can be joined together into larger rectangles, so that fewer, larger rectangles would have to be copied. This would boost the efficiency of the low-level copying code, albeit at the cost of some cycles in the dirty-list management code.

You might also try taking advantage of the natural coherence of animated graphics screens. In particular, because the rectangle used to erase an image at its old location often overlaps the rectangle within which the image resides at its new location, you could just directly generate the two or three nonoverlapped rectangles required to copy both the erase rectangle and the new-image rectangle for any single moving image. The calculation of these rectangles could be very efficient, given that you know in advance the direction of motion of your images. Handling this particular overlap case would eliminate most overlapped drawing, at a minimal cost. You might then decide to ignore overlapped drawing between different images, which tends to be both less common and more expensive to identify and handle.

Drawing Order and Visual Quality

A final note on dirty-rectangle animation concerns the quality of the displayed screen image. In the last chapter, we simply stuffed dirty rectangles into a list in the order they became dirty, and then copied all of the rectangles in that same order. Unfortunately, this caused all of the erase rectangles to be copied first, followed by all of the rectangles of the images at their new locations. Consequently, there was a significant delay between the appearance of the erase rectangle for a given image and the appearance of the new rectangle. A byproduct was the fact that a partially complete—part old, part new—image was visible long enough to be noticed. In short, although the pixels ended up correct, they were in an intermediate, incorrect state for a sufficient period of time to make the animation look wrong.

This violated a fundamental rule of animation: *No pixel should ever be displayed in a perceptibly incorrect state.* To correct the problem, I've sorted the dirty rectangles first by Y coordinate, and secondly by X coordinate. This means the screen updates from the top down, and from left to right, so the several nonoverlapping rectangles copied to draw a given image should be drawn nearly simultaneously. Run the code from the last chapter and then this chapter; you'll see quite a difference in appearance.

Avoid the trap of thinking animation is merely a matter of drawing the right pixels, one after another. Animation is the art of drawing *the right pixels at the right times* so that the eye and brain see what you want them to see. Animation is a lot more challenging than merely cranking out pixels, and it sure as heck isn't a purely linear process.

Mode X: 256-Color VGA Magic

Chapter 32

Introducing the VGA's Undocumented "Animation-Optimal" Mode

At a recent book signing for my book *Zen of Code Optimization*, an attractive young woman came up to me, holding my book, and said, "You're Michael Abrash, aren't you?" I confessed that I was, prepared to respond in an appropriately modest yet proud way to the compliments I was sure would follow. (It was my own book signing, after all.) It didn't work out quite that way, though. The first thing out of her mouth was:

"'Mode X' is a stupid name for a graphics mode." As my jaw started to drop, she added, "And you didn't invent the mode, either. My husband did it before you did."

And they say there are no groupies in programming!

Well. I never claimed that I invented the mode (which is a 320×240 256-color mode with some very special properties, as we'll see shortly). I did discover it independently, but so did other people in the game business, some of them no doubt before I did. The difference is that all those other people held onto this powerful mode as a trade secret, while I didn't; instead, I spread the word as broadly as I could in my column in *Dr. Dobb's Journal*, on the theory that the more people knew about this mode, the more valuable it would be. And I succeeded, as evidenced by the fact that this now widely-used mode is universally known by the name I gave it in *DDJ*, "Mode X." Neither do I think that's a bad name; it's short, catchy, and easy to remember, and it befits the mystery status of this mode, which was omitted entirely from IBM's documentation of the VGA.

In fact, when all is said and done, Mode X is one of my favorite accomplishments. I remember reading that Charles Schultz, creator of "Peanuts," was particularly proud of having introduced the phrase "security blanket" to the English language. I feel much the same way about Mode X; it's now a firmly-entrenched part of the computer lexicon, and how often do any of us get a chance to do that? And that's not to mention all the excellent games that would not have been as good without Mode X.

So, in the end, I'm thoroughly pleased with Mode X; the world is a better place for it, even if it did cost me my one potential female fan. (Contrary to popular belief, the lives of computer columnists and rock stars are not, repeat, *not*, all that similar.) This and the following two chapters are based on the *DDJ* columns that started it all back in 1991, three columns that generated a tremendous amount of interest and spawned a ton of games, and about which I still regularly get letters and e-mail. Ladies and gentlemen, I give you...Mode X.

What Makes Mode X Special?

Consider the strange case of the VGA's 320×240 256-color mode—Mode X—which is undeniably complex to program and isn't even documented by IBM—but which is, nonetheless, perhaps the single best mode the VGA has to offer, especially for animation.

We've seen the VGA's undocumented 256-color modes, in Chapters 9 and 10, but now it's time to delve into the wonders of Mode X itself. (Most of the performance tips I'll discuss for this mode also apply to the other non-standard 256-color modes, however.) Five features set Mode X apart from other VGA modes. First, it has a 1:1 aspect ratio, resulting in equal pixel spacing horizontally and vertically (that is, square pixels). Square pixels make for the most attractive displays, and avoid considerable programming effort that would otherwise be necessary to adjust graphics primitives and images to match the screen's pixel spacing. (For example, with square pixels, a circle can be drawn as a circle; otherwise, it must be drawn as an ellipse that corrects for the aspect ratio—a slower and considerably more complicated process.) In contrast, mode 13H, the only documented 256-color mode, provides a nonsquare 320×200 resolution.

Second, Mode X allows page flipping, a prerequisite for the smoothest possible animation. Mode 13H does not allow page flipping, nor does mode 12H, the VGA's high-resolution 640×480 16-color mode.

Third, Mode X allows the VGA's plane-oriented hardware to be used to process pixels in parallel, improving performance by up to four times over mode 13H.

Fourth, like mode 13H but unlike all other VGA modes, Mode X is a byte-per-pixel mode (each pixel is controlled by one byte in display memory), eliminating the slow read-before-write and bit-masking operations often required in 16-color modes, where each byte of display memory represents more than a single pixel. In addition to cutting the number of memory accesses in half, this is important because the 486/Pentium write FIFO and the memory caching schemes used by many VGA clones speed up writes more than reads.

Fifth, unlike mode 13H, Mode X has plenty of offscreen memory free for image storage. This is particularly effective in conjunction with the use of the VGA's latches; together, the latches and the off-screen memory allow images to be copied to the screen four pixels at a time.

There's a sixth feature of Mode X that's *not* so terrific: It's hard to program efficiently. As Part I of this book demonstrates, 16-color VGA programming can be demanding. Mode X is often as demanding as 16-color programming, and operates by a set of rules that turns everything you've learned in 16-color mode sideways. Programming Mode X is nothing like programming the nice, flat bitmap of mode 13H, or, for that matter, the flat, linear (albeit banked) bitmap used by 256-color SuperVGA modes. (I't's important to remember that Mode X works on *all* VGAs, not just SuperVGAs.) Many programmers I talk to love the flat bitmap model, and think that it's the ideal organization for display memory because it's so straightforward to program. Here, however, the complexity of Mode X is opportunity—opportunity for the best combination of performance and appearance the VGA has to offer. If you do 256-color programming, and especially if you use animation, you're missing the boat if you're not using Mode X.

Although some developers have taken advantage of Mode X, its use is certainly not universal, being entirely undocumented; only an experienced VGA programmer would have the slightest inkling that it even exists, and figuring out how to make it perform beyond the write pixel/read pixel level is no mean feat. Little other than my *DDJ* columns has been published about it, although John Bridges has widely distributed his code for a number of undocumented 256-color resolutions, and I'd like to acknowledge the influence of his code on the mode set routine presented in this chapter.

Given the tremendous advantages of Mode X over the documented mode 13H, I'd very much like to get it into the hands of as many developers as possible, so I'm going to spend the next few chapters exploring this odd but worthy mode. I'll provide mode set code, delineate the bitmap organization, and show how the basic write pixel and read pixel operations work. Then, I'll move on to the magic stuff: rectangle fills, screen clears, scrolls, image copies, pixel inversion, and, yes, polygon fills (just a different driver for the polygon code), all blurry fast; hardware raster ops; and page flipping. In the end, I'll build a working animation program that shows many of the features of Mode X in action.

The mode set code is the logical place to begin.

Selecting 320x240 256-Color Mode

We could, if we wished, write our own mode set code for Mode X from scratch—but why bother? Instead, we'll let the BIOS do most of the work by having it set up mode 13H, which we'll then turn into Mode X by changing a few registers. Listing 32.1 does exactly that.

The code in Listing 32.1 has been around for some time, and the very first version had a bug that serves up an interesting lesson. The original *DDJ* version made images roll on IBM's fixed-frequency VGA monitors, a problem that didn't come to my attention until the code was in print and shipped to 100,000 readers.

The bug came about this way: The code I modified to make the Mode X mode set code used the VGA's 28-MHz clock. Mode X should have used the 25-MHz clock, a simple matter of setting bit 2 of the Miscellaneous Output register (3C2H) to 0 instead of 1.

Alas, I neglected to change that single bit, so frames were drawn at a faster rate than they should have been; however, both of my monitors are multifrequency types, and they automatically compensated for the faster frame rate. Consequently, my clock-selection bug was invisible and innocuous—until it was distributed broadly and everybody started banging on it.

IBM makes only fixed-frequency VGA monitors, which require very specific frame rates; if they don't get what you've told them to expect, the image rolls. The corrected version is the one shown here as Listing 32.1; it does select the 25-MHz clock, and works just fine on fixed-frequency monitors.

Why didn't I catch this bug? Neither I nor a single one of my testers had a fixed-frequency monitor! This nicely illustrates how difficult it is these days to test code in all the PC-compatible environments in which it might run. The problem is particularly severe for small developers, who can't afford to buy every model of every hardware component from every manufacturer; just imagine trying to test network-aware software in all possible configurations!

When people ask why software isn't bulletproof; why it crashes or doesn't coexist with certain programs; why PC clones aren't always compatible; why, in short, the myriad irritations of using a PC exist—this is a big part of the reason. I guess that's just the price we pay for the unfettered creativity and vast choice of the PC market.

LISTING 32.1 L32-1.ASM

```
; Mode X (320x240, 256 colors) mode set routine. Works on all VGAs.
; ****************************************************************
; * Revised 6/19/91 to select correct clock; fixes vertical roll *
; * problems on fixed-frequency (IBM 851X-type) monitors.        *
; ****************************************************************
; C near-callable as:
;       void Set320x240Mode(void);
; Tested with TASM
; Modified from public-domain mode set code by John Bridges.

SC_INDEX        equ   03c4h   ;Sequence Controller Index
CRTC_INDEX      equ   03d4h   ;CRT Controller Index
MISC_OUTPUT     equ   03c2h   ;Miscellaneous Output register
SCREEN_SEG      equ   0a000h  ;segment of display memory in mode X

        .model  small
        .data
; Index/data pairs for CRT Controller registers that differ between
; mode 13h and mode X.
CRTParms label  word
        dw      00d06h  ;vertical total
        dw      03e07h  ;overflow (bit 8 of vertical counts)
        dw      04109h  ;cell height (2 to double-scan)
        dw      0ea10h  ;v sync start
        dw      0ac11h ;v sync end and protect cr0-cr7
        dw      0df12h ;vertical displayed
        dw      00014h ;turn off dword mode
        dw      0e715h ;v blank start
        dw      00616h ;v blank end
        dw      0e317h ;turn on byte mode
CRT_PARM_LENGTH equ     (($-CRTParms)/2)

        .code
        public  _Set320x240Mode
_Set320x240Mode proc    near
        push    bp      ;preserve caller's stack frame
        push    si      ;preserve C register vars
        push    di      ; (don't count on BIOS preserving anything)

        mov     ax,13h  ;let the BIOS set standard 256-color
        int     10h     ; mode (320x200 linear)

        mov     dx,SC_INDEX
        mov     ax,0604h
        out     dx,ax  ;disable chain4 mode
        mov     ax,0100h
        out     dx,ax  ;synchronous reset while setting Misc Output
                        ; for safety, even though clock unchanged
        mov     dx,MISC_OUTPUT
        mov     al,0e3h
        out     dx,al   ;select 25 MHz dot clock & 60 Hz scanning rate

        mov     dx,SC_INDEX
        mov     ax,0300h
        out     dx,ax  ;undo reset (restart sequencer)

        mov     dx,CRTC_INDEX ;reprogram the CRT Controller
        mov     al,11h ;VSync End reg contains register write
        out     dx,al   ; protect bit
        inc     dx      ;CRT Controller Data register
        in      al,dx   ;get current VSync End register setting
        and     al,7fh ;remove write protect on various
        out     dx,al   ; CRTC registers
        dec     dx      ;CRT Controller Index
        cld
        mov     si,offset CRTParms ;point to CRT parameter table
        mov     cx,CRT_PARM_LENGTH ;# of table entries
SetCRTParmsLoop:
        lodsw           ;get the next CRT Index/Data pair
        out     dx,ax  ;set the next CRT Index/Data pair
        loop    SetCRTParmsLoop

        mov     dx,SC_INDEX
        mov     ax,0f02h
        out     dx,ax  ;enable writes to all four planes
        mov     ax,SCREEN_SEG ;now clear all display memory, 8 pixels
        mov     es,ax         ; at a time
        sub     di,di  ;point ES:DI to display memory
        sub     ax,ax  ;clear to zero-value pixels
        mov     cx,8000h ;# of words in display memory
        rep     stosw   ;clear all of display memory

        pop     di      ;restore C register vars
        pop     si
        pop     bp      ;restore caller's stack frame
        ret
_Set320x240Mode endp
        end
```

After setting up mode 13H, Listing 32.1 alters the vertical counts and timings to select 480 visible scan lines. (There's no need to alter any horizontal values, because mode 13H and Mode X both have 320-pixel horizontal resolutions.) The Maximum Scan Line register is programmed to double scan each line (that is, repeat each scan line twice), however, so we get an effective vertical resolution of 240 scan lines. It is, in fact, possible to get 400 or 480 independent scan lines in 256-color mode, as discussed in Chapter 9 and 10; however, 400-scan-line modes lack square pixels and can't support simultaneous offscreen memory and page flipping. Furthermore, 480-scan-line modes lack page flipping altogether, due to memory constraints.

At the same time, Listing 32.1 programs the VGA's bitmap to a planar organization that is similar to that used by the 16-color modes, and utterly different from the linear bitmap of mode 13H. The bizarre bitmap organization of Mode X is shown in Figure 32.1. The first pixel (the pixel at the upper left corner of the screen) is controlled by the byte at offset 0 in plane 0. (The one thing that Mode X blessedly has in common with mode 13H is that each pixel is controlled by a single byte, eliminating the need to

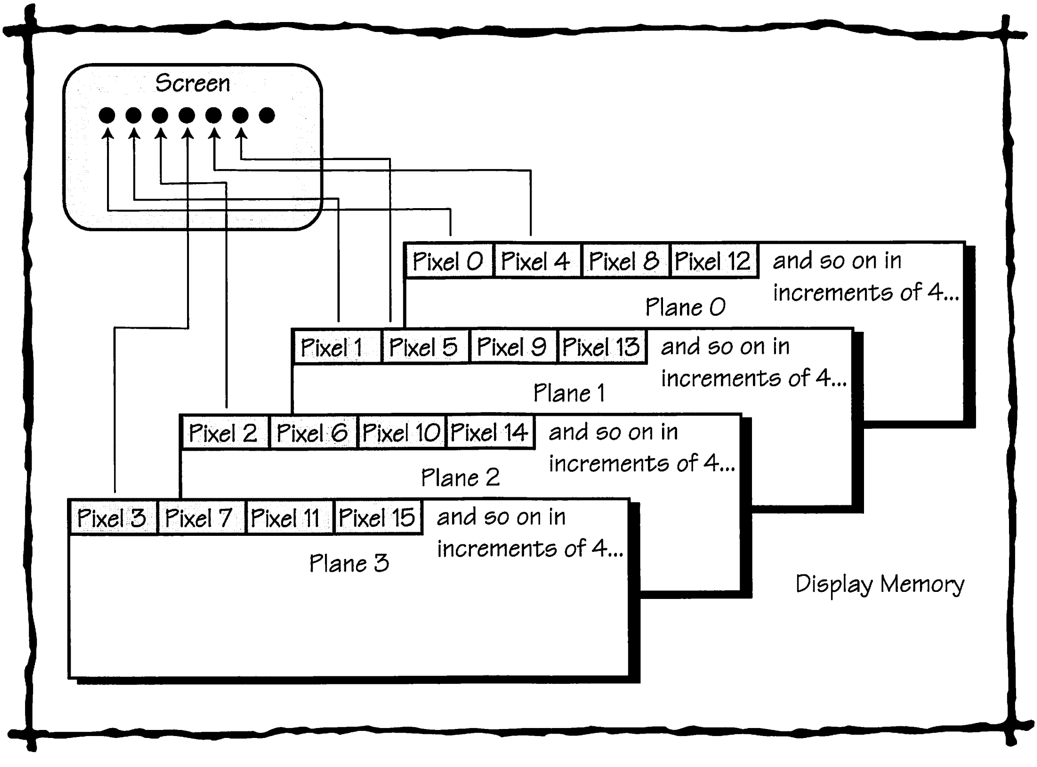


Figure 32.1 Mode X Display Memory Organization

mask out individual bits of display memory.) The second pixel, immediately to the right of the first pixel, is controlled by the byte at offset 0 in plane 1. The third pixel comes from offset 0 in plane 2, and the fourth pixel from offset 0 in plane 3. Then, the fifth pixel is controlled by the byte at offset 1 in plane 0, and that cycle continues, with each group of four pixels spread across the four planes at the same address. The offset M of pixel N in display memory is M = N/4, and the plane P of pixel N is P = N mod 4. For display memory writes, the plane is selected by setting bit P of the Map Mask register (Sequence Controller register 2) to 1 and all other bits to 0; for display memory reads, the plane is selected by setting the Read Map register (Graphics Controller register 4) to P.

It goes without saying that this is one ugly bitmap organization, requiring a lot of overhead to manipulate a single pixel. The write pixel code shown in Listing 32.2 must determine the appropriate plane and perform a 16-bit **OUT** to select that plane for each pixel written, and likewise for the read pixel code shown in Listing 32.3. Calculating and mapping in a plane once for each pixel written is scarcely a recipe for performance.

That's all right, though, because most graphics software spends little time drawing individual pixels. I've provided the write and read pixel routines as basic primitives, and so you'll understand how the bitmap is organized, but the building blocks of high-performance graphics software are fills, copies, and bitblts, and it's there that Mode X shines.

LISTING 32.2 L32-2.ASM

```
; Mode X (320x240, 256 colors) write pixel routine. Works on all VGAs.
; No clipping is performed.
; C near-callable as:
;
;    void WritePixelX(int X, int Y, unsigned int PageBase, int Color);

SC_INDEX        equ     03c4h       ;Sequence Controller Index
MAP_MASK        equ     02h         ;index in SC of Map Mask register
SCREEN_SEG      equ     0a000h      ;segment of display memory in mode X
SCREEN_WIDTH    equ     80          ;width of screen in bytes from one scan line
                                    ; to the next

parms   struc
        dw      2 dup (?)           ;pushed BP and return address
X       dw      ?                   ;X coordinate of pixel to draw
Y       dw      ?                   ;Y coordinate of pixel to draw
PageBase dw     ?                   ;base offset in display memory of page in
                                    ; which to draw pixel
Color   dw      ?                   ;color in which to draw pixel
parms   ends

        .model  small
        .code
        public  _WritePixelX
_WritePixelX    proc    near
        push    bp                  ;preserve caller's stack frame
        mov     bp,sp               ;point to local stack frame

        mov     ax,SCREEN_WIDTH
        mul     [bp+Y]                 ;offset of pixel's scan line in page
        mov     bx,[bp+X]
        shr     bx,1
        shr     bx,1                   ;X/4 = offset of pixel in scan line
        add     bx,ax                  ;offset of pixel in page
        add     bx,[bp+PageBase]       ;offset of pixel in display memory
        mov     ax,SCREEN_SEG
        mov     es,ax                  ;point ES:BX to the pixel's address

        mov     cl,byte ptr [bp+X]
        and     cl,011b                ;CL = pixel's plane
        mov     ax,0100h + MAP_MASK    ;AL = index in SC of Map Mask reg
        shl     ah,cl                  ;set only the bit for the pixel's plane to 1
        mov     dx,SC_INDEX            ;set the Map Mask to enable only the
        out     dx,ax                  ; pixel's plane

        mov     al,byte ptr [bp+Color]
        mov     es:[bx],al             ;draw the pixel in the desired color

        pop     bp                     ;restore caller's stack frame
        ret
_WritePixelX    endp
        end
```

LISTING 32.3 L32-3.ASM

```
; Mode X (320x240, 256 colors) read pixel routine. Works on all VGAs.
; No clipping is performed.
; C near-callable as:
;
;    unsigned int ReadPixelX(int X, int Y, unsigned int PageBase);

GC_INDEX         equ  03ceh            ;Graphics Controller Index
READ_MAP         equ  04h              ;index in GC of the Read Map register
SCREEN_SEG       equ  0a000h           ;segment of display memory in mode X
SCREEN_WIDTH     equ  80               ;width of screen in bytes from one scan line
                                       ; to the next
parms   struc
        dw      2 dup (?)              ;pushed BP and return address
X       dw      ?                      ;X coordinate of pixel to read
Y       dw      ?                      ;Y coordinate of pixel to read
PageBase dw     ?                      ;base offset in display memory of page from
                                       ; which to read pixel
parms   ends

        .model  small
        .code
        public  _ReadPixelX
_ReadPixelX     proc    near
        push    bp                     ;preserve caller's stack frame
        mov     bp,sp                  ;point to local stack frame

        mov     ax,SCREEN_WIDTH
        mul     [bp+Y]                 ;offset of pixel's scan line in page
        mov     bx,[bp+X]
        shr     bx,1
        shr     bx,1                   ;X/4 = offset of pixel in scan line
        add     bx,ax                  ;offset of pixel in page
        add     bx,[bp+PageBase]       ;offset of pixel in display memory
        mov     ax,SCREEN_SEG
        mov     es,ax                   ;point ES:BX to the pixel's address

        mov     ah,byte ptr [bp+X]
        and     ah,011b                 ;AH = pixel's plane
        mov     al,READ_MAP             ;AL = index in GC of the Read Map reg
        mov     dx,GC_INDEX             ;set the Read Map to read the pixel's
        out     dx,ax                   ; plane

        mov     al,es:[bx]              ;read the pixel's color
        sub     ah,ah                   ;convert it to an unsigned int

        pop     bp                      ;restore caller's stack frame
        ret
_ReadPixelX     endp
        end
```

Designing from a Mode X Perspective

Listing 32.4 shows Mode X rectangle fill code. The plane is selected for each pixel in turn, with drawing cycling from plane 0 to plane 3, then wrapping back to plane 0. This is the sort of code that stems from a write-pixel line of thinking; it reflects not a whit of the unique perspective that Mode X demands, and although it looks reasonably efficient, it is in fact some of the slowest graphics code you will ever see. I've provided Listing 32.4 partly for illustrative purposes, but mostly so we'll have a point of reference for the substantial speed-up that's possible with code that's designed from a Mode X perspective.

LISTING 32.4 L32-4.ASM

```
; Mode X (320x240, 256 colors) rectangle fill routine. Works on all
; VGAs. Uses slow approach that selects the plane explicitly for each
; pixel. Fills up to but not including the column at EndX and the row
; at EndY. No clipping is performed.
; C near-callable as:
;
;    void FillRectangleX(int StartX, int StartY, int EndX, int EndY,
;       unsigned int PageBase, int Color);

SC_INDEX         equ   03c4h            ;Sequence Controller Index
MAP_MASK         equ   02h              ;index in SC of Map Mask register
SCREEN_SEG       equ   0a000h           ;segment of display memory in mode X
SCREEN_WIDTH     equ   80               ;width of screen in bytes from one scan line
                                        ; to the next
parms   struc
        dw      2 dup (?)               ;pushed BP and return address
StartX  dw      ?                       ;X coordinate of upper left corner of rect
StartY  dw      ?                       ;Y coordinate of upper left corner of rect
EndX    dw      ?                       ;X coordinate of lower right corner of rect
                                        ; (the row at EndX is not filled)
EndY    dw      ?                       ;Y coordinate of lower right corner of rect
                                        ; (the column at EndY is not filled)
PageBase dw     ?                       ;base offset in display memory of page in
                                        ; which to fill rectangle
Color   dw      ?                       ;color in which to draw pixel
```

```
parms   ends

        .model  small
        .code
        public  _FillRectangleX
_FillRectangleX proc    near
        push    bp                     ;preserve caller's stack frame
        mov     bp,sp                  ;point to local stack frame
        push    si                     ;preserve caller's register variables
        push    di

        mov     ax,SCREEN_WIDTH
        mul     [bp+StartY]            ;offset in page of top rectangle scan line
        mov     di,[bp+StartX]
        shr     di,1
        shr     di,1                   ;X/4 = offset of first rectangle pixel in scan
                                       ; line
        add     di,ax                  ;offset of first rectangle pixel in page
        add     di,[bp+PageBase]       ;offset of first rectangle pixel in
                                       ; display memory
        mov     ax,SCREEN_SEG
        mov     es,ax                  ;point ES:DI to the first rectangle pixel's
                                       ; address
        mov     dx,SC_INDEX            ;set the Sequence Controller Index to
        mov     al,MAP_MASK            ; point to the Map Mask register
        out     dx,al
        inc     dx                     ;point DX to the SC Data register
        mov     cl,byte ptr [bp+StartX]
        and     cl,011b                ;CL = first rectangle pixel's plane
        mov     al,01h
        shl     al,cl                  ;set only the bit for the pixel's plane to 1
        mov     ah,byte ptr [bp+Color] ;color with which to fill
        mov     bx,[bp+EndY]
        sub     bx,[bp+StartY]         ;BX = height of rectangle
        jle     FillDone               ;skip if 0 or negative height
        mov     si,[bp+EndX]
        sub     si,[bp+StartX]         ;CX = width of rectangle
        jle     FillDone               ;skip if 0 or negative width
FillRowsLoop:
        push    ax                     ;remember the plane mask for the left edge
        push    di                     ;remember the start offset of the scan line
        mov     cx,si                  ;set count of pixels in this scan line
FillScanLineLoop:
        out     dx,al                  ;set the plane for this pixel
        mov     es:[di],ah             ;draw the pixel
        shl     al,1                   ;adjust the plane mask for the next pixel's
        and     al,01111b              ; bit, modulo 4
        jnz     AddressSet             ;advance address if we turned over from
        inc     di                     ; plane 3 to plane 0
        mov     al,00001b              ;set plane mask bit for plane 0
AddressSet:
        loop    FillScanLineLoop
        pop     di                     ;retrieve the start offset of the scan line
        add     di,SCREEN_WIDTH        ;point to the start of the next scan
                                       ; line of the rectangle
        pop     ax                     ;retrieve the plane mask for the left edge
        dec     bx                     ;count down scan lines
        jnz     FillRowsLoop
FillDone:
        pop     di                     ;restore caller's register variables
        pop     si
        pop     bp                      ;restore caller's stack frame
        ret
_FillRectangleX endp
        end
```

The two major weaknesses of Listing 32.4 both result from selecting the plane on a pixel by pixel basis. First, endless **OUT**s (which are particularly slow on 386s, 486s, and Pentiums, much slower than accesses to display memory) must be performed, and, second, **REP STOS** can't be used. Listing 32.5 overcomes both these problems by tailoring the fill technique to the organization of display memory. Each plane is filled in its entirety in one burst before the next plane is processed, so only five **OUT**s are required in all, and **REP STOS** can indeed be used; I've used **REP STOSB** in Listings 32.5 and 32.6. **REP STOSW** could be used and would improve performance on most VGAs; however, **REP STOSW** requires extra overhead to set up, so it can be slower for small rectangles, especially on 8-bit VGAs. Note that doing an entire plane at a time can produce a "fading-in" effect for large images, because all columns for one plane are drawn before any columns for the next. If this is a problem, the four planes can be cycled through once for each scan line, rather than once for the entire rectangle.

Listing 32.5 is 2.5 times faster than Listing 32.4 at clearing the screen on a 20-MHz cached 386 with a Paradise VGA. Although Listing 32.5 is slightly slower than an equivalent mode 13H fill routine would be, it's not grievously so.

*In general, performing plane-at-a-time operations can make almost any Mode X operation, at the worst, nearly as fast as the same operation in mode 13H (although this sort of Mode X programming is admittedly fairly complex). In this pursuit, it can help to organize data structures with Mode X in mind. For example, icons could be prearranged in system memory with the pixels organized into four plane-oriented sets (or, again, in four sets per scan line to avoid a fading-in effect) to facilitate copying to the screen a plane at a time with **REP MOVS**.*

LISTING 32.5 L32-5.ASM

```
; Mode X (320x240, 256 colors) rectangle fill routine. Works on all
; VGAs. Uses medium-speed approach that selects each plane only once
; per rectangle; this results in a fade-in effect for large
; rectangles. Fills up to but not including the column at EndX and the
; row at EndY. No clipping is performed.
; C near-callable as:
;
;    void FillRectangleX(int StartX, int StartY, int EndX, int EndY,
;       unsigned int PageBase, int Color);

SC_INDEX        equ   03c4h            ;Sequence Controller Index
```

```
MAP_MASK         equ  02h                 ;index in SC of Map Mask register
SCREEN_SEG       equ  0a000h              ;segment of display memory in mode X
SCREEN_WIDTH     equ  80                  ;width of screen in bytes from one scan line
                                          ; to the next
parms struc
           dw      2 dup (?)              ;pushed BP and return address
StartX     dw      ?                      ;X coordinate of upper left corner of rect
StartY     dw      ?                      ;Y coordinate of upper left corner of rect
EndX       dw      ?                      ;X coordinate of lower right corner of rect
                                          ; (the row at EndX is not filled)
EndY       dw      ?                      ;Y coordinate of lower right corner of rect
                                          ; (the column at EndY is not filled)
PageBase   dw     ?                       ;base offset in display memory of page in
                                          ; which to fill rectangle
Color      dw      ?                      ;color in which to draw pixel
parms ends

StartOffset       equ  -2                 ;local storage for start offset of rectangle
Width             equ  -4                 ;local storage for address width of rectangle
Height            equ  -6                 ;local storage for height of rectangle
PlaneInfo         equ  -8                 ;local storage for plane # and plane mask
STACK_FRAME_SIZE equ   8

        .model  small
        .code
        public  _FillRectangleX
_FillRectangleX proc     near
        push    bp                        ;preserve caller's stack frame
        mov     bp,sp                     ;point to local stack frame
        sub     sp,STACK_FRAME_SIZE       ;allocate space for local vars
        push    si                        ;preserve caller's register variables
        push    di

        cld
        mov     ax,SCREEN_WIDTH
        mul     [bp+StartY]               ;offset in page of top rectangle scan line
        mov     di,[bp+StartX]
        shr     di,1
        shr     di,1                      ;X/4 = offset of first rectangle pixel in scan
                                          ; line
        add     di,ax                     ;offset of first rectangle pixel in page
        add     di,[bp+PageBase]          ;offset of first rectangle pixel in
                                          ; display memory
        mov     ax,SCREEN_SEG
        mov     es,ax                     ;point ES:DI to the first rectangle pixel's
        mov     [bp+StartOffset],di       ; address
        mov     dx,SC_INDEX               ;set the Sequence Controller Index to
        mov     al,MAP_MASK               ; point to the Map Mask register
        out     dx,al
        mov     bx,[bp+EndY]
        sub     bx,[bp+StartY]            ;BX = height of rectangle
        jle     FillDone                  ;skip if 0 or negative height
        mov     [bp+Height],bx
        mov     dx,[bp+EndX]
        mov     cx,[bp+StartX]
        cmp     dx,cx
        jle     FillDone                  ;skip if 0 or negative width
        dec     dx
        and     cx,not 011b
        sub     dx,cx
        shr     dx,1
        shr     dx,1
        inc     dx                      ;# of addresses across rectangle to fill
        mov     [bp+Width],dx
        mov     word ptr [bp+PlaneInfo],0001h
                                        ;lower byte = plane mask for plane 0,
                                        ; upper byte = plane # for plane 0
FillPlanesLoop:
        mov     ax,word ptr [bp+PlaneInfo]
        mov     dx,SC_INDEX+1           ;point DX to the SC Data register
        out     dx,al                   ;set the plane for this pixel
        mov     di,[bp+StartOffset]     ;point ES:DI to rectangle start
        mov     dx,[bp+Width]
        mov     cl,byte ptr [bp+StartX]
        and     cl,011b                 ;plane # of first pixel in initial byte
        cmp     ah,cl                   ;do we draw this plane in the initial byte?
        jae     InitAddrSet             ;yes
        dec     dx                      ;no, so skip the initial byte
        jz      FillLoopBottom          ;skip this plane if no pixels in it
        inc     di
InitAddrSet:
        mov     cl,byte ptr [bp+EndX]
        dec     cl
        and     cl,011b                 ;plane # of last pixel in final byte
        cmp     ah,cl                   ;do we draw this plane in the final byte?
        jbe     WidthSet                ;yes
        dec     dx                      ;no, so skip the final byte
        jz      FillLoopBottom          ;skip this planes if no pixels in it
WidthSet:
        mov     si,SCREEN_WIDTH
        sub     si,dx                   ;distance from end of one scan line to start
                                        ; of next
        mov     bx,[bp+Height]          ;# of lines to fill
        mov     al,byte ptr [bp+Color]  ;color with which to fill
FillRowsLoop:
        mov     cx,dx                   ;# of bytes across scan line
        rep     stosb                   ;fill the scan line in this plane
        add     di,si                   ;point to the start of the next scan
                                        ; line of the rectangle
        dec     bx                      ;count down scan lines
        jnz     FillRowsLoop
FillLoopBottom:
        mov     ax,word ptr [bp+PlaneInfo]
        shl     al,1                    ;set the plane bit to the next plane
        inc     ah                      ;increment the plane #
        mov     word ptr [bp+PlaneInfo],ax
        cmp     ah,4                    ;have we done all planes?
        jnz     FillPlanesLoop          ;continue if any more planes
FillDone:
        pop     di                      ;restore caller's register variables
        pop     si
        mov     sp,bp                   ;discard storage for local variables
        pop     bp                      ;restore caller's stack frame
        ret
_FillRectangleX endp
        end
```

Hardware Assist from an Unexpected Quarter

Listing 32.5 illustrates the benefits of designing code from a Mode X perspective; this is the software aspect of Mode X optimization, which suffices to make Mode X about as fast as mode 13H. That alone makes Mode X an attractive mode, given its square pixels, page flipping, and offscreen memory, but superior performance would nonetheless be a pleasant addition to that list. Superior performance is indeed possible in Mode X, although, oddly enough, it comes courtesy of the VGA's hardware, which was never designed to be used in 256-color modes.

All of the VGA's hardware assist features are available in Mode X, although some are not particularly useful. The VGA hardware feature that's truly the key to Mode X performance is the ability to process four planes' worth of data in parallel; this includes both the latches and the capability to fan data out to any or all planes. For rectangular fills, we'll just need to fan the data out to various planes, so I'll defer a discussion of other hardware features for now. (By the way, the ALUs, bit mask, and most other VGA hardware features are also available in mode 13H—but parallel data processing is not.)

In planar modes, such as Mode X, a byte written by the CPU to display memory may actually go to anywhere between zero and four planes, as shown in Figure 32.2. Each plane for which the setting of the corresponding bit in the Map Mask register is 1 receives the CPU data, and each plane for which the corresponding bit is 0 is not modified.

In 16-color modes, each plane contains one-quarter of each of eight pixels, with the 4 bits of each pixel spanning all four planes. Not so in Mode X. Look at Figure 32.1

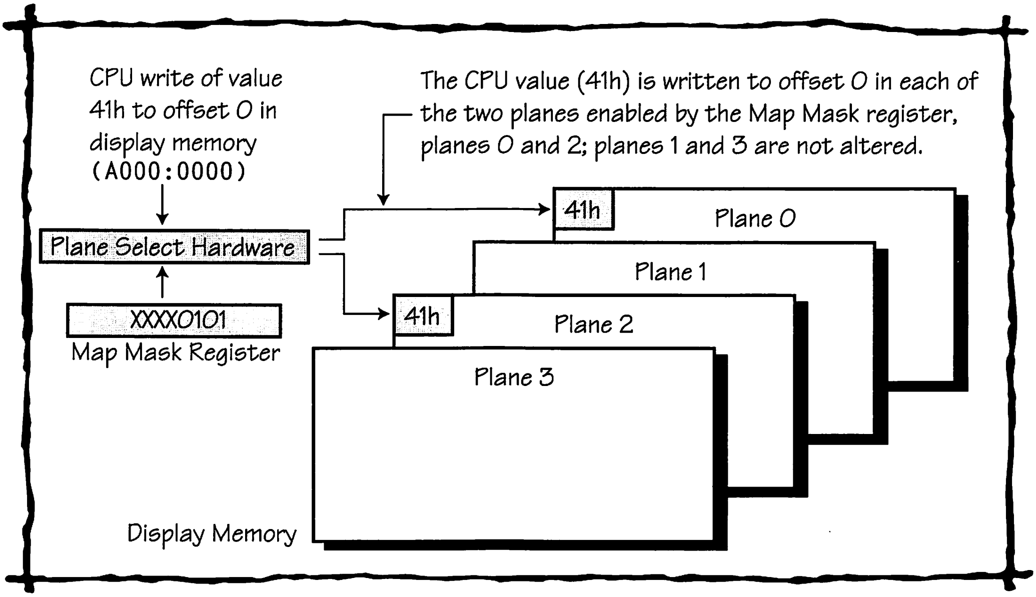

CPU write of value 41h to offset 0 in display memory (A000:0000)
The CPU value (41h) is written to offset 0 in each of the two planes enabled by the Map Mask register, planes 0 and 2; planes 1 and 3 are not altered.
Plane Select Hardware
XXXX0101
Map Mask Register
41h
Plane 0
Plane 1
41h
Plane 2
Plane 3
Display Memory

Figure 32.2 Selecting Planes with the Map Mask Register

again; each plane contains one pixel in its entirety, with four pixels at any given address, one per plane. Still, the Map Mask register does the same job in Mode X as in 16-color modes; set it to 0FH (all 1-bits), and all four planes will be written to by each CPU access. Thus, it would seem that up to four pixels could be set by a single Mode X byte-sized write to display memory, potentially speeding up operations like rectangle fills by four times.

And, as it turns out, four-plane parallelism works quite nicely indeed. Listing 32.6 is yet another rectangle-fill routine, this time using the Map Mask to set up to four pixels per STOS. The only trick to Listing 32.6 is that any left or right edge that isn't aligned to a multiple-of-four pixel column (that is, a column at which one four-pixel set ends and the next begins) must be clipped via the Map Mask register, because not all pixels at the address containing the edge are modified. Performance is as expected; Listing 32.6 is nearly ten times faster at clearing the screen than Listing 32.4 and just about four times faster than Listing 32.5—and also about four times faster than the same rectangle fill in mode 13H. Understanding the bitmap organization and display hardware of Mode X does indeed pay.

Note that the return from Mode X's parallelism is not always 4×; some adapters lack the underlying memory bandwidth to write data that fast. However, Mode X parallel access should always be faster than mode 13H access; the only question on any given adapter is how *much* faster.

LISTING 32.6 L32-6.ASM

```
; Mode X (320x240, 256 colors) rectangle fill routine. Works on all
; VGAs. Uses fast approach that fans data out to up to four planes at
; once to draw up to four pixels at once. Fills up to but not
; including the column at EndX and the row at EndY. No clipping is
; performed.
; C near-callable as:
;    void FillRectangleX(int StartX, int StartY, int EndX, int EndY,
;       unsigned int PageBase, int Color);

SC_INDEX         equ  03c4h            ;Sequence Controller Index
MAP_MASK         equ  02h              ;index in SC of Map Mask register
SCREEN_SEG       equ  0a000h           ;segment of display memory in mode X
SCREEN_WIDTH     equ  80               ;width of screen in bytes from one scan line
                                       ; to the next

parms   struc
           dw      2 dup (?)           ;pushed BP and return address
StartX     dw      ?                   ;X coordinate of upper left corner of rect
StartY     dw      ?                   ;Y coordinate of upper left corner of rect
EndX       dw      ?                   ;X coordinate of lower right corner of rect
                                       ; (the row at EndX is not filled)
EndY       dw      ?                   ;Y coordinate of lower right corner of rect
                                       ; (the column at EndY is not filled)
PageBase   dw      ?                   ;base offset in display memory of page in
                                       ; which to fill rectangle
Color      dw      ?                   ;color in which to draw pixel
parms   ends
```

```
        .model  small
        .data
; Plane masks for clipping left and right edges of rectangle.
LeftClipPlaneMask       db      00fh,00eh,00ch,008h
RightClipPlaneMask      db      00fh,001h,003h,007h
        .code
        public  _FillRectangleX
_FillRectangleX proc    near
        push    bp                      ;preserve caller's stack frame
        mov     bp,sp                   ;point to local stack frame
        push    si                      ;preserve caller's register variables
        push    di

        cld
        mov     ax,SCREEN_WIDTH
        mul     [bp+StartY]             ;offset in page of top rectangle scan line
        mov     di,[bp+StartX]
        shr     di,1                    ;X/4 = offset of first rectangle pixel in scan
        shr     di,1                    ; line
        add     di,ax                   ;offset of first rectangle pixel in page
        add     di,[bp+PageBase]        ;offset of first rectangle pixel in
                                        ; display memory
        mov     ax,SCREEN_SEG           ;point ES:DI to the first rectangle
        mov     es,ax                   ; pixel's address
        mov     dx,SC_INDEX             ;set the Sequence Controller Index to
        mov     al,MAP_MASK             ; point to the Map Mask register
        out     dx,al
        inc     dx                      ;point DX to the SC Data register
        mov     si,[bp+StartX]
        and     si,0003h                ;look up left edge plane mask
        mov     bh,LeftClipPlaneMask[si] ; to clip & put in BH
        mov     si,[bp+EndX]
        and     si,0003h                ;look up right edge plane
        mov     bl,RightClipPlaneMask[si] ; mask to clip & put in BL

        mov     cx,[bp+EndX]            ;calculate # of addresses across rect
        mov     si,[bp+StartX]
        cmp     cx,si
        jle     FillDone                ;skip if 0 or negative width
        dec     cx
        and     si,not 011b
        sub     cx,si
        shr     cx,1
        shr     cx,1                    ;# of addresses across rectangle to fill - 1
        jnz     MasksSet                ;there's more than one byte to draw
        and     bh,bl                   ;there's only one byte, so combine the left
                                        ; and right edge clip masks
MasksSet:
        mov     si,[bp+EndY]
        sub     si,[bp+StartY]          ;BX = height of rectangle
        jle     FillDone                ;skip if 0 or negative height
        mov     ah,byte ptr [bp+Color]  ;color with which to fill
        mov     bp,SCREEN_WIDTH         ;stack frame isn't needed any more
        sub     bp,cx                   ;distance from end of one scan line to start
        dec     bp                      ; of next
FillRowsLoop:
        push    cx                      ;remember width in addresses - 1
        mov     al,bh                   ;put left-edge clip mask in AL
        out     dx,al                   ;set the left-edge plane (clip) mask
        mov     al,ah                   ;put color in AL
        stosb                           ;draw the left edge
        dec     cx                      ;count off left edge byte
        js      FillLoopBottom          ;that's the only byte
        jz      DoRightEdge             ;there are only two bytes
        mov     al,00fh                 ;middle addresses are drawn 4 pixels at a pop
        out     dx,al                   ;set the middle pixel mask to no clip
        mov     al,ah                   ;put color in AL
        rep     stosb                   ;draw the middle addresses four pixels apiece
DoRightEdge:
        mov     al,bl                   ;put right-edge clip mask in AL
        out     dx,al                   ;set the right-edge plane (clip) mask
        mov     al,ah                   ;put color in AL
        stosb                           ;draw the right edge
FillLoopBottom:
        add     di,bp                   ;point to the start of the next scan line of
                                        ; the rectangle
        pop     cx                      ;retrieve width in addresses - 1
        dec     si                      ;count down scan lines
        jnz     FillRowsLoop
FillDone:
        pop     di                      ;restore caller's register variables
        pop     si
        pop     bp                      ;restore caller's stack frame
        ret
_FillRectangleX endp
        end
```

Just so you can see Mode X in action, Listing 32.7 is a sample program that selects Mode X and draws a number of rectangles. Listing 32.7 links to any of the rectangle fill routines I've presented.

And now, I hope, you're beginning to see why I'm so fond of Mode X. In the next chapter, we'll continue with Mode X by exploring the wonders that the latches and parallel plane hardware can work on scrolls, copies, blits, and pattern fills.

LISTING 32.7 L32-7.C

```
/* Program to demonstrate mode X (320x240, 256-colors) rectangle
   fill by drawing adjacent 20x20 rectangles in successive colors from
   0 on up across and down the screen */
#include <conio.h>
#include <dos.h>

void Set320x240Mode(void);
void FillRectangleX(int, int, int, int, unsigned int, int);

void main() {
   int i,j;
   union REGS regset;

   Set320x240Mode();
   FillRectangleX(0,0,320,240,0,0); /* clear the screen to black */
   for (j = 1; j < 220; j += 21) {
      for (i = 1; i < 300; i += 21) {
         FillRectangleX(i, j, i+20, j+20, 0, ((j/21*15)+i/21) & 0xFF);
      }
   }
   getch();
   regset.x.ax = 0x0003;   /* switch back to text mode and done */
   int86(0x10, &regset, &regset);
}
```

Mode X Marks the Latch

Chapter 33

The Internals of Animation's Best Video Display Mode

In the previous chapter, I introduced you to what I call Mode X, an undocumented 320×240 256-color mode of the VGA. Mode X is distinguished from mode 13H, the documented 320×200 256-color VGA mode, in that it supports page flipping, makes off-screen memory available, has square pixels, and, above all, lets you use the VGA's hardware to increase performance by as much as four times. (Of course, those four times come at the cost of more complex and demanding programming, to be sure—but end users care about results, not how hard the code was to write, and Mode X delivers results in a big way.) In the previous chapter we saw how the VGA's plane-oriented hardware can be used to speed solid fills. That's a nice technique, but now we're going to move up to the big guns—the VGA latches.

The VGA has four latches, one for each plane of display memory. Each latch stores exactly one byte, and that byte is always the last byte read from the corresponding plane of display memory, as shown in Figure 33.1. Furthermore, whenever a given address in display memory is read, all four planes' bytes at that address are read and stored in the corresponding latches, regardless of which plane supplied the byte returned to the CPU (as determined by the Read Map register). As with so much else about the VGA, the above will make little sense to VGA neophytes, but the important point is this: By reading one display memory byte, 4 bytes—one from each plane—can be loaded into the latches at once. Any or all of those 4 bytes can then be written anywhere in display memory with a single byte-sized write, as shown in Figure 33.2.

The upshot is that the latches make it possible to copy data around from one part of display memory to another, 32 bits (four pixels) at a time—four times as fast as normal. (Recall from the previous chapter that in Mode X, pixels are stored one per byte, with four pixels in a row stored in successive planes at the same address, one pixel per plane.) However, any one latch can only be loaded from and written to the corresponding

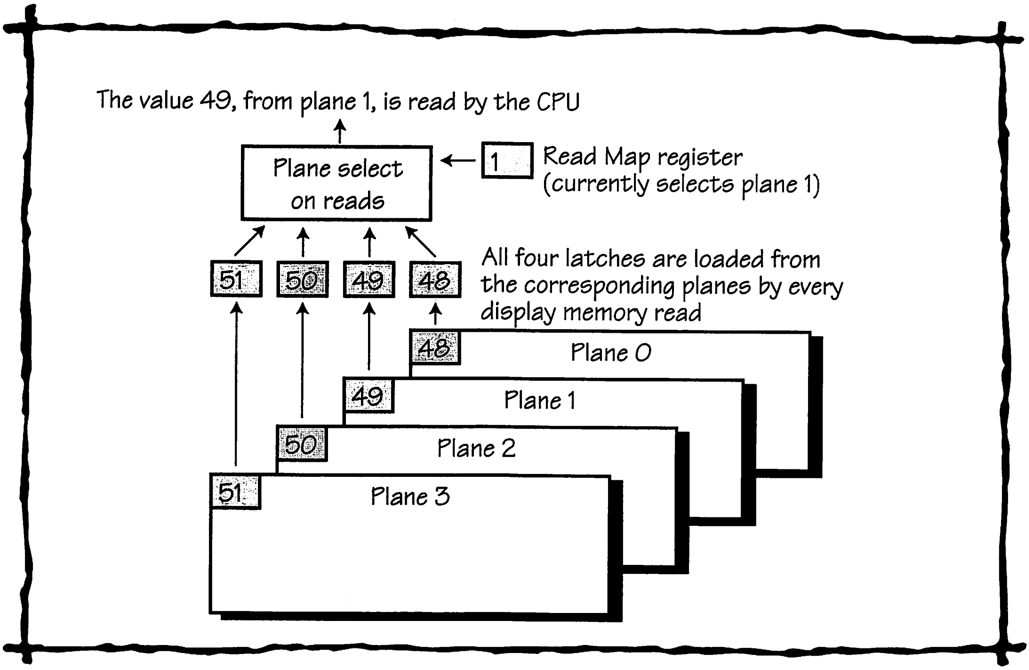

The value 49, from plane 1, is read by the CPU
Plane select on reads
1
Read Map register (currently selects plane 1)
51
50
49
48
All four latches are loaded from the corresponding planes by every display memory read
48
Plane 0
49
Plane 1
50
Plane 2
51
Plane 3

Figure 33.1 How the VGA Latches Are Loaded

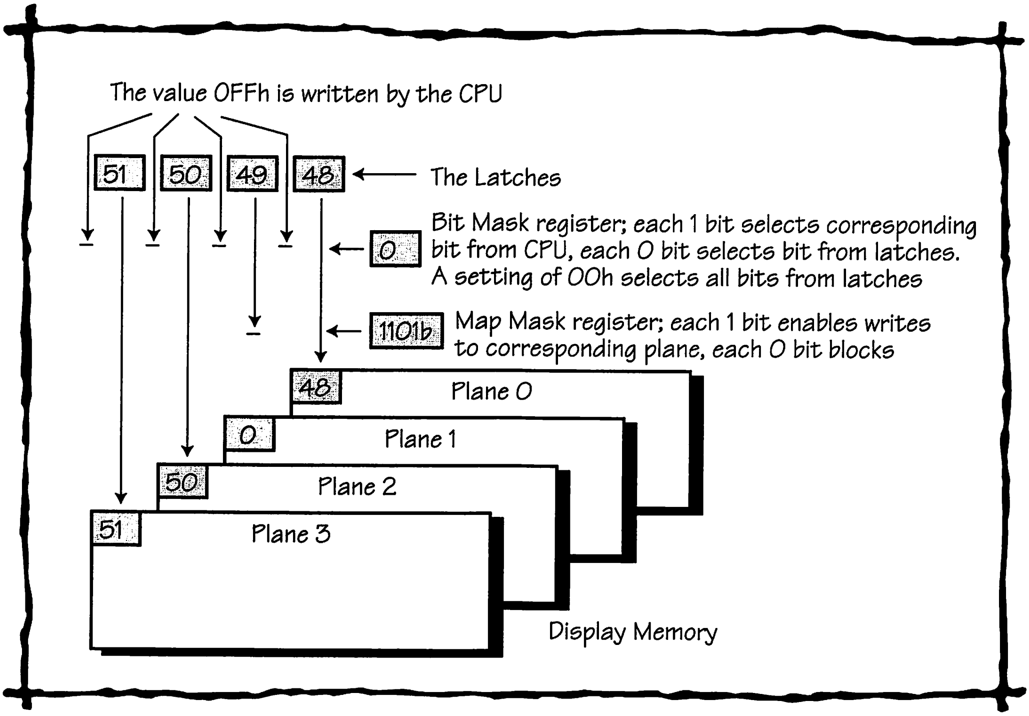

The value 0FFh is written by the CPU
51
50
49
48
The Latches
0
Bit Mask register; each 1 bit selects corresponding bit from CPU, each 0 bit selects bit from latches. A setting of 00h selects all bits from latches
1101b
Map Mask register; each 1 bit enables writes to corresponding plane, each 0 bit blocks
48
Plane 0
0
Plane 1
50
Plane 2
51
Plane 3
Display Memory

Figure 33.2 Writing 4 Bytes to Display Memory in a Single Operation

plane, so an individual latch can only work with every fourth pixel on the screen; the latch for plane 0 can work with pixels 0, 4, 8..., the latch for plane 1 with pixels 1, 5, 9..., and so on.

The latches aren't intended for use in 256-color mode—they were designed to allow individual bits of display memory to be modified in 16-color mode—but they are nonetheless very useful in Mode X, particularly for patterned fills and screen-to-screen copies, including scrolls. Patterned filling is a good place to start, because patterns are widely used in windowing environments for desktops, window backgrounds, and scroll bars, and for textures and color dithering in drawing and game software.

Fast Mode X fills using patterns that are four pixels in width can be performed by drawing the pattern once to the four pixels at any one address in display memory, reading that address to load the pattern into the latches, setting the Bit Mask register to 0 to specify that all bits drawn to display memory should come from the latches, and then performing the fill pretty much as we did in the previous chapter—except that each line of the pattern must be loaded into the latches before the corresponding scan line on the screen is filled. Listings 33.1 and 33.2 together demonstrate a variety of fast Mode X four-by-four pattern fills. (The mode set function called by Listing 33.1 is from the previous chapter's listings.)

LISTING 33.1 L33-1.C

```
/* Program to demonstrate Mode X (320x240, 256 colors) patterned
   rectangle fills by filling the screen with adjacent 80x60
   rectangles in a variety of patterns. Tested with Borland C++
   in C compilation mode and the small model */
#include <conio.h>
#include <dos.h>

void Set320x240Mode(void);
void FillPatternX(int, int, int, int, unsigned int, char*);

/* 16 4x4 patterns */
static char Patt0[]={10,0,10,0,0,10,0,10,10,0,10,0,0,10,0,10};
static char Patt1[]={9,0,0,0,0,9,0,0,0,0,9,0,0,0,0,9};
static char Patt2[]={5,0,0,0,0,0,5,0,5,0,0,0,0,0,5,0};
static char Patt3[]={14,0,0,14,0,14,14,0,0,14,14,0,14,0,0,14};
static char Patt4[]={15,15,15,1,15,15,1,1,15,1,1,1,1,1,1,1};
static char Patt5[]={12,12,12,12,6,6,6,12,6,6,6,12,6,6,6,12};
static char Patt6[]={80,80,80,80,80,80,80,80,80,80,80,80,80,80,80,15};
static char Patt7[]={78,78,78,78,80,80,80,80,82,82,82,82,84,84,84,84};
static char Patt8[]={78,80,82,84,80,82,84,78,82,84,78,80,84,78,80,82};
static char Patt9[]={78,80,82,84,78,80,82,84,78,80,82,84,78,80,82,84};
static char Patt10[]={0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15};
static char Patt11[]={0,1,2,3,0,1,2,3,0,1,2,3,0,1,2,3};
static char Patt12[]={14,14,9,9,14,9,9,14,9,9,14,14,9,14,14,9};
static char Patt13[]={15,8,8,8,15,15,15,8,15,15,15,8,15,8,8,8};
static char Patt14[]={3,3,3,3,3,7,7,3,3,7,7,3,3,3,3,3};
static char Patt15[]={0,0,0,0,0,64,0,0,0,0,0,0,0,0,0,89};
/* Table of pointers to the 16 4x4 patterns with which to draw */
static char* PattTable[] = {Patt0,Patt1,Patt2,Patt3,Patt4,Patt5,Patt6,
     Patt7,Patt8,Patt9,Patt10,Patt11,Patt12,Patt13,Patt14,Patt15};
```

```
void main() {
   int i,j;
   union REGS regset;

   Set320x240Mode();
   for (j = 0; j < 4; j++) {
      for (i = 0; i < 4; i++) {
         FillPatternX(i*80,j*60,i*80+80,j*60+60,0,PattTable[j*4+i]);
      }
   }
   getch();
   regset.x.ax = 0x0003;   /* switch back to text mode and done */
   int86(0x10, &regset, &regset);
}
```

LISTING 33.2 L33-2.ASM

```
; Mode X (320x240, 256 colors) rectangle 4x4 pattern fill routine.
; Upper left corner of pattern is always aligned to a multiple-of-4
; row and column. Works on all VGAs. Uses approach of copying the
; pattern to off-screen display memory, then loading the latches with
; the pattern for each scan line and filling each scan line four
; pixels at a time. Fills up to but not including the column at EndX
; and the row at EndY. No clipping is performed. All ASM code tested
; with TASM. C near-callable as:
;
;    void FillPatternX(int StartX, int StartY, int EndX, int EndY,
;       unsigned int PageBase, char* Pattern);

SC_INDEX        equ   03c4h             ;Sequence Controller Index register port
MAP_MASK        equ   02h               ;index in SC of Map Mask register
GC_INDEX        equ   03ceh             ;Graphics Controller Index register port
BIT_MASK        equ   08h               ;index in GC of Bit Mask register
PATTERN_BUFFER  equ   0fffch            ;offset in screen memory of the buffer used
                                        ; to store each pattern during drawing
SCREEN_SEG      equ   0a000h            ;segment of display memory in Mode X
SCREEN_WIDTH    equ   80                ;width of screen in addresses from one scan
                                        ; line to the next
parms   struc
        dw      2 dup (?)               ;pushed BP and return address
StartX  dw      ?                       ;X coordinate of upper left corner of rect
StartY  dw      ?                       ;Y coordinate of upper left corner of rect
EndX    dw      ?                       ;X coordinate of lower right corner of rect
                                        ; (the row at EndX is not filled)
EndY    dw      ?                       ;Y coordinate of lower right corner of rect
                                        ; (the column at EndY is not filled)
PageBase dw     ?                       ;base offset in display memory of page in
                                        ; which to fill rectangle
Pattern dw      ?                       ;4x4 pattern with which to fill rectangle
parms   ends

NextScanOffset   equ  -2                ;local storage for distance from end of one
                                        ; scan line to start of next
RectAddrWidth    equ   -4               ;local storage for address width of rectangle
Height           equ   -6               ;local storage for height of rectangle
STACK_FRAME_SIZE equ   6

        .model  small
        .data
```

```
; Plane masks for clipping left and right edges of rectangle.
LeftClipPlaneMask       db      00fh,00eh,00ch,008h
RightClipPlaneMask      db      00fh,001h,003h,007h
        .code
        public  _FillPatternX
_FillPatternX proc    near
        push    bp                      ;preserve caller's stack frame
        mov     bp,sp                   ;point to local stack frame
        sub     sp,STACK_FRAME_SIZE     ;allocate space for local vars
        push    si                      ;preserve caller's register variables
        push    di

        cld
        mov     ax,SCREEN_SEG           ;point ES to display memory
        mov     es,ax
                                        ;copy pattern to display memory buffer
        mov     si,[bp+Pattern]         ;point to pattern to fill with
        mov     di,PATTERN_BUFFER       ;point ES:DI to pattern buffer
        mov     dx,SC_INDEX             ;point Sequence Controller Index to
        mov     al,MAP_MASK             ; Map Mask
        out     dx,al
        inc     dx                      ;point to SC Data register
        mov     cx,4                    ;4 pixel quadruplets in pattern
DownloadPatternLoop:
        mov     al,1                    ;
        out     dx,al                   ;select plane 0 for writes
        movsb                           ;copy over next plane 0 pattern pixel
        dec     di                      ;stay at same address for next plane
        mov     al,2                    ;
        out     dx,al                   ;select plane 1 for writes
        movsb                           ;copy over next plane 1 pattern pixel
        dec     di                      ;stay at same address for next plane
        mov     al,4                    ;
        out     dx,al                   ;select plane 2 for writes
        movsb                           ;copy over next plane 2 pattern pixel
        dec     di                      ;stay at same address for next plane
        mov     al,8                    ;
        out     dx,al                   ;select plane 3 for writes
        movsb                           ;copy over next plane 3 pattern pixel
                                        ; and advance address
        loop    DownloadPatternLoop

        mov     dx,GC_INDEX             ;set the bit mask to select all bits
        mov     ax,00000h+BIT_MASK      ; from the latches and none from
        out     dx,ax                   ; the CPU, so that we can write the
                                        ; latch contents directly to memory
        mov     ax,[bp+StartY]          ;top rectangle scan line
        mov     si,ax
        and     si,011b                 ;top rect scan line modulo 4
        add     si,PATTERN_BUFFER       ;point to pattern scan line that
                                        ; maps to top line of rect to draw
        mov     dx,SCREEN_WIDTH
        mul     dx                      ;offset in page of top rectangle scan line
        mov     di,[bp+StartX]
        mov     bx,di
        shr     di,1                    ;X/4 = offset of first rectangle pixel in scan
        shr     di,1                    ; line
        add     di,ax                   ;offset of first rectangle pixel in page
        add     di,[bp+PageBase]        ;offset of first rectangle pixel in
                                        ; display memory
        and     bx,0003h                     ;look up left edge plane mask
        mov     ah,LeftClipPlaneMask[bx]     ; to clip
        mov     bx,[bp+EndX]
        and     bx,0003h                     ;look up right edge plane
        mov     al,RightClipPlaneMask[bx]    ; mask to clip
        mov     bx,ax                        ;put the masks in BX

        mov     cx,[bp+EndX]            ;calculate # of addresses across rect
        mov     ax,[bp+StartX]
        cmp     cx,ax
        jle     FillDone                ;skip if 0 or negative width
        dec     cx
        and     ax,not 011b
        sub     cx,ax
        shr     cx,1
        shr     cx,1                    ;# of addresses across rectangle to fill - 1
        jnz     MasksSet                ;there's more than one pixel to draw
        and     bh,bl                   ;there's only one pixel, so combine the left
                                        ; and right edge clip masks
MasksSet:
        mov     ax,[bp+EndY]
        sub     ax,[bp+StartY]          ;AX = height of rectangle
        jle     FillDone                ;skip if 0 or negative height
        mov     [bp+Height],ax
        mov     ax,SCREEN_WIDTH
        sub     ax,cx                   ;distance from end of one scan line to start
        dec     ax                      ; of next
        mov     [bp+NextScanOffset],ax
        mov     [bp+RectAddrWidth],cx   ;remember width in addresses - 1
        mov     dx,SC_INDEX+1           ;point to Sequence Controller Data reg
                                        ; (SC Index still points to Map Mask)
FillRowsLoop:
        mov     cx,[bp+RectAddrWidth]   ;width across - 1
        mov     al,es:[si]              ;read display memory to latch this scan
                                        ; line's pattern
        inc     si                      ;point to the next pattern scan line, wrapping
        jnz     short NoWrap            ; back to the start of the pattern if
        sub     si,4                    ; we've run off the end
NoWrap:
        mov     al,bh                   ;put left-edge clip mask in AL
        out     dx,al                   ;set the left-edge plane (clip) mask
        stosb                           ;draw the left edge (pixels come from latches;
                                        ; value written by CPU doesn't matter)
        dec     cx                      ;count off left edge address
        js      FillLoopBottom          ;that's the only address
        jz      DoRightEdge             ;there are only two addresses
        mov     al,00fh                 ;middle addresses are drawn 4 pixels at a pop
        out     dx,al                   ;set the middle pixel mask to no clip
        rep     stosb                   ;draw the middle addresses four pixels apiece
                                        ; (from latches; value written doesn't matter)
DoRightEdge:
        mov     al,bl                   ;put right-edge clip mask in AL
        out     dx,al                   ;set the right-edge plane (clip) mask
        stosb                           ;draw the right edge (from latches; value
                                        ; written doesn't matter)
FillLoopBottom:
        add     di,[bp+NextScanOffset]       ;point to the start of the next scan
                                             ; line of the rectangle
        dec     word ptr [bp+Height]         ;count down scan lines
        jnz     FillRowsLoop
```

```
FillDone:
        mov     dx,GC_INDEX+1               ;restore the bit mask to its default,
        mov     al,0ffh                     ; which selects all bits from the CPU
        out     dx,al                       ; and none from the latches (the GC
                                            ; Index still points to Bit Mask)
        pop     di                          ;restore caller's register variables
        pop     si
        mov     sp,bp                       ;discard storage for local variables
        pop     bp                          ;restore caller's stack frame
        ret
_FillPatternX endp
        end
```

Four-pixel-wide patterns are more useful than you might imagine. There are actually 2^{128} possible patterns (16 pixels, each with 2^8 possible colors); that set is certainly large enough for most color-dithering purposes, and includes many often-used patterns, such as halftones, diagonal stripes, and crosshatches.

Furthermore, eight-wide patterns, which are widely used, can be drawn with two passes, one for each half of the pattern. This principle can in fact be extended to patterns of arbitrary multiple-of-four widths. (Widths that aren't multiples of four are considerably more difficult to handle, because the latches are four pixels wide; one possible solution is expanding such patterns via repetition until they are multiple-of-four widths.)

Allocating Memory in Mode X

Listing 33.2 raises some interesting questions about the allocation of display memory in Mode X. In Listing 33.2, whenever a pattern is to be drawn, that pattern is first drawn in its entirety at the very end of display memory; the latches are then loaded from that copy of the pattern before each scan line of the actual fill is drawn. Why this double copying process, and why is the pattern stored in that particular area of display memory?

The double copying process is used because it's the easiest way to load the latches. Remember, there's no way to get information directly from the CPU to the latches; the information must first be written to some location in display memory, because the latches can be loaded *only* from display memory. By writing the pattern to off-screen memory, we don't have to worry about interfering with whatever is currently displayed on the screen.

As for why the pattern is stored exactly where it is, that's part of a master memory allocation plan that will come to fruition in the next chapter, when I implement a Mode X animation program. Figure 33.3 shows this master plan; the first two pages of memory (each 76,800 pixels long, spanning 19,200 addresses—that is, 19,200 pixel quadruplets—in display memory) are reserved for page flipping, the next page of memory (also 76,800 pixels long) is reserved for storing the background (which is used to restore the holes left after images move), the last 16 pixels (four addresses) of display

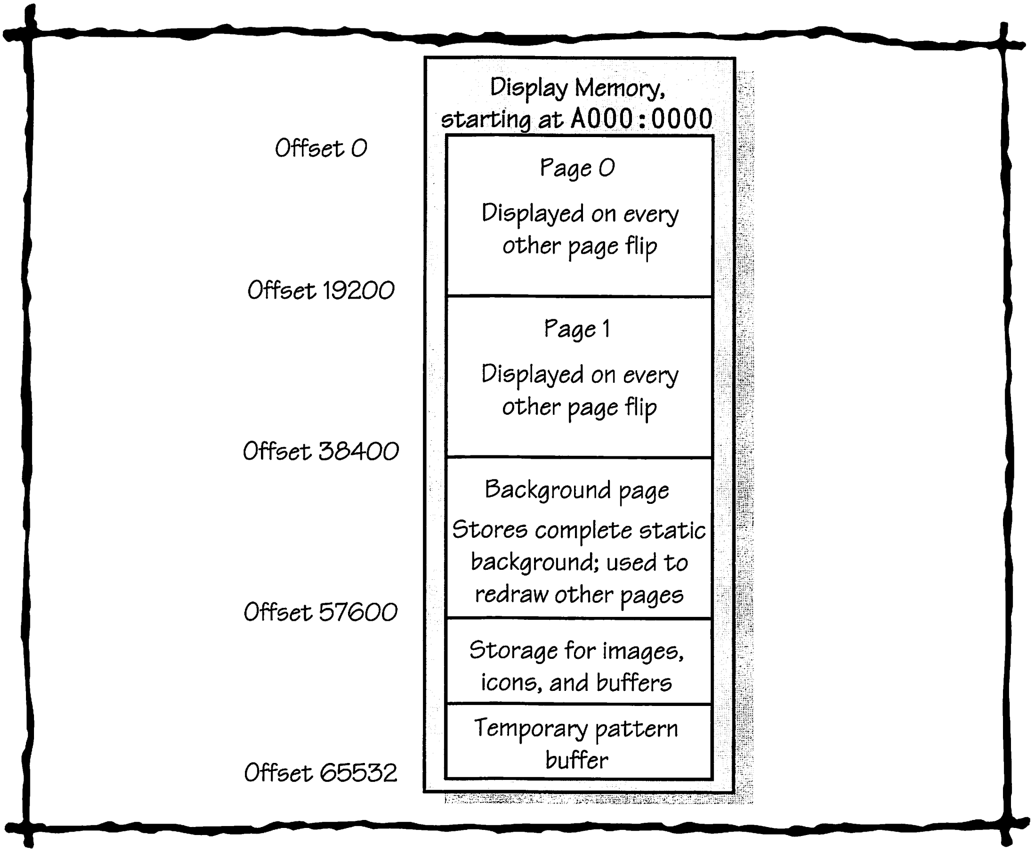

Display Memory, starting at A000:0000
Offset 0
Page 0
Displayed on every other page flip
Offset 19200
Page 1
Displayed on every other page flip
Offset 38400
Background page
Stores complete static background; used to redraw other pages
Offset 57600
Storage for images, icons, and buffers
Temporary pattern buffer
Offset 65532

Figure 33.3 A Useful Mode X Display Memory Layout

memory are reserved for the pattern buffer, and the remaining 31,728 pixels (7,932 addresses) of display memory are free for storage of icons, images, temporary buffers, or whatever.

This is an efficient organization for animation, but there are certainly many other possible setups. For example, you might choose to have a solid-colored background, in which case you could dispense with the background page (instead using the solid rectangle fill routine to replace the background after images move), freeing up another 76,800 pixels of off-screen storage for images and buffers. You could even eliminate page-flipping altogether if you needed to free up a great deal of display memory. For example, with enough free display memory it is possible in Mode X to create a virtual bitmap three times larger than the screen, with the screen becoming a scrolling window onto that larger bitmap. This technique has been used to good effect in a number of animated games, with and without the use of Mode X.

Copying Pixel Blocks within Display Memory

Another fine use for the latches is copying pixels from one place in display memory to another. Whenever both the source and the destination share the same nibble alignment (that is, their start addresses modulo four are the same), it is not only possible but quite easy to use the latches to copy four pixels at a time. Listing 33.3 shows a routine that copies via the latches. (When the source and destination do not share the same nibble alignment, the latches cannot be used because the source and destination planes for any given pixel differ. In that case, you can set the Read Map register to select a source plane and the Map Mask register to select the corresponding destination plane. Then, copy all pixels in that plane, repeating for all four planes.)

Although copying through the latches is, in general, a speedy technique, especially on slower VGAs, it's not always a win. Reading video memory tends to be quite a bit slower than writing, and on a fast VLB or PCI adapter, it can be faster to copy from main memory to display memory than it is to copy from display memory to display memory via the latches.

LISTING 33.3 L33-3.ASM

```
; Mode X (320x240, 256 colors) display memory to display memory copy
; routine. Left edge of source rectangle modulo 4 must equal left edge
; of destination rectangle modulo 4. Works on all VGAs. Uses approach
; of reading 4 pixels at a time from the source into the latches, then
; writing the latches to the destination. Copies up to but not
; including the column at SourceEndX and the row at SourceEndY. No
; clipping is performed. Results are not guaranteed if the source and
; destination overlap. C near-callable as:
;
;    void CopyScreenToScreenX(int SourceStartX, int SourceStartY,
;       int SourceEndX, int SourceEndY, int DestStartX,
;       int DestStartY, unsigned int SourcePageBase,
;       unsigned int DestPageBase, int SourceBitmapWidth,
;       int DestBitmapWidth);

SC_INDEX        equ  03c4h          ;Sequence Controller Index register port
MAP_MASK        equ  02h            ;index in SC of Map Mask register
GC_INDEX        equ  03ceh          ;Graphics Controller Index register port
BIT_MASK        equ  08h            ;index in GC of Bit Mask register
SCREEN_SEG      equ  0a000h         ;segment of display memory in Mode X

parms   struc
                dw   2 dup (?)      ;pushed BP and return address
SourceStartX    dw   ?              ;X coordinate of upper left corner of source
SourceStartY    dw   ?              ;Y coordinate of upper left corner of source
SourceEndX      dw   ?              ;X coordinate of lower right corner of source
                                    ; (the row at SourceEndX is not copied)
SourceEndY      dw   ?              ;Y coordinate of lower right corner of source
                                    ; (the column at SourceEndY is not copied)
DestStartX      dw   ?              ;X coordinate of upper left corner of dest
```

```
DestStartY         dw    ?              ;Y coordinate of upper left corner of dest
SourcePageBase     dw    ?              ;base offset in display memory of page in
                                        ; which source resides
DestPageBase       dw    ?              ;base offset in display memory of page in
                                        ; which dest resides
SourceBitmapWidth  dw    ?              ;# of pixels across source bitmap
                                        ; (must be a multiple of 4)
DestBitmapWidth    dw    ?              ;# of pixels across dest bitmap
                                        ; (must be a multiple of 4)
parms   ends

SourceNextScanOffset  equ   -2          ;local storage for distance from end of
                                        ; one source scan line to start of next
DestNextScanOffset    equ   -4          ;local storage for distance from end of
                                        ; one dest scan line to start of next
RectAddrWidth         equ   -6          ;local storage for address width of rectangle
Height                equ   -8          ;local storage for height of rectangle
STACK_FRAME_SIZE      equ   8

        .model  small
        .data
; Plane masks for clipping left and right edges of rectangle.
LeftClipPlaneMask       db      00fh,00eh,00ch,008h
RightClipPlaneMask      db      00fh,001h,003h,007h
        .code
        public  _CopyScreenToScreenX
_CopyScreenToScreenX proc    near
        push    bp                      ;preserve caller's stack frame
        mov     bp,sp                   ;point to local stack frame
        sub     sp,STACK_FRAME_SIZE     ;allocate space for local vars
        push    si                      ;preserve caller's register variables
        push    di
        push    ds

        cld
        mov     dx,GC_INDEX             ;set the bit mask to select all bits
        mov     ax,00000h+BIT_MASK      ; from the latches and none from
        out     dx,ax                   ; the CPU, so that we can write the
                                        ; latch contents directly to memory
        mov     ax,SCREEN_SEG           ;point ES to display memory
        mov     es,ax
        mov     ax,[bp+DestBitmapWidth]
        shr     ax,1                    ;convert to width in addresses
        shr     ax,1
        mul     [bp+DestStartY]         ;top dest rect scan line
        mov     di,[bp+DestStartX]
        shr     di,1                    ;X/4 = offset of first dest rect pixel in
        shr     di,1                    ; scan line
        add     di,ax                   ;offset of first dest rect pixel in page
        add     di,[bp+DestPageBase]    ;offset of first dest rect pixel
                 ; in display memory
        mov     ax,[bp+SourceBitmapWidth]
        shr     ax,1                    ;convert to width in addresses
        shr     ax,1
        mul     [bp+SourceStartY]       ;top source rect scan line
        mov     si,[bp+SourceStartX]
        mov     bx,si
        shr     si,1                    ;X/4 = offset of first source rect pixel in
        shr     si,1                    ; scan line
        add     si,ax                   ;offset of first source rect pixel in page
        add     si,[bp+SourcePageBase]       ;offset of first source rect
                                             ; pixel in display memory
        and     bx,0003h                     ;look up left edge plane mask
        mov     ah,LeftClipPlaneMask[bx]     ; to clip
        mov     bx,[bp+SourceEndX]
        and     bx,0003h                     ;look up right edge plane
        mov     al,RightClipPlaneMask[bx]    ; mask to clip
        mov     bx,ax                        ;put the masks in BX

        mov     cx,[bp+SourceEndX]           ;calculate # of addresses across
        mov     ax,[bp+SourceStartX]         ; rect
        cmp     cx,ax
        jle     CopyDone                     ;skip if 0 or negative width
        dec     cx
        and     ax,not 011b
        sub     cx,ax
        shr     cx,1
        shr     cx,1                    ;# of addresses across rectangle to copy - 1
        jnz     MasksSet                ;there's more than one address to draw
        and     bh,bl                   ;there's only one address, so combine the
                                        ; left and right edge clip masks
MasksSet:
        mov     ax,[bp+SourceEndY]
        sub     ax,[bp+SourceStartY]    ;AX = height of rectangle
        jle     CopyDone                ;skip if 0 or negative height
        mov     [bp+Height],ax
        mov     ax,[bp+DestBitmapWidth]
        shr     ax,1                    ;convert to width in addresses
        shr     ax,1
        sub     ax,cx                   ;distance from end of one dest scan line to
        dec     ax                      ; start of next
        mov     [bp+DestNextScanOffset],ax
        mov     ax,[bp+SourceBitmapWidth]
        shr     ax,1                    ;convert to width in addresses
        shr     ax,1
        sub     ax,cx                   ;distance from end of one source scan line to
        dec     ax                      ; start of next
        mov     [bp+SourceNextScanOffset],ax
        mov     [bp+RectAddrWidth],cx   ;remember width in addresses - 1
;----------------------BUG FIX
mov     dx,SC_INDEX
        mov     al,MAP_MASK
        out     dx,al       ;point SC Index reg to Map Mask
        inc     dx          ;point to SC Data reg
;----------------------BUG FIX
        mov     ax,es                   ;DS=ES=screen segment for MOVS
        mov     ds,ax
CopyRowsLoop:
        mov     cx,[bp+RectAddrWidth]   ;width across - 1
        mov     al,bh                   ;put left-edge clip mask in AL
        out     dx,al                   ;set the left-edge plane (clip) mask
        movsb                           ;copy the left edge (pixels go through
                                        ; latches)
        dec     cx                      ;count off left edge address
        js      CopyLoopBottom          ;that's the only address
        jz      DoRightEdge             ;there are only two addresses
        mov     al,00fh                 ;middle addresses are drawn 4 pixels at a pop
        out     dx,al                   ;set the middle pixel mask to no clip
        rep     movsb                   ;draw the middle addresses four pixels apiece
                                        ; (pixels copied through latches)
```

```
DoRightEdge:
        mov     al,bl                   ;put right-edge clip mask in AL
        out     dx,al                   ;set the right-edge plane (clip) mask
        movsb                           ;draw the right edge (pixels copied through
                                        ; latches)
CopyLoopBottom:
        add     si,[bp+SourceNextScanOffset]     ;point to the start of
        add     di,[bp+DestNextScanOffset]       ; next source & dest lines
        dec     word ptr [bp+Height]             ;count down scan lines
        jnz     CopyRowsLoop
CopyDone:
        mov     dx,GC_INDEX+1           ;restore the bit mask to its default,
        mov     al,0ffh                 ; which selects all bits from the CPU
        out     dx,al                   ; and none from the latches (the GC
                                        ; Index still points to Bit Mask)
        pop     ds
        pop     di                      ;restore caller's register variables
        pop     si
        mov     sp,bp                   ;discard storage for local variables
        pop     bp                      ;restore caller's stack frame
        ret
_CopyScreenToScreenX endp
        end
```

Listing 33.3 has an important limitation: It does not guarantee proper handling when the source and destination overlap, as in the case of a downward scroll, for example. Listing 33.3 performs top-to-bottom, left-to-right copying. Downward scrolls require bottom-to-top copying; likewise, rightward horizontal scrolls require right-to-left copying. As it happens, my intended use for Listing 33.3 is to copy images between off-screen memory and on-screen memory, and to save areas under pop-up menus and the like, so I don't really need overlap handling—and I do really need to keep the complexity of this discussion down. However, you will surely want to add overlap handling if you plan to perform arbitrary scrolling and copying in display memory.

Now that we have a fast way to copy images around in display memory, we can draw icons and other images as much as four times faster than in mode 13H, depending on the speed of the VGA's display memory. (In case you're worried about the nibble-alignment limitation on fast copies, don't be; I'll address that fully in due time, but the secret is to store all four possible rotations in off-screen memory, then select the correct one for each copy.) However, before our fast display memory-to-display memory copy routine can do us any good, we must have a way to get pixel patterns from system memory into display memory, so that they can then be copied with the fast copy routine.

Copying to Display Memory

The final piece of the puzzle is the system memory to display-memory-copy-routine shown in Listing 33.4. This routine assumes that pixels are stored in system memory in exactly the order in which they will ultimately appear on the screen; that is, in the same linear order that mode 13H uses. It would be more efficient to store all the pixels for one plane first, then all the pixels for the next plane, and so on for all four planes, because many OUTs could be avoided, but that would make images rather hard to create. And, while it is true that the speed of drawing images is, in general, often a critical performance factor, the speed of copying images from system memory to display memory is not particularly critical in Mode X. Important images can be stored in off-screen memory and copied to the screen via the latches much faster than even the speediest system memory-to-display memory copy routine could manage.

I'm not going to present a routine to perform Mode X copies from display memory to system memory, but such a routine would be a straightforward inverse of Listing 33.4.

LISTING 33.4 L33-4.ASM

```
; Mode X (320x240, 256 colors) system memory to display memory copy
; routine. Uses approach of changing the plane for each pixel copied;
; this is slower than copying all pixels in one plane, then all pixels
; in the next plane, and so on, but it is simpler; besides, images for
; which performance is critical should be stored in off-screen memory
; and copied to the screen via the latches. Copies up to but not
; including the column at SourceEndX and the row at SourceEndY. No
; clipping is performed. C near-callable as:
;
;    void CopySystemToScreenX(int SourceStartX, int SourceStartY,
;       int SourceEndX, int SourceEndY, int DestStartX,
;       int DestStartY, char* SourcePtr, unsigned int DestPageBase,
;       int SourceBitmapWidth, int DestBitmapWidth);

SC_INDEX        equ   03c4h            ;Sequence Controller Index register port
MAP_MASK        equ   02h              ;index in SC of Map Mask register
SCREEN_SEG      equ   0a000h           ;segment of display memory in Mode X

parms   struc
                  dw    2 dup (?)      ;pushed BP and return address
SourceStartX      dw    ?              ;X coordinate of upper left corner of source
SourceStartY      dw    ?              ;Y coordinate of upper left corner of source
SourceEndX        dw    ?              ;X coordinate of lower right corner of source
                                       ; (the row at EndX is not copied)
SourceEndY        dw    ?              ;Y coordinate of lower right corner of source
                                       ; (the column at EndY is not copied)
DestStartX        dw    ?              ;X coordinate of upper left corner of dest
DestStartY        dw    ?              ;Y coordinate of upper left corner of dest
SourcePtr         dw    ?              ;pointer in DS to start of bitmap in which
                                       ; source resides
DestPageBase      dw    ?              ;base offset in display memory of page in
                                       ; which dest resides
SourceBitmapWidth  dw    ?             ;# of pixels across source bitmap
DestBitmapWidth    dw    ?             ;# of pixels across dest bitmap
                                       ; (must be a multiple of 4)
parms   ends

RectWidth        equ    -2             ;local storage for width of rectangle
LeftMask         equ    -4             ;local storage for left rect edge plane mask
STACK_FRAME_SIZE equ    4

        .model  small
        .code
        public  _CopySystemToScreenX
_CopySystemToScreenX proc    near
        push    bp                              ;preserve caller's stack frame
        mov     bp,sp                           ;point to local stack frame
        sub     sp,STACK_FRAME_SIZE             ;allocate space for local vars
        push    si                              ;preserve caller's register variables
        push    di

        cld
        mov     ax,SCREEN_SEG                   ;point ES to display memory
        mov     es,ax
        mov     ax,[bp+SourceBitmapWidth]
        mul     [bp+SourceStartY]               ;top source rect scan line
        add     ax,[bp+SourceStartX]
        add     ax,[bp+SourcePtr]               ;offset of first source rect pixel
        mov     si,ax                           ; in DS

        mov     ax,[bp+DestBitmapWidth]
        shr     ax,1                            ;convert to width in addresses
        shr     ax,1
        mov     [bp+DestBitmapWidth],ax         ;remember address width
        mul     [bp+DestStartY]                 ;top dest rect scan line
        mov     di,[bp+DestStartX]
        mov     cx,di
        shr     di,1                            ;X/4 = offset of first dest rect pixel in
        shr     di,1                            ; scan line
        add     di,ax                           ;offset of first dest rect pixel in page
        add     di,[bp+DestPageBase]            ;offset of first dest rect pixel
                                                ; in display memory
        and     cl,011b                         ;CL = first dest pixel's plane
        mov     al,11h                          ;upper nibble comes into play when
                                                ; plane wraps from 3 back to 0
        shl     al,cl                           ;set the bit for the first dest pixel's
        mov     [bp+LeftMask],al                ; plane in each nibble to 1

        mov     cx,[bp+SourceEndX]              ;calculate # of pixels across
        sub     cx,[bp+SourceStartX]            ; rect
        jle     CopyDone                        ;skip if 0 or negative width
        mov     [bp+RectWidth],cx
        mov     bx,[bp+SourceEndY]
        sub     bx,[bp+SourceStartY]            ;BX = height of rectangle
        jle     CopyDone                        ;skip if 0 or negative height
        mov     dx,SC_INDEX                     ;point to SC Index register
        mov     al,MAP_MASK
        out     dx,al                           ;point SC Index reg to the Map Mask
        inc     dx                              ;point DX to SC Data reg
CopyRowsLoop:
        mov     ax,[bp+LeftMask]
        mov     cx,[bp+RectWidth]
        push    si                              ;remember the start offset in the source
        push    di                              ;remember the start offset in the dest
CopyScanLineLoop:
        out     dx,al                           ;set the plane for this pixel
        movsb                                   ;copy the pixel to the screen
        rol     al,1                            ;set mask for next pixel's plane
        cmc                                     ;advance destination address only when
        sbb     di,0                            ; wrapping from plane 3 to plane 0
                                                ; (else undo INC DI done by MOVSB)
        loop    CopyScanLineLoop
        pop     di                              ;retrieve the dest start offset
        add     di,[bp+DestBitmapWidth]      ;point to the start of the
                                             ; next scan line of the dest
        pop     si                           ;retrieve the source start offset
        add     si,[bp+SourceBitmapWidth]    ;point to the start of the
                                             ; next scan line of the source
        dec     bx                           ;count down scan lines
        jnz     CopyRowsLoop
CopyDone:
        pop     di                           ;restore caller's register variables
        pop     si
        mov     sp,bp                        ;discard storage for local variables
        pop     bp                           ;restore caller's stack frame
        ret
_CopySystemToScreenX endp
        end
```

Who Was that Masked Image Copier?

At this point, it's getting to be time for us to take all the Mode X tools we've developed, together with one more tool—masked image copying—and the remaining unexplored feature of Mode X, page flipping, and build an animation application. I hope that when we're done, you'll agree with me that Mode X is *the* way to animate on the PC.

In truth, though, it matters less whether or not *you* think that Mode X is the best way to animate than whether or not your users think it's the best way based on results; end users care only about results, not how you produced them. For my writing, you folks are the end users—and notice how remarkably little you care about how this book gets written and produced. You care that it turned up in the bookstore, and you care about the contents, but you sure as heck don't care about how it got that far from a bin of tree pulp. When you're a creator, the process matters. When you're a buyer, results are everything. All important. *Sine qua non.* The whole enchilada.

If you catch my drift.

Mode X 256-Color Animation

Chapter 34

How to Make the VGA Really Get up and Dance

OK—no amusing stories or informative anecdotes to kick off this chapter; lotta ground to cover, gotta hurry—you're impatient, I can smell it. I won't talk about the time a friend made the mistake of loudly saying "$100 bill" during an animated discussion while walking among the bums on Market Street in San Francisco one night, thereby graphically illustrating that context is everything. I can't spare a word about how my daughter thinks my 11-year-old floppy-disk-based CP/M machine is more powerful than my 386 with its 100-Mbyte hard disk because the CP/M machine's word processor loads and runs twice as fast as the 386's Windows-based word processor, demonstrating that progress is not the neat exponential curve we'd like to think it is, and that features and performance are often conflicting notions. And, lord knows, I can't take the time to discuss the habits of small white dogs, notwithstanding that such dogs seem to be relevant to just about every aspect of computing, as Jeff Duntemann's writings make manifest. No lighthearted fluff for us; we have real work to do, for today we animate with 256 colors in Mode X.

Masked Copying

Over the past two chapters, we've put together most of the tools needed to implement animation in the VGA's undocumented 320 × 240 256-color Mode X. We now have mode set code, solid and 4 × 4 pattern fills, system memory-to-display memory block copies, and display memory-to-display memory block copies. The final piece of the puzzle is the ability to copy a nonrectangular image to display memory. I call this *masked copying.*

Masked copying is sort of like drawing through a stencil, in that only certain pixels within the destination rectangle are drawn. The objective is to fit the image seamlessly into the background, without the rectangular fringe that results when nonrectangular images are drawn by block copying their bounding rectangle. This is accomplished by using a second rectangular bitmap, separate from the image but corresponding to it on a pixel-by-pixel basis, to control which destination pixels are set from the source and which are left unchanged. With a masked copy, only those pixels properly belonging to an image are drawn, and the image fits perfectly into the background, with no rectangular border. In fact, masked copying even makes it possible to have transparent areas within images.

Note that another way to achieve this effect is to implement copying code that supports a transparent color; that is, a color that doesn't get copied but rather leaves the destination unchanged. Transparent copying makes for more compact images, because no separate mask is needed, and is generally faster in a software-only implementation. However, Mode X supports masked copying but not transparent copying in hardware, so we'll use masked copying in this chapter.

The system memory to display memory masked copy routine in Listing 34.1 implements masked copying in a straightforward fashion. In the main drawing loop, the corresponding mask byte is consulted as each image pixel is encountered, and the image pixel is copied only if the mask byte is nonzero. As with most of the system-to-display code I've presented, Listing 34.1 is not heavily optimized, because it's inherently slow; there's a better way to go when performance matters, and that's to use the VGA's hardware.

LISTING 34.1 L34-1.ASM

```
; Mode X (320x240, 256 colors) system memory-to-display memory masked copy
; routine. Not particularly fast; images for which performance is critical
; should be stored in off-screen memory and copied to screen via latches. Works
; on all VGAs. Copies up to but not including column at SourceEndX and row at
; SourceEndY. No clipping is performed. Mask and source image are both byte-
; per-pixel, and must be of same widths and reside at same coordinates in their
; respective bitmaps. Assembly code tested with TASM C near-callable as:
;
;    void CopySystemToScreenMaskedX(int SourceStartX,
;       int SourceStartY, int SourceEndX, int SourceEndY,
;       int DestStartX, int DestStartY, char * SourcePtr,
;       unsigned int DestPageBase, int SourceBitmapWidth,
;       int DestBitmapWidth, char * MaskPtr);

SC_INDEX         equ  03c4h            ;Sequence Controller Index register port
MAP_MASK         equ  02h              ;index in SC of Map Mask register
SCREEN_SEG       equ  0a000h           ;segment of display memory in mode X

parms   struc
                 dw   2 dup (?)        ;pushed BP and return address
SourceStartX     dw   ?                ;X coordinate of upper left corner of source
                                       ; (source is in system memory)
SourceStartY     dw   ?                ;Y coordinate of upper left corner of source
SourceEndX       dw   ?                ;X coordinate of lower right corner of source
                                       ; (the column at EndX is not copied)
SourceEndY       dw   ?                ;Y coordinate of lower right corner of source
                                       ; (the row at EndY is not copied)
```

```
DestStartX       dw    ?    ;X coordinate of upper left corner of dest
                            ; (destination is in display memory)
DestStartY       dw    ?    ;Y coordinate of upper left corner of dest
SourcePtr        dw    ?    ;pointer in DS to start of bitmap which source resides
DestPageBase     dw    ?    ;base offset in display memory of page in
                            ; which dest resides
SourceBitmapWidth  dw  ?    ;# of pixels across source bitmap (also must
                            ; be width across the mask)
DestBitmapWidth    dw  ?    ;# of pixels across dest bitmap (must be multiple of 4)
MaskPtr            dw  ?    ;pointer in DS to start of bitmap in which mask
                            ; resides (byte-per-pixel format, just like the source
                            ; image; 0-bytes mean don't copy corresponding source
                            ; pixel, 1-bytes mean do copy)
parms   ends

RectWidth        equ   -2   ;local storage for width of rectangle
RectHeight       equ   -4   ;local storage for height of rectangle
LeftMask         equ   -6   ;local storage for left rect edge plane mask
STACK_FRAME_SIZE equ 6
        .model  small
        .code
        public  _CopySystemToScreenMaskedX
_CopySystemToScreenMaskedX proc    near
        push    bp                     ;preserve caller's stack frame
        mov     bp,sp                  ;point to local stack frame
        sub     sp,STACK_FRAME_SIZE    ;allocate space for local vars
        push    si                     ;preserve caller's register variables
        push    di

        mov     ax,SCREEN_SEG          ;point ES to display memory
        mov     es,ax
        mov     ax,[bp+SourceBitmapWidth]
        mul     [bp+SourceStartY]      ;top source rect scan line
        add     ax,[bp+SourceStartX]
        mov     bx,ax
        add     ax,[bp+SourcePtr]      ;offset of first source rect pixel
        mov     si,ax                  ; in DS
        add     bx,[bp+MaskPtr]        ;offset of first mask pixel in DS

        mov     ax,[bp+DestBitmapWidth]
        shr     ax,1                   ;convert to width in addresses
        shr     ax,1
        mov     [bp+DestBitmapWidth],ax ;remember address width
        mul     [bp+DestStartY] ;top dest rect scan line
        mov     di,[bp+DestStartX]
        mov     cx,di
        shr     di,1                   ;X/4 = offset of first dest rect pixel in
        shr     di,1                   ; scan line
        add     di,ax                  ;offset of first dest rect pixel in page
        add     di,[bp+DestPageBase]   ;offset of first dest rect pixel
                                       ; in display memory
        and     cl,011b                ;CL = first dest pixel's plane
        mov     al,11h                 ;upper nibble comes into play when plane wraps
                                       ; from 3 back to 0
        shl     al,cl                  ;set the bit for the first dest pixel's plane
        mov     [bp+LeftMask],al       ; in each nibble to 1

        mov     ax,[bp+SourceEndX]     ;calculate # of pixels across
        sub     ax,[bp+SourceStartX]   ; rect
        jle     CopyDone               ;skip if 0 or negative width
        mov     [bp+RectWidth],ax
        sub     word ptr [bp+SourceBitmapWidth],ax
                    ;distance from end of one source scan line to start of next
        mov     ax,[bp+SourceEndY]
        sub     ax,[bp+SourceStartY]        ;height of rectangle
        jle     CopyDone                    ;skip if 0 or negative height
        mov     [bp+RectHeight],ax
        mov     dx,SC_INDEX                 ;point to SC Index register
        mov     al,MAP_MASK
        out     dx,al                       ;point SC Index reg to the Map Mask
        inc     dx                          ;point DX to SC Data reg
CopyRowsLoop:
        mov     al,[bp+LeftMask]
        mov     cx,[bp+RectWidth]
        push    di                          ;remember the start offset in the dest
CopyScanLineLoop:
        cmp     byte ptr [bx],0             ;is this pixel mask-enabled?
        jz      MaskOff                     ;no, so don't draw it
                                            ;yes, draw the pixel
        out     dx,al                       ;set the plane for this pixel
        mov     ah,[si]                     ;get the pixel from the source
        mov     es:[di],ah                  ;copy the pixel to the screen
MaskOff:
        inc     bx                          ;advance the mask pointer
        inc     si                          ;advance the source pointer
        rol     al,1                        ;set mask for next pixel's plane
        adc     di,0                        ;advance destination address only when
                                            ; wrapping from plane 3 to plane 0
        loop    CopyScanLineLoop
        pop     di                          ;retrieve the dest start offset
        add     di,[bp+DestBitmapWidth]     ;point to the start of the
                                            ; next scan line of the dest
        add     si,[bp+SourceBitmapWidth]   ;point to the start of the
                                            ; next scan line of the source
        add     bx,[bp+SourceBitmapWidth]   ;point to the start of the
                                            ; next scan line of the mask
        dec     word ptr [bp+RectHeight]    ;count down scan lines
        jnz     CopyRowsLoop
CopyDone:
        pop     di                          ;restore caller's register variables
        pop     si
        mov     sp,bp                       ;discard storage for local variables
        pop     bp                          ;restore caller's stack frame
        ret
_CopySystemToScreenMaskedX endp
        end
```

Faster Masked Copying

In the previous chapter we saw how the VGA's latches can be used to copy four pixels at a time from one area of display memory to another in Mode X. We've further seen that in Mode X the Map Mask register can be used to select which planes are copied. That's all we need to know to be able to perform fast masked copies; we can store an image in off-screen display memory, and set the Map Mask to the appropriate mask value as up to four pixels at a time are copied.

There's a slight hitch, though. The latches can only be used when the source and destination left edge coordinates, modulo four, are the same, as explained in the previous chapter. The solution is to copy all four possible alignments of each image to display memory, each properly positioned for one of the four possible destination-left-edge-modulo-four cases. These aligned images must be accompanied by the four possible alignments of the image mask, stored in system memory. Given all four image and mask alignments, masked copying is a simple matter of selecting the alignment that's appropriate for the destination's left edge, then setting the Map Mask with the 4-bit mask corresponding to each four-pixel set as we copy four pixels at a time via the latches.

Listing 34.2 performs fast masked copying. This code expects to receive a pointer to a **MaskedImage** structure, which in turn points to four **AlignedMaskedImage** structures that describe the four possible image and mask alignments. The aligned images are already stored in display memory, and the aligned masks are already stored in system memory; further, the masks are predigested into Map Mask register-compatible form. Given all that ready-to-use data, Listing 34.2 selects and works with the appropriate image-mask pair for the destination's left edge alignment.

LISTING 34.2 L34-2.ASM

```
; Mode X (320x240, 256 colors) display memory to display memory masked copy
; routine. Works on all VGAs. Uses approach of reading 4 pixels at a time from
; source into latches, then writing latches to destination, using Map Mask
; register to perform masking. Copies up to but not including column at
; SourceEndX and row at SourceEndY. No clipping is performed. Results are not
; guaranteed if source and destination overlap. C near-callable as:
;
;    void CopyScreenToScreenMaskedX(int SourceStartX,
;       int SourceStartY, int SourceEndX, int SourceEndY,
;       int DestStartX, int DestStartY, MaskedImage * Source,
;       unsigned int DestPageBase, int DestBitmapWidth);

SC_INDEX        equu    03c4h     ;Sequence Controller Index register port
MAP_MASK        equ     02h       ;index in SC of Map Mask register
GC_INDEX        equ     03ceh     ;Graphics Controller Index register port
BIT_MASK        equ     08h       ;index in GC of Bit Mask register
SCREEN_SEG      equ     0a000h    ;segment of display memory in mode X

parms   struc
                dw    2 dup (?)   ;pushed BP and return address
SourceStartX    dw    ?           ;X coordinate of upper left corner of source
SourceStartY    dw    ?           ;Y coordinate of upper left corner of source
SourceEndX      dw    ?           ;X coordinate of lower right corner of source
                                  ; (the column at SourceEndX is not copied)
SourceEndY      dw    ?           ;Y coordinate of lower right corner of source
                                  ; (the row at SourceEndY is not copied)
DestStartX      dw    ?           ;X coordinate of upper left corner of dest
DestStartY      dw    ?           ;Y coordinate of upper left corner of dest
Source          dw    ?           ;pointer to MaskedImage struct for source
                                  ; which source resides
DestPageBase    dw    ?           ;base offset in display memory of page in
                                  ; which dest resides
DestBitmapWidth dw    ?           ;# of pixels across dest bitmap (must be multiple of 4)
parms   ends
```

```
SourceNextScanOffset  equu  -2        ;local storage for distance from end of
                                      ; one source scan line to start of next
DestNextScanOffset    equ   -4        ;local storage for distance from end of
                                      ; one dest scan line to start of next
RectAddrWidth         equ   -6        ;local storage for address width of rectangle
RectHeight            equ   -8        ;local storage for height of rectangle
SourceBitmapWidth     equ   -10       ;local storage for width of source bitmap
                                      ; (in addresses)
STACK_FRAME_SIZE      equ   10
MaskedImage     struc
 Alignments           dw  4 dup(?)    ;pointers to AlignedMaskedImages for the
                                      ; 4 possible destination image alignments
MaskedImage     ends
AlignedMaskedImage      struc
 ImageWidth     dw      ?   ;image width in addresses (also mask width in bytes)
 ImagePtr       dw      ?   ;offset of image bitmap in display memory
 MaskPtr        dw      ?   ;pointer to mask bitmap in DS
AlignedMaskedImage      ends
        .model  small
        .code
        public  _CopyScreenToScreenMaskedX
_CopyScreenToScreenMaskedX proc    near
        push    bp                    ;preserve caller's stack frame
        mov     bp,sp                 ;point to local stack frame
        sub     sp,STACK_FRAME_SIZE   ;allocate space for local vars
        push    si                    ;preserve caller's register variables
        push    di

        cld
        mov     dx,GC_INDEX           ;set the bit mask to select all bits
        mov     ax,00000h+BIT_MASK    ; from the latches and none from
        out     dx,ax                 ; the CPU, so that we can write the
                                      ; latch contents directly to memory
        mov     ax,SCREEN_SEG         ;point ES to display memory
        mov     es,ax
        mov     ax,[bp+DestBitmapWidth]
        shr     ax,1                  ;convert to width in addresses
        shr     ax,1
        mul     [bp+DestStartY]       ;top dest rect scan line
        mov     di,[bp+DestStartX]
        mov     si,di
        shr     di,1                  ;X/4 = offset of first dest rect pixel in
        shr     di,1                  ; scan line
        add     di,ax                 ;offset of first dest rect pixel in page
        add     di,[bp+DestPageBase]  ;offset of first dest rect pixel in display
                                      ; memory. now look up the image that's
                                      ; aligned to match left-edge alignment
                                      ; of destination
        and     si,3                  ;DestStartX modulo 4
        mov     cx,si                 ;set aside alignment for later
        shl     si,1                  ;prepare for word look-up
        mov     bx,[bp+Source]        ;point to source MaskedImage structure
        mov     bx,[bx+Alignments+si] ;point to AlignedMaskedImage
                                      ; struc for current left edge alignment
        mov     ax,[bx+ImageWidth]    ;image width in addresses
        mov     [bp+SourceBitmapWidth],ax    ;remember image width in addresses
        mul     [bp+SourceStartY]     ;top source rect scan line
        mov     si,[bp+SourceStartX]
        shr     si,1                  ;X/4 = address of first source rect pixel in
        shr     si,1                  ; scan line
        add     si,ax                 ;offset of first source rect pixel in image
        mov     ax,si
        add     si,[bx+MaskPtr]       ;point to mask offset of first mask pixel in DS
        mov     bx,[bx+ImagePtr]      ;offset of first source rect pixel
        add     bx,ax                 ; in display memory

        mov     ax,[bp+SourceStartX]  ;calculate # of addresses across
        add     ax,cx                 ; rect, shifting if necessary to
        add     cx,[bp+SourceEndX]    ; account for alignment
        cmp     cx,ax
        jle     CopyDone              ;skip if 0 or negative width
        add     cx,3
        and     ax,not 011b
        sub     cx,ax
        shr     cx,1
        shr     cx,1                  ;# of addresses across rectangle to copy
        mov     ax,[bp+SourceEndY]
        sub     ax,[bp+SourceStartY]  ;AX = height of rectangle
        jle     CopyDone              ;skip if 0 or negative height
        mov     [bp+RectHeight],ax
        mov     ax,[bp+DestBitmapWidth]
        shr     ax,1                  ;convert to width in addresses
        shr     ax,1
        sub     ax,cx      ;distance from end of one dest scan line to start of next
        mov     [bp+DestNextScanOffset],ax
        mov     ax,[bp+SourceBitmapWidth]   ;width in addresses
        sub     ax,cx      ;distance from end of source scan line to start of next
        mov     [bp+SourceNextScanOffset],ax
        mov     [bp+RectAddrWidth],cx ;remember width in addresses

        mov     dx,SC_INDEX
        mov     al,MAP_MASK
        out     dx,al                 ;point SC Index register to Map Mask
        inc     dx                    ;point to SC Data register
CopyRowsLoop:
        mov     cx,[bp+RectAddrWidth] ;width across
CopyScanLineLoop:
        lodsb                         ;get the mask for this four-pixel set
                                      ; and advance the mask pointer
        out     dx,al                 ;set the mask
        mov     al,es:[bx]            ;load the latches with 4-pixel set from source
        mov     es:[di],al            ;copy the four-pixel set to the dest
        inc     bx                    ;advance the source pointer
        inc     di                    ;advance the destination pointer
        dec     cx                    ;count off four-pixel sets
        jnz     CopyScanLineLoop

        mov     ax,[bp+SourceNextScanOffset]
        add     si,ax                       ;point to the start of
        add     bx,ax                       ; the next source, mask,
        add     di,[bp+DestNextScanOffset]  ; and dest lines
        dec     word ptr [bp+RectHeight]    ;count down scan lines
        jnz     CopyRowsLoop
CopyDone:
        mov     dx,GC_INDEX+1         ;restore the bit mask to its default,
        mov     al,0ffh               ; which selects all bits from the CPU
        out     dx,al                 ; and none from the latches (the GC
                                      ; Index still points to Bit Mask)
        pop     di                    ;restore caller's register variables
        pop     si
        mov     sp,bp                 ;discard storage for local variables
        pop     bp                    ;restore caller's stack frame
        ret
_CopyScreenToScreenMaskedX endp
        end
```

It would be handy to have a function that, given a base image and mask, generates the four image and mask alignments and fills in the **MaskedImage** structure. Listing 34.3, together with the include file in Listing 34.4 and the system memory-to-display memory block-copy routine in Listing 33.4 (in the previous chapter) does just that. It would be faster if Listing 34.3 were in assembly language, but there's no reason to think that generating aligned images needs to be particularly fast; in such cases, I prefer to use C, for reasons of coding speed, fewer bugs, and maintainability.

LISTING 34.3 L34-3.C

```
/* Generates all four possible mode X image/mask alignments, stores image
alignments in display memory, allocates memory for and generates mask
alignments, and fills out an AlignedMaskedImage structure. Image and mask must
both be in byte-per-pixel form, and must both be of width ImageWidth. Mask
maps isomorphically (one to one) onto image, with each 0-byte in mask masking
off corresponding image pixel (causing it not to be drawn), and each non-0-byte
allowing corresponding image pixel to be drawn. Returns 0 if failure, or # of
display memory addresses (4-pixel sets) used if success. For simplicity,
allocated memory is not deallocated in case of failure. Compiled with
Borland C++ in C compilation mode. */

#include <stdio.h>
#include <stdlib.h>
#include "maskim.h"

extern void CopySystemToScreenX(int, int, int, int, int, int, char *,
   unsigned int, int, int);
unsigned int CreateAlignedMaskedImage(MaskedImage * ImageToSet,
   unsigned int DispMemStart, char * Image, int ImageWidth,
   int ImageHeight, char * Mask)
{
   int Align, ScanLine, BitNum, Size, TempImageWidth;
   unsigned char MaskTemp;
   unsigned int DispMemOffset = DispMemStart;
   AlignedMaskedImage *WorkingAMImage;
   char *NewMaskPtr, *OldMaskPtr;
   /* Generate each of the four alignments in turn. */
   for (Align = 0; Align < 4; Align++) {
      /* Allocate space for the AlignedMaskedImage struct for this alignment. */
      if ((WorkingAMImage = ImageToSet->Alignments[Align] =
            malloc(sizeof(AlignedMaskedImage))) == NULL)
         return 0;
      WorkingAMImage->ImageWidth =
            (ImageWidth + Align + 3) / 4; /* width in 4-pixel sets */
      WorkingAMImage->ImagePtr = DispMemOffset; /* image dest */
      /* Download this alignment of the image. */
      CopySystemToScreenX(0, 0, ImageWidth, ImageHeight, Align, 0,
            Image, DispMemOffset, ImageWidth, WorkingAMImage->ImageWidth * 4);
      /* Calculate the number of bytes needed to store the mask in
         nibble (Map Mask-ready) form, then allocate that space. */
      Size = WorkingAMImage->ImageWidth * ImageHeight;
      if ((WorkingAMImage->MaskPtr = malloc(Size)) == NULL)
```

```
         return 0;
      /* Generate this nibble oriented (Map Mask-ready) alignment of
         the mask, one scan line at a time. */
      OldMaskPtr = Mask;
      NewMaskPtr = WorkingAMImage->MaskPtr;
      for (ScanLine = 0; ScanLine < ImageHeight; ScanLine++) {
         BitNum = Align;
         MaskTemp = 0;
         TempImageWidth = ImageWidth;
         do {
            /* Set the mask bit for next pixel according to its alignment. */
            MaskTemp |= (*OldMaskPtr++ != 0) << BitNum;
            if (++BitNum > 3) {
               *NewMaskPtr++ = MaskTemp;
               MaskTemp = BitNum = 0;
            }
         } while (--TempImageWidth);
         /* Set any partial final mask on this scan line. */
         if (BitNum != 0) *NewMaskPtr++ = MaskTemp;
      }
      DispMemOffset += Size; /* mark off the space we just used */
   }
   return DispMemOffset - DispMemStart;
}
```

LISTING 34.4 MASKIM.H

```
/* MASKIM.H: structures used for storing and manipulating masked
   images */

/* Describes one alignment of a mask-image pair. */
typedef struct {
   int ImageWidth; /* image width in addresses in display memory (also
                      mask width in bytes) */
   unsigned int ImagePtr; /* offset of image bitmap in display mem */
   char *MaskPtr;  /* pointer to mask bitmap */
} AlignedMaskedImage;

/* Describes all four alignments of a mask-image pair. */
typedef struct {
   AlignedMaskedImage *Alignments[4]; /* ptrs to AlignedMaskedImage
                                         structs for four possible destination
                                         image alignments */
} MaskedImage;
```

Notes on Masked Copying

Listings 34.1 and 34.2, like all Mode X code I've presented, perform no clipping, because clipping code would complicate the listings too much. While clipping can be implemented directly in the low-level Mode X routines (at the beginning of Listing 34.1, for instance), another, potentially simpler approach would be to perform clipping at a higher level, modifying the coordinates and dimensions passed to low-level routines such as Listings 34.1 and 34.2 as necessary to accomplish the desired clipping. It is for precisely this reason that the low-level Mode X routines support programmable start coordinates in the source images, rather than assuming (0,0); likewise for the distinction between the width of the image and the width of the area of the image to draw.

Also, it would be more efficient to make up structures that describe the source and destination bitmaps, with dimensions and coordinates built in, and simply pass pointers to these structures to the low level, rather than passing many separate parameters, as is now the case. I've used separate parameters for simplicity and flexibility.

Be aware that as nifty as Mode X hardware-assisted masked copying is, whether or not it's actually faster than software-only masked or transparent copying depends upon the processor and the video adapter. The advantage of Mode X masked copying is the 32-bit parallelism; the disadvantages are the need to read display memory and the need to perform an ***OUT*** *for every four pixels. (****OUT*** *is a slow 486/Pentium instruction, and most VGAs respond to* ***OUTs*** *much more slowly than to display memory writes.)*

Animation

Gosh. There's just no way I can discuss high-level animation fundamentals in any detail here; I could spend an entire (and entirely separate) book on animation techniques alone. You might want to have a look at Part VII before attacking the code in this chapter; that will have to do us for the present volume. (I will return to *3-D* animation in Part IX of this book.)

Basically, I'm going to perform page-flipped animation, in which one page (that is, a bitmap large enough to hold a full screen) of display memory is displayed while another page is drawn to. When the drawing is finished, the newly modified page is displayed, and the other—now invisible—page is drawn to. The process repeats ad infinitum. For further information, some good places to start are *Computer Graphics*, by Foley and van Dam (Addison-Wesley); *Principles of Interactive Computer Graphics*, by Newman and Sproull (McGraw Hill); and "Real-Time Animation" by Rahner James (January 1990, *Dr. Dobb's Journal*);

Some of the code in this chapter was adapted for Mode X from the code in Chapter 29—yet another reason to read that chapter before finishing this one.

Mode X Animation in Action

Listing 34.5 ties together everything I've discussed about Mode X so far in a compact but surprisingly powerful animation package. Listing 34.5 first uses solid and patterned fills and system-memory-to-screen-memory masked copying to draw a static background containing a mountain, a sun, a plain, water, and a house with puffs of smoke coming out of the chimney, and sets up the four alignments of a masked kite image. The background is transferred to both display pages, and drawing of twenty kite images in the nondisplayed page using fast masked copying begins. After all images have been drawn, the page is flipped to show the newly updated screen, and the kites are moved and drawn in the other page, which is no longer displayed. Kites are erased at their old positions in the nondisplayed page by block copying from the background page. (See the discussion in the previous chapter for the display memory organization used by Listing 34.5.) So far as the displayed image is concerned, there is never any hint of flicker or disturbance of the background. This continues at a rate of up to 60 times a second until Esc is pressed to exit the program. See Figure 34.1 for a screen shot of the resulting image—add the animation in your imagination.

LISTING 34.5 L34-5.C

```
/* Sample mode X VGA animation program. Portions of this code first appeared
   in PC Techniques. Compiled with Borland C++ 2.0 in C compilation mode. */

#include <stdio.h>
#include <conio.h>
#include <dos.h>
#include <math.h>
#include "maskim.h"

#define SCREEN_SEG          0xA000
#define SCREEN_WIDTH        320
#define SCREEN_HEIGHT       240
#define PAGE0_START_OFFSET 0
#define PAGE1_START_OFFSET (((long)SCREEN_HEIGHT*SCREEN_WIDTH)/4)
#define BG_START_OFFSET    (((long)SCREEN_HEIGHT*SCREEN_WIDTH*2)/4)
#define DOWNLOAD_START_OFFSET (((long)SCREEN_HEIGHT*SCREEN_WIDTH*3)/4)
```

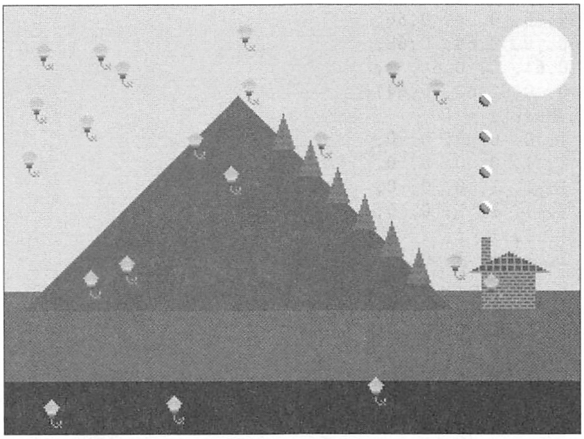


Figure 34.1 An animated Mode X Screen

```
static unsigned int PageStartOffsets[2] = {PAGE0_START_OFFSET,PAGE1_START_OFFSET};
static char GreenAndBrownPattern[] = {2,6,2,6, 6,2,6,2, 2,6,2,6, 6,2,6,2};
static char PineTreePattern[] = {2,2,2,2, 2,6,2,6, 2,2,6,2, 2,2,2,2};
static char BrickPattern[] = {6,6,7,6, 7,7,7,7, 7,6,6,6, 7,7,7,7,};
static char RoofPattern[] = {8,8,8,7, 7,7,7,7, 8,8,8,7, 8,8,8,7};

#define SMOKE_WIDTH  7
#define SMOKE_HEIGHT 7
static char SmokePixels[] = {
   0, 0,15,15,15, 0, 0,
   0, 7, 7,15,15,15, 0,
   8, 7, 7, 7,15,15,15,
   8, 7, 7, 7, 7,15,15,
   0, 8, 7, 7, 7, 7,15,
   0, 0, 8, 7, 7, 7, 0,
   0, 0, 0, 8, 8, 0, 0};
static char SmokeMask[] = {
   0, 0, 1, 1, 1, 0, 0,
   0, 1, 1, 1, 1, 1, 0,
   1, 1, 1, 1, 1, 1, 1,
   1, 1, 1, 1, 1, 1, 1,
   1, 1, 1, 1, 1, 1, 1,
   0, 1, 1, 1, 1, 1, 0,
   0, 0, 1, 1, 1, 0, 0};
#define KITE_WIDTH  10
#define KITE_HEIGHT 16
static char KitePixels[] = {
   0, 0, 0, 0,45, 0, 0, 0, 0, 0,
   0, 0, 0,46,46,46, 0, 0, 0, 0,
   0, 0,47,47,47,47,47, 0, 0, 0,
   0,48,48,48,48,48,48,48, 0, 0,
  49,49,49,49,49,49,49,49,49, 0,
   0,50,50,50,50,50,50,50, 0, 0,
   0,51,51,51,51,51,51,51, 0, 0,
   0, 0,52,52,52,52,52, 0, 0, 0,
   0, 0,53,53,53,53,53, 0, 0, 0,
   0, 0, 0,54,54,54, 0, 0, 0, 0,
   0, 0, 0,55,55,55, 0, 0, 0, 0,
   0, 0, 0, 0,58, 0, 0, 0, 0, 0,
   0, 0, 0, 0,59, 0, 0, 0, 0,66,
   0, 0, 0, 0,60, 0, 0,64, 0,65,
   0, 0, 0, 0, 0,61, 0, 0,64, 0,
   0, 0, 0, 0, 0, 0,62,63, 0,64};
static char KiteMask[] = {
   0, 0, 0, 0, 1, 0, 0, 0, 0, 0,
   0, 0, 0, 1, 1, 1, 0, 0, 0, 0,
   0, 0, 1, 1, 1, 1, 1, 0, 0, 0,
   0, 1, 1, 1, 1, 1, 1, 1, 0, 0,
   1, 1, 1, 1, 1, 1, 1, 1, 1, 0,
   0, 1, 1, 1, 1, 1, 1, 1, 0, 0,
   0, 1, 1, 1, 1, 1, 1, 1, 0, 0,
   0, 0, 1, 1, 1, 1, 1, 0, 0, 0,
   0, 0, 1, 1, 1, 1, 1, 0, 0, 0,
   0, 0, 0, 1, 1, 1, 0, 0, 0, 0,
   0, 0, 0, 1, 1, 1, 0, 0, 0, 0,
   0, 0, 0, 0, 1, 0, 0, 0, 0, 0,
   0, 0, 0, 0, 1, 0, 0, 0, 0, 1,
   0, 0, 0, 0, 1, 0, 0, 1, 0, 1,
   0, 0, 0, 0, 0, 1, 0, 0, 1, 0,
   0, 0, 0, 0, 0, 0, 1, 1, 0, 1};
static MaskedImage KiteImage;
```

```
#define NUM_OBJECTS  20
typedef struct {
   int X,Y,Width,Height,XDir,YDir,XOtherPage,YOtherPage;
   MaskedImage *Image;
} AnimatedObject;
AnimatedObject AnimatedObjects[] = {
   {  0,  0,KITE_WIDTH,KITE_HEIGHT, 1, 1,  0,  0,&KiteImage},
   { 10, 10,KITE_WIDTH,KITE_HEIGHT, 0, 1, 10, 10,&KiteImage},
   { 20, 20,KITE_WIDTH,KITE_HEIGHT,-1, 1, 20, 20,&KiteImage},
   { 30, 30,KITE_WIDTH,KITE_HEIGHT,-1,-1, 30, 30,&KiteImage},
   { 40, 40,KITE_WIDTH,KITE_HEIGHT, 1,-1, 40, 40,&KiteImage},
   { 50, 50,KITE_WIDTH,KITE_HEIGHT, 0,-1, 50, 50,&KiteImage},
   { 60, 60,KITE_WIDTH,KITE_HEIGHT, 1, 0, 60, 60,&KiteImage},
   { 70, 70,KITE_WIDTH,KITE_HEIGHT,-1, 0, 70, 70,&KiteImage},
   { 80, 80,KITE_WIDTH,KITE_HEIGHT, 1, 2, 80, 80,&KiteImage},
   { 90, 90,KITE_WIDTH,KITE_HEIGHT, 0, 2, 90, 90,&KiteImage},
   {100,100,KITE_WIDTH,KITE_HEIGHT,-1, 2,100,100,&KiteImage},
   {110,110,KITE_WIDTH,KITE_HEIGHT,-1,-2,110,110,&KiteImage},
   {120,120,KITE_WIDTH,KITE_HEIGHT, 1,-2,120,120,&KiteImage},
   {130,130,KITE_WIDTH,KITE_HEIGHT, 0,-2,130,130,&KiteImage},
   {140,140,KITE_WIDTH,KITE_HEIGHT, 2, 0,140,140,&KiteImage},
   {150,150,KITE_WIDTH,KITE_HEIGHT,-2, 0,150,150,&KiteImage},
   {160,160,KITE_WIDTH,KITE_HEIGHT, 2, 2,160,160,&KiteImage},
   {170,170,KITE_WIDTH,KITE_HEIGHT,-2, 2,170,170,&KiteImage},
   {180,180,KITE_WIDTH,KITE_HEIGHT,-2,-2,180,180,&KiteImage},
   {190,190,KITE_WIDTH,KITE_HEIGHT, 2,-2,190,190,&KiteImage},
};
void main(void);
void DrawBackground(unsigned int);
void MoveObject(AnimatedObject *);
extern void Set320x240Mode(void);
extern void FillRectangleX(int, int, int, int, unsigned int, int);
extern void FillPatternX(int, int, int, int, unsigned int, char*);
extern void CopySystemToScreenMaskedX(int, int, int, int, int, int,
   char *, unsigned int, int, int, char *);
extern void CopyScreenToScreenX(int, int, int, int, int, int,
   unsigned int, unsigned int, int, int);
extern unsigned int CreateAlignedMaskedImage(MaskedImage *,
   unsigned int, char *, int, int, char *);
extern void CopyScreenToScreenMaskedX(int, int, int, int, int, int,
   MaskedImage *, unsigned int, int);
extern void ShowPage(unsigned int);

void main()
{
   int DisplayedPage, NonDisplayedPage, Done, i;
   union REGS regset;
   Set320x240Mode();
   /* Download the kite image for fast copying later. */
   if (CreateAlignedMaskedImage(&KiteImage, DOWNLOAD_START_OFFSET,
         KitePixels, KITE_WIDTH, KITE_HEIGHT, KiteMask) == 0) {
      regset.x.ax = 0x0003; int86(0x10, &regset, &regset);
      printf("Couldn't get memory\n"); exit();
   }
   /* Draw the background to the background page. */
   DrawBackground(BG_START_OFFSET);
   /* Copy the background to both displayable pages. */
   CopyScreenToScreenX(0, 0, SCREEN_WIDTH, SCREEN_HEIGHT, 0, 0,
         BG_START_OFFSET, PAGE0_START_OFFSET, SCREEN_WIDTH, SCREEN_WIDTH);
   CopyScreenToScreenX(0, 0, SCREEN_WIDTH, SCREEN_HEIGHT, 0, 0,
         BG_START_OFFSET, PAGE1_START_OFFSET, SCREEN_WIDTH, SCREEN_WIDTH);
   /* Move the objects and update their images in the nondisplayed
      page, then flip the page, until Esc is pressed. */
   Done = DisplayedPage = 0;
   do {
      NonDisplayedPage = DisplayedPage ^ 1;
      /* Erase each object in nondisplayed page by copying block from
            background page at last location in that page. */
      for (i=0; i<NUM_OBJECTS; i++) {
         CopyScreenToScreenX(AnimatedObjects[i].XOtherPage,
               AnimatedObjects[i].YOtherPage,
               AnimatedObjects[i].XOtherPage +
               AnimatedObjects[i].Width,
               AnimatedObjects[i].YOtherPage +
               AnimatedObjects[i].Height,
               AnimatedObjects[i].XOtherPage,
               AnimatedObjects[i].YOtherPage, BG_START_OFFSET,
               PageStartOffsets[NonDisplayedPage], SCREEN_WIDTH, SCREEN_WIDTH);
      }
      /* Move and draw each object in the nondisplayed page. */
      for (i=0; i<NUM_OBJECTS; i++) {
         MoveObject(&AnimatedObjects[i]);
         /* Draw object into nondisplayed page at new location */
         CopyScreenToScreenMaskedX(0, 0, AnimatedObjects[i].Width,
               AnimatedObjects[i].Height, AnimatedObjects[i].X,
               AnimatedObjects[i].Y, AnimatedObjects[i].Image,
               PageStartOffsets[NonDisplayedPage], SCREEN_WIDTH);
      }
      /* Flip to the page into which we just drew. */
      ShowPage(PageStartOffsets[DisplayedPage = NonDisplayedPage]);
      /* See if it's time to end. */
      if (kbhit()) {
         if (getch() == 0x1B) Done = 1;   /* Esc to end */
      }
   } while (!Done);
   /* Restore text mode and done. */
   regset.x.ax = 0x0003; int86(0x10, &regset, &regset);
}
void DrawBackground(unsigned int PageStart)
{
   int i,j,Temp;
   /* Fill the screen with cyan. */
   FillRectangleX(0, 0, SCREEN_WIDTH, SCREEN_HEIGHT, PageStart, 11);
   /* Draw a green and brown rectangle to create a flat plain. */
   FillPatternX(0, 160, SCREEN_WIDTH, SCREEN_HEIGHT, PageStart,
                GreenAndBrownPattern);
   /* Draw blue water at the bottom of the screen. */
   FillRectangleX(0, SCREEN_HEIGHT-30, SCREEN_WIDTH, SCREEN_HEIGHT,
                  PageStart, 1);
   /* Draw a brown mountain rising out of the plain. */
   for (i=0; i<120; i++)
      FillRectangleX(SCREEN_WIDTH/2-30-i, 51+i, SCREEN_WIDTH/2-30+i+1,
                     51+i+1, PageStart, 6);
   /* Draw a yellow sun by overlapping rects of various shapes. */
   for (i=0; i<=20; i++) {
      Temp = (int)(sqrt(20.0*20.0 - (float)i*(float)i) + 0.5);
      FillRectangleX(SCREEN_WIDTH-25-i, 30-Temp, SCREEN_WIDTH-25+i+1,
                     30+Temp+1, PageStart, 14);
   }
   /* Draw green trees down the side of the mountain. */
   for (i=10; i<90; i += 15)
```

```
      for (j=0; j<20; j++)
         FillPatternX(SCREEN_WIDTH/2+i-j/3-15, i+j+51,SCREEN_WIDTH/2+i+j/3-15+1,
                                        i+j+51+1, PageStart, PineTreePattern);
   /* Draw a house on the plain. */
   FillPatternX(265, 150, 295, 170, PageStart, BrickPattern);
   FillPatternX(265, 130, 270, 150, PageStart, BrickPattern);
   for (i=0; i<12; i++)
      FillPatternX(280-i*2, 138+i, 280+i*2+1, 138+i+1, PageStart, RoofPattern);
   /* Finally, draw puffs of smoke rising from the chimney. */
   for (i=0; i<4; i++)
      CopySystemToScreenMaskedX(0, 0, SMOKE_WIDTH, SMOKE_HEIGHT, 264,
        110-i*20, SmokePixels, PageStart, SMOKE_WIDTH,SCREEN_WIDTH, SmokeMask);
}
/* Move the specified object, bouncing at the edges of the screen and
   remembering where the object was before the move for erasing next time. */
void MoveObject(AnimatedObject * ObjectToMove) {
   int X, Y;
   X = ObjectToMove->X + ObjectToMove->XDir;
   Y = ObjectToMove->Y + ObjectToMove->YDir;
   if ((X < 0) || (X > (SCREEN_WIDTH - ObjectToMove->Width))) {
      ObjectToMove->XDir = -ObjectToMove->XDir;
      X = ObjectToMove->X + ObjectToMove->XDir;
   }
   if ((Y < 0) || (Y > (SCREEN_HEIGHT - ObjectToMove->Height))) {
      ObjectToMove->YDir = -ObjectToMove->YDir;
      Y = ObjectToMove->Y + ObjectToMove->YDir;
   }
   /* Remember previous location for erasing purposes. */
   ObjectToMove->XOtherPage = ObjectToMove->X;
   ObjectToMove->YOtherPage = ObjectToMove->Y;
   ObjectToMove->X = X; /* set new location */
   ObjectToMove->Y = Y;
}
```

Here's something worth noting: The animation is extremely smooth on a 20 MHz 386. It is somewhat more jerky on an 8 MHz 286, because only 30 frames a second can be processed. If animation looks jerky on your PC, try reducing the number of kites.

The kites draw perfectly into the background, with no interference or fringe, thanks to masked copying. In fact, the kites also cross with no interference (the last-drawn kite is always in front), although that's not readily apparent because they all look the same anyway and are moving fast. Listing 34.5 isn't inherently limited to kites; create your own images and initialize the object list to display a mix of those images and see the full power of Mode X animation.

The external functions called by Listing 34.5 can be found in Listings 34.1, 34.2, 34.3, and 34.6, and in the listings for the previous two chapters.

LISTING 34.6 L34-6.ASM

```
; Shows the page at the specified offset in the bitmap. Page is displayed when
; this routine returns.
; C near-callable as: void ShowPage(unsigned int StartOffset);
INPUT_STATUS_1      equu  03dah      ;Input Status 1 register
CRTC_INDEX          equ   03d4h      ;CRT Controller Index reg
START_ADDRESS_HIGH  equ   0ch        ;bitmap start address high byte
START_ADDRESS_LOW   equ   0dh        ;bitmap start address low byte
```

```
ShowPageParms   struc
                 dw    2 dup (?)        ;pushed BP and return address
StartOffset      dw    ?                ;offset in bitmap of page to display
ShowPageParms   ends
        .model  small
        .code
        public  _ShowPage
_ShowPage       proc    near
        push    bp                      ;preserve caller's stack frame
        mov     bp,sp                   ;point to local stack frame
; Wait for display enable to be active (status is active low), to be
; sure both halves of the start address will take in the same frame.
        mov     bl,START_ADDRESS_LOW            ;preload for fastest
        mov     bh,byte ptr StartOffset[bp]     ; flipping once display
        mov     cl,START_ADDRESS_HIGH           ; enable is detected
        mov     ch,byte ptr StartOffset+1[bp]
        mov     dx,INPUT_STATUS_1
WaitDE:
        in      al,dx
        test    al,01h
        jnz     WaitDE                    ;display enable is active low (0 = active)
; Set the start offset in display memory of the page to display.
        mov     dx,CRTC_INDEX
        mov     ax,bx
        out     dx,ax                     ;start address low
        mov     ax,cx
        out     dx,ax                     ;start address high
; Now wait for vertical sync, so the other page will be invisible when
; we start drawing to it.
        mov     dx,INPUT_STATUS_1
WaitVS:
        in      al,dx
        test    al,08h
        jz      WaitVS                    ;vertical sync is active high (1 = active)
        pop     bp                        ;restore caller's stack frame
        ret
_ShowPage       endp
        end
```

Works Fast, Looks Great

We now end our exploration of Mode X, although we'll use it again shortly for 3-D animation. Mode X admittedly has its complexities; that's why I've provided a broad and flexible primitive set. Still, so what if it *is* complex? Take a look at Listing 34.5 in action. That sort of colorful, high-performance animation is worth jumping through a few hoops for; drawing 20, or even 10, fair-sized objects at a rate of 60 Hz, with no flicker, interference, or fringe, is no mean accomplishment, even on a 386.

There's much more we could do with animation in general and with Mode X in particular, but it's time to move on to new challenges. In closing, I'd like to point out that all of the VGA's hardware features, including the built-in AND, OR, and XOR functions, are available in Mode X, just as they are in the standard VGA modes. If you understand the VGA's hardware in mode 12H, try applying that knowledge to Mode X; you might be surprised at what you find you can do.

Adding a Dimension

Chapter 35

3-D Animation Using Mode X

When I first started programming micros, more than 11 years ago now, there wasn't much money in it, or visibility, or anything you could call a promising career. Sometimes, it was a way to accomplish things that would never have gotten done otherwise because minicomputer time cost too much; other times, it paid the rent; mostly, though, it was just for fun. Given free computer time for the first time in my life, I went wild, writing versions of all sorts of software I had seen on mainframes, in arcades, wherever. It was a wonderful way to learn how computers work: Trial and error in an environment where nobody minded the errors, with no meter ticking.

Many sorts of software demanded no particular skills other than a quick mind and a willingness to experiment: Space Invaders, for instance, or full-screen operating system shells. Others, such as compilers, required a good deal of formal knowledge. Still others required not only knowledge but also more horse-power than I had available. The latter I filed away on my ever-growing wish list, and then forgot about for a while.

Three-dimensional animation was the most alluring of the areas I passed over long ago. The information needed to do rotation, projection, rendering, and the like was neither so well developed nor widely so available then as it is now, although, in truth, it seemed more intimidating than it ultimately proved to be. Even had I possessed the knowledge, though, it seems unlikely that I could have coaxed satisfactory 3-D animation out of a 4 MHz Z80 system with 160×72 monochrome graphics. In those days, 3-D was pretty much limited to outrageously expensive terminals attached to minis or mainframes.

Times change, and they seem to do so much faster in computer technology than in other parts of the universe. A 486 is capable of decent 3-D animation, owing to its integrated math coprocessor; not in the class of, say, an i860, but pretty good nonetheless. A 386 is less satisfactory, though; the 387 is no match for the 486's coprocessor, and most 386 systems lack coprocessors. However, all is not lost; 32-bit registers and built-in integer multiply and divide hardware make it possible to do some very interesting 3-D animation on a 386 with fixed-point arithmetic. Actually, it's possible to do a surprising amount of 3-D animation in real mode, and even on lesser x86 processors; in fact, the code in this article will perform real-time 3-D animation (admittedly very simple, but nonetheless real-time and 3-D) on a 286 without a 287, even though the code is written in real-mode C and uses floating-point arithmetic. In short, the potential for 3-D animation on the x86 family is considerable.

With this chapter, we kick off an exploration of some of the sorts of 3-D animation that can be performed on the x86 family. Mind you, I'm talking about real-time 3-D animation, with all calculations and drawing performed on-the-fly. Generating frames ahead of time and playing them back is an excellent technique, but I'm interested in seeing how far we can push purely real-time animation. Granted, we're not going to make it to the level of Terminator 2, but we should have some fun nonetheless. The first few chapters in this final section of the book may seem pretty basic to those of you experienced with 3-D programming, and, at the same time, 3-D neophytes will inevitably be distressed at the amount of material I skip or skim over. That can't be helped, but at least there'll be working code, the references mentioned later, and some explanation; that should be enough to start you on your way with 3-D.

Animating in three dimensions is a complex task, so this will be the largest single section of the book, with later chapters building on earlier ones; and even this first 3-D chapter will rely on polygon fill and page-flip code from earlier chapters.

In a sense, I've saved the best for last, because, to my mind, real-time 3-D animation is one of the most exciting things of any stripe that can be done with a computer—and because, with today's hardware, it can in fact be done. Nay, it can be done amazingly well.

References on 3-D Drawing

There are several good sources for information about 3-D graphics. Foley and van Dam's *Computer Graphics: Principles and Practice* (Second Edition, Addison-Wesley, 1990) provides a lengthy discussion of the topic and a great many references for further study. Unfortunately, this book is heavy going at times; a more approachable discussion is provided in *Principles of Interactive Computer Graphics*, by Newman and Sproull (McGraw-Hill, 1979). Although the latter book lacks the last decade's worth of graphics developments, it nonetheless provides a good overview of basic 3-D techniques, including many of the approaches likely to work well in real time on a PC.

A source that you may or may not find useful is the series of six books on C graphics by Lee Adams, as exemplified by *High-Performance CAD Graphics in C* (Windcrest/Tab, 1986). (I don't know if all six books discuss 3-D graphics, but the four I've seen do.) To be honest, this book has a number of problems, including: Relatively little theory and explanation; incomplete and sometimes erroneous discussions of graphics hardware; use of nothing but global variables, with cryptic names like "array3" and

"B21;" and—well, you get the idea. On the other hand, the book at least touches on a great many aspects of 3-D drawing, and there's a lot of C code to back that up. A number of people have spoken warmly to me of Adams' books as their introduction to 3-D graphics. I wouldn't recommend these books as your only 3-D references, but if you're just starting out, you might want to look at one and see if it helps you bridge the gap between the theory and implementation of 3-D graphics.

The 3-D Drawing Pipeline

Each 3-D object that we'll handle will be built out of polygons that represent the surface of the object. Figure 35.1 shows the stages a polygon goes through enroute to being drawn on the screen. (For the present, we'll avoid complications such as clipping, lighting,

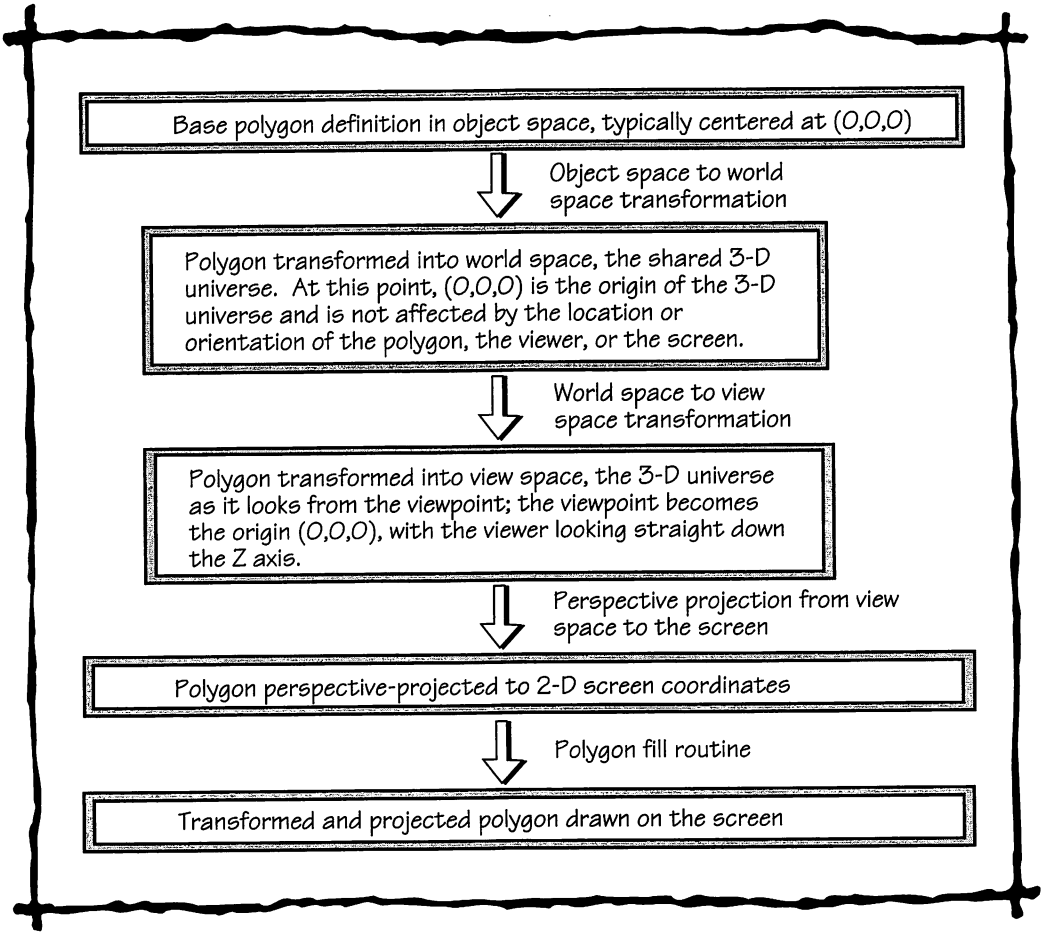

Base polygon definition in object space, typically centered at (0,0,0)
Object space to world space transformation
Polygon transformed into world space, the shared 3-D universe. At this point, (0,0,0) is the origin of the 3-D universe and is not affected by the location or orientation of the polygon, the viewer, or the screen.
World space to view space transformation
Polygon transformed into view space, the 3-D universe as it looks from the viewpoint; the viewpoint becomes the origin (0,0,0), with the viewer looking straight down the Z axis.
Perspective projection from view space to the screen
Polygon perspective-projected to 2-D screen coordinates
Polygon fill routine
Transformed and projected polygon drawn on the screen

Figure 35.1 The 3-D Drawing Pipeline

and shading.) First, the polygon is transformed from object space, the coordinate system the object is defined in, to world space, the coordinate system of the 3-D universe. Transformation may involve rotating, scaling, and moving the polygon. Fortunately, applying the desired transformation to each of the polygon vertices in an object is equivalent to transforming the polygon; in other words, transformation of a polygon is fully defined by transformation of its vertices, so it is not necessary to transform every point in a polygon, just the vertices. Likewise, transformation of all the polygon vertices in an object fully transforms the object.

Once the polygon is in world space, it must again be transformed, this time into view space, the space defined such that the viewpoint is at (0,0,0), looking down the Z axis, with the Y axis straight up and the X axis off to the right. Once in view space, the polygon can be perspective-projected to the screen, with the projected X and Y coordinates of the vertices finally being used to draw the polygon.

That's really all there is to basic 3-D drawing: transformation from object space to world space to view space to the screen. Next, we'll look at the mechanics of transformation.

One note: I'll use a purely *right-handed* convention for coordinate systems. Right-handed means that if you hold your right hand with your fingers curled and the thumb sticking out, the thumb points along the Z axis and the fingers point in the direction of rotation from the X axis to the Y axis, as shown in Figure 35.2. Rotations about an axis are counter-clockwise, as viewed looking down an axis toward the origin. The handedness of a coordinate system is just a convention, and left-handed would do equally well; however, right-handed is generally used for object and world space. Sometimes, the handedness is flipped for view space, so that increasing Z equals increasing distance from the viewer along the line of sight, but I have chosen not to do that here, to avoid confusion. Therefore, Z decreases as distance along the line of sight increases; a view space coordinate of (0,0,-1000) is directly ahead, twice as far away as a coordinate of (0,0,-500).

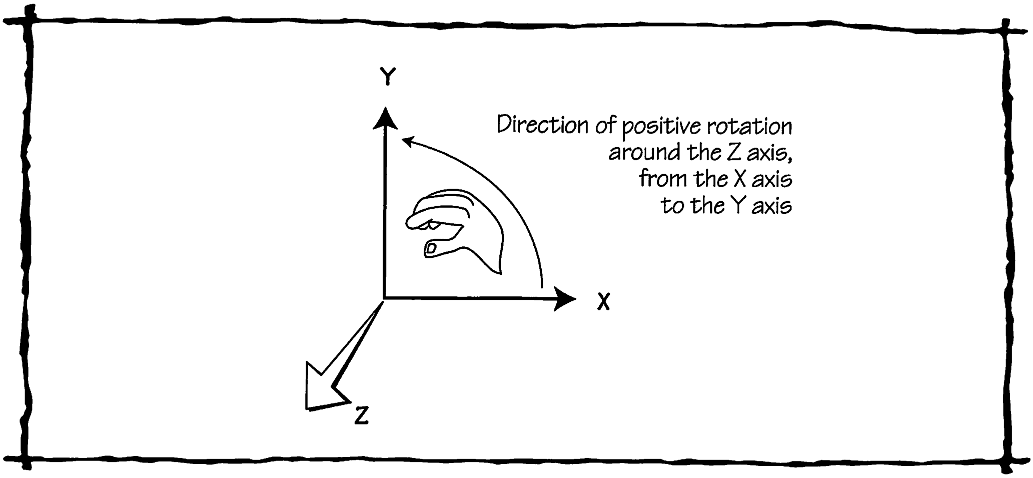


Figure 35.2 A Right-Handed Coordinate System

Projection

Working backward from the final image, we want to take the vertices of a polygon, as transformed into view space, and project them to 2-D coordinates on the screen, which, for projection purposes, is assumed to be centered on and perpendicular to the Z axis in view space, at some distance from the screen. We're after visual realism, so we'll want to do a perspective projection, in order that farther objects look smaller than nearer objects, and so that the field of view will widen with distance. This is done by scaling the X and Y coordinates of each point proportionately to the Z distance of the point from the viewer, a simple matter of similar triangles, as shown in Figure 35.3. It doesn't really matter how far down the Z axis the screen is assumed to be; what matters is the ratio of the distance of the screen from the viewpoint to the width of the screen. This ratio defines the rate of divergence of the viewing pyramid—the full field of view—and is used for performing all perspective projections. Once perspective projection has been performed, all that remains before calling the polygon filler is to convert the projected X and Y coordinates to integers, appropriately clipped and adjusted as necessary to center the origin on the screen or otherwise map the image into a window, if desired.

Translation

Translation means adding X, Y, and Z offsets to a coordinate to move it linearly through space. Translation is as simple as it seems; it requires nothing more than an addition for each axis. Translation is, for example, used to move objects from object space, in which the center of the object is typically the origin (0,0,0), into world space, where the object may be located anywhere.

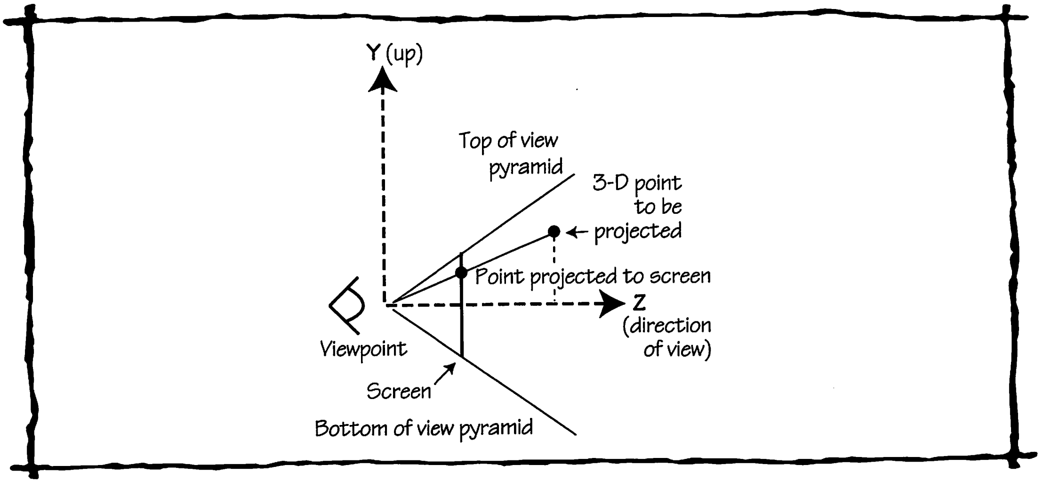


Figure 35.3 Perspective Projection

Rotation

Rotation is the process of circularly moving coordinates around the origin. For our present purposes, it's necessary only to rotate objects about their centers in object space, so as to turn them to the desired attitude before translating them into world space.

Rotation of a point about an axis is accomplished by transforming it according to the formulas shown in Figure 35.4. These formulas map into the more generally useful matrix-multiplication forms also shown in Figure 35.4. Matrix representation is more useful for two reasons: First, it is possible to concatenate multiple rotations into a single matrix by multiplying them together in the desired order; that single matrix can then be used to perform the rotations more efficiently.

(a)

newx = x
newy = cos(theta) * y - sin(theta) * z
newz = sin(theta) * y + cos(theta) * z

Matrix form of rotation around X axis:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(theta) & -\sin(theta) \\ 0 & \sin(theta) & \cos(theta) \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

(b)

newx = cos(theta) * x + sin(theta) * z
newy = y
newz = -sin(theta) * x + cos(theta) * z

Matrix form of rotation around Y axis:

$$\begin{bmatrix} \cos(theta) & 0 & \sin(theta) \\ 0 & 1 & 0 \\ -\sin(theta) & 0 & \cos(theta) \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

(c)

newx = cos(theta) * x - sin(theta) * y
newy = sin(theta) * x + cos(theta) * y
newz = z

Matrix form of rotation around Z axis:

$$\begin{bmatrix} \cos(theta) & -\sin(theta) & 0 \\ \sin(theta) & \cos(theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Figure 35.4 3-D Rotation Formulas

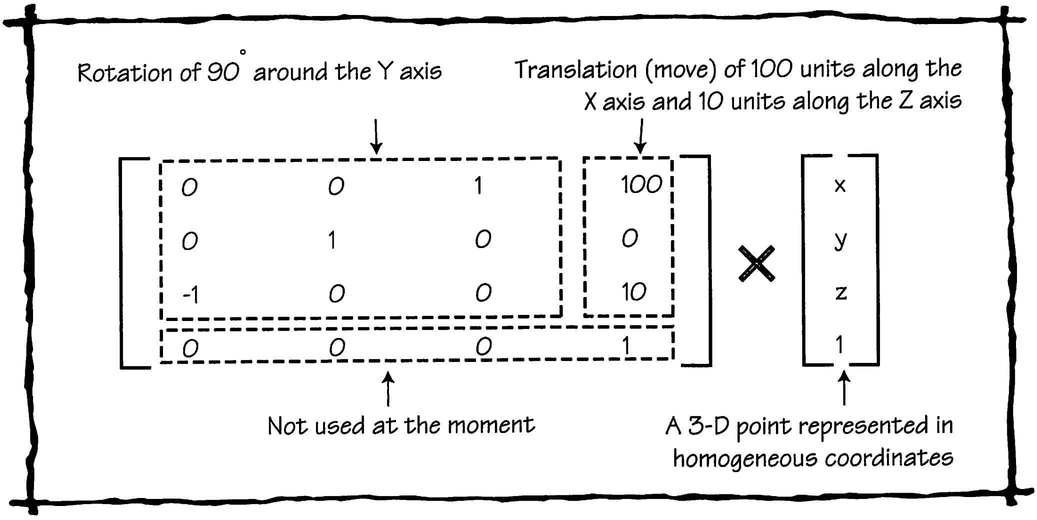

Rotation of 90° around the Y axis
Translation (move) of 100 units along the X axis and 10 units along the Z axis
0 0 1 100
0 1 0 0
-1 0 0 10
0 0 0 1
×
x
y
z
1
Not used at the moment
A 3-D point represented in homogeneous coordinates

Figure 35.5 A 4x4 Transformation Matrix

Second, 3×3 rotation matrices can become the upper-left-hand portions of 4×4 matrices that also perform translation (and scaling as well, but we won't need scaling in the near future), as shown in Figure 35.5. A 4×4 matrix of this sort utilizes homogeneous coordinates; that's a topic way beyond this book, but, basically, homogeneous coordinates allow you to handle both rotations and translations with 4×4 matrices, thereby allowing the same code to work with either, and making it possible to concatenate a long series of rotations and translations into a single matrix that performs the same transformation as the sequence of rotations and transformations.

There's much more to be said about transformations and the supporting matrix math, but, in the interests of getting to working code in this chapter, I'll leave that to be discussed as the need arises.

A Simple 3-D Example

At this point, we know enough to be able to put together a simple working 3-D animation example. The example will do nothing more complicated than display a single polygon as it sits in 3-D space, rotating around the Y axis. To make things a little more interesting, we'll let the user move the polygon around in space with the arrow keys, and with the "A" (away), and "T" (toward) keys. The sample program requires two sorts of functionality: The ability to transform and project the polygon from object space onto the screen (3-D functionality), and the ability to draw the projected polygon (complete with clipping) and handle the other details of animation (2-D functionality).

Happily (and not coincidentally), we put together a nice 2-D animation framework back in Part VIII, during our exploratory discussion of Mode X, so we don't have much to worry about in terms of non-3-D details. Basically, we'll use Mode X (320×240, 256 colors, as discussed in Part VIII), and we'll flip between two display pages, drawing to one while the other is displayed. One new 2-D element that we need is the ability to clip polygons; while we could avoid this for the moment by restricting the range of motion of the polygon so that it stays fully on the screen, certainly in the long run we'll want to be able to handle partially or fully clipped polygons. Listing 35.1 is the low-level code for a Mode X polygon filler that supports clipping. (The high-level polygon fill code is mode independent, and is the same as that presented in Part V, as noted further on.) The clipping is implemented at the low level, by trimming the Y extent of the scan line list up front, then clipping the X coordinates of each scan line in turn. This is not a particularly fast approach to clipping—ideally, the polygon would be clipped before it was scanned into a line list, avoiding potentially wasted scanning and eliminating the line-by-line X clipping—but it's much simpler, and, as we shall see, polygon filling performance is the least of our worries at the moment.

LISTING 35.1 L35-1.ASM

```
; Draws all pixels in the list of horizontal lines passed in, in
; Mode X, the VGA's undocumented 320x240 256-color mode. Clips to
; the rectangle specified by (ClipMinX,ClipMinY),(ClipMaxX,ClipMaxY).
; Draws to the page specified by CurrentPageBase.
; C near-callable as:
;
;     void DrawHorizontalLineList(struct HLineList * HLineListPtr,
;          int Color);
;
; All assembly code tested with TASM and MASM

SCREEN_WIDTH    equ   320
SCREEN_SEGMENT  equ   0a000h
SC_INDEX        equ   03c4h          ;Sequence Controller Index
MAP_MASK        equ   2              ;Map Mask register index in SC

HLine           struc
XStart          dw     ?             ;X coordinate of leftmost pixel in line
XEnd            dw     ?             ;X coordinate of rightmost pixel in line
HLine           ends

HLineList struc
Lngth           dw     ?             ;# of horizontal lines
YStart          dw     ?             ;Y coordinate of topmost line
HLinePtr        dw     ?             ;pointer to list of horz lines
HLineList       ends

Parms   struc
                dw     2 dup(?)      ;return address & pushed BP
HLineListPtr    dw     ?             ;pointer to HLineList structure
Color           dw     ?             ;color with which to fill
Parms   ends
        .model small
        .data
        extrn   _CurrentPageBase:word,_ClipMinX:word
        extrn   _ClipMinY:word,_ClipMaxX:word,_ClipMaxY:word
```

```
; Plane masks for clipping left and right edges of rectangle.
LeftClipPlaneMask       db      00fh,00eh,00ch,008h
RightClipPlaneMask      db      001h,003h,007h,00fh
        .code
        align   2
ToFillDone:
        jmp     FillDone
        public _DrawHorizontalLineList
        align   2
_DrawHorizontalLineList proc
        push    bp                     ;preserve caller's stack frame
        mov     bp,sp                  ;point to our stack frame
        push    si                     ;preserve caller's register variables
        push    di
        cld                            ;make string instructions inc pointers
        mov     dx,SC_INDEX
        mov     al,MAP_MASK
        out     dx,al                  ;point SC Index to the Map Mask
        mov     ax,SCREEN_SEGMENT
        mov     es,ax                  ;point ES to display memory for REP STOS
        mov     si,[bp+HLineListPtr]   ;point to the line list
        mov     bx,[si+HLinePtr]       ;point to the XStart/XEnd descriptor
                                       ; for the first (top) horizontal line
        mov     cx,[si+YStart]         ;first scan line to draw
        mov     si,[si+Lngth]          ;# of scan lines to draw
        cmp     si,0                   ;are there any lines to draw?
        jle     ToFillDone             ;no, so we're done
        cmp     cx,[_ClipMinY]         ;clipped at top?
        jge     MinYNotClipped         ;no
        neg     cx                     ;yes, discard however many lines are
        add     cx,[_ClipMinY]         ; clipped
        sub     si,cx                  ;that many fewer lines to draw
        jle     ToFillDone             ;no lines left to draw
        shl     cx,1                   ;lines to skip*2
        shl     cx,1                   ;lines to skip*4
        add     bx,cx                  ;advance through the line list
        mov     cx,[_ClipMinY]         ;start at the top clip line
MinYNotClipped:
        mov     dx,si
        add     dx,cx                  ;bottom row to draw + 1
        cmp     dx,[_ClipMaxY]         ;clipped at bottom?
        jle     MaxYNotClipped         ;no
        sub     dx,[_ClipMaxY]         ;# of lines to clip off the bottom
        sub     si,dx                  ;# of lines left to draw
        jle     ToFillDone             ;all lines are clipped
MaxYNotClipped:
        mov     ax,SCREEN_WIDTH/4      ;point to the start of the first
        mul     cx                     ; scan line on which to draw
        add     ax,[_CurrentPageBase]  ;offset of first line
        mov     dx,ax                  ;ES:DX points to first scan line to draw
        mov     ah,byte ptr [bp+Color] ;color with which to fill
FillLoop:
        push    bx                     ;remember line list location
        push    dx                     ;remember offset of start of line
        push    si                     ;remember # of lines to draw
        mov     di,[bx+XStart]         ;left edge of fill on this line
        cmp     di,[_ClipMinX]         ;clipped to left edge?
        jge     MinXNotClipped         ;no
        mov     di,[_ClipMinX]         ;yes, clip to the left edge
MinXNotClipped:
        mov     si,di
        mov     cx,[bx+XEnd]            ;right edge of fill
        cmp     cx,[_ClipMaxX]          ;clipped to right edge?
        jl      MaxXNotClipped          ;no
        mov     cx,[_ClipMaxX]          ;yes, clip to the right edge
        dec     cx
MaxXNotClipped:
        cmp     cx,di
        jl      LineFillDone            ;skip if negative width
        shr     di,1                    ;X/4 = offset of first rect pixel in scan
        shr     di,1                    ; line
        add     di,dx                   ;offset of first rect pixel in display mem
        mov     dx,si                   ;XStart
        and     si,0003h                ;look up left edge plane mask
        mov     bh,LeftClipPlaneMask[si]     ; to clip & put in BH
        mov     si,cx
        and     si,0003h                     ;look up right edge plane
        mov     bl,RightClipPlaneMask[si]    ; mask to clip & put in BL
        and     dx,not 011b                  ;calculate # of addresses across rect
        sub     cx,dx
        shr     cx,1
        shr     cx,1                    ;# of addresses across rectangle to fill - 1
        jnz     MasksSet                ;there's more than one byte to draw
        and     bh,bl                   ;there's only one byte, so combine the left
                                        ; and right edge clip masks
MasksSet:
        mov     dx,SC_INDEX+1           ;already points to the Map Mask reg
FillRowsLoop:
        mov     al,bh                   ;put left-edge clip mask in AL
        out     dx,al                   ;set the left-edge plane (clip) mask
        mov     al,ah                   ;put color in AL
        stosb                           ;draw the left edge
        dec     cx                      ;count off left edge byte
        js      FillLoopBottom          ;that's the only byte
        jz      DoRightEdge             ;there are only two bytes
        mov     al,00fh                 ;middle addresses are drawn 4 pixels at a pop
        out     dx,al                   ;set the middle pixel mask to no clip
        mov     al,ah                   ;put color in AL
        rep     stosb                   ;draw the middle addresses four pixels apiece
DoRightEdge:
        mov     al,bl                   ;put right-edge clip mask in AL
        out     dx,al                   ;set the right-edge plane (clip) mask
        mov     al,ah                   ;put color in AL
        stosb                           ;draw the right edge
FillLoopBottom:
LineFillDone:
        pop     si                      ;retrieve # of lines to draw
        pop     dx                      ;retrieve offset of start of line
        pop     bx                      ;retrieve line list location
        add     dx,SCREEN_WIDTH/4       ;point to start of next line
        add     bx,size HLine           ;point to the next line descriptor
        dec     si                      ;count down lines
        jnz     FillLoop
FillDone:
        pop     di                      ;restore caller's register variables
        pop     si
        pop     bp                      ;restore caller's stack frame
        ret
_DrawHorizontalLineList endp
        end
```

The other 2-D element we need is some way to erase the polygon at its old location before it's moved and redrawn. We'll do that by remembering the bounding rectangle of the polygon each time it's drawn, then erasing by clearing that area with a rectangle fill.

With the 2-D side of the picture well under control, we're ready to concentrate on the good stuff. Listings 35.2 through 35.5 are the sample 3-D animation program. Listing 35.2 provides matrix multiplication functions in a straightforward fashion. Listing 35.3 transforms, projects, and draws polygons. Listing 35.4 is the general header file for the program, and Listing 35.5 is the main animation program.

Other modules required are: Listings 32.1 and 32.6 from Chapter 32 (Mode X mode set, rectangle fill); Listing 34.6 from Chapter 34; Listing 22.4 from Chapter 22 (polygon edge scan); and the **FillConvexPolygon()** function from Listing 21.1 in Chapter 21. All necessary code modules, along with a project file, are present in the subdirectory for this chapter on the listings diskette, whether they were presented in this chapter or some earlier chapter. This will be the case for the next several chapters as well, where listings from previous chapters are referenced. This scheme may crowd the listings diskette a little bit, but it will certainly reduce confusion!

LISTING 35.2 L35-2.C

```
/* Matrix arithmetic functions.
   Tested with Borland C++ in the small model. */

/* Matrix multiplies Xform by SourceVec, and stores the result in
   DestVec. Multiplies a 4x4 matrix times a 4x1 matrix; the result
   is a 4x1 matrix, as follows:
   --     --     -- --     -- --
   |       |     | 4 |     | 4 |
   |  4x4  |  X  | x |  =  | x |
   |       |     | 1 |     | 1 |
   --     --     -- --     -- -- */
void XformVec(double Xform[4][4], double * SourceVec,
   double * DestVec)
{
   int i,j;

   for (i=0; i<4; i++) {
      DestVec[i] = 0;
      for (j=0; j<4; j++)
         DestVec[i] += Xform[i][j] * SourceVec[j];
   }
}

/* Matrix multiplies SourceXform1 by SourceXform2 and stores the
   result in DestXform. Multiplies a 4x4 matrix times a 4x4 matrix;
   the result is a 4x4 matrix, as follows:
   --     --     --     --     --     --
   |       |     |       |     |       |
   |  4x4  |  X  |  4x4  |  =  |  4x4  |
   |       |     |       |     |       |
   --     --     --     --     --     -- */
void ConcatXforms(double SourceXform1[4][4], double SourceXform2[4][4],
   double DestXform[4][4])
```

```
{
   int i,j,k;

   for (i=0; i<4; i++) {
      for (j=0; j<4; j++) {
         DestXform[i][j] = 0;
         for (k=0; k<4; k++)
            DestXform[i][j] += SourceXform1[i][k] * SourceXform2[k][j];
      }
   }
}
```

LISTING 35.3 L35-3.C

```
/* Transforms convex polygon Poly (which has PolyLength vertices),
   performing the transformation according to Xform (which generally
   represents a transformation from object space through world space
   to view space), then projects the transformed polygon onto the
   screen and draws it in color Color. Also updates the extent of the
   rectangle (EraseRect) that's used to erase the screen later.
   Tested with Borland C++ in the small model. */
#include "polygon.h"

void XformAndProjectPoly(double Xform[4][4], struct Point3 * Poly,
   int PolyLength, int Color)
{
   int i;
   struct Point3 XformedPoly[MAX_POLY_LENGTH];
   struct Point ProjectedPoly[MAX_POLY_LENGTH];
   struct PointListHeader Polygon;

   /* Transform to view space, then project to the screen */
   for (i=0; i<PolyLength; i++) {
      /* Transform to view space */
      XformVec(Xform, (double *)&Poly[i], (double *)&XformedPoly[i]);
      /* Project the X & Y coordinates to the screen, rounding to the
         nearest integral coordinates. The Y coordinate is negated to
         flip from view space, where increasing Y is up, to screen
         space, where increasing Y is down. Add in half the screen
         width and height to center on the screen */
      ProjectedPoly[i].X = ((int) (XformedPoly[i].X/XformedPoly[i].Z *
            PROJECTION_RATIO*(SCREEN_WIDTH/2.0)+0.5))+SCREEN_WIDTH/2;
      ProjectedPoly[i].Y = ((int) (XformedPoly[i].Y/XformedPoly[i].Z *
            -1.0 * PROJECTION_RATIO * (SCREEN_WIDTH / 2.0) + 0.5)) +
            SCREEN_HEIGHT/2;
      /* Appropriately adjust the extent of the rectangle used to
         erase this page later */
         if (ProjectedPoly[i].X > EraseRect[NonDisplayedPage].Right)
          if (ProjectedPoly[i].X < SCREEN_WIDTH)
            EraseRect[NonDisplayedPage].Right = ProjectedPoly[i].X;
          else EraseRect[NonDisplayedPage].Right = SCREEN_WIDTH;
         if (ProjectedPoly[i].Y > EraseRect[NonDisplayedPage].Bottom)
          if (ProjectedPoly[i].Y < SCREEN_HEIGHT)
            EraseRect[NonDisplayedPage].Bottom = ProjectedPoly[i].Y;
          else EraseRect[NonDisplayedPage].Bottom = SCREEN_HEIGHT;
         if (ProjectedPoly[i].X < EraseRect[NonDisplayedPage].Left)
          if (ProjectedPoly[i].X > 0)
            EraseRect[NonDisplayedPage].Left = ProjectedPoly[i].X;
          else EraseRect[NonDisplayedPage].Left = 0;
         if (ProjectedPoly[i].Y < EraseRect[NonDisplayedPage].Top)
          if (ProjectedPoly[i].Y > 0)
            EraseRect[NonDisplayedPage].Top = ProjectedPoly[i].Y;
          else EraseRect[NonDisplayedPage].Top = 0;
   }
   /* Draw the polygon */
   DRAW_POLYGON(ProjectedPoly, PolyLength, Color, 0, 0);
}
```

LISTING 35.4 POLYGON.H

```
/* POLYGON.H: Header file for polygon-filling code, also includes
   a number of useful items for 3-D animation. */

#define MAX_POLY_LENGTH 4  /* four vertices is the max per poly */
#define SCREEN_WIDTH 320
#define SCREEN_HEIGHT 240
#define PAGE0_START_OFFSET 0
#define PAGE1_START_OFFSET (((long)SCREEN_HEIGHT*SCREEN_WIDTH)/4)
/* Ratio: distance from viewpoint to projection plane / width of
   projection plane. Defines the width of the field of view. Lower
   absolute values = wider fields of view; higher values = narrower */
#define PROJECTION_RATIO   -2.0 /* negative because visible Z
                                   coordinates are negative */
/* Draws the polygon described by the point list PointList in color
   Color with all vertices offset by (X,Y) */
#define DRAW_POLYGON(PointList,NumPoints,Color,X,Y)         \
   Polygon.Length = NumPoints;                              \
   Polygon.PointPtr = PointList;                            \
   FillConvexPolygon(&Polygon, Color, X, Y);

/* Describes a single 2-D point */
struct Point {
   int X;   /* X coordinate */
   int Y;   /* Y coordinate */
};
/* Describes a single 3-D point in homogeneous coordinates */
struct Point3 {
   double X;   /* X coordinate */
   double Y;   /* Y coordinate */
   double Z;   /* Z coordinate */
   double W;
};
/* Describes a series of points (used to store a list of vertices that
   describe a polygon; each vertex is assumed to connect to the two
   adjacent vertices, and the last vertex is assumed to connect to the
   first) */
struct PointListHeader {
   int Length;                /* # of points */
   struct Point * PointPtr;   /* pointer to list of points */
};

/* Describes the beginning and ending X coordinates of a single
   horizontal line */
struct HLine {
   int XStart; /* X coordinate of leftmost pixel in line */
   int XEnd;   /* X coordinate of rightmost pixel in line */
};
```

```
/* Describes a Length-long series of horizontal lines, all assumed to
   be on contiguous scan lines starting at YStart and proceeding
   downward (used to describe a scan-converted polygon to the
   low-level hardware-dependent drawing code) */
struct HLineList {
   int Length;                /* # of horizontal lines */
   int YStart;                /* Y coordinate of topmost line */
   struct HLine * HLinePtr;   /* pointer to list of horz lines */
};
struct Rect { int Left, Top, Right, Bottom; };

extern void XformVec(double Xform[4][4], double * SourceVec,
   double * DestVec);
extern void ConcatXforms(double SourceXform1[4][4],
   double SourceXform2[4][4], double DestXform[4][4]);
extern void XformAndProjectPoly(double Xform[4][4],
   struct Point3 * Poly, int PolyLength, int Color);
extern int FillConvexPolygon(struct PointListHeader *, int, int, int);
extern void Set320x240Mode(void);
extern void ShowPage(unsigned int StartOffset);
extern void FillRectangleX(int StartX, int StartY, int EndX,
   int EndY, unsigned int PageBase, int Color);
extern int DisplayedPage, NonDisplayedPage;
extern struct Rect EraseRect[];
```

LISTING 35.5 L35-5.C

```
/* Simple 3D drawing program to view a polygon as it rotates in
   Mode X. View space is congruent with world space, with the
   viewpoint fixed at the origin (0,0,0) of world space, looking in
   the direction of increasingly negative Z. A right-handed
   coordinate system is used throughout.
   Tested with Borland C++ in the small model. */
#include <conio.h>
#include <stdio.h>
#include <dos.h>
#include <math.h>
#include "polygon.h"
void main(void);

/* Base offset of page to which to draw */
unsigned int CurrentPageBase = 0;
/* Clip rectangle; clips to the screen */
int ClipMinX=0, ClipMinY=0;
int ClipMaxX=SCREEN_WIDTH, ClipMaxY=SCREEN_HEIGHT;
/* Rectangle specifying extent to be erased in each page */
struct Rect EraseRect[2] = { {0, 0, SCREEN_WIDTH, SCREEN_HEIGHT},
   {0, 0, SCREEN_WIDTH, SCREEN_HEIGHT} };
/* Transformation from polygon's object space to world space.
   Initially set up to perform no rotation and to move the polygon
   into world space -140 units away from the origin down the Z axis.
   Given the viewing point, -140 down the Z axis means 140 units away
   straight ahead in the direction of view. The program dynamically
   changes the rotation and translation. */
static double PolyWorldXform[4][4] = {
   {1.0, 0.0, 0.0, 0.0},
   {0.0, 1.0, 0.0, 0.0},
   {0.0, 0.0, 1.0, -140.0},
   {0.0, 0.0, 0.0, 1.0} };
```

```
/* Transformation from world space into view space. In this program,
   the view point is fixed at the origin of world space, looking down
   the Z axis in the direction of increasingly negative Z, so view
   space is identical to world space; this is the identity matrix. */
static double WorldViewXform[4][4] = {
   {1.0, 0.0, 0.0, 0.0},
   {0.0, 1.0, 0.0, 0.0},
   {0.0, 0.0, 1.0, 0.0},
   {0.0, 0.0, 0.0, 1.0}
};
static unsigned int PageStartOffsets[2] =
   {PAGE0_START_OFFSET,PAGE1_START_OFFSET};
int DisplayedPage, NonDisplayedPage;

void main() {
   int Done = 0;
   double WorkingXform[4][4];
   static struct Point3 TestPoly[] =
         {{-30,-15,0,1},{0,15,0,1},{10,-5,0,1}};
#define TEST_POLY_LENGTH   (sizeof(TestPoly)/sizeof(struct Point3))
   double Rotation = M_PI / 60.0; /* initial rotation = 3 degrees */
   union REGS regset;

   Set320x240Mode();
   ShowPage(PageStartOffsets[DisplayedPage = 0]);
   /* Keep rotating the polygon, drawing it to the undisplayed page,
      and flipping the page to show it */
   do {
      CurrentPageBase =    /* select other page for drawing to */
            PageStartOffsets[NonDisplayedPage = DisplayedPage ^ 1];
      /* Modify the object space to world space transformation matrix
         for the current rotation around the Y axis */
      PolyWorldXform[0][0] = PolyWorldXform[2][2] = cos(Rotation);
      PolyWorldXform[2][0] = -(PolyWorldXform[0][2] = sin(Rotation));
      /* Concatenate the object-to-world and world-to-view
         transformations to make a transformation matrix that will
         convert vertices from object space to view space in a single
         operation */
      ConcatXforms(WorldViewXform, PolyWorldXform, WorkingXform);
      /* Clear the portion of the non-displayed page that was drawn
         to last time, then reset the erase extent */
      FillRectangleX(EraseRect[NonDisplayedPage].Left,
            EraseRect[NonDisplayedPage].Top,
            EraseRect[NonDisplayedPage].Right,
            EraseRect[NonDisplayedPage].Bottom, CurrentPageBase, 0);
      EraseRect[NonDisplayedPage].Left =
            EraseRect[NonDisplayedPage].Top = 0x7FFF;
      EraseRect[NonDisplayedPage].Right =
         EraseRect[NonDisplayedPage].Bottom = 0;
      /* Transform the polygon, project it on the screen, draw it */
      XformAndProjectPoly(WorkingXform, TestPoly, TEST_POLY_LENGTH,9);
      /* Flip to display the page into which we just drew */
      ShowPage(PageStartOffsets[DisplayedPage = NonDisplayedPage]);
      /* Rotate 6 degrees farther around the Y axis */
      if ((Rotation += (M_PI/30.0)) >= (M_PI*2)) Rotation -= M_PI*2;
      if (kbhit()) {
         switch (getch()) {
            case 0x1B:     /* Esc to exit */
               Done = 1; break;
            case 'A': case 'a':      /* away (-Z) */
               PolyWorldXform[2][3] -= 3.0; break;
            case 'T':      /* towards (+Z). Don't allow to get too */
            case 't':      /* close, so Z clipping isn't needed */
               if (PolyWorldXform[2][3] < -40.0)
                     PolyWorldXform[2][3] += 3.0; break;
            case 0:     /* extended code */
               switch (getch()) {
                  case 0x4B:  /* left (-X) */
                     PolyWorldXform[0][3] -= 3.0; break;
                  case 0x4D:  /* right (+X) */
                     PolyWorldXform[0][3] += 3.0; break;
                  case 0x48:  /* up (+Y) */
                     PolyWorldXform[1][3] += 3.0; break;
                  case 0x50:  /* down (-Y) */
                     PolyWorldXform[1][3] -= 3.0; break;
                  default:
                     break;
               }
               break;
            default:       /* any other key to pause */
               getch(); break;
         }
      }
   } while (!Done);
   /* Return to text mode and exit */
   regset.x.ax = 0x0003;   /* AL = 3 selects 80x25 text mode */
   int86(0x10, &regset, &regset);
}
```

Notes on the 3-D Animation Example

The sample program transforms the polygon's vertices from object space to world space to view space to the screen, as described earlier. In this case, world space and view space are congruent—we're looking right down the negative Z axis of world space—so the transformation matrix from world to view is the identity matrix; you might want to experiment with changing this matrix to change the viewpoint. The sample program uses 4×4 homogeneous coordinate matrices to perform transformations, as described above. Floating-point arithmetic is used for all 3-D calculations. Setting the translation from object space to world space is a simple matter of changing the appropriate entry in the fourth column of the object-to-world transformation matrix. Setting the rotation around the Y axis is almost as simple, requiring only the setting of the four matrix entries that control the Y rotation to the sines and cosines of the desired rotation. However, rotations involving more than one axis require multiple rotation matrices, one for each axis rotated around; those matrices are then concatenated together to produce the object-to-world transformation. This area is trickier than it might initially appear to be; more in the near future.

The maximum translation along the Z axis is limited to -40; this keeps the polygon from extending past the viewpoint to positive Z coordinates. This would wreak havoc with the projection and 2-D clipping, and would require 3-D clipping, which is far more complicated than 2-D. We'll get to 3-D clipping at some point, but, for now, it's much simpler just to limit all vertices to negative Z coordinates. The polygon does get mighty close to the viewpoint, though; run the program and use the "T" key to move the polygon as close as possible—the near vertex swinging past provides a striking sense of perspective.

The performance of Listing 35.5 is, perhaps, surprisingly good, clocking in at 16 frames per second on a 20 MHz 386 with a VGA of average speed and no 387, although there is, of course, only one polygon being drawn, rather than the hundreds or thousands we'd ultimately like. What's far more interesting is where the execution time goes. Even though the program is working with only one polygon, 73 percent of the time goes for transformation and projection. An additional 7 percent is spent waiting to flip the screen. Only 20 percent of the total time is spent in all other activity—and only 2 percent is spent actually drawing polygons. Clearly, we'll want to tackle transformation and projection first when we look to speed things up. (Note, however, that a math coprocessor would considerably decrease the time taken by floating-point calculations.)

In Listing 35.3, when the extent of the bounding rectangle is calculated for later erasure purposes, that extent is clipped to the screen. This is due to the lack of clipping in the rectangle fill code from Listing 32.5 in Chapter 32; the problem would more appropriately be addressed by putting clipping into the fill code, but, unfortunately, I lack the space to do that here.

Finally, observe the jaggies crawling along the edges of the polygon as it rotates. This is temporal aliasing at its finest! We won't address antialiasing further, real-time antialiasing being decidedly nontrivial, but this should give you an idea of why antialiasing is so desirable.

An Ongoing Journey

In the next chapter, we'll assign fronts and backs to polygons, and start drawing only those that are facing the viewer. That will enable us to handle convex polyhedrons, such as tetrahedrons and cubes. We'll also look at interactively controllable rotation, and at more complex rotations than the simple rotation around the Y axis that we did this time. In time, we'll use fixed-point arithmetic to speed things up, and do some shading and texture mapping. The journey has only begun; we'll get to all that and more soon.

Sneakers in Space

Chapter 36

Using Backface Removal to Eliminate Hidden Surfaces

As I'm fond of pointing out, computer animation isn't a matter of mathematically exact modeling or raw technical prowess, but rather of fooling the eye and the mind. That's especially true for 3-D animation, where we're not only trying to convince viewers that they're seeing objects on a screen—when in truth that screen contains no objects at all, only gaggles of pixels—but we're also trying to create the illusion that the objects exist in three-space, possessing four dimensions (counting movement over time as a fourth dimension) of their own. To make this magic happen, we must provide cues for the eye not only to pick out boundaries, but also to detect depth, orientation, and motion. This involves perspective, shading, proper handling of hidden surfaces, and rapid and smooth screen updates; the whole deal is considerably more difficult to pull off on a PC than 2-D animation.

In some senses, however, 3-D animation is easier than 2-D. Because there's more going on in 3-D animation, the eye and brain tend to make more assumptions, and so are more apt to see what they expect to see, rather than what's actually there.

If you're piloting a (virtual) ship through a field of thousands of asteroids at high speed, you're unlikely to notice if the more distant asteroids occasionally seem to go right through each other, or if the topographic detail on the asteroids' surfaces sometimes shifts about a bit. You'll be busy viewing the asteroids in their primary role, as objects to be navigated around, and the mere presence of topographic detail will suffice; without being aware of it, you'll fill in the blanks. Your mind will see the topography peripherally, recognize it for what it is supposed to be, and, unless the landscape does something really obtrusive such as vanishing altogether or suddenly shooting a spike miles into space, you will see what you expect to see: a bunch of nicely detailed asteroids tumbling around you.

To what extent can you rely on the eye and mind to make up for imperfections in the 3-D animation process? In some areas, hardly at all; for example, jaggies crawling along edges stick out like red flags, and likewise for flicker. In other areas, though, the human perceptual system is more forgiving than you'd think. Consider this: At the end of *Return of the Jedi*, in the battle to end all battles around the Death Star, there is a sequence of about five seconds in which several spaceships are visible in the background. One of those spaceships (and it's not very far in the background, either) looks a bit unusual. What it looks like is a sneaker. In fact, it *is* a sneaker—but unless you know to look for it, you'll never notice it, because your mind is busy making simplifying assumptions about the complex scene it's seeing—and one of those assumptions is that medium-sized objects floating in space are spaceships, unless proven otherwise. (Thanks to Chris Hecker for pointing this out. I'd never have noticed the sneaker, myself, without being tipped off—which is, of course, the whole point.)

If it's good enough for George Lucas, it's good enough for us. And with that, let's resume our quest for real-time 3-D animation on the PC.

One-sided Polygons: Backface Removal

In the previous chapter, we implemented the basic polygon drawing pipeline, transforming a polygon all the way from its basic definition in object space, through the shared 3-D world space, and into the 3-D space as seen from the viewpoint, called *view space*. From view space, we performed a perspective projection to convert the polygon into screen space, then mapped the transformed and projected vertices to the nearest screen coordinates and filled the polygon. Armed with code that implemented this pipeline, we were able to watch as a polygon rotated about its Y axis, and were able to move the polygon around in space freely.

One of the drawbacks of the previous chapter's approach was that the polygon had two visible sides. Why is that a drawback? It isn't, necessarily, but in our case we want to use polygons to build solid objects with continuous surfaces, and in that context, only one side of a polygon is visible; the other side always faces the inside of the object, and can never be seen. It would save time and simplify the process of hidden surface removal if we could quickly and easily determine whether the inside or outside face of each polygon was facing us, so that we could draw each polygon only if it were visible (that is, had the outside face pointing toward the viewer). On average, half the polygons in an object could be instantly rejected by a test of this sort. Such testing of polygon visibility goes by a number of names in the literature, including backplane culling, backface removal, and assorted variations thereon; I'll refer to it as *backface removal*.

For a single convex polyhedron, removal of polygons that aren't facing the viewer would solve all hidden surface problems. In a convex polyhedron, any polygon facing the viewer can never be obscured by any other polygon in that polyhedron; this falls out of the definition of a convex polyhedron. Likewise, any polygon facing away from the viewer can never be visible. Therefore, in order to draw a convex polyhedron, if you draw all polygons facing toward the viewer but none facing away from the viewer, everything will work out properly, with no additional checking for overlap and hidden surfaces needed.

Unfortunately, backface removal completely solves the hidden surface problem for convex polyhedrons *only*, and only if there's a single convex polyhedron involved; when convex polyhedrons overlap, other methods must be used. Nonetheless, backface removal does instantly halve the number of polygons to be handled in rendering any particular scene. Backface removal can also speed hidden-surface handling if objects are built out of convex polyhedrons. In this chapter, though, we have only one convex polyhedron to deal with, so backface removal alone will do the trick.

Given that I've convinced you that backface removal would be a handy thing to have, how do we actually do it? A logical approach, often implemented in the PC literature, would be to calculate the plane equation for the plane in which the polygon lies, and see which way the normal (perpendicular) vector to the plane points. That works, but there's a more efficient way to calculate the normal to the polygon: as the cross-product of two of the polygon's edges.

The cross-product of two vectors is defined as the vector shown in Figure 36.1. One interesting property of the cross-product vector is that it is perpendicular to the plane in which the two original vectors lie. If we take the cross-product of the vectors that form two edges of a polygon, the result will be a vector perpendicular to the polygon; then, we'll know that the polygon is visible if and only if the cross-product vector points toward the viewer. We need one more thing to make the cross-product approach work, though. The cross-product can actually point either way, depending on which edges of the polygon we choose to work with and the order in which we evaluate them, so we must establish some conventions for defining polygons and evaluating the cross-product.

$$V = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \qquad W = \begin{bmatrix} W_1 \\ W_2 \\ W_3 \end{bmatrix} \qquad V \times W = \begin{bmatrix} V_2W_3 - V_3W_2 \\ V_3W_1 - V_1W_3 \\ V_1W_2 - V_2W_1 \end{bmatrix}$$

Figure 36.1 The Cross-Product of Two Vectors

We'll define only convex polygons, with the vertices defined in clockwise order, as viewed from the outside; that is, if you're looking at the visible side of the polygon, the vertices will appear in the polygon definition in clockwise order. With those assumptions, the cross-product becomes a quick and easy indicator of polygon orientation with respect to the viewer; we'll calculate it as the cross-product of the first and last vectors in a polygon, as shown in Figure 36.2, and if it's pointing toward the viewer, we'll know that the polygon is visible. Actually, we don't even have to calculate the entire cross-product vector, because the Z component alone suffices to tell us which way the polygon is facing: positive Z means visible, negative Z means not. The Z component can be calculated very efficiently, with only two multiplies and a subtraction.

The question remains of the proper space in which to perform backface removal. There's a temptation to perform it in view space, which is, after all, the space defined with respect to the viewer, but view space is not a good choice. Screen space—the space in which perspective projection has been performed—is the best choice. The purpose of backface removal is to determine whether each polygon is visible to the viewer, and, despite its name, view space does not provide that information; unlike screen space, it does not reflect perspective effects.

Backface removal may also be performed using the polygon vertices in screen coordinates, which are integers. This is less accurate than using the screen space coordinates, which are floating point, but is, by the same token, faster. In Listing 36.3, which we'll discuss shortly, backface removal is performed in screen coordinates in the interests of speed.

Backface removal, as implemented in Listing 36.3, will not work reliably if the polygon is not convex, if the vertices don't appear in clockwise order, if either the first or last edge in a polygon has zero length, or if the first and last edges are collinear. These latter two points are the reason it's preferable to work in screen space rather than screen coordinates (which suffer from rounding problems), speed considerations aside.

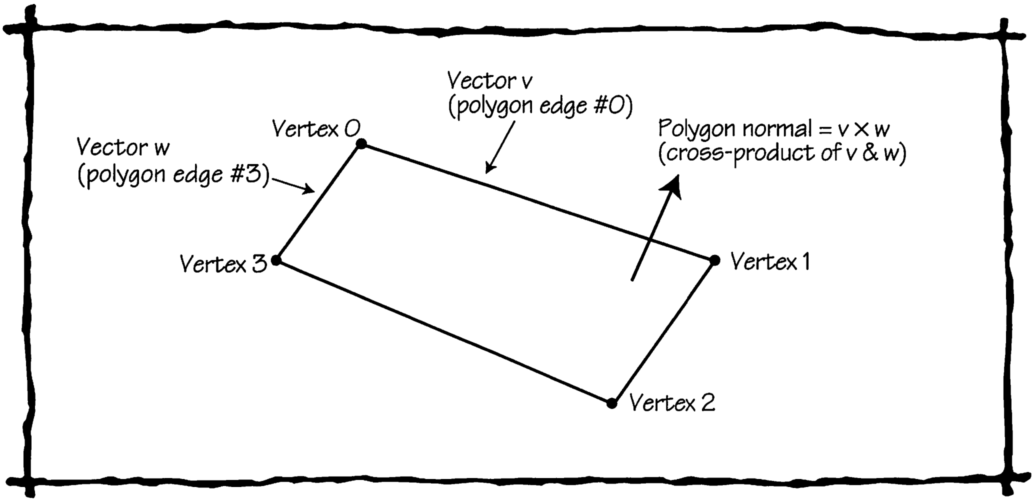


Figure 36.2 Using the Cross Product to Generate a Polygon Normal

Backface Removal in Action

Listings 36.1 through 36.5 together form a program that rotates a solid cube in real time under user control. Listing 36.1 is the main program; Listing 36.2 performs transformation and projection; Listing 36.3 performs backface removal and draws visible faces; Listing 36.4 concatenates incremental rotations to the object-to-world transformation matrix; Listing 36.5 is the general header file. Also required from previous chapters are: Listings 35.1 and 35.2 from Chapter 35 (draw clipped line list, matrix math functions); Listings 32.1 and 32.6 from Chapter 32, (Mode X mode set, rectangle fill); Listing 34.6 from Chapter 34; Listing 22.4 from Chapter 22 (polygon edge scan); and the **FillConvexPolygon**() function from Listing 21.1 from Chapter 21. All necessary modules, along with a project file, will be present in the subdirectory for this chapter on the listings diskette, whether they were presented in this chapter or some earlier chapter. This may crowd the listings diskette a little bit, but it will certainly reduce confusion!

LISTING 36.1 L36-1.C

```
/* 3D animation program to view a cube as it rotates in Mode X. The viewpoint
   is fixed at the origin (0,0,0) of world space, looking in the direction of
   increasingly negative Z. A right-handed coordinate system is used throughout.
   All C code tested with Borland C++ in C compilation mode. */
#include <conio.h>
#include <dos.h>
#include <math.h>
#include "polygon.h"

#define ROTATION  (M_PI / 30.0)  /* rotate by 6 degrees at a time */

/* base offset of page to which to draw */
unsigned int CurrentPageBase = 0;
/* Clip rectangle; clips to the screen */
int ClipMinX=0, ClipMinY=0;
int ClipMaxX=SCREEN_WIDTH, ClipMaxY=SCREEN_HEIGHT;
/* Rectangle specifying extent to be erased in each page. */
struct Rect EraseRect[2] = { {0, 0, SCREEN_WIDTH, SCREEN_HEIGHT},
   {0, 0, SCREEN_WIDTH, SCREEN_HEIGHT} };
static unsigned int PageStartOffsets[2] =
   {PAGE0_START_OFFSET,PAGE1_START_OFFSET};
int DisplayedPage, NonDisplayedPage;
/* Transformation from cube's object space to world space. Initially
   set up to perform no rotation and to move the cube into world
   space -100 units away from the origin down the Z axis. Given the
   viewing point, -100 down the Z axis means 100 units away in the
   direction of view. The program dynamically changes both the
   translation and the rotation. */
static double CubeWorldXform[4][4] = {
   {1.0, 0.0, 0.0, 0.0},
   {0.0, 1.0, 0.0, 0.0},
   {0.0, 0.0, 1.0, -100.0},
   {0.0, 0.0, 0.0, 1.0} };
/* Transformation from world space into view space. Because in this
   application the view point is fixed at the origin of world space,
   looking down the Z axis in the direction of increasing Z, view space is
   identical to world space, and this is the identity matrix. */
```

```
static double WorldViewXform[4][4] = {
   {1.0, 0.0, 0.0, 0.0},
   {0.0, 1.0, 0.0, 0.0},
   {0.0, 0.0, 1.0, 0.0},
   {0.0, 0.0, 0.0, 1.0}
};
/* all vertices in the cube */
static struct Point3 CubeVerts[] = {
   {15,15,15,1},{15,15,-15,1},{15,-15,15,1},{15,-15,-15,1},
   {-15,15,15,1},{-15,15,-15,1},{-15,-15,15,1},{-15,-15,-15,1}};
/* vertices after transformation */
static struct Point3
      XformedCubeVerts[sizeof(CubeVerts)/sizeof(struct Point3)];
/* vertices after projection */
static struct Point3
      ProjectedCubeVerts[sizeof(CubeVerts)/sizeof(struct Point3)];
/* vertices in screen coordinates */
static struct Point
      ScreenCubeVerts[sizeof(CubeVerts)/sizeof(struct Point3)];
/* vertex indices for individual faces */
static int Face1[] = {1,3,2,0};
static int Face2[] = {5,7,3,1};
static int Face3[] = {4,5,1,0};
static int Face4[] = {3,7,6,2};
static int Face5[] = {5,4,6,7};
static int Face6[] = {0,2,6,4};
/* list of cube faces */
static struct Face CubeFaces[] = {{Face1,4,15},{Face2,4,14},
   {Face3,4,12},{Face4,4,11},{Face5,4,10},{Face6,4,9}};
/* master description for cube */
static struct Object Cube = {sizeof(CubeVerts)/sizeof(struct Point3),
   CubeVerts, XformedCubeVerts, ProjectedCubeVerts, ScreenCubeVerts,
   sizeof(CubeFaces)/sizeof(struct Face), CubeFaces};

void main() {
   int Done = 0, RecalcXform = 1;
   double WorkingXform[4][4];
   union REGS regset;

   /* Set up the initial transformation */
   Set320x240Mode(); /* set the screen to Mode X */
   ShowPage(PageStartOffsets[DisplayedPage = 0]);
   /* Keep transforming the cube, drawing it to the undisplayed page,
      and flipping the page to show it */
   do {
      /* Regenerate the object->view transformation and
         retransform/project if necessary */
      if (RecalcXform) {
         ConcatXforms(WorldViewXform, CubeWorldXform, WorkingXform);
         /* Transform and project all the vertices in the cube */
         XformAndProjectPoints(WorkingXform, &Cube);
         RecalcXform = 0;
      }
      CurrentPageBase =    /* select other page for drawing to */
            PageStartOffsets[NonDisplayedPage = DisplayedPage ^ 1];
      /* Clear the portion of the non-displayed page that was drawn
         to last time, then reset the erase extent */
      FillRectangleX(EraseRect[NonDisplayedPage].Left,
            EraseRect[NonDisplayedPage].Top,
            EraseRect[NonDisplayedPage].Right,
            EraseRect[NonDisplayedPage].Bottom, CurrentPageBase, 0);
      EraseRect[NonDisplayedPage].Left =
            EraseRect[NonDisplayedPage].Top = 0x7FFF;
      EraseRect[NonDisplayedPage].Right =
            EraseRect[NonDisplayedPage].Bottom = 0;
      /* Draw all visible faces of the cube */
      DrawVisibleFaces(&Cube);
      /* Flip to display the page into which we just drew */
      ShowPage(PageStartOffsets[DisplayedPage = NonDisplayedPage]);
      while (kbhit()) {
         switch (getch()) {
            case 0x1B:    /* Esc to exit */
               Done = 1; break;
            case 'A': case 'a':     /* away (-Z) */
               CubeWorldXform[2][3] -= 3.0; RecalcXform = 1; break;
            case 'T':     /* towards (+Z). Don't allow to get too */
            case 't':     /* close, so Z clipping isn't needed */
               if (CubeWorldXform[2][3] < -40.0) {
                     CubeWorldXform[2][3] += 3.0;
                     RecalcXform = 1;
               }
               break;
            case '4':        /* rotate clockwise around Y */
               AppendRotationY(CubeWorldXform, -ROTATION);
               RecalcXform=1; break;
            case '6':        /* rotate counterclockwise around Y */
               AppendRotationY(CubeWorldXform, ROTATION);
               RecalcXform=1; break;
            case '8':        /* rotate clockwise around X */
               AppendRotationX(CubeWorldXform, -ROTATION);
               RecalcXform=1; break;
            case '2':        /* rotate counterclockwise around X */
               AppendRotationX(CubeWorldXform, ROTATION);
               RecalcXform=1; break;
            case 0:    /* extended code */
               switch (getch()) {
                  case 0x3B:  /* rotate counterclockwise around Z */
                     AppendRotationZ(CubeWorldXform, ROTATION);
                     RecalcXform=1; break;
                  case 0x3C:  /* rotate clockwise around Z */
                     AppendRotationZ(CubeWorldXform, -ROTATION);
                     RecalcXform=1; break;
                  case 0x4B:  /* left (-X) */
                    CubeWorldXform[0][3] -= 3.0; RecalcXform=1; break;
                  case 0x4D:  /* right (+X) */
                    CubeWorldXform[0][3] += 3.0; RecalcXform=1; break;
                  case 0x48:  /* up (+Y) */
                    CubeWorldXform[1][3] += 3.0; RecalcXform=1; break;
                  case 0x50:  /* down (-Y) */
                    CubeWorldXform[1][3] -= 3.0; RecalcXform=1; break;
                  default:
                    break;
               }
               break;
            default:      /* any other key to pause */
               getch(); break;
         }
      }
   } while (!Done);
   /* Return to text mode and exit */
   regset.x.ax = 0x0003;   /* AL = 3 selects 80x25 text mode */
   int86(0x10, &regset, &regset);
}
```

LISTING 36.2 L36-2.C

```
/* Transforms all vertices in the specified object into view space, then
   perspective projects them to screen space and maps them to screen coordinates,
   storing the results in the object. */
#include <math.h>
#include "polygon.h"/

void XformAndProjectPoints(double Xform[4][4],
   struct Object * ObjectToXform)
{
   int i, NumPoints = ObjectToXform->NumVerts;
   struct Point3 * Points = ObjectToXform->VertexList;
   struct Point3 * XformedPoints = ObjectToXform->XformedVertexList;
   struct Point3 * ProjectedPoints = ObjectToXform->ProjectedVertexList;
   struct Point * ScreenPoints = ObjectToXform->ScreenVertexList;

   for (i=0; i<NumPoints; i++, Points++, XformedPoints++,
         ProjectedPoints++, ScreenPoints++) {
      /* Transform to view space */
      XformVec(Xform, (double *)Points, (double *)XformedPoints);
      /* Perspective-project to screen space */
      ProjectedPoints->X = XformedPoints->X / XformedPoints->Z *
            PROJECTION_RATIO * (SCREEN_WIDTH / 2.0);
      ProjectedPoints->Y = XformedPoints->Y / XformedPoints->Z *
            PROJECTION_RATIO * (SCREEN_WIDTH / 2.0);
      ProjectedPoints->Z = XformedPoints->Z;
      /* Convert to screen coordinates. The Y coord is negated to
         flip from increasing Y being up to increasing Y being down,
         as expected by the polygon filler. Add in half the screen
         width and height to center on the screen. */
      ScreenPoints->X = ((int) floor(ProjectedPoints->X + 0.5)) + SCREEN_WIDTH/2;
      ScreenPoints->Y = (-((int) floor(ProjectedPoints->Y + 0.5))) +
               SCREEN_HEIGHT/2;
   }
}
```

LISTING 36.3 L36-3.C

```
/* Draws all visible faces (faces pointing toward the viewer) in the specified
   object. The object must have previously been transformed and projected, so
   that the ScreenVertexList array is filled in. */
#include "polygon.h"

void DrawVisibleFaces(struct Object * ObjectToXform)
{
   int i, j, NumFaces = ObjectToXform->NumFaces, NumVertices;
   int * VertNumsPtr;
   struct Face * FacePtr = ObjectToXform->FaceList;
   struct Point * ScreenPoints = ObjectToXform->ScreenVertexList;
   long v1,v2,w1,w2;
   struct Point Vertices[MAX_POLY_LENGTH];
   struct PointListHeader Polygon;

   /* Draw each visible face (polygon) of the object in turn */
   for (i=0; i<NumFaces; i++, FacePtr++) {
      NumVertices = FacePtr->NumVerts;
      /* Copy over the face's vertices from the vertex list */
      for (j=0, VertNumsPtr=FacePtr->VertNums; j<NumVertices; j++)
         Vertices[j] = ScreenPoints[*VertNumsPtr++];
      /* Draw only if outside face showing (if the normal to the
         polygon points toward the viewer; that is, has a positive
         Z component) */
      v1 = Vertices[1].X - Vertices[0].X;
      w1 = Vertices[NumVertices-1].X - Vertices[0].X;
      v2 = Vertices[1].Y - Vertices[0].Y;
      w2 = Vertices[NumVertices-1].Y - Vertices[0].Y;
      if ((v1*w2 - v2*w1) > 0) {
         /* It is facing the screen, so draw */
         /* Appropriately adjust the extent of the rectangle used to
            erase this page later */
         for (j=0; j<NumVertices; j++) {
            if (Vertices[j].X > EraseRect[NonDisplayedPage].Right)
               if (Vertices[j].X < SCREEN_WIDTH)
                  EraseRect[NonDisplayedPage].Right = Vertices[j].X;
               else EraseRect[NonDisplayedPage].Right = SCREEN_WIDTH;
            if (Vertices[j].Y > EraseRect[NonDisplayedPage].Bottom)
               if (Vertices[j].Y < SCREEN_HEIGHT)
                  EraseRect[NonDisplayedPage].Bottom = Vertices[j].Y;
               else EraseRect[NonDisplayedPage].Bottom=SCREEN_HEIGHT;
            if (Vertices[j].X < EraseRect[NonDisplayedPage].Left)
               if (Vertices[j].X > 0)
                  EraseRect[NonDisplayedPage].Left = Vertices[j].X;
               else EraseRect[NonDisplayedPage].Left = 0;
            if (Vertices[j].Y < EraseRect[NonDisplayedPage].Top)
               if (Vertices[j].Y > 0)
                  EraseRect[NonDisplayedPage].Top = Vertices[j].Y;
               else EraseRect[NonDisplayedPage].Top = 0;
         }
         /* Draw the polygon */
         DRAW_POLYGON(Vertices, NumVertices, FacePtr->Color, 0, 0);
      }
   }
}
```

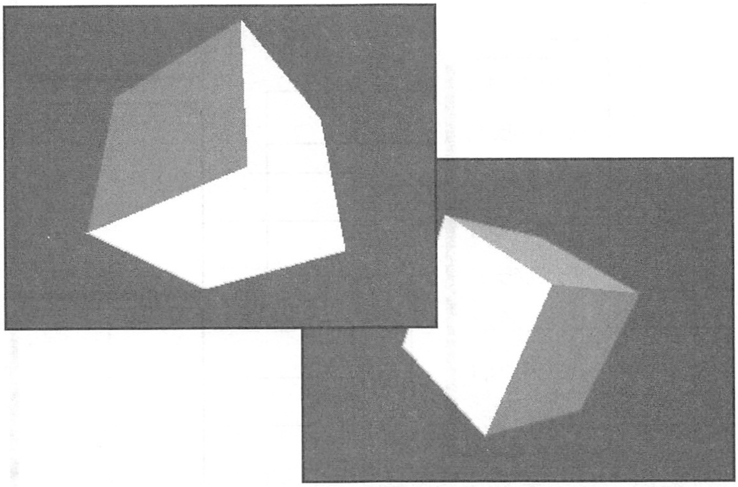


Figure 36.3 Sample Screens from the 3-D Cube Program

The sample program, as shjown in Figure 36.3, places a cube, floating in three-space, under the complete control of the user. The arrow keys may be used to move the cube left, right, up, and down, and the A and T keys may be used to move the cube away from or toward the viewer. The F1 and F2 keys perform rotation around the Z axis, the axis running from the viewer straight into the screen. The 4 and 6 keys perform rotation around the Y (vertical) axis, and the 2 and 8 keys perform rotation around the X axis, which runs horizontally across the screen; the latter four keys are most conveniently used by flipping the keypad to the numeric state.

The demo involves six polygons, one for each side of the cube. Each of the polygons must be transformed and projected, so it would seem that 24 vertices (four for each polygon) must be handled, but some steps have been taken to improve performance. All vertices for the object have been stored in a single list; the definition of each face contains not the vertices for that face themselves, but rather indexes into the object's vertex list, as shown in Figure 36.4. This reduces the number of vertices to be manipulated from 24 to 8, for there are, after all, only eight vertices in a cube, with three faces sharing each vertex. In this way, the transformation burden is lightened by two-thirds. Also, as mentioned earlier, backface removal is performed with integers, in screen coordinates, rather than with floating-point values in screen space. Finally, the **RecalcXForm**

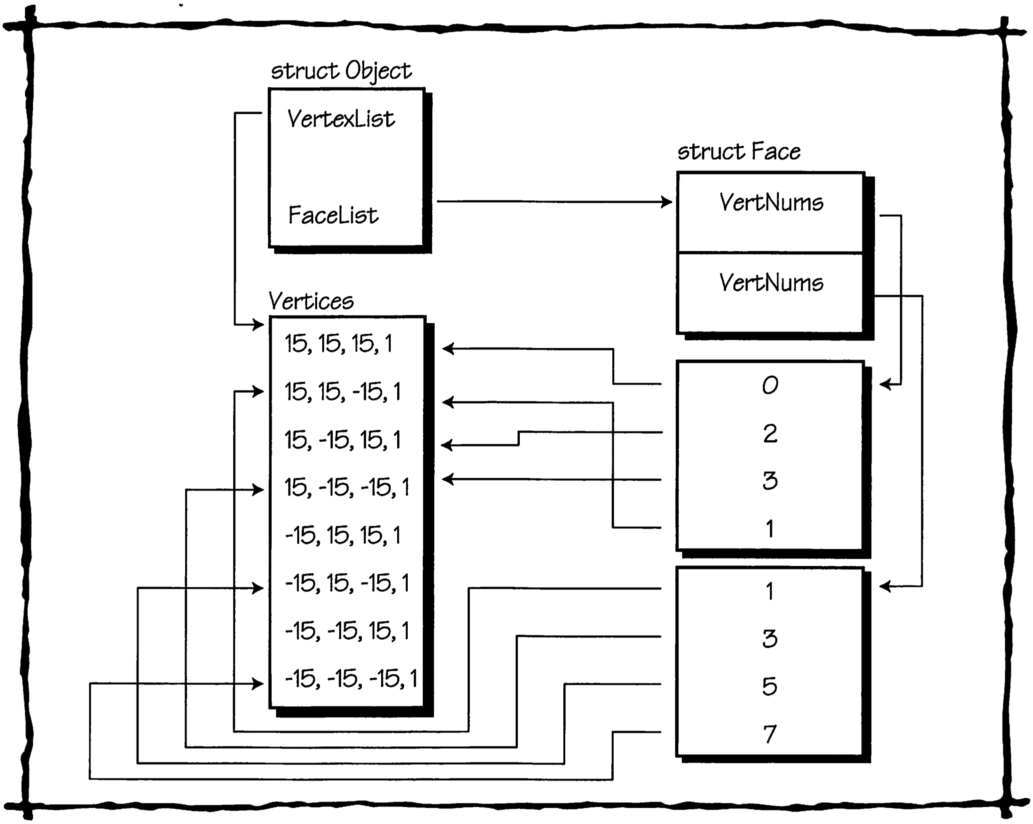


Figure 36.4 The Object Data Structure

flag is set whenever the user changes the object-to-world transformation. Only when this flag is set is the full object-to-view transformation recalculated and the object's vertices transformed and projected again; otherwise, the values already stored within the object are reused. In the sample application, this brings no visual improvement, because there's only the one object, but the underlying mechanism is sound: In a full-blown 3-D animation application, with multiple objects moving about the screen, it would help a great deal to flag which of the objects had moved with respect to the viewer, performing a new transformation and projection only for those that had.

With the above optimizations, the sample program is certainly adequately responsive on a 20 MHz 386 (sans 387; I'm sure it's wonderfully responsive with a math coprocessor). Still, it couldn't quite keep up with the keyboard when I modified it to read only one key each time through the loop—and we're talking about only eight vertices here. This indicates that we're already near the limit of animation complexity possible with our current approach. It's time to start rethinking that approach; over two-thirds of the overall time is spent in floating-point calculations, and it's there that we'll begin to attack the performance bottleneck we find ourselves up against.

Incremental Transformation

Listing 36.4 contains three functions; each concatenates an additional rotation around one of the three axes to an existing rotation. To improve performance, only the matrix entries that are affected in a rotation around each particular axis are recalculated (all but four of the entries in a single-axis rotation matrix are either 0 or 1, as shown in Chapter 35). This cuts the number of floating-point multiplies from the 64 required for the multiplication of two 4×4 matrices to just 12, and floating point adds from 48 to 6.

Be aware that Listing 36.4 performs an incremental rotation on top of whatever rotation is already in the matrix. The cube may already have been turned left, right, up, down, and sideways; regardless, Listing 36.4 just tacks the specified rotation onto whatever already exists. In this way, the object-to-world transformation matrix contains a history of all the rotations ever specified by the user, concatenated one after another onto the original matrix. Potential loss of precision is a problem associated with using such an approach to represent a very long concatenation of transformations, especially with fixed-point arithmetic; that's not a problem for us yet, but we'll run into it eventually.

LISTING 36.4 L36-4.C

```
/* Routines to perform incremental rotations around the three axes */
#include <math.h>
#include "polygon.h"

/* Concatenate a rotation by Angle around the X axis to the transformation in
   XformToChange, placing result back in XformToChange. */
   void AppendRotationX(double XformToChange[4][4], double Angle)
{
   double Temp10, Temp11, Temp12, Temp20, Temp21, Temp22;
   double CosTemp = cos(Angle), SinTemp = sin(Angle);
   /* Calculate the new values of the four affected matrix entries */
   Temp10 = CosTemp*XformToChange[1][0]+ -SinTemp*XformToChange[2][0];
   Temp11 = CosTemp*XformToChange[1][1]+ -SinTemp*XformToChange[2][1];
   Temp12 = CosTemp*XformToChange[1][2]+ -SinTemp*XformToChange[2][2];
   Temp20 = SinTemp*XformToChange[1][0]+ CosTemp*XformToChange[2][0];
   Temp21 = SinTemp*XformToChange[1][1]+ CosTemp*XformToChange[2][1];
   Temp22 = SinTemp*XformToChange[1][2]+ CosTemp*XformToChange[2][2];
   /* Put the results back into XformToChange */
   XformToChange[1][0] = Temp10; XformToChange[1][1] = Temp11;
   XformToChange[1][2] = Temp12; XformToChange[2][0] = Temp20;
   XformToChange[2][1] = Temp21; XformToChange[2][2] = Temp22;
}

/* Concatenate a rotation by Angle around the Y axis to the transformation in
   XformToChange, placing result back in XformToChange. */
   void AppendRotationY(double XformToChange[4][4], double Angle)
{
   double Temp00, Temp01, Temp02, Temp20, Temp21, Temp22;
   double CosTemp = cos(Angle), SinTemp = sin(Angle);

   /* Calculate the new values of the four affected matrix entries */
   Temp00 = CosTemp*XformToChange[0][0]+ SinTemp*XformToChange[2][0];
   Temp01 = CosTemp*XformToChange[0][1]+ SinTemp*XformToChange[2][1];
   Temp02 = CosTemp*XformToChange[0][2]+ SinTemp*XformToChange[2][2];
   Temp20 = -SinTemp*XformToChange[0][0]+ CosTemp*XformToChange[2][0];
   Temp21 = -SinTemp*XformToChange[0][1]+ CosTemp*XformToChange[2][1];
   Temp22 = -SinTemp*XformToChange[0][2]+ CosTemp*XformToChange[2][2];
   /* Put the results back into XformToChange */
   XformToChange[0][0] = Temp00; XformToChange[0][1] = Temp01;
   XformToChange[0][2] = Temp02; XformToChange[2][0] = Temp20;
   XformToChange[2][1] = Temp21; XformToChange[2][2] = Temp22;
}

/* Concatenate a rotation by Angle around the Z axis to the transformation in
   XformToChange, placing result back in XformToChange. */
   void AppendRotationZ(double XformToChange[4][4], double Angle)
{
   double Temp00, Temp01, Temp02, Temp10, Temp11, Temp12;
   double CosTemp = cos(Angle), SinTemp = sin(Angle);
   /* Calculate the new values of the four affected matrix entries */
   Temp00 = CosTemp*XformToChange[0][0]+ -SinTemp*XformToChange[1][0];
   Temp01 = CosTemp*XformToChange[0][1]+ -SinTemp*XformToChange[1][1];
   Temp02 = CosTemp*XformToChange[0][2]+ -SinTemp*XformToChange[1][2];
   Temp10 = SinTemp*XformToChange[0][0]+ CosTemp*XformToChange[1][0];
   Temp11 = SinTemp*XformToChange[0][1]+ CosTemp*XformToChange[1][1];
   Temp12 = SinTemp*XformToChange[0][2]+ CosTemp*XformToChange[1][2];
   /* Put the results back into XformToChange */
   XformToChange[0][0] = Temp00; XformToChange[0][1] = Temp01;
   XformToChange[0][2] = Temp02; XformToChange[1][0] = Temp10;
   XformToChange[1][1] = Temp11; XformToChange[1][2] = Temp12;
}
```

LISTING 36.5 POLYGON.H

```
/* POLYGON.H: Header file for polygon-filling code, also includes a number of
   useful items for 3D animation. */
#define MAX_POLY_LENGTH 4  /* four vertices is the max per poly */
#define SCREEN_WIDTH 320
#define SCREEN_HEIGHT 240
```

```
#define PAGE0_START_OFFSET 0
#define PAGE1_START_OFFSET (((long)SCREEN_HEIGHT*SCREEN_WIDTH)/4)
/* Ratio: distance from viewpoint to projection plane / width of projection
   plane. Defines the width of the field of view. Lower absolute values = wider
   fields of view; higher values = narrower. */
#define PROJECTION_RATIO   -2.0 /* negative because visible Z coordinates are negative */
/* Draws the polygon described by the point list PointList in color Color with
   all vertices offset by (X,Y) */
#define DRAW_POLYGON(PointList,NumPoints,Color,X,Y)          \
   Polygon.Length = NumPoints; Polygon.PointPtr = PointList; \
   FillConvexPolygon(&Polygon, Color, X, Y);
/* Describes a single 2D point */
struct Point {
   int X;   /* X coordinate */
   int Y;   /* Y coordinate */
};
/* Describes a single 3D point in homogeneous coordinates */
struct Point3 {
   double X;   /* X coordinate */
   double Y;   /* Y coordinate */
   double Z;   /* Z coordinate */
   double W;
};
/* Describes a series of points (used to store a list of vertices that
   describe a polygon; each vertex is assumed to connect to the two adjacent
   vertices, and the last vertex is assumed to connect to the first) */
   struct PointListHeader {
   int Length;                /* # of points */
   struct Point * PointPtr;   /* pointer to list of points */
};
/* Describes beginning and ending X coordinates of a single horizontal line */
struct HLine {
   int XStart; /* X coordinate of leftmost pixel in line */
   int XEnd;   /* X coordinate of rightmost pixel in line */
};
/* Describes a Length-long series of horizontal lines, all assumed to be on
   contiguous scan lines starting at YStart and proceeding downward (describes
   a scan-converted polygon to low-level hardware-dependent drawing code) */
struct HLineList {
   int Length;                /* # of horizontal lines */
   int YStart;                /* Y coordinate of topmost line */
   struct HLine * HLinePtr;   /* pointer to list of horz lines */
};
struct Rect { int Left, Top, Right, Bottom; };
/* Structure describing one face of an object (one polygon) */
struct Face {
   int * VertNums;   /* pointer to vertex ptrs */
   int NumVerts;     /* # of vertices */
   int Color;        /* polygon color */
};
/* Structure describing an object */
struct Object {
   int NumVerts;
   struct Point3 * VertexList;
   struct Point3 * XformedVertexList;
   struct Point3 * ProjectedVertexList;
   struct Point * ScreenVertexList;
   int NumFaces;
   struct Face * FaceList;
};
extern void XformVec(double Xform[4][4], double * SourceVec, double * DestVec);
extern void ConcatXforms(double SourceXform1[4][4],
   double SourceXform2[4][4], double DestXform[4][4]);
extern void XformAndProjectPoly(double Xform[4][4],
   struct Point3 * Poly, int PolyLength, int Color);
extern int FillConvexPolygon(struct PointListHeader *, int, int, int);
extern void Set320x240Mode(void);
extern void ShowPage(unsigned int StartOffset);
extern void FillRectangleX(int StartX, int StartY, int EndX,
   int EndY, unsigned int PageBase, int Color);
extern void XformAndProjectPoints(double Xform[4][4],struct Object * ObjectToXform);
extern void DrawVisibleFaces(struct Object * ObjectToXform);
extern void AppendRotationX(double XformToChange[4][4], double Angle);
extern void AppendRotationY(double XformToChange[4][4], double Angle);
extern void AppendRotationZ(double XformToChange[4][4], double Angle);
extern int DisplayedPage, NonDisplayedPage;
extern struct Rect EraseRect[];
```

A Note on Rounding Negative Numbers

In the previous chapter, I added 0.5 and truncated in order to round values from floating-point to integer format. Here, in Listing 36.2, I've switched to adding 0.5 and using the **floor()** function. For positive values, the two approaches are equivalent; for negative values, only the **floor()** approach works properly.

Object Representation

Each object consists of a list of vertices and a list of faces, with the vertices of each face defined by pointers into the vertex list; this allows each vertex to be transformed exactly once, even though several faces may share a single vertex. Each object contains the vertices not only in their original, untransformed state, but in three other forms as well: transformed to view space, transformed and projected to screen space, and converted to screen coordinates. Earlier, we saw that it can be convenient to store the screen coordinates within the object, so that if the object hasn't moved with respect to the viewer, it can be redrawn without the need for recalculation, but why bother storing the view and screen space forms of the vertices as well?

The screen space vertices are useful for some sorts of hidden surface removal. For example, to determine whether two polygons overlap as seen by the viewer, you must first know how they look to the viewer, accounting for perspective; screen space provides that information. (So do the final screen coordinates, but with less accuracy, and without any Z information.) The view space vertices are useful for collision and proximity detection; screen space can't be used here, because objects are distorted by the perspective projection into screen space. World space would serve as well as view space for collision detection, but because it's possible to transform directly from object space to view space with a single matrix, it's often preferable to skip over world space. It's not mandatory that vertices be stored for all these different spaces, but the coordinates in all those spaces have to be calculated as intermediate steps anyway, so we might as well keep them around for those occasions when they're needed.

Fast 3-D Animation: Meet X-Sharp

Chapter 37

The First Iteration of a Generalized 3-D Animation Package

Across the lake from Vermont, a few miles into upstate New York, the Ausable River has carved out a fairly impressive gorge known as "Ausable Chasm." Impressive for the East, anyway; you might think of it as the poor man's Grand Canyon. Some time back, I did the tour with my wife and five-year-old, and it was fun, although I confess that I didn't loosen my grip on my daughter's hand until we were on the bus and headed for home; that gorge is deep, and the railings tend to be of the single-bar, rusted-out variety.

New Yorkers can drive straight to this wonder of nature, but Vermonters must take their cars across on the ferry; the alternative is driving three hours around the south end of Lake Champlain. No problem; the ferry ride is an hour well spent on a beautiful lake. Or, rather, no problem—once you're on the ferry. Getting to New York is easy, but, as we found out, the line of cars waiting to come back from Ausable Chasm gets lengthy about mid-afternoon. The ferry can hold only so many cars, and we wound up spending an unexpected hour exploring the wonders of the ferry docks. Not a big deal, with a good-natured kid and an entertaining mom; we got ice cream, explored the beach, looked through binoculars, and told stories. It was a fun break, actually, and before we knew it, the ferry was steaming back to pick us up.

A friend of mine, an elementary-school teacher, helped take 65 sixth graders to Ausable Chasm. Never mind the potential for trouble with 65 kids loose on a ferry. Never mind what it was like trying to herd that group around a gorge that looks like it was designed to swallow children and small animals without a trace. The hard part was getting back to the docks and finding they'd have to wait an hour for the next ferry. As my friend put it, "Let me tell you, an hour is an eternity with 65 sixth graders screaming the song 'You Are My Sunshine.'"

Apart from reminding you how lucky you are to be working in a quiet, air-conditioned room, in front of a gently humming computer, free to think deep thoughts and eat Cheetos to your heart's content, this story provides a useful perspective on the malleable nature of time. An hour isn't just an hour—it can be forever, or it can be the wink of an eye. Just think of the last hour you spent working under a deadline; I bet it went past in a flash. Which is not to say, mind you, that I recommend working in a bus full of screaming kids in order to make time pass more slowly; there are quality issues here as well.

In our 3-D animation work so far, we've used floating-point arithmetic. Floating-point arithmetic—even with a floating-point processor but especially *without* one—is the microcomputer animation equivalent of working in a school bus: It takes forever to do anything, and you just *know* you're never going to accomplish as much as you want to. In this chapter, we'll address fixed-point arithmetic, which will give us an instant order-of-magnitude performance boost. We'll also give our 3-D animation code a much more powerful and extensible framework, making it easy to add new and different sorts of objects. Taken together, these alterations will let us start to do some really interesting real-time animation.

This Chapter's Demo Program

Three-dimensional animation is a complicated business, and it takes an astonishing amount of functionality just to get off the launching pad: page flipping, polygon filling, clipping, transformations, list management, and so forth. I've been building toward a critical mass of animation functionality over the course of this book, and this chapter's code builds on the code from no fewer than five previous chapters. The code that's required in order to link this chapter's animation demo program is the following:

- Listing 35.1 from Chapter 35 (draw clipped line list);
- Listings 32.1 and 32.6 from Chapter 32 (Mode X mode set, rectangle fill);
- Listing 34.6 from Chapter 34;
- Listing 22.4 from Chapter 22 (polygon edge scan); and
- The **FillConvexPolygon( )** function from Listing 21.1 from Chapter 21. Note that the **struct** keywords in **FillConvexPolygon( )** must be removed to reflect the **switch** to **typedefs** in the animation header file.

As always, all required files are in this chapter's subdirectory on the listings diskette.

LISTING 37.1 L37-1.C

```
/* 3-D animation program to rotate 12 cubes. Uses fixed point. All C code
   tested with Borland C++ in C compilation mode and the small model. */

#include <conio.h>
#include <dos.h>
#include "polygon.h"
```

```
/* base offset of page to which to draw */
unsigned int CurrentPageBase = 0;
/* clip rectangle; clips to the screen */
int ClipMinX = 0, ClipMinY = 0;
int ClipMaxX = SCREEN_WIDTH, ClipMaxY = SCREEN_HEIGHT;
static unsigned int PageStartOffsets[2] =
   {PAGE0_START_OFFSET,PAGE1_START_OFFSET};
int DisplayedPage, NonDisplayedPage;
int RecalcAllXforms = 1, NumObjects = 0;
Xform WorldViewXform;  /* initialized from floats */
/* pointers to objects */
Object *ObjectList[MAX_OBJECTS];

void main() {
   int Done = 0, i;
   Object *ObjectPtr;
   union REGS regset;

   InitializeFixedPoint(); /* set up fixed-point data */
   InitializeCubes();      /* set up cubes and add them to object list; other
                              objects would be initialized now, if there were any */
   Set320x240Mode();       /* set the screen to mode X */
   ShowPage(PageStartOffsets[DisplayedPage = 0]);
   /* Keep transforming the cube, drawing it to the undisplayed page,
      and flipping the page to show it */
   do {
      /* For each object, regenerate viewing info, if necessary */
      for (i=0; i<NumObjects; i++) {
         if ((ObjectPtr = ObjectList[i])->RecalcXform ||
               RecalcAllXforms) {
            ObjectPtr->RecalcFunc(ObjectPtr);
            ObjectPtr->RecalcXform = 0;
         }
      }
      RecalcAllXforms = 0;
      CurrentPageBase =    /* select other page for drawing to */
            PageStartOffsets[NonDisplayedPage = DisplayedPage ^ 1];
      /* For each object, clear the portion of the non-displayed page
         that was drawn to last time, then reset the erase extent */
      for (i=0; i<NumObjects; i++) {
         ObjectPtr = ObjectList[i];
         FillRectangleX(ObjectPtr->EraseRect[NonDisplayedPage].Left,
            ObjectPtr->EraseRect[NonDisplayedPage].Top,
            ObjectPtr->EraseRect[NonDisplayedPage].Right,
            ObjectPtr->EraseRect[NonDisplayedPage].Bottom,
            CurrentPageBase, 0);
         ObjectPtr->EraseRect[NonDisplayedPage].Left =
              ObjectPtr->EraseRect[NonDisplayedPage].Top = 0x7FFF;
         ObjectPtr->EraseRect[NonDisplayedPage].Right =
               ObjectPtr->EraseRect[NonDisplayedPage].Bottom = 0;
      }
      /* Draw all objects */
      for (i=0; i<NumObjects; i++)
         ObjectList[i]->DrawFunc(ObjectList[i]);
      /* Flip to display the page into which we just drew */
      ShowPage(PageStartOffsets[DisplayedPage = NonDisplayedPage]);
      /* Move and reorient each object */
      for (i=0; i<NumObjects; i++)
         ObjectList[i]->MoveFunc(ObjectList[i]);
      if (kbhit())
         if (getch() == 0x1B) Done = 1;   /* Esc to exit */
   } while (!Done);
   /* Return to text mode and exit */
   regset.x.ax = 0x0003;   /* AL = 3 selects 80x25 text mode */
   int86(0x10, &regset, &regset);
   exit(1);
}
```

LISTING 37.2 L37-2.C

```
/* Transforms all vertices in the specified polygon-based object into view
   space, then perspective projects them to screen space and maps them to screen
   coordinates, storing results in the object. Recalculates object->view
   transformation because only if transform changes would we bother
   to retransform the vertices. */

#include <math.h>
#include "polygon.h"

void XformAndProjectPObject(PObject * ObjectToXform)
{
   int i, NumPoints = ObjectToXform->NumVerts;
   Point3 * Points = ObjectToXform->VertexList;
   Point3 * XformedPoints = ObjectToXform->XformedVertexList;
   Point3 * ProjectedPoints = ObjectToXform->ProjectedVertexList;
   Point * ScreenPoints = ObjectToXform->ScreenVertexList;

   /* Recalculate the object->view transform */
   ConcatXforms(WorldViewXform, ObjectToXform->XformToWorld,
             ObjectToXform->XformToView);
   /* Apply that new transformation and project the points */
   for (i=0; i<NumPoints; i++, Points++, XformedPoints++,
         ProjectedPoints++, ScreenPoints++) {
      /* Transform to view space */
      XformVec(ObjectToXform->XformToView, (Fixedpoint *) Points,
            (Fixedpoint *) XformedPoints);
      /* Perspective-project to screen space */
      ProjectedPoints->X =
            FixedMul(FixedDiv(XformedPoints->X, XformedPoints->Z),
            DOUBLE_TO_FIXED(PROJECTION_RATIO * (SCREEN_WIDTH/2)));
      ProjectedPoints->Y =
            FixedMul(FixedDiv(XformedPoints->Y, XformedPoints->Z),
            DOUBLE_TO_FIXED(PROJECTION_RATIO * (SCREEN_WIDTH/2)));
      ProjectedPoints->Z = XformedPoints->Z;
      /* Convert to screen coordinates. The Y coord is negated to flip from
         increasing Y being up to increasing Y being down, as expected by polygon
         filler. Add in half the screen width and height to center on screen. */
      ScreenPoints->X = ((int) ((ProjectedPoints->X +
            DOUBLE_TO_FIXED(0.5)) >> 16)) + SCREEN_WIDTH/2;
      ScreenPoints->Y = (-((int) ((ProjectedPoints->Y +
            DOUBLE_TO_FIXED(0.5)) >> 16))) + SCREEN_HEIGHT/2;
   }
}
```

LISTING 37.3 L37-3.C

```
/* Routines to perform incremental rotations around the three axes. */

#include <math.h>
#include "polygon.h"
```

```
/* Concatenate a rotation by Angle around the X axis to transformation in
   XformToChange, placing the result back into XformToChange. */
void AppendRotationX(Xform XformToChange, double Angle)
{
   Fixedpoint Temp10, Temp11, Temp12, Temp20, Temp21, Temp22;
   Fixedpoint CosTemp = DOUBLE_TO_FIXED(cos(Angle));
   Fixedpoint SinTemp = DOUBLE_TO_FIXED(sin(Angle));

   /* Calculate the new values of the six affected matrix entries */
   Temp10 = FixedMul(CosTemp, XformToChange[1][0]) +
         FixedMul(-SinTemp, XformToChange[2][0]);
   Temp11 = FixedMul(CosTemp, XformToChange[1][1]) +
         FixedMul(-SinTemp, XformToChange[2][1]);
   Temp12 = FixedMul(CosTemp, XformToChange[1][2]) +
         FixedMul(-SinTemp, XformToChange[2][2]);
   Temp20 = FixedMul(SinTemp, XformToChange[1][0]) +
         FixedMul(CosTemp, XformToChange[2][0]);
   Temp21 = FixedMul(SinTemp, XformToChange[1][1]) +
         FixedMul(CosTemp, XformToChange[2][1]);
   Temp22 = FixedMul(SinTemp, XformToChange[1][2]) +
         FixedMul(CosTemp, XformToChange[2][2]);
   /* Put the results back into XformToChange */
   XformToChange[1][0] = Temp10; XformToChange[1][1] = Temp11;
   XformToChange[1][2] = Temp12; XformToChange[2][0] = Temp20;
   XformToChange[2][1] = Temp21; XformToChange[2][2] = Temp22;
}
/* Concatenate a rotation by Angle around the Y axis to transformation in
   XformToChange, placing the result back into XformToChange. */
void AppendRotationY(Xform XformToChange, double Angle)
{
   Fixedpoint Temp00, Temp01, Temp02, Temp20, Temp21, Temp22;
   Fixedpoint CosTemp = DOUBLE_TO_FIXED(cos(Angle));
   Fixedpoint SinTemp = DOUBLE_TO_FIXED(sin(Angle));

   /* Calculate the new values of the six affected matrix entries */
   Temp00 = FixedMul(CosTemp, XformToChange[0][0]) +
         FixedMul(SinTemp, XformToChange[2][0]);
   Temp01 = FixedMul(CosTemp, XformToChange[0][1]) +
         FixedMul(SinTemp, XformToChange[2][1]);
   Temp02 = FixedMul(CosTemp, XformToChange[0][2]) +
         FixedMul(SinTemp, XformToChange[2][2]);
   Temp20 = FixedMul(-SinTemp, XformToChange[0][0]) +
         FixedMul( CosTemp, XformToChange[2][0]);
   Temp21 = FixedMul(-SinTemp, XformToChange[0][1]) +
         FixedMul(CosTemp, XformToChange[2][1]);
   Temp22 = FixedMul(-SinTemp, XformToChange[0][2]) +
         FixedMul(CosTemp, XformToChange[2][2]);
   /* Put the results back into XformToChange */
   XformToChange[0][0] = Temp00; XformToChange[0][1] = Temp01;
   XformToChange[0][2] = Temp02; XformToChange[2][0] = Temp20;
   XformToChange[2][1] = Temp21; XformToChange[2][2] = Temp22;
}

/* Concatenate a rotation by Angle around the Z axis to transformation in
   XformToChange, placing the result back into XformToChange. */
void AppendRotationZ(Xform XformToChange, double Angle)
{
   Fixedpoint Temp00, Temp01, Temp02, Temp10, Temp11, Temp12;
   Fixedpoint CosTemp = DOUBLE_TO_FIXED(cos(Angle));
   Fixedpoint SinTemp = DOUBLE_TO_FIXED(sin(Angle));
   /* Calculate the new values of the six affected matrix entries */
   Temp00 = FixedMul(CosTemp, XformToChange[0][0]) +
         FixedMul(-SinTemp, XformToChange[1][0]);
   Temp01 = FixedMul(CosTemp, XformToChange[0][1]) +
         FixedMul(-SinTemp, XformToChange[1][1]);
   Temp02 = FixedMul(CosTemp, XformToChange[0][2]) +
         FixedMul(-SinTemp, XformToChange[1][2]);
   Temp10 = FixedMul(SinTemp, XformToChange[0][0]) +
         FixedMul(CosTemp, XformToChange[1][0]);
   Temp11 = FixedMul(SinTemp, XformToChange[0][1]) +
         FixedMul(CosTemp, XformToChange[1][1]);
   Temp12 = FixedMul(SinTemp, XformToChange[0][2]) +
         FixedMul(CosTemp, XformToChange[1][2]);
   /* Put the results back into XformToChange */
   XformToChange[0][0] = Temp00; XformToChange[0][1] = Temp01;
   XformToChange[0][2] = Temp02; XformToChange[1][0] = Temp10;
   XformToChange[1][1] = Temp11; XformToChange[1][2] = Temp12;
}
```

LISTING 37.4 L37-4.C

```
/* Fixed point matrix arithmetic functions. */

#include "polygon.h"

/* Matrix multiplies Xform by SourceVec, and stores the result in DestVec.
   Multiplies a 4x4 matrix times a 4x1 matrix; the result is a 4x1 matrix. Cheats
   by assuming the W coord is 1 and bottom row of matrix is 0 0 0 1, and doesn't
   bother to set the W coordinate of the destination. */
void XformVec(Xform WorkingXform, Fixedpoint *SourceVec,
   Fixedpoint *DestVec)
{
   int i;

   for (i=0; i<3; i++)
      DestVec[i] = FixedMul(WorkingXform[i][0], SourceVec[0]) +
            FixedMul(WorkingXform[i][1], SourceVec[1]) +
            FixedMul(WorkingXform[i][2], SourceVec[2]) +
            WorkingXform[i][3];   /* no need to multiply by W = 1 */
}

/* Matrix multiplies SourceXform1 by SourceXform2 and stores result in
   DestXform. Multiplies a 4x4 matrix times a 4x4 matrix; result is a 4x4 matrix.
   Cheats by assuming bottom row of each matrix is 0 0 0 1, and doesn't bother
   to set the bottom row of the destination. */
void ConcatXforms(Xform SourceXform1, Xform SourceXform2,
   Xform DestXform)
{
   int i, j;

   for (i=0; i<3; i++) {
      for (j=0; j<4; j++)
         DestXform[i][j] =
               FixedMul(SourceXform1[i][0], SourceXform2[0][j]) +
               FixedMul(SourceXform1[i][1], SourceXform2[1][j]) +
               FixedMul(SourceXform1[i][2], SourceXform2[2][j]) +
               SourceXform1[i][3];
   }
}
```

LISTING 37.5 L37-5.C

```
/* Set up basic data that needs to be in fixed point, to avoid data
   definition hassles. */

#include "polygon.h"

/* All vertices in the basic cube */
static IntPoint3 IntCubeVerts[NUM_CUBE_VERTS] = {
   {15,15,15},{15,15,-15},{15,-15,15},{15,-15,-15},
   {-15,15,15},{-15,15,-15},{-15,-15,15},{-15,-15,-15} };
/* Transformation from world space into view space (no transformation,
   currently) */
static int IntWorldViewXform[3][4] = {
   {1,0,0,0}, {0,1,0,0}, {0,0,1,0}};

void InitializeFixedPoint()
{
   int i, j;

   for (i=0; i<3; i++)
      for (j=0; j<4; j++)
         WorldViewXform[i][j] = INT_TO_FIXED(IntWorldViewXform[i][j]);
   for (i=0; i<NUM_CUBE_VERTS; i++) {
      CubeVerts[i].X = INT_TO_FIXED(IntCubeVerts[i].X);
      CubeVerts[i].Y = INT_TO_FIXED(IntCubeVerts[i].Y);
      CubeVerts[i].Z = INT_TO_FIXED(IntCubeVerts[i].Z);
   }
}
```

LISTING 37.6 L37-6.C

```
/* Rotates and moves a polygon-based object around the three axes.
   Movement is implemented only along the Z axis currently. */

#include "polygon.h"

void RotateAndMovePObject(PObject * ObjectToMove)
{
   if (--ObjectToMove->RDelayCount == 0) {   /* rotate */
      ObjectToMove->RDelayCount = ObjectToMove->RDelayCountBase;
      if (ObjectToMove->Rotate.RotateX != 0.0)
         AppendRotationX(ObjectToMove->XformToWorld,
               ObjectToMove->Rotate.RotateX);
      if (ObjectToMove->Rotate.RotateY != 0.0)
         AppendRotationY(ObjectToMove->XformToWorld,
               ObjectToMove->Rotate.RotateY);
      if (ObjectToMove->Rotate.RotateZ != 0.0)
         AppendRotationZ(ObjectToMove->XformToWorld,
               ObjectToMove->Rotate.RotateZ);
      ObjectToMove->RecalcXform = 1;
   }
   /* Move in Z, checking for bouncing and stopping */
   if (--ObjectToMove->MDelayCount == 0) {
      ObjectToMove->MDelayCount = ObjectToMove->MDelayCountBase;
      ObjectToMove->XformToWorld[2][3] += ObjectToMove->Move.MoveZ;
      if (ObjectToMove->XformToWorld[2][3]>ObjectToMove->Move.MaxZ)
         ObjectToMove->Move.MoveZ = 0; /* stop if close enough */
      ObjectToMove->RecalcXform = 1;
   }
}
```

LISTING 37.7 L37-7.C

```
/* Draws all visible faces in specified polygon-based object. Object must have
   previously been transformed and projected, so that ScreenVertexList array is
   filled in. */

#include "polygon.h"

void DrawPObject(PObject * ObjectToXform)
{
   int i, j, NumFaces = ObjectToXform->NumFaces, NumVertices;
   int * VertNumsPtr;
   Face * FacePtr = ObjectToXform->FaceList;
   Point * ScreenPoints = ObjectToXform->ScreenVertexList;
   long v1, v2, w1, w2;
   Point Vertices[MAX_POLY_LENGTH];
   PointListHeader Polygon;

   /* Draw each visible face (polygon) of the object in turn */
   for (i=0; i<NumFaces; i++, FacePtr++) {
      NumVertices = FacePtr->NumVerts;
      /* Copy over the face's vertices from the vertex list */
      for (j=0, VertNumsPtr=FacePtr->VertNums; j<NumVertices; j++)
         Vertices[j] = ScreenPoints[*VertNumsPtr++];
      /* Draw only if outside face showing (if the normal to the
         polygon points toward viewer; that is, has a positive Z component) */
      v1 = Vertices[1].X - Vertices[0].X;
      w1 = Vertices[NumVertices-1].X - Vertices[0].X;
      v2 = Vertices[1].Y - Vertices[0].Y;
      w2 = Vertices[NumVertices-1].Y - Vertices[0].Y;
      if ((v1*w2 - v2*w1) > 0) {
         /* It is facing the screen, so draw */
         /* Appropriately adjust the extent of the rectangle used to
            erase this object later */
         for (j=0; j<NumVertices; j++) {
            if (Vertices[j].X >
                  ObjectToXform->EraseRect[NonDisplayedPage].Right)
               if (Vertices[j].X < SCREEN_WIDTH)
                  ObjectToXform->EraseRect[NonDisplayedPage].Right =
                        Vertices[j].X;
               else ObjectToXform->EraseRect[NonDisplayedPage].Right =
                     SCREEN_WIDTH;
            if (Vertices[j].Y >
                  ObjectToXform->EraseRect[NonDisplayedPage].Bottom)
               if (Vertices[j].Y < SCREEN_HEIGHT)
                  ObjectToXform->EraseRect[NonDisplayedPage].Bottom =
                        Vertices[j].Y;
               else ObjectToXform->EraseRect[NonDisplayedPage].Bottom=
                     SCREEN_HEIGHT;
            if (Vertices[j].X <
                  ObjectToXform->EraseRect[NonDisplayedPage].Left)
               if (Vertices[j].X > 0)
                  ObjectToXform->EraseRect[NonDisplayedPage].Left =
                        Vertices[j].X;
               else ObjectToXform->EraseRect[NonDisplayedPage].Left=0;
            if (Vertices[j].Y <
                  ObjectToXform->EraseRect[NonDisplayedPage].Top)
               if (Vertices[j].Y > 0)
                  ObjectToXform->EraseRect[NonDisplayedPage].Top =
                        Vertices[j].Y;
               else ObjectToXform->EraseRect[NonDisplayedPage].Top=0;
         }
         /* Draw the polygon */
         DRAW_POLYGON(Vertices, NumVertices, FacePtr->Color, 0, 0);
      }
   }
}
```

LISTING 37.8 L37-8.C

```
/* Initializes the cubes and adds them to the object list. */

#include <stdlib.h>
#include <math.h>
#include "polygon.h"

#define ROT_6  (M_PI / 30.0)     /* rotate 6 degrees at a time */
#define ROT_3  (M_PI / 60.0)     /* rotate 3 degrees at a time */
#define ROT_2  (M_PI / 90.0)     /* rotate 2 degrees at a time */
#define NUM_CUBES 12             /* # of cubes */

Point3 CubeVerts[NUM_CUBE_VERTS]; /* set elsewhere, from floats */
/* vertex indices for individual cube faces */
static int Face1[] = {1,3,2,0};
static int Face2[] = {5,7,3,1};
static int Face3[] = {4,5,1,0};
static int Face4[] = {3,7,6,2};
static int Face5[] = {5,4,6,7};
static int Face6[] = {0,2,6,4};
static int *VertNumList[]={Face1, Face2, Face3, Face4, Face5, Face6};
static int VertsInFace[]={ sizeof(Face1)/sizeof(int),
   sizeof(Face2)/sizeof(int), sizeof(Face3)/sizeof(int),
   sizeof(Face4)/sizeof(int), sizeof(Face5)/sizeof(int),
   sizeof(Face6)/sizeof(int) };
/* X, Y, Z rotations for cubes */
static RotateControl InitialRotate[NUM_CUBES] = {
   {0.0,ROT_6,ROT_6},{ROT_3,0.0,ROT_3},{ROT_3,ROT_3,0.0},
   {ROT_3,-ROT_3,0.0},{-ROT_3,ROT_2,0.0},{-ROT_6,-ROT_3,0.0},
   {ROT_3,0.0,-ROT_6},{-ROT_2,0.0,ROT_3},{-ROT_3,0.0,-ROT_3},
   {0.0,ROT_2,-ROT_2},{0.0,-ROT_3,ROT_3},{0.0,-ROT_6,-ROT_6},};
static MoveControl InitialMove[NUM_CUBES] = {
   {0,0,80,0,0,0,0,0,-350},{0,0,80,0,0,0,0,0,-350},
   {0,0,80,0,0,0,0,0,-350},{0,0,80,0,0,0,0,0,-350},
   {0,0,80,0,0,0,0,0,-350},{0,0,80,0,0,0,0,0,-350},
   {0,0,80,0,0,0,0,0,-350},{0,0,80,0,0,0,0,0,-350},
   {0,0,80,0,0,0,0,0,-350},{0,0,80,0,0,0,0,0,-350},
   {0,0,80,0,0,0,0,0,-350},{0,0,80,0,0,0,0,0,-350}, };
/* face colors for various cubes */
static int Colors[NUM_CUBES][NUM_CUBE_FACES] = {
   {15,14,12,11,10,9},{1,2,3,4,5,6},{35,37,39,41,43,45},
   {47,49,51,53,55,57},{59,61,63,65,67,69},{71,73,75,77,79,81},
   {83,85,87,89,91,93},{95,97,99,101,103,105},
   {107,109,111,113,115,117},{119,121,123,125,127,129},
   {131,133,135,137,139,141},{143,145,147,149,151,153} };
/* starting coordinates for cubes in world space */
static int CubeStartCoords[NUM_CUBES][3] = {
   {100,0,-6000},  {100,70,-6000}, {100,-70,-6000}, {33,0,-6000},
   {33,70,-6000},  {33,-70,-6000}, {-33,0,-6000},   {-33,70,-6000},
   {-33,-70,-6000},{-100,0,-6000}, {-100,70,-6000}, {-100,-70,-6000}};
/* delay counts (speed control) for cubes */
static int InitRDelayCounts[NUM_CUBES] = {1,2,1,2,1,1,1,1,1,2,1,1};
static int BaseRDelayCounts[NUM_CUBES] = {1,2,1,2,2,1,1,1,2,2,2,1};
static int InitMDelayCounts[NUM_CUBES] = {1,1,1,1,1,1,1,1,1,1,1,1};
static int BaseMDelayCounts[NUM_CUBES] = {1,1,1,1,1,1,1,1,1,1,1,1};

void InitializeCubes()
{
   int i, j, k;
   PObject *WorkingCube;

   for (i=0; i<NUM_CUBES; i++) {
      if ((WorkingCube = malloc(sizeof(PObject))) == NULL) {
         printf("Couldn't get memory\n"); exit(1); }
      WorkingCube->DrawFunc = DrawPObject;
      WorkingCube->RecalcFunc = XformAndProjectPObject;
      WorkingCube->MoveFunc = RotateAndMovePObject;
      WorkingCube->RecalcXform = 1;
      for (k=0; k<2; k++) {
         WorkingCube->EraseRect[k].Left =
            WorkingCube->EraseRect[k].Top = 0x7FFF;
         WorkingCube->EraseRect[k].Right = 0;
         WorkingCube->EraseRect[k].Bottom = 0;
      }
      WorkingCube->RDelayCount = InitRDelayCounts[i];
      WorkingCube->RDelayCountBase = BaseRDelayCounts[i];
      WorkingCube->MDelayCount = InitMDelayCounts[i];
      WorkingCube->MDelayCountBase = BaseMDelayCounts[i];
      /* Set the object->world xform to none */
      for (j=0; j<3; j++)
         for (k=0; k<4; k++)
            WorkingCube->XformToWorld[j][k] = INT_TO_FIXED(0);
      WorkingCube->XformToWorld[0][0] =
         WorkingCube->XformToWorld[1][1] =
         WorkingCube->XformToWorld[2][2] =
         WorkingCube->XformToWorld[3][3] = INT_TO_FIXED(1);
      /* Set the initial location */
      for (j=0; j<3; j++) WorkingCube->XformToWorld[j][3] =
            INT_TO_FIXED(CubeStartCoords[i][j]);
      WorkingCube->NumVerts = NUM_CUBE_VERTS;
      WorkingCube->VertexList = CubeVerts;
      WorkingCube->NumFaces = NUM_CUBE_FACES;
      WorkingCube->Rotate = InitialRotate[i];
      WorkingCube->Move.MoveX = INT_TO_FIXED(InitialMove[i].MoveX);
      WorkingCube->Move.MoveY = INT_TO_FIXED(InitialMove[i].MoveY);
      WorkingCube->Move.MoveZ = INT_TO_FIXED(InitialMove[i].MoveZ);
      WorkingCube->Move.MinX = INT_TO_FIXED(InitialMove[i].MinX);
      WorkingCube->Move.MinY = INT_TO_FIXED(InitialMove[i].MinY);
      WorkingCube->Move.MinZ = INT_TO_FIXED(InitialMove[i].MinZ);
      WorkingCube->Move.MaxX = INT_TO_FIXED(InitialMove[i].MaxX);
      WorkingCube->Move.MaxY = INT_TO_FIXED(InitialMove[i].MaxY);
      WorkingCube->Move.MaxZ = INT_TO_FIXED(InitialMove[i].MaxZ);
      if ((WorkingCube->XformedVertexList =
            malloc(NUM_CUBE_VERTS*sizeof(Point3))) == NULL) {
         printf("Couldn't get memory\n"); exit(1); }
      if ((WorkingCube->ProjectedVertexList =
            malloc(NUM_CUBE_VERTS*sizeof(Point3))) == NULL) {
         printf("Couldn't get memory\n"); exit(1); }
      if ((WorkingCube->ScreenVertexList =
            malloc(NUM_CUBE_VERTS*sizeof(Point))) == NULL) {
         printf("Couldn't get memory\n"); exit(1); }
      if ((WorkingCube->FaceList =
            malloc(NUM_CUBE_FACES*sizeof(Face))) == NULL) {
         printf("Couldn't get memory\n"); exit(1); }
      /* Initialize the faces */
      for (j=0; j<NUM_CUBE_FACES; j++) {
         WorkingCube->FaceList[j].VertNums = VertNumList[j];
         WorkingCube->FaceList[j].NumVerts = VertsInFace[j];
         WorkingCube->FaceList[j].Color = Colors[i][j];
      }
      ObjectList[NumObjects++] = (Object *)WorkingCube;
   }
}
```

LISTING 37.9 L37-9.ASM

```
; 386-specific fixed point multiply and divide.
;
; C near-callable as: Fixedpoint FixedMul(Fixedpoint M1, Fixedpoint M2);
;                 Fixedpoint FixedDiv(Fixedpoint Dividend, Fixedpoint Divisor);
;
; Tested with TASM
;
        .model small
        .386
        .code
        public  _FixedMul,_FixedDiv
; Multiplies two fixed-point values together.
FMparms struc
        dw      2 dup(?)        ;return address & pushed BP
M1      dd      ?
M2      dd      ?
FMparms ends
        align   2
_FixedMul       proc    near
        push    bp
        mov     bp,sp
        mov     eax,[bp+M1]
        imul    dword ptr [bp+M2] ;multiply
        add     eax,8000h       ;round by adding 2^(-16)
        adc     edx,0           ;whole part of result is in DX
        shr     eax,16          ;put the fractional part in AX
        pop     bp
        ret
_FixedMul       endp
; Divides one fixed-point value by another.
FDparms struc
        dw      2 dup(?)        ;return address & pushed BP
Dividend dd     ?
Divisor  dd     ?
FDparms ends
        align   2
_FixedDiv       proc    near
        push    bp
        mov     bp,sp
        sub     cx,cx           ;assume positive result
        mov     eax,[bp+Dividend]
        and     eax,eax         ;positive dividend?
        jns     FDP1            ;yes
        inc     cx              ;mark it's a negative dividend
        neg     eax             ;make the dividend positive
FDP1:   sub     edx,edx         ;make it a 64-bit dividend, then shift
                                ; left 16 bits so that result will be in EAX
        rol     eax,16          ;put fractional part of dividend in
                                ; high word of EAX
        mov     dx,ax           ;put whole part of dividend in DX
        sub     ax,ax           ;clear low word of EAX
        mov     ebx,dword ptr [bp+Divisor]
        and     ebx,ebx         ;positive divisor?
        jns     FDP2            ;yes
        dec     cx              ;mark it's a negative divisor
        neg     ebx             ;make divisor positive
FDP2:   div     ebx             ;divide
        shr     ebx,1           ;divisor/2, minus 1 if the divisor is
        adc     ebx,0           ; even
        dec     ebx
        cmp     ebx,edx         ;set Carry if remainder is at least
        adc     eax,0           ; half as large as the divisor, then
                                ; use that to round up if necessary
        and     cx,cx           ;should the result be made negative?
        jz      FDP3            ;no
        neg     eax             ;yes, negate it
FDP3:   mov     edx,eax         ;return result in DX:AX; fractional
                                ; part is already in AX
        shr     edx,16          ;whole part of result in DX
        pop     bp
        ret
_FixedDiv       endp
        end
```

LISTING 37.10 POLYGON.H

```
/* POLYGON.H: Header file for polygon-filling code, also includes
   a number of useful items for 3-D animation. */

#define MAX_OBJECTS  100   /* max simultaneous # objects supported */
#define MAX_POLY_LENGTH 4  /* four vertices is the max per poly */
#define SCREEN_WIDTH 320
#define SCREEN_HEIGHT 240
#define PAGE0_START_OFFSET 0
#define PAGE1_START_OFFSET (((long)SCREEN_HEIGHT*SCREEN_WIDTH)/4)
#define NUM_CUBE_VERTS 8              /* # of vertices per cube */
#define NUM_CUBE_FACES 6              /* # of faces per cube */
/* Ratio: distance from viewpoint to projection plane / width of
   projection plane. Defines the width of the field of view. Lower
   absolute values = wider fields of view; higher values = narrower */
#define PROJECTION_RATIO -2.0 /* negative because visible Z
                                 coordinates are negative */
/* Draws the polygon described by the point list PointList in color
   Color with all vertices offset by (X,Y) */
#define DRAW_POLYGON(PointList,NumPoints,Color,X,Y)          \
   Polygon.Length = NumPoints; Polygon.PointPtr = PointList; \
   FillConvexPolygon(&Polygon, Color, X, Y);
#define INT_TO_FIXED(x) (((long)(int)x) << 16)
#define DOUBLE_TO_FIXED(x) ((long) (x * 65536.0 + 0.5))

typedef long Fixedpoint;
typedef Fixedpoint Xform[3][4];
/* Describes a single 2D point */
typedef struct { int X; int Y; } Point;
/* Describes a single 3D point in homogeneous coordinates; the W
   coordinate isn't present, though; assumed to be 1 and implied */
typedef struct { Fixedpoint X, Y, Z; } Point3;
typedef struct { int X; int Y; int Z; } IntPoint3;
```

```
/* Describes a series of points (used to store a list of vertices that
   describe a polygon; each vertex is assumed to connect to the two
   adjacent vertices; last vertex is assumed to connect to first) */
typedef struct { int Length; Point * PointPtr; } PointListHeader;
/* Describes the beginning and ending X coordinates of a single
   horizontal line */
typedef struct { int XStart; int XEnd; } HLine;
/* Describes a Length-long series of horizontal lines, all assumed to
   be on contiguous scan lines starting at YStart and proceeding
   downward (used to describe a scan-converted polygon to the
   low-level hardware-dependent drawing code). */
typedef struct { int Length; int YStart; HLine * HLinePtr;} HLineList;
typedef struct { int Left, Top, Right, Bottom; } Rect;
/* structure describing one face of an object (one polygon) */
typedef struct { int * VertNums; int NumVerts; int Color; }  Face;
typedef struct { double RotateX, RotateY, RotateZ; } RotateControl;
typedef struct { Fixedpoint MoveX, MoveY, MoveZ, MinX, MinY, MinZ,
   MaxX, MaxY, MaxZ; } MoveControl;
/* fields common to every object */
#define BASE_OBJECT                                                 \
   void (*DrawFunc)();     /* draws object */                       \
   void (*RecalcFunc)();   /* prepares object for drawing */        \
   void (*MoveFunc)();     /* moves object */                       \
   int RecalcXform;        /* 1 to indicate need to recalc */       \
   Rect EraseRect[2];      /* rectangle to erase in each page */
/* basic object */
typedef struct { BASE_OBJECT } Object;
/* structure describing a polygon-based object */
typedef struct {
   BASE_OBJECT
   int RDelayCount, RDelayCountBase; /* controls rotation speed */
   int MDelayCount, MDelayCountBase; /* controls movement speed */
   Xform XformToWorld;        /* transform from object->world space */
   Xform XformToView;         /* transform from object->view space */
   RotateControl Rotate;      /* controls rotation change over time */
   MoveControl Move;          /* controls object movement over time */
   int NumVerts;              /* # vertices in VertexList */
   Point3 * VertexList;       /* untransformed vertices */
   Point3 * XformedVertexList;   /* transformed into view space */
   Point3 * ProjectedVertexList; /* projected into screen space */
   Point * ScreenVertexList;     /* converted to screen coordinates */
   int NumFaces;              /* # of faces in object */
   Face * FaceList;           /* pointer to face info */
} PObject;

extern void XformVec(Xform, Fixedpoint *, Fixedpoint *);
extern void ConcatXforms(Xform, Xform, Xform);
extern int FillConvexPolygon(PointListHeader *, int, int, int);
extern void Set320x240Mode(void);
extern void ShowPage(unsigned int);
extern void FillRectangleX(int, int, int, int, unsigned int, int);
extern void XformAndProjectPObject(PObject *);
extern void DrawPObject(PObject *);
extern void AppendRotationX(Xform, double);
extern void AppendRotationY(Xform, double);
extern void AppendRotationZ(Xform, double);
extern near Fixedpoint FixedMul(Fixedpoint, Fixedpoint);
extern near Fixedpoint FixedDiv(Fixedpoint, Fixedpoint);
extern void InitializeFixedPoint(void);
extern void RotateAndMovePObject(PObject *);
extern void InitializeCubes(void);
extern int DisplayedPage, NonDisplayedPage, RecalcAllXforms;
extern int NumObjects;
extern Xform WorldViewXform;
extern Object *ObjectList[];
extern Point3 CubeVerts[];
```

A New Animation Framework: X-Sharp

Listings 37.1 through 37.10 shown earlier represent not merely faster animation in library form, but also a nearly complete, extensible, data-driven animation framework. Whereas much of the earlier animation code I've presented in this book was hardwired to demonstrate certain concepts, this chapter's code is intended to serve as the basis for a solid animation package. Objects are stored, in their entirety, in customizable structures; new structures can be devised for new sorts of objects. Drawing, preparing for drawing, and moving are all vectored functions, so that variations such as shading or texturing, or even radically different sorts of graphics objects, such as scaled bitmaps, could be supported. The cube initialization is entirely data driven; more or different cubes, or other sorts of convex polyhedrons, could be added by simply changing the initialization data in Listing 37.8.

Somewhere along the way in writing the material that became this section of the book, I realized that I had a generally useful animation package by the tail and gave it a name: X-Sharp. (*X* for Mode X, *sharp* because good animation looks sharp, and, well, who would want a flat animation package?)

Note that the X-Sharp library as presented in this chapter (and, indeed, in this book) is not a fully complete 3-D library. Movement is supported only along the Z axis in this chapter's version, and then in a non-general fashion. More interesting movement isn't supported at this point because of one of the two missing features in X-Sharp: hidden-surface removal. (The other missing feature is general 3-D clipping.) Without hidden surface removal, nothing can safely overlap. It would actually be easy enough to perform hidden-surface removal by keeping the cubes in different Z bands and drawing them back to front, but this gets into sorting and list issues, and is not a complete solution—and I've crammed as much as will fit into one chapter's code, anyway.

I'm working toward a goal in this last section of the book, and there are many lessons to be learned and stories to be told along the way. So as X-Sharp grows, you'll find its evolving implementations in the chapter subdirectories on the listings diskette. This chapter's subdirectory, for example, contains the self-extracting archive file XSHARP14.EXE, (to extract its contents you simply run it as though it were a program) and the code in that archive is the code I'm speaking of specifically in this chapter, with all the limitations mentioned above. Chapter 38's subdirectory, however, contains the file XSHARP15.EXE, which is the next step in the evolution of X-Sharp, and it is the version that I'll be specifically talking about in that chapter. Later chapters will have their own implementations in their respective chapter subdirectories, in files of the form XSHARPxx.EXE, where xx is an ascending number indicating the version. The final and most recent X-Sharp version will be present in its own subdirectory called XSHARP22. If you're intending to use X-Sharp in a real project, use the most recent version to be sure that you avail yourself of all new features and bug fixes.

Three Keys to Real-Time Animation Performance

As of the previous chapter, we were at the point where we could rotate, move, and draw a solid cube in real time. Not too shabby...but the code I'm presenting in this chapter goes a bit further, rotating 12 solid cubes at an update rate of about 15 frames per second (fps) on a 20 MHz 386 with a slow VGA. That's 12 transformation matrices, 72 polygons, and 96 vertices being handled in real time; not Star Wars, granted, but a giant step beyond a single cube. Run the program if you get a chance; you may be surprised at just how effective this level of animation is. I'd like to point out, in case anyone missed it, that this is fully *general* 3-D. I'm not using any shortcuts or tricks, like prestoring coordinates or pregenerating bitmaps; if you were to feed in different rotations or vertices, the animation would change accordingly.

The keys to the performance increase manifested in this chapter's code are three. The first key is fixed-point arithmetic. In the previous two chapters, we worked with floating-point coordinates and transformation matrices. Those values are now stored as 32-bit fixed-point numbers, in the form 16.16 (16 bits of whole number, 16 bits of fraction). 32-bit fixed-point numbers allow sufficient precision for 3-D animation, but can be manipulated with fast integer operations, rather than by slow floating-point processor operations or excruciatingly slow floating-point emulator operations. Although the speed advantage of fixed-point varies depending on the operation, on the processor, and on whether or not a coprocessor is present, fixed-point multiplication can be as much as 100 times faster than the emulated floating-point equivalent. (I'd like to take a moment to thank Chris Hecker for his invaluable input in this area.)

The second performance key is the use of the 386's native 32-bit multiply and divide instructions. C compilers operating in real mode call library routines to perform multiplications and divisions involving 32-bit values, and those library functions are fairly slow, especially for division. On a 386, 32-bit multiplication and division can be handled with the bit of code in Listing 37.9—and most of even that code is only for rounding.

The third performance key is maintaining and operating on only the relevant portions of transformation matrices and coordinates. The bottom row of every transformation matrix we'll use (in this book) is [0 0 0 1], so why bother using or recalculating it when concatenating transforms and transforming points? Likewise for the fourth element of a 3-D vector in homogeneous coordinates, which is always 1. Basically, transformation matrices are treated as consisting of a 3×3 rotation matrix and a 3×1 translation vector, and coordinates are treated as 3×1 vectors. This saves a great many multiplications in the course of transforming each point.

Just for fun, I reimplemented the animation of Listings 37.1 through 37.10 with floating-point instructions. Together, the preceeding optimizations improve the performance of the entire animation—including drawing time and overhead, and not just math—by more than ten times over the code that uses the floating-point emulator. Amazing what one can accomplish with a few dozen lines of assembly and a switch in number format, isn't it? Note that no assembly code other than the native 386 multiply and divide is used in Listings 37.1 through 37.10, although the polygon fill code is of course mostly in assembly; we've achieved 12 cubes animated at 15 fps while doing the 3-D work almost entirely in Borland C++, and we're *still* doing sine and cosine via the floating-point emulator. Happily, we're still nowhere near the upper limit on the animation potential of the PC.

Drawbacks

The techniques we've used to turbocharge 3-D animation are very powerful, but there's a dark side to them as well. Obviously, native 386 instructions won't work on 8088 and 286 machines. That's rectifiable; equivalent multiplication and division routines could be implemented for real mode and performance would still be reasonable. It sure is nice to be able to plug in a 32-bit **IMUL** or **DIV** and be done with it, though. More importantly, 32-bit fixed-point arithmetic has limitations in range and accuracy. Points outside a 64K×64K×64K space can't be handled, imprecision tends to creep in over the course of multiple matrix concatenations, and it's quite possible to generate the dreaded divide by 0 interrupt if Z coordinates with absolute values less than one are used.

I don't have space to discuss these issues in detail, but here are some brief thoughts: The working 64K×64K×64K fixed-point space can be paged into a larger virtual space. Imprecision of a pixel or two rarely matters in terms of display quality, and deterioration of concatenated rotations can be corrected by restoring orthogonality, for example by periodically calculating one row of the matrix as the cross-product of the other two (forcing it to be perpendicular to both). Alternatively, transformations can be calculated from scratch each time an object or the viewer moves, so there's no chance for cumulative error. 3-D clipping with a front clip plane of -1 or less can prevent divide overflow.

Where the Time Goes

The distribution of execution time in the animation code is no longer wildly biased toward transformation, but sine and cosine are certainly still sucking up cycles. Likewise, the overhead in the calls to **FixedMul()** and **FixedDiv()** is costly. Much of this is correctable with a little carefully crafted assembly language and a lookup table; I'll provide that shortly.

Regardless, with this chapter we have made the critical jump to a usable level of performance and a serviceable general-purpose framework. From here on out, it's the fun stuff.

Raw Speed and More

Chapter 38

The Naked Truth About Speed in 3-D Animation

Years ago, this friend of mine—let's call him Bert—went to Hawaii with three other fellows to celebrate their graduation from high school. This was an unchaperoned trip, and they behaved pretty much as responsibly as you'd expect four teenagers to behave, which is to say, not; there's a story about a rental car that, to this day, Bert can't bring himself to tell. They had a good time, though, save for one thing: no girls.

By and by, they met a group of girls by the pool, but the boys couldn't get past the hi-howya-doin stage, so they retired to their hotel room to plot a better approach. This being the early '70s, and them being slightly tipsy teenagers with raging hormones and the effective combined IQ of four eggplants, it took them no time at all to come up with a brilliant plan: streaking. The girls had mentioned their room number, so the boys piled into the elevator, pushed the button for the girls' floor, shucked their clothes as fast as they could, and sprinted to the girls' door. They knocked on the door and ran on down the hall. As the girls opened their door, Bert and his crew raced past, toward the elevator, laughing hysterically.

Bert was by far the fastest of them all. He whisked between the elevator doors just as they started to close; by the time his friends got there, it was too late, and the doors slid shut in their faces. As the elevator began to move, Bert could hear the frantic pounding of six fists thudding on the closed doors. As Bert stood among the clothes littering the elevator floor, the thought of his friends stuck in the hall, naked as jaybirds, was just too much, and he doubled over with helpless laughter, tears streaming down his face. The universe had blessed him with one of those exceedingly rare moments of perfect timing and execution.

The universe wasn't done with Bert quite yet, though. He was still contorted with laughter—and still quite thoroughly undressed—when the elevator doors opened again. On the lobby.

And with that, we come to this chapter's topics: raw speed and hidden surfaces.

Raw Speed, Part 1: Assembly Language

I would like to state, here and for the record, that I am not an assembly language fanatic. Frankly, I prefer programming in C; assembly language is hard work, and I can get a whole lot more done with fewer hassles in C. However, I *am* a performance fanatic, performance being defined as having programs be as nimble as possible in those areas where the user wants fast response. And, in the course of pursuing performance, there are times when a little assembly language goes a long way.

We're now four chapters into development of the X-Sharp 3-D animation package. In real-time animation, performance is *sine qua non* (Latin for "Make it fast or find another line of work"), so some judiciously applied assembly language is in order. In the previous chapter, we got up to a serviceable performance level by switching to fixed-point math, then implementing the fixed-point multiplication and division functions in assembly in order to take advantage of the 386's 32-bit capabilities. There's another area of the program that fairly cries out for assembly language: matrix math. The function to multiply a matrix by a vector (**XformVec()**) and the function to concatenate matrices (**ConcatXforms()**) both loop heavily around calls to **FixedMul()**; a lot of calling and looping can be eliminated by converting these functions to pure assembly language.

Listing 38.1 is the module FIXED.ASM from this chapter's iteration of X-Sharp, with **XformVec()** and **ConcatXforms()** implemented in assembly language. The code is heavily optimized, to the extent of completely unrolling the loops via macros so that looping is eliminated altogether. FIXED.ASM is highly effective; the time taken for matrix math is now down to the point where it's a fairly minor component of execution time, representing less than ten percent of the total. It's time to turn our optimization sights elsewhere.

LISTING 38.1 FIXED.ASM

```
; 386-specific fixed point routines.
; Tested with TASM
ROUNDING_ON      equ  1          ;1 for rounding, 0 for no rounding
                                 ;no rounding is faster, rounding is
                                 ; more accurate
ALIGNMENT        equ  2
     .model      small
     .386
     .code
;=====================================================================
; Multiplies two fixed-point values together.
; C near-callable as:
;    Fixedpoint FixedMul(Fixedpoint M1, Fixedpoint M2);
;    Fixedpoint FixedDiv(Fixedpoint Dividend, Fixedpoint Divisor);
FMparms struc
           dw       2 dup(?)     ;return address & pushed BP
M1         dd       ?
M2         dd       ?
FMparms    ends
           align    ALIGNMENT
           public   _FixedMul
_FixedMul        proc     near
         push     bp
        mov     bp,sp
        mov     eax,[bp+M1]
        imul    dword ptr [bp+M2]       ;multiply
if ROUNDING_ON
        add     eax,8000h               ;round by adding 2^(-17)
        adc     edx,0                   ;whole part of result is in DX
endif ;ROUNDING_ON
        shr     eax,16                  ;put the fractional part in AX
        pop     bp
        ret
_FixedMul       endp
;=====================================================================
; Divides one fixed-point value by another.
; C near-callable as:
;    Fixedpoint FixedDiv(Fixedpoint Dividend, Fixedpoint Divisor);
FDparms struc
           dw    2 dup(?)               ;return address & pushed BP
Dividend   dd    ?
Divisor    dd    ?
FDparms    ends
      align ALIGNMENT
      public      _FixedDiv
_FixedDiv       proc    near
        push    bp
        mov     bp,sp

if ROUNDING_ON
        sub     cx,cx                   ;assume positive result
        mov     eax,[bp+Dividend]
        and     eax,eax                 ;positive dividend?
        jns     FDP1                    ;yes
        inc     cx                      ;mark it's a negative dividend
        neg     eax                     ;make the dividend positive
FDP1:   sub     edx,edx                 ;make it a 64-bit dividend, then shift
                                        ; left 16 bits so that result will be
                                        ; in EAX
        rol     eax,16                  ;put fractional part of dividend in
                                        ; high word of EAX
        mov     dx,ax                   ;put whole part of dividend in DX
        sub     ax,ax                   ;clear low word of EAX
        mov     ebx,dword ptr [bp+Divisor]
        and     ebx,ebx                 ;positive divisor?
        jns     FDP2                    ;yes
        dec     cx                      ;mark it's a negative divisor
        neg     ebx                     ;make divisor positive
FDP2:   div     ebx                     ;divide
        shr     ebx,1                   ;divisor/2, minus 1 if the divisor is
        adc     ebx,0                   ; even
        dec     ebx
        cmp     ebx,edx                 ;set Carry if remainder is at least
        adc     eax,0                   ; half as large as the divisor, then
                                        ; use that to round up if necessary
        and     cx,cx                   ;should the result be made negative?
        jz      FDP3                    ;no
        neg     eax                     ;yes., negate it
FDP3:
else ;  !ROUNDING_ON
        mov     edx,[bp+Dividend]
        sub      eax,eax
        shrd     eax,edx,16                  ;position so that result ends up
        sar      edx,16                      ; in EAX
        idiv     dword ptr [bp+Divisor]
endif                                        ;ROUNDING_ON
        shld     edx,eax,16                  ;whole part of result in DX;
                                             ; fractional part is already in AX
        pop      bp
        ret
_FixedDiv       endp
;======================================================================
; Returns the sine and cosine of an angle.
; C near-callable as:
;     void CosSin(TAngle Angle, Fixedpoint *Cos, Fixedpoint *);

      align ALIGNMENT
CosTable label dword
      include costable.inc

SCparms struc
           dw    2 dup(?)              ;return address & pushed BP
Angle      dw    ?                     ;angle to calculate sine & cosine for
Cos        dw    ?                     ;pointer to cos destination
Sin        dw    ?                     ;pointer to sin destination
SCparms    ends

      align ALIGNMENT
      public _CosSin
_CosSin    proc  near
      push  bp                         ;preserve stack frame
      mov   bp,sp                      ;set up local stack frame

      mov   bx,[bp].Angle
      and   bx,bx                      ;make sure angle's between 0 and 2*pi
      jns   CheckInRange
MakePos:                               ;less than 0, so make it positive
      add   bx,360*10
      js    MakePos
      jmp   short CheckInRange

      align ALIGNMENT
MakeInRange:                           ;make sure angle is no more than 2*pi
      sub   bx,360*10
CheckInRange:
      cmp   bx,360*10
      jg    MakeInRange

      cmp   bx,180*10                  ;figure out which quadrant
      ja    BottomHalf                 ;quadrant 2 or 3
      cmp   bx,90*10                   ;quadrant 0 or 1
      ja    Quadrant1
                                       ;quadrant 0
      shl   bx,2
      mov   eax,CosTable[bx]           ;look up sine
      neg   bx                         ;sin(Angle) = cos(90-Angle)
      mov   edx,CosTable[bx+90*10*4]   ;look up cosine
      jmp   short CSDone

      align ALIGNMENT
Quadrant1:
      neg   bx
```

```
        add     bx,180*10                  ;convert to angle between 0 and 90
        shl     bx,2
        mov     eax,CosTable[bx]           ;look up cosine
        neg     eax                        ;negative in this quadrant
        neg     bx                         ;sin(Angle) = cos(90-Angle)
        mov     edx,CosTable[bx+90*10*4]   ;look up cosine
        jmp     short CSDone

        align   ALIGNMENT
BottomHalf:                                ;quadrant 2 or 3
        neg     bx
        add     bx,360*10                  ;convert to angle between 0 and 180
        cmp     bx,90*10                   ;quadrant 2 or 3
        ja      Quadrant2
                                           ;quadrant 3
        shl     bx,2
        mov     eax,CosTable[bx]           ;look up cosine
        neg     bx                         ;sin(Angle) = cos(90-Angle)
        mov     edx,CosTable[90*10*4+bx]   ;look up sine
        neg     edx                        ;negative in this quadrant
        jmp     short CSDone

        align   ALIGNMENT
Quadrant2:
        neg     bx
        add     bx,180*10                  ;convert to angle between 0 and 90
        shl     bx,2
        mov     eax,CosTable[bx]           ;look up cosine
        neg     eax                        ;negative in this quadrant
        neg     bx                         ;sin(Angle) = cos(90-Angle)
        mov     edx,CosTable[90*10*4+bx]   ;look up sine
        neg     edx                        ;negative in this quadrant
CSDone:
        mov     bx,[bp].Cos
        mov     [bx],eax
        mov     bx,[bp].Sin
        mov     [bx],edx

        pop     bp                         ;restore stack frame
        ret
_CosSin endp
;=====================================================================
; Matrix multiplies Xform by SourceVec, and stores the result in
; DestVec. Multiplies a 4x4 matrix times a 4x1 matrix; the result
; is a 4x1 matrix. Cheats by assuming the W coord is 1 and the
; bottom row of the matrix is 0 0 0 1, and doesn't bother to set
; the W coordinate of the destination.
; C near-callable as:
;     void XformVec(Xform WorkingXform, Fixedpoint *SourceVec,
;           Fixedpoint *DestVec);
;
; This assembly code is equivalent to this C code:
;   int i;
;
;   for (i=0; i<3; i++)
;      DestVec[i] = FixedMul(WorkingXform[i][0], SourceVec[0]) +
;         FixedMul(WorkingXform[i][1], SourceVec[1]) +
;         FixedMul(WorkingXform[i][2], SourceVec[2]) +
;         WorkingXform[i][3];   /* no need to multiply by W = 1 */

XVparms struc
```

```
                 dw    2 dup(?)         ;return address & pushed BP
WorkingXform     dw    ?                ;pointer to transform matrix
SourceVec        dw    ?                ;pointer to source vector
DestVec          dw    ?                ;pointer to destination vector
XVparms          ends

      align ALIGNMENT
      public _XformVec
_XformVec  proc  near
      push  bp                          ;preserve stack frame
      mov   bp,sp                       ;set up local stack frame
      push  si                          ;preserve register variables
      push  di

      mov   si,[bp].WorkingXform        ;SI points to xform matrix
      mov   bx,[bp].SourceVec           ;BX points to source vector
      mov   di,[bp].DestVec             ;DI points to dest vector

soff=0
doff=0
      REPT 3                            ;do once each for dest X, Y, and Z
      mov   eax,[si+soff]               ;column 0 entry on this row
      imul  dword ptr [bx]              ;xform entry times source X entry
if ROUNDING_ON
      add   eax,8000h                   ;round by adding 2^(-17)
      adc   edx,0                       ;whole part of result is in DX
endif ;ROUNDING_ON
      shrd  eax,edx,16                  ;shift the result back to 16.16 form
      mov   ecx,eax                     ;set running total

      mov   eax,[si+soff+4]             ;column 1 entry on this row
      imul  dword ptr [bx+4]            ;xform entry times source Y entry
if ROUNDING_ON
      add   eax,8000h                   ;round by adding 2^(-17)
      adc   edx,0                       ;whole part of result is in DX
endif ;ROUNDING_ON
      shrd  eax,edx,16                  ;shift the result back to 16.16 form
      add   ecx,eax                     ;running total for this row

      mov   eax,[si+soff+8]             ;column 2 entry on this row
      imul  dword ptr [bx+8]            ;xform entry times source Z entry
if ROUNDING_ON
      add   eax,8000h                   ;round by adding 2^(-17)
      adc   edx,0                       ;whole part of result is in DX
endif ;ROUNDING_ON
      shrd  eax,edx,16                  ;shift the result back to 16.16 form
      add   ecx,eax                     ;running total for this row

      add   ecx,[si+soff+12]            ;add in translation
      mov   [di+doff],ecx               ;save the result in the dest vector
soff=soff+16
doff=doff+4
      ENDM

      pop   di                          ;restore register variables
      pop   si
      pop   bp                          ;restore stack frame
      ret
_XformVec  endp
;=====================================================================
; Matrix multiplies SourceXform1 by SourceXform2 and stores the
; result in DestXform. Multiplies a 4x4 matrix times a 4x4 matrix;
; the result is a 4x4 matrix. Cheats by assuming the bottom row of
; each matrix is 0 0 0 1, and doesn't bother to set the bottom row
; of the destination.
; C near-callable as:
;       void ConcatXforms(Xform SourceXform1, Xform SourceXform2,
;               Xform DestXform)
;
; This assembly code is equivalent to this C code:
;   int i, j;
;
;   for (i=0; i<3; i++) {
;      for (j=0; j<3; j++)
;         DestXform[i][j] =
;               FixedMul(SourceXform1[i][0], SourceXform2[0][j]) +
;               FixedMul(SourceXform1[i][1], SourceXform2[1][j]) +
;               FixedMul(SourceXform1[i][2], SourceXform2[2][j]);
;      DestXform[i][3] =
;            FixedMul(SourceXform1[i][0], SourceXform2[0][3]) +
;            FixedMul(SourceXform1[i][1], SourceXform2[1][3]) +
;            FixedMul(SourceXform1[i][2], SourceXform2[2][3]) +
;            SourceXform1[i][3];
;   }

CXparms struc
                 dw    2 dup(?)        ;return address & pushed BP
SourceXform1     dw    ?               ;pointer to first source xform matrix
SourceXform2     dw    ?               ;pointer to second source xform matrix
DestXform        dw    ?               ;pointer to destination xform matrix
CXparms          ends

      align ALIGNMENT
      public _ConcatXforms
_ConcatXforms    proc  near
      push  bp                         ;preserve stack frame
      mov   bp,sp                      ;set up local stack frame
      push  si                         ;preserve register variables
      push  di

      mov   bx,[bp].SourceXform2       ;BX points to xform2 matrix
      mov   si,[bp].SourceXform1       ;SI points to xform1 matrix
      mov   di,[bp].DestXform          ;DI points to dest xform matrix

roff=0                                 ;row offset
      REPT 3                           ;once for each row
coff=0                                 ;column offset
      REPT 3                           ;once for each of the first 3 columns,
                                       ; assuming 0 as the bottom entry (no
                                       ; translation)
      mov   eax,[si+roff]              ;column 0 entry on this row
      imul  dword ptr [bx+coff]        ;times row 0 entry in column
if ROUNDING_ON
      add   eax,8000h                  ;round by adding 2^(-17)
      adc   edx,0                      ;whole part of result is in DX
endif ;ROUNDING_ON
      shrd  eax,edx,16                 ;shift the result back to 16.16 form
      mov   ecx,eax                    ;set running total

      mov   eax,[si+roff+4]            ;column 1 entry on this row
      imul  dword ptr [bx+coff+16]     ;times row 1 entry in col
if ROUNDING_ON
```

```
     add   eax,8000h                        ;round by adding 2^(-17)
     adc   edx,0                            ;whole part of result is in DX
endif ;ROUNDING_ON
     shrd  eax,edx,16                       ;shift the result back to 16.16 form
     add   ecx,eax                          ;running total

     mov   eax,[si+roff+8]                  ;column 2 entry on this row
     imul  dword ptr [bx+coff+32]           ;times row 2 entry in col
if ROUNDING_ON
     add   eax,8000h                        ;round by adding 2^(-17)
     adc   edx,0                            ;whole part of result is in DX
endif ;ROUNDING_ON
     shrd  eax,edx,16                       ;shift the result back to 16.16 form
     add   ecx,eax                          ;running total

     mov   [di+coff+roff],ecx               ;save the result in dest matrix
coff=coff+4                                 ;point to next col in xform2 & dest
     ENDM

                                            ;now do the fourth column, assuming
                                            ; 1 as the bottom entry, causing
                                            ; translation to be performed
     mov   eax,[si+roff]                    ;column 0 entry on this row
     imul  dword ptr [bx+coff]              ;times row 0 entry in column
if ROUNDING_ON
     add   eax,8000h                        ;round by adding 2^(-17)
     adc   edx,0                            ;whole part of result is in DX
endif ;ROUNDING_ON
     shrd  eax,edx,16                       ;shift the result back to 16.16 form
     mov   ecx,eax                          ;set running total

     mov   eax,[si+roff+4]                  ;column 1 entry on this row
     imul  dword ptr [bx+coff+16]           ;times row 1 entry in col
if ROUNDING_ON
     add   eax,8000h                        ;round by adding 2^(-17)
     adc   edx,0                            ;whole part of result is in DX
endif ;ROUNDING_ON
     shrd  eax,edx,16                       ;shift the result back to 16.16 form
     add   ecx,eax                          ;running total

     mov   eax,[si+roff+8]                  ;column 2 entry on this row
     imul  dword ptr [bx+coff+32]           ;times row 2 entry in col
if ROUNDING_ON
     add   eax,8000h                        ;round by adding 2^(-17)
     adc   edx,0                            ;whole part of result is in DX
endif ;ROUNDING_ON
     shrd  eax,edx,16                       ;shift the result back to 16.16 form
     add   ecx,eax                          ;running total

     add   ecx,[si+roff+12]                 ;add in translation

     mov   [di+coff+roff],ecx               ;save the result in dest matrix
coff=coff+4                                 ;point to next col in xform2 & dest

roff=roff+16                                ;point to next col in xform2 & dest
     ENDM

     pop   di                               ;restore register variables
     pop   si
     pop   bp                               ;restore stack frame
     ret
_ConcatXforms    endp
     end
```

Raw Speed, Part II: Look it Up

It's a funny thing about Turbo Profiler: Time spent in the Borland C++ 80x87 emulator doesn't show up directly anywhere that I can see in the timing results. The only way to detect it is by way of the line that reports what percent of total time is represented by all the areas that were profiled; if you're profiling all areas, whatever's not explicitly accounted for seems to be the floating-point emulator time. This quirk fooled me for a while, leading me to think sine and cosine weren't major drags on performance, because the **sin()** and **cos()** functions spend most of their time in the emulator, and that time doesn't show up in Turbo Profiler's statistics on those functions. Once I figured out what was going on, it turned out that not only were **sin()** and **cos()** major drags, they were taking up over half the total execution time by themselves.

The solution is a lookup table. Listing 38.1 contains a function called **CosSin()** that calculates both the sine and cosine of an angle, via a lookup table. The function accepts angles in tenths of degrees; I decided to use tenths of degrees rather than radians because that way it's always possible to look up the sine and cosine of the exact angle requested, rather than approximating, as would be required with radians. Tenths of degrees should be fine enough control for most purposes; if not, it's easy to alter **CosSin()** for finer gradations yet. GENCOS.C, the program used to generate the lookup table (COSTABLE.INC), included in Listing 38.1, can be found in the XSHARP22 subdirectory on the listings diskette. GENCOS.C can generate a cosine table with any integral number of steps per degree.

FIXED.ASM (Listing 38.1) speeds X-Sharp up quite a bit, and it changes the performance balance a great deal. When we started out with 3-D animation, calculation time was the dragon we faced; more than 90 percent of the total time was spent doing matrix and projection math. Additional optimizations in the area of math could still be made (using 32-bit multiplies in the backface-removal code, for example), but fixed-point math, the sine and cosine lookup, and selective assembly optimizations have done a pretty good job already. The bulk of the time taken by X-Sharp is now spent drawing polygons, drawing rectangles (to erase objects), and waiting for the page to flip. In other words, we've slain the dragon of 3-D math, or at least wounded it grievously; now we're back to the dragon of polygon filling. We'll address faster polygon filling soon, but for the moment, we have more than enough horsepower to have some fun with. First, though, we need one more feature: hidden surfaces.

Hidden Surfaces

So far, we've made a number of simplifying assumptions in order to get the animation to look good; for example, all objects must currently be convex polyhedrons. What's more, right now, objects can never pass behind or in front of each other. What that means is that it's time to have a look at hidden surfaces.

There are a passel of ways to do hidden surfaces. Way off at one end (the slow end) of the spectrum is Z-buffering, whereby each pixel of each polygon is checked as it's drawn to see whether it's the frontmost version of the pixel at those coordinates. At the other end is the technique of simply drawing the objects in back-to-front order, so that nearer objects are drawn on top of farther objects. The latter approach, depth sorting, is the one we'll take today. (Actually, true depth sorting involves detecting and resolving possible ambiguities when objects overlap in Z; in this chapter, we'll simply sort the objects on Z and leave it at that.)

This limited version of depth sorting is fast but less than perfect. For one thing, it doesn't address the issue of nonconvex objects, so we'll have to stick with convex polyhedrons. For another, there's the question of what part of each object to use as the sorting key; the nearest point, the center, and the farthest point are all possibilities—and, whichever point is used, depth sorting doesn't handle some overlap cases properly. Figure 38.1 illustrates one case in which back-to-front sorting doesn't work, regardless of what point is used as the sorting key.

For photo-realistic rendering, these are serious problems. For fast PC-based animation, however, they're manageable. Choose objects that aren't too elongated; arrange their paths of travel so they don't intersect in problematic ways; and, if they do overlap incorrectly, trust that the glitch will be lost in the speed of the animation and the complexity of the screen.

Listing 38.2 shows X-Sharp file OLIST.C, which includes the key routines for depth sorting. Objects are now stored in a linked list. The initial, empty list, created by

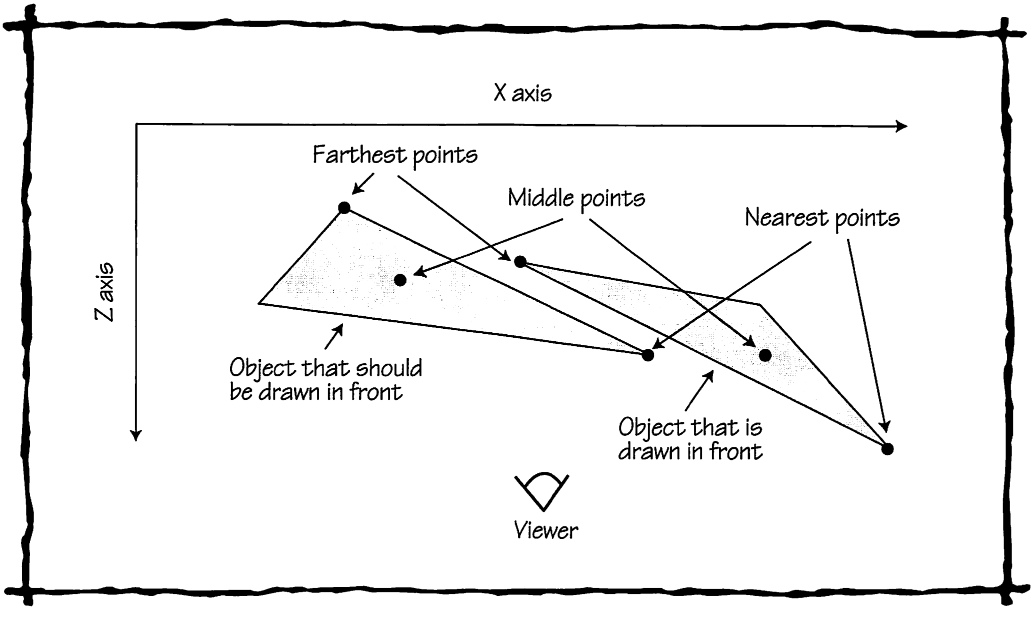

X axis
Z axis
Farthest points
Middle points
Nearest points
Object that should be drawn in front
Object that is drawn in front
Viewer

Figure 38.1 Why Back-to-Front Sorting Doesn't Always Work Properly

InitializeObjectList(), consists of a sentinel entry at either end, one at the farthest possible z coordinate, and one at the nearest. New entries are inserted by **AddObject()** in z-sorted order. Each time the objects are moved, before they're drawn at their new locations, **SortObjects()** is called to Z-sort the object list, so that drawing will proceed from back to front. The Z-sorting is done on the basis of the objects' center points; a center-point field has been added to the object structure to support this, and the center point for each object is now transformed along with the vertices. That's really all there is to depth sorting—and now we can have objects that overlap in X and Y.

LISTING 38.2 OLIST.C

```
/* Object list-related functions. */
#include <stdio.h>
#include "polygon.h"

/* Set up the empty object list, with sentinels at both ends to
  terminate searches */
void InitializeObjectList()
{
   ObjectListStart.NextObject = &ObjectListEnd;
   ObjectListStart.PreviousObject = NULL;
   ObjectListStart.CenterInView.Z = INT_TO_FIXED(-32768);
   ObjectListEnd.NextObject = NULL;
   ObjectListEnd.PreviousObject = &ObjectListStart;
   ObjectListEnd.CenterInView.Z = 0x7FFFFFFFL;
   NumObjects = 0;
}

/* Adds an object to the object list, sorted by center Z coord. */
void AddObject(Object *ObjectPtr)
{
   Object *ObjectListPtr = ObjectListStart.NextObject;

   /* Find the insertion point. Guaranteed to terminate because of
      the end sentinel */
   while (ObjectPtr->CenterInView.Z > ObjectListPtr->CenterInView.Z) {
      ObjectListPtr = ObjectListPtr->NextObject;
   }

   /* Link in the new object */
   ObjectListPtr->PreviousObject->NextObject = ObjectPtr;
   ObjectPtr->NextObject = ObjectListPtr;
   ObjectPtr->PreviousObject = ObjectListPtr->PreviousObject;
   ObjectListPtr->PreviousObject = ObjectPtr;
   NumObjects++;
}

/* Resorts the objects in order of ascending center Z coordinate in view space,
   by moving each object in turn to the correct position in the object list. */
void SortObjects()
{
   int i;
   Object *ObjectPtr, *ObjectCmpPtr, *NextObjectPtr;

   /* Start checking with the second object */
   ObjectCmpPtr = ObjectListStart.NextObject;
   ObjectPtr = ObjectCmpPtr->NextObject;
   for (i=1; i<NumObjects; i++) {
      /* See if we need to move backward through the list */
      if (ObjectPtr->CenterInView.Z < ObjectCmpPtr->CenterInView.Z) {
         /* Remember where to resume sorting with the next object */
         NextObjectPtr = ObjectPtr->NextObject;
         /* Yes, move backward until we find the proper insertion
            point. Termination guaranteed because of start sentinel */
         do {
            ObjectCmpPtr = ObjectCmpPtr->PreviousObject;
         } while (ObjectPtr->CenterInView.Z <
               ObjectCmpPtr->CenterInView.Z);

         /* Now move the object to its new location */
         /* Unlink the object at the old location */
         ObjectPtr->PreviousObject->NextObject =
               ObjectPtr->NextObject;
         ObjectPtr->NextObject->PreviousObject =
               ObjectPtr->PreviousObject;

         /* Link in the object at the new location */
         ObjectCmpPtr->NextObject->PreviousObject = ObjectPtr;
         ObjectPtr->PreviousObject = ObjectCmpPtr;
         ObjectPtr->NextObject = ObjectCmpPtr->NextObject;
         ObjectCmpPtr->NextObject = ObjectPtr;

         /* Advance to the next object to sort */
         ObjectCmpPtr = NextObjectPtr->PreviousObject;
         ObjectPtr = NextObjectPtr;
      } else {
         /* Advance to the next object to sort */
         ObjectCmpPtr = ObjectPtr;
         ObjectPtr = ObjectPtr->NextObject;
      }
   }
}
```

Rounding

FIXED.ASM contains the equate **ROUNDING_ON**. When this equate is 1, the results of multiplications and divisions are rounded to the nearest fixed-point values; when it's 0, the results are truncated. The difference between the results produced by the two approaches is, at most, 2^{-16}; you wouldn't think that would make much difference, now, would you? But it does. When the animation is run with rounding disabled, the cubes start to distort visibly after a few minutes, and after a few minutes more they look like they've been run over. In contrast, I've never seen any significant distortion with rounding on, even after a half-hour or so. I think the difference with rounding is not that it's so much more accurate, but rather that the errors are evenly distributed; with truncation, the errors are biased, and biased errors become very visible when they're applied to right-angle objects. Even with rounding, though, the errors will eventually creep in, and reorthogonalization will become necessary at some point.

The performance cost of rounding is small, and the benefits are highly visible. Still, truncation errors become significant only when they accumulate over time, as, for example, when rotation matrices are repeatedly concatenated over the course of many transformations. Some time could be saved by rounding only in such cases. For example, division is performed only in the course of projection, and the results do not accumulate over time, so it would be reasonable to disable rounding for division.

Having a Ball

So far in our exploration of 3-D animation, we've had nothing to look at but triangles and cubes. It's time for something a little more visually appealing, so the demonstration program now features a 72-sided ball. What's particularly interesting about this ball is that it's created by the GENBALL.C program in the BALL subdirectory of X-Sharp, and both the size of the ball and the number of bands of faces are programmable. GENBALL.C spits out to a file all the arrays of vertices and faces needed to create the ball, ready for inclusion in INITBALL.C. True, if you change the number of bands, you must change the **Colors** array in INITBALL.C to match, but that's a tiny detail; by and large, the process of generating a ball-shaped object is now automated. In fact, we're not limited to ball-shaped objects; substitute a different vertex and face generation program for GENBALL.C, and you can make whatever convex polyhedron you want; again, all you have to do is change the **Colors** array correspondingly. You can easily create multiple versions of the base object, too; INITCUBE.C is an example of this, creating 11 different cubes.

What we have here is the first glimmer of an object-editing system. GENBALL.C is the prototype for object definition, and INITBALL.C is the prototype for general-purpose object instantiation. Certainly, it would be nice to someday have an interactive 3-D object editing tool and resource management setup. We have our hands full with the drawing end of things at the moment, though, and for now it's enough to be able to create objects in a semiautomated way.

3-D Shading

Chapter 39

Putting Realistic Surfaces on Animated 3-D Objects

At the end of the previous chapter, X-Sharp had just acquired basic hidden-surface capability, and performance had been vastly improved through the use of fixed-point arithmetic. In this chapter, we're going to add quite a bit more: support for 8088 and 80286 PCs, a general color model, and shading. That's an awful lot to cover in one chapter (actually, it'll spill over into the next chapter), so let's get to it!

Support for Older Processors

To date, X-Sharp has run on only the 386 and 486, because it uses 32-bit multiply and divide instructions that sub-386 processors don't support. I chose 32-bit instructions for two reasons: They're much faster for 16.16 fixed-point arithmetic than any approach that works on the 8088 and 286; and they're much easier to implement than any other approach. In short, I was after maximum performance, and I was perhaps just a little lazy.

I should have known better than to try to sneak this one by you. The most common feedback I've gotten on X-Sharp is that I should make it support the 8088 and 286. Well, I can take a hint as well as the next guy. Listing 39.1 is an improved version of FIXED.ASM, containing dual 386/8088 versions of **CosSin()**, **XformVec()**, and **ConcatXforms()**, as well as **FixedMul()** and **FixedDiv()**.

Given the new version of FIXED.ASM, with **USE386** set to 0, X-Sharp will now run on any processor. That's not to say that it will run fast on any processor, or at least not as fast as it used to. The switch to 8088 instructions makes X-Sharp's fixed-point calculations about 2.5 times slower overall. Since a PC is perhaps 40 times slower than a 486/33, we're talking about a hundred-times speed difference between the low end and mainstream. A 486/33 can animate a 72-sided ball, complete with shading (as discussed later), at 60 frames per second (fps), with plenty of cycles to spare; an 8-MHz AT can animate the same ball at about 6 fps. Clearly, the level of animation an application uses must be tailored to the available CPU horsepower.

The implementation of a 32-bit multiply using 8088 instructions is a simple matter of adding together four partial products. A 32-bit divide is not so simple, however. In fact, in Listing 39.1 I've chosen not to implement a full 32×32 divide, but rather only a 32×16 divide. The reason is simple: performance. A 32×16 divide can be implemented on an 8088 with two **DIV** instructions, but a 32×32 divide takes a great deal more work, so far as I can see. (If anyone has a fast 32×32 divide, or has a faster way to handle signed multiplies and divides than the approach taken by Listing 39.1, please drop me a line care of the publisher.) In X-Sharp, division is used only to divide either X or Y by Z in the process of projecting from view space to screen space, so the cost of using a 32×16 divide is merely some inaccuracy in calculating screen coordinates, especially when objects get very close to the Z = 0 plane. This error is not cumulative (that is, it doesn't carry over to later frames), and in my experience doesn't cause noticeable image degradation; therefore, given the already slow performance of the 8088 and 286, I've opted for performance over precision.

At any rate, please keep in mind that the non-386 version of **FixedDiv()** is *not* a general-purpose 32×32 fixed-point division routine. In fact, it will generate a divide-by-zero error if passed a fixed-point divisor between -1 and 1. As I've explained, the non-386 version of **Fixed-Div()** is designed to do just what X-Sharp needs, and no more, as quickly as possible.

LISTING 39.1 FIXED.ASM

```
; Fixed point routines.
; Tested with TASM

USE386          equu  1     ;1 for 386-specific opcodes, 0 for
                            ; 8088 opcodes
MUL_ROUNDING_ON equ  1      ;1 for rounding on multiplies,
                            ; 0 for no rounding. Not rounding is faster,
                            ; rounding is more accurate and generally a
                            ; good idea
DIV_ROUNDING_ON equ  0      ;1 for rounding on divides,
                            ; 0 for no rounding. Not rounding is faster,
                            ; rounding is more accurate, but because
                            ; division is only performed to project to
                            ; the screen, rounding quotients generally
                            ; isn't necessary
ALIGNMENT       equ  2

        .model small
        .386
        .code

;=====================================================================
; Multiplies two fixed-point values together.
; C near-callable as:
;       Fixedpoint FixedMul(Fixedpoint M1, Fixedpoint M2);
```

```
FMparms struc
          dw   2 dup(?)              ;return address & pushed BP
M1        dd   ?
M2        dd   ?
FMparms ends
     align ALIGNMENT
     public    _FixedMul
_FixedMul proc near
     push bp
     mov  bp,sp

if USE386

     mov  eax,[bp+M1]
     imul dword ptr [bp+M2]          ;multiply
if MUL_ROUNDING_ON
     add  eax,8000h                  ;round by adding 2^(-17)
     adc  edx,0                      ;whole part of result is in DX
endif ;MUL_ROUNDING_ON
     shr  eax,16                     ;put the fractional part in AX

else ;!USE386

                                     ;do four partial products and
                                     ; add them together, accumulating
                                     ; the result in CX:BX
     push si                         ;preserve C register variables
     push di

                                     ;figure out signs, so we can use
                                     ; unsigned multiplies
     sub  cx,cx                      ;assume both operands positive
     mov  ax,word ptr [bp+M1+2]
     mov  si,word ptr [bp+M1]
     and  ax,ax                      ;first operand negative?
     jns  CheckSecondOperand         ;no
     neg  ax                         ;yes, so negate first operand
     neg  si
     sbb  ax,0
     inc  cx                         ;mark that first operand is negative
CheckSecondOperand:
     mov  bx,word ptr [bp+M2+2]
     mov  di,word ptr [bp+M2]
     and  bx,bx                      ;second operand negative?
     jns  SaveSignStatus             ;no
     neg  bx                         ;yes, so negate second operand
     neg  di
     sbb  bx,0
     xor  cx,1                       ;mark that second operand is negative
SaveSignStatus:
     push cx                         ;remember sign of result; 1 if result
                                     ; negative, 0 if result nonnegative
     push ax                         ;remember high word of M1
     mul  bx                         ;high word M1 times high word M2
     mov  cx,ax                      ;accumulate result in CX:BX (BX not used
                                     ; until next operation, however)
                                     ;assume no overflow into DX
     mov  ax,si                      ;low word M1 times high word M2
     mul  bx
     mov  bx,ax
     add  cx,dx                      ;accumulate result in CX:BX
     pop  ax                         ;retrieve high word of M1
```

```
        mul     di                              ;high word M1 times low word M2
        add     bx,ax
        adc     cx,dx                           ;accumulate result in CX:BX
        mov     ax,si                           ;low word M1 times low word M2
        mul     di
if MUL_ROUNDING_ON
        add     ax,8000h                        ;round by adding 2^(-17)
        adc     bx,dx
else ;!MUL_ROUNDING_ON
        add     bx,dx                           ;don't round
endif ;MUL_ROUNDING_ON
        adc     cx,0                            ;accumulate result in CX:BX
        mov     dx,cx
        mov     ax,bx
        pop     cx
        and     cx,cx                           ;is the result negative?
        jz      FixedMulDone                    ;no, we're all set
        neg     dx                              ;yes, so negate DX:AX
        neg     ax
        sbb     dx,0
FixedMulDone:

        pop     di                              ;restore C register variables
        pop     si

endif ;USE386

        pop     bp
        ret
_FixedMul       endp

;=====================================================================
; Divides one fixed-point value by another.
; C near-callable as:
;       Fixedpoint FixedDiv(Fixedpoint Dividend, Fixedpoint Divisor);
FDparms struc
                dw      2 dup(?)                ;return address & pushed BP
Dividend        dd      ?
Divisor         dd      ?
FDparms ends
        align   ALIGNMENT
        public  _FixedDiv
_FixedDiv       proc    near
        push    bp
        mov     bp,sp

if USE386

if DIV_ROUNDING_ON
        sub     cx,cx                           ;assume positive result
        mov     eax,[bp+Dividend]
        and     eax,eax                         ;positive dividend?
        jns     FDP1                            ;yes
        inc     cx                              ;mark it's a negative dividend
        neg     eax                             ;make the dividend positive
FDP1:   sub     edx,edx                         ;make it a 64-bit dividend, then shift
                                                ; left 16 bits so that result will be in EAX
        rol     eax,16                          ;put fractional part of dividend in
                                                ; high word of EAX
        mov     dx,ax                           ;put whole part of dividend in DX
        sub     ax,ax                           ;clear low word of EAX
        mov     ebx,dword ptr [bp+Divisor]
        and     ebx,ebx                 ;positive divisor?
        jns     FDP2                    ;yes
        dec     cx                      ;mark it's a negative divisor
        neg     ebx                     ;make divisor positive
FDP2:   div     ebx                     ;divide
        shr     ebx,1                   ;divisor/2, minus 1 if the divisor is
        adc     ebx,0                   ; even
        dec     ebx
        cmp     ebx,edx                 ;set Carry if the remainder is at least
        adc     eax,0                   ; half as large as the divisor, then
                                        ; use that to round up if necessary
        and     cx,cx                   ;should the result be made negative?
        jz      FDP3                    ;no
        neg     eax                     ;yes, negate it
FDP3:
else ;!DIV_ROUNDING_ON
        mov     edx,[bp+Dividend]
        sub     eax,eax
        shrd    eax,edx,16              ;position so that result ends up
        sar     edx,16                  ; in EAX
        idiv    dword ptr [bp+Divisor]
endif ;DIV_ROUNDING_ON
        shld    edx,eax,16              ;whole part of result in DX;
                                        ; fractional part is already in AX

else                                    ;!USE386

        ;NOTE!!! Non-386 division uses a 32-bit dividend but only the upper 16 bits
        ; of the divisor; in other words, only the integer part of the divisor is
        ; used. This is done so that the division can be accomplished with two fast
        ; hardware divides instead of a slow software implementation, and is (in my
        ; opinion) acceptable because division is only used to project points to the
        ; screen (normally, the divisor is a Z coordinate), so there's no cumulative
        ; error, although there will be some error in pixel placement (the magnitude
        ; of the error is less the farther away from the Z=0 plane objects are). This
        ; is *not* a general-purpose divide, though; if the divisor is less than 1,
        ; for instance, a divide-by-zero error will result! For this reason, non-386
        ; projection can't be performed for points closer to the viewpoint than Z=1.

                                            ;figure out signs, so we can use
                                            ; unsigned divisions
       sub     cx,cx                        ;assume both operands positive
       mov     ax,word ptr [bp+Dividend+2]
       and     ax,ax                        ;first operand negative?
       jns     CheckSecondOperandD ;no
       neg     ax                           ;yes, so negate first operand
       neg     word ptr [bp+Dividend]
       sbb     ax,0
       inc     cx                           ;mark that first operand is negative
CheckSecondOperandD:
       mov     bx,word ptr [bp+Divisor+2]
       and     bx,bx                        ;second operand negative?
       jns     SaveSignStatusD              ;no
       neg     bx                           ;yes, so negate second operand
       neg     word ptr [bp+Divisor]
       sbb     bx,0
       xor     cx,1                         ;mark that second operand is negative
SaveSignStatusD:
       push    cx                           ;remember sign of result; 1 if result
                                            ; negative, 0 if result nonnegative
        sub     dx,dx                          ;put Dividend+2 (integer part) in DX:AX
        div     bx                             ;first half of 32/16 division, integer part
                                               ; divided by integer part
        mov     cx,ax                          ;set aside integer part of result
        mov     ax,word ptr [bp+Dividend]      ;concatenate the fractional part of
                                               ; the dividend to the remainder (fractional
                                               ; part) of the result from dividing the
                                               ; integer part of the dividend
        div     bx                             ;second half of 32/16 division

if DIV_ROUNDING_ON EQ 0
        shr     bx,1                           ;divisor/2, minus 1 if the divisor is
        adc     bx,0                           ; even
        dec     bx
        cmp     bx,dx                          ;set Carry if the remainder is at least
        adc     ax,0                           ; half as large as the divisor, then
        adc     cx,0                           ; use that to round up if necessary
endif ;DIV_ROUNDING_ON

        mov     dx,cx                          ;absolute value of result in DX:AX
        pop     cx
        and     cx,cx                          ;is the result negative?
        jz      FixedDivDone                   ;no, we're all set
        neg     dx                             ;yes, so negate DX:AX
        neg     ax
        sbb     dx,0
FixedDivDone:

endif ;USE386

        pop     bp
        ret
_FixedDiv       endp

;======================================================================
; Returns the sine and cosine of an angle.
; C near-callable as:
;       void CosSin(TAngle Angle, Fixedpoint *Cos, Fixedpoint *);

        align ALIGNMENT
CosTable label dword
        include costable.inc

SCparms struc
                dw      2 dup(?)               ;return address & pushed BP
Angle           dw      ?                      ;angle to calculate sine & cosine for
Cos             dw      ?                      ;pointer to cos destination
Sin             dw      ?                      ;pointer to sin destination
SCparms         ends

        align ALIGNMENT
        public _CosSin
_CosSin         proc near
        push    bp                             ;preserve stack frame
        mov     bp,sp                          ;set up local stack frame

if USE386

        mov     bx,[bp].Angle
        and     bx,bx                          ;make sure angle's between 0 and 2*pi
        jns     CheckInRange
```

```
MakePos:                                ;less than 0, so make it positive
        add     bx,360*10
        js      MakePos
        jmp     short CheckInRange

        align   ALIGNMENT
MakeInRange:                            ;make sure angle is no more than 2*pi
        sub     bx,360*10
CheckInRange:
        cmp     bx,360*10
        jg      MakeInRange

        cmp     bx,180*10               ;figure out which quadrant
        ja      BottomHalf              ;quadrant 2 or 3
        cmp     bx,90*10                ;quadrant 0 or 1
        ja      Quadrant1
                                        ;quadrant 0
        shl     bx,2
        mov     eax,CosTable[bx]        ;look up sine
        neg     bx                      ;sin(Angle) = cos(90-Angle)
        mov     edx,CosTable[bx+90*10*4] ;look up cosine
        jmp     short CSDone

        align   ALIGNMENT
Quadrant1:
        neg     bx
        add     bx,180*10               ;convert to angle between 0 and 90
        shl     bx,2
        mov     eax,CosTable[bx]        ;look up cosine
        neg     eax                     ;negative in this quadrant
        neg     bx                      ;sin(Angle) = cos(90-Angle)
        mov     edx,CosTable[bx+90*10*4] ;look up cosine
        jmp     short CSDone

        align   ALIGNMENT
BottomHalf:                             ;quadrant 2 or 3
        neg     bx
        add     bx,360*10               ;convert to angle between 0 and 180
        cmp     bx,90*10                ;quadrant 2 or 3
        ja      Quadrant2
                                        ;quadrant 3
        shl     bx,2
        mov     eax,CosTable[bx]        ;look up cosine
        neg     bx                      ;sin(Angle) = cos(90-Angle)
        mov     edx,CosTable[90*10*4+bx] ;look up sine
        neg     edx                     ;negative in this quadrant
        jmp     short CSDone

        align   ALIGNMENT
Quadrant2:
        neg     bx
        add     bx,180*10               ;convert to angle between 0 and 90
        shl     bx,2
        mov     eax,CosTable[bx]        ;look up cosine
        neg     eax                     ;negative in this quadrant
        neg     bx                      ;sin(Angle) = cos(90-Angle)
        mov     edx,CosTable[90*10*4+bx] ;look up sine
        neg     edx                     ;negative in this quadrant
CSDone:
        mov     bx,[bp].Cos
        mov     [bx],eax
```

```
          mov   bx,[bp].Sin
          mov   [bx],edx

else ;!USE386

          mov   bx,[bp].Angle
          and   bx,bx                         ;make sure angle's between 0 and 2*pi
          jns   CheckInRange
MakePos:                                      ;less than 0, so make it positive
          add   bx,360*10
          js    MakePos
          jmp   short CheckInRange

          align ALIGNMENT
MakeInRange:                                  ;make sure angle is no more than 2*pi
          sub   bx,360*10
CheckInRange:
          cmp   bx,360*10
          jg    MakeInRange

          cmp   bx,180*10                     ;figure out which quadrant
          ja    BottomHalf                    ;quadrant 2 or 3
          cmp   bx,90*10                      ;quadrant 0 or 1
          ja    Quadrant1
                                              ;quadrant 0
          shl   bx,2
          mov   ax,word ptr CosTable[bx]      ;look up sine
          mov   dx,word ptr CosTable[bx+2]
          neg   bx                            ;sin(Angle) = cos(90-Angle)
          mov   cx,word ptr CosTable[bx+90*10*4+2] ;look up cosine
          mov   bx,word ptr CosTable[bx+90*10*4]
          jmp   CSDone

          align ALIGNMENT
Quadrant1:
          neg   bx
          add   bx,180*10                     ;convert to angle between 0 and 90
          shl   bx,2
          mov   ax,word ptr CosTable[bx]      ;look up cosine
          mov   dx,word ptr CosTable[bx+2]
          neg   dx                            ;negative in this quadrant
          neg   ax
          sbb   dx,0
          neg   bx                            ;sin(Angle) = cos(90-Angle)
          mov   cx,word ptr CosTable[bx+90*10*4+2] ;look up cosine
          mov   bx,word ptr CosTable[bx+90*10*4]
          jmp   short CSDone

          align ALIGNMENT
BottomHalf:                                   ;quadrant 2 or 3
          neg   bx
          add   bx,360*10                     ;convert to angle between 0 and 180
          cmp   bx,90*10                      ;quadrant 2 or 3
          ja    Quadrant2
                                              ;quadrant 3
          shl   bx,2
          mov   ax,word ptr CosTable[bx]      ;look up cosine
          mov   dx,word ptr CosTable[bx+2]
          neg   bx                            ;sin(Angle) = cos(90-Angle)
          mov   cx,word ptr CosTable[90*10*4+bx+2] ;look up sine
          mov   bx,word ptr CosTable[90*10*4+bx]
```

```
     neg   cx                                ;negative in this quadrant
     neg   bx
     sbb   cx,0
     jmp   short CSDone

     align ALIGNMENT
Quadrant2:
     neg   bx
     add   bx,180*10                         ;convert to angle between 0 and 90
     shl   bx,2
     mov   ax,word ptr CosTable[bx]          ;look up cosine
     mov   dx,word ptr CosTable[bx+2]
     neg   dx                                ;negative in this quadrant
     neg   ax
     sbb   dx,0
     neg   bx                                ;sin(Angle) = cos(90-Angle)
     mov   cx,word ptr CosTable[90*10*4+bx+2] ;look up sine
     mov   bx,word ptr CosTable[90*10*4+bx]
     neg   cx                                ;negative in this quadrant
     neg   bx
     sbb   cx,0
CSDone:
     push  bx
     mov   bx,[bp].Cos
     mov   [bx],ax
     mov   [bx+2],dx
     mov   bx,[bp].Sin
     pop   ax
     mov   [bx],ax
     mov   [bx+2],cx

endif ;USE386

     pop   bp                                ;restore stack frame
     ret
_CosSin    endp

;======================================================================
; Matrix multiplies Xform by SourceVec, and stores the result in
; DestVec. Multiplies a 4x4 matrix times a 4x1 matrix; the result
; is a 4x1 matrix. Cheats by assuming the W coord is 1 and the
; bottom row of the matrix is 0 0 0 1, and doesn't bother to set
; the W coordinate of the destination.
; C near-callable as:
;     void XformVec(Xform WorkingXform, Fixedpoint *SourceVec,
;           Fixedpoint *DestVec);
;
; This assembly code is equivalent to this C code:
;   int i;
;
;   for (i=0; i<3; i++)
;      DestVec[i] = FixedMul(WorkingXform[i][0], SourceVec[0]) +
;          FixedMul(WorkingXform[i][1], SourceVec[1]) +
;          FixedMul(WorkingXform[i][2], SourceVec[2]) +
;          WorkingXform[i][3];   /* no need to multiply by W = 1 */

XVparms struc
                 dw    2 dup(?)              ;return address & pushed BP
WorkingXform     dw    ?                     ;pointer to transform matrix
SourceVec        dw    ?                     ;pointer to source vector
DestVec          dw    ?                     ;pointer to destination vector
XVparms ends
```

```
; Macro for non-386 multiply. AX, BX, CX, DX destroyed.
FIXED_MUL  MACRO M1,M2
     local CheckSecondOperand,SaveSignStatus,FixedMulDone

                                     ;do four partial products and
                                     ; add them together, accumulating
                                     ; the result in CX:BX
                                     ;figure out signs, so we can use
                                     ; unsigned multiplies
     sub  cx,cx                      ;assume both operands positive
     mov  bx,word ptr [&M1&+2]
     and  bx,bx                      ;first operand negative?
     jns  CheckSecondOperand         ;no
     neg  bx                         ;yes, so negate first operand
     neg  word ptr [&M1&]
     sbb  bx,0
     mov  word ptr [&M1&+2],bx
     inc  cx                         ;mark that first operand is negative
CheckSecondOperand:
     mov  bx,word ptr [&M2&+2]
     and  bx,bx                      ;second operand negative?
     jns  SaveSignStatus             ;no
     neg  bx                         ;yes, so negate second operand
     neg  word ptr [&M2&]
     sbb  bx,0
     mov  word ptr [&M2&+2],bx
     xor  cx,1                       ;mark that second operand is negative
SaveSignStatus:
     push cx                         ;remember sign of result; 1 if result
                                     ; negative, 0 if result nonnegative
     mov  ax,word ptr [&M1&+2]       ;high word times high word
     mul  word ptr [&M2&+2]
     mov  cx,ax      ;
                                     ;assume no overflow into DX
     mov  ax,word ptr [&M1&+2]       ;high word times low word
     mul  word ptr [&M2&]
     mov  bx,ax
     add  cx,dx
     mov  ax,word ptr [&M1&]         ;low word times high word
     mul  word ptr [&M2&+2]
     add  bx,ax
     adc  cx,dx
     mov  ax,word ptr [&M1&]         ;low word times low word
     mul  word ptr [&M2&]
if MUL_ROUNDING_ON
       add     ax,8000h              ;round by adding 2^(-17)
     adc  bx,dx
else ;!MUL_ROUNDING_ON
     add  bx,dx                      ;don't round
endif ;MUL_ROUNDING_ON
     adc  cx,0
     mov  dx,cx
     mov  ax,bx
     pop  cx
     and  cx,cx                      ;is the result negative?
     jz   FixedMulDone               ;no, we're all set
     neg  dx                         ;yes, so negate DX:AX
     neg  ax
     sbb  dx,0
FixedMulDone:
     ENDM
```

```
      align ALIGNMENT
      public _XformVec
_XformVec  proc  near
      push  bp                      ;preserve stack frame
      mov   bp,sp                   ;set up local stack frame
      push  si                      ;preserve register variables
      push  di

if USE386

      mov   si,[bp].WorkingXform    ;SI points to xform matrix
      mov   bx,[bp].SourceVec       ;BX points to source vector
      mov   di,[bp].DestVec         ;DI points to dest vector

soff=0
doff=0
      REPT 3                        ;do once each for dest X, Y, and Z
      mov   eax,[si+soff]           ;column 0 entry on this row
      imul  dword ptr [bx]          ;xform entry times source X entry
if MUL_ROUNDING_ON
      add   eax,8000h               ;round by adding 2^(-17)
      adc   edx,0                   ;whole part of result is in DX
endif ;MUL_ROUNDING_ON
      shrd  eax,edx,16              ;shift the result back to 16.16 form
      mov   ecx,eax                 ;set running total

      mov   eax,[si+soff+4]         ;column 1 entry on this row
      imul  dword ptr [bx+4]        ;xform entry times source Y entry
if MUL_ROUNDING_ON
      add   eax,8000h               ;round by adding 2^(-17)
      adc   edx,0                   ;whole part of result is in DX
endif ;MUL_ROUNDING_ON
      shrd  eax,edx,16              ;shift the result back to 16.16 form
      add   ecx,eax                 ;running total for this row

      mov   eax,[si+soff+8]         ;column 2 entry on this row
      imul  dword ptr [bx+8]        ;xform entry times source Z entry
if MUL_ROUNDING_ON
      add   eax,8000h               ;round by adding 2^(-17)
      adc   edx,0                   ;whole part of result is in DX
endif ;MUL_ROUNDING_ON
      shrd  eax,edx,16              ;shift the result back to 16.16 form
      add   ecx,eax                 ;running total for this row

      add   ecx,[si+soff+12]        ;add in translation
      mov   [di+doff],ecx           ;save the result in the dest vector
soff=soff+16
doff=doff+4
      ENDM

else ;!USE386

      mov   si,[bp].WorkingXform    ;SI points to xform matrix
      mov   di,[bp].SourceVec       ;DI points to source vector
      mov   bx,[bp].DestVec         ;BX points to dest vector
      push  bp                      ;preserve stack frame pointer

soff=0
doff=0
      REPT 3                        ;do once each for dest X, Y, and Z
      push  bx                      ;remember dest vector pointer
      push  word ptr [si+soff+2]
      push  word ptr [si+soff]
      push  word ptr [di+2]
      push  word ptr [di]
      call  _FixedMul                         ;xform entry times source X entry
      add   sp,8                              ;clear parameters from stack
      mov   cx,ax ;set running total
      mov   bp,dx

      push  cx                                ;preserve low word of running total
      push  word ptr [si+soff+4+2]
      push  word ptr [si+soff+4]
      push  word ptr [di+4+2]
      push  word ptr [di+4]
      call  _FixedMul                         ;xform entry times source Y entry
      add   sp,8                              ;clear parameters from stack
      pop   cx                                ;restore low word of running total
      add   cx,ax                             ;running total for this row
      adc   bp,dx

      push  cx                                ;preserve low word of running total
      push  word ptr [si+soff+8+2]
      push  word ptr [si+soff+8]
      push  word ptr [di+8+2]
      push  word ptr [di+8]
      call  _FixedMul                         ;xform entry times source Z entry
      add   sp,8                              ;clear parameters from stack
      pop   cx                                ;restore low word of running total
      add   cx,ax                             ;running total for this row
      adc   bp,dx

      add   cx,[si+soff+12]                   ;add in translation
      adc   bp,[si+soff+12+2]
      pop   bx                                ;restore dest vector pointer
      mov   [bx+doff],cx                      ;save the result in the dest vector
      mov   [bx+doff+2],bp
soff=soff+16
doff=doff+4
      ENDM

      pop   bp                                ;restore stack frame pointer

endif ;USE386

      pop   di                                ;restore register variables
      pop   si
      pop   bp                                ;restore stack frame
      ret
_XformVec   endp

;=======================================================================
; Matrix multiplies SourceXform1 by SourceXform2 and stores the
; result in DestXform. Multiplies a 4x4 matrix times a 4x4 matrix;
; the result is a 4x4 matrix. Cheats by assuming the bottom row of
; each matrix is 0 0 0 1, and doesn't bother to set the bottom row
; of the destination.
; C near-callable as:
;       void ConcatXforms(Xform SourceXform1, Xform SourceXform2,
;               Xform DestXform)
;
```

```
; This assembly code is equivalent to this C code:
;   int i, j;
;
;   for (i=0; i<3; i++) {
;      for (j=0; j<3; j++)
;         DestXform[i][j] =
;               FixedMul(SourceXform1[i][0], SourceXform2[0][j]) +
;               FixedMul(SourceXform1[i][1], SourceXform2[1][j]) +
;               FixedMul(SourceXform1[i][2], SourceXform2[2][j]);
;      DestXform[i][3] =
;            FixedMul(SourceXform1[i][0], SourceXform2[0][3]) +
;            FixedMul(SourceXform1[i][1], SourceXform2[1][3]) +
;            FixedMul(SourceXform1[i][2], SourceXform2[2][3]) +
;            SourceXform1[i][3];
;   }

CXparms struc
                 dw    2 dup(?)             ;return address & pushed BP
SourceXform1     dw    ?                    ;pointer to first source xform matrix
SourceXform2     dw    ?                    ;pointer to second source xform matrix
DestXform        dw    ?                    ;pointer to destination xform matrix
CXparms ends

      align   ALIGNMENT
      public _ConcatXforms
_ConcatXforms proc    near
      push    bp                            ;preserve stack frame
      mov     bp,sp                         ;set up local stack frame
      push    si                            ;preserve register variables
      push    di

if USE386

      mov     bx,[bp].SourceXform2          ;BX points to xform2 matrix
      mov     si,[bp].SourceXform1          ;SI points to xform1 matrix
      mov     di,[bp].DestXform             ;DI points to dest xform matrix

roff=0                                      ;row offset
      REPT 3                                ;once for each row
coff=0                                      ;column offset
      REPT 3                                ;once for each of the first 3 columns,
                                            ; assuming 0 as the bottom entry (no
                                            ; translation)
      mov     eax,[si+roff]                 ;column 0 entry on this row
      imul    dword ptr [bx+coff]           ;times row 0 entry in column
if MUL_ROUNDING_ON
      add     eax,8000h                     ;round by adding 2^(-17)
      adc     edx,0                         ;whole part of result is in DX
endif ;MUL_ROUNDING_ON
      shrd    eax,edx,16                    ;shift the result back to 16.16 form
      mov     ecx,eax                       ;set running total

      mov     eax,[si+roff+4]               ;column 1 entry on this row
      imul    dword ptr [bx+coff+16]        ;times row 1 entry in col
if MUL_ROUNDING_ON
      add     eax,8000h                     ;round by adding 2^(-17)
      adc     edx,0                         ;whole part of result is in DX
endif ;MUL_ROUNDING_ON
      shrd    eax,edx,16                    ;shift the result back to 16.16 form
      add     ecx,eax                       ;running total
```

```
        mov     eax,[si+roff+8]                 ;column 2 entry on this row
        imul    dword ptr [bx+coff+32]          ;times row 2 entry in col
if MUL_ROUNDING_ON
        add     eax,8000h                       ;round by adding 2^(-17)
        adc     edx,0                           ;whole part of result is in DX
endif ;MUL_ROUNDING_ON
        shrd    eax,edx,16                      ;shift the result back to 16.16 form
        add     ecx,eax                         ;running total

        mov     [di+coff+roff],ecx              ;save the result in dest matrix
coff=coff+4                                     ;point to next col in xform2 & dest
        ENDM
                                                ;now do the fourth column, assuming
                                                ; 1 as the bottom entry, causing
                                                ; translation to be performed
        mov     eax,[si+roff]                   ;column 0 entry on this row
        imul    dword ptr [bx+coff]             ;times row 0 entry in column
if MUL_ROUNDING_ON
        add     eax,8000h                       ;round by adding 2^(-17)
        adc     edx,0                           ;whole part of result is in DX
endif ;MUL_ROUNDING_ON
        shrd    eax,edx,16                      ;shift the result back to 16.16 form
        mov     ecx,eax                         ;set running total

        mov     eax,[si+roff+4]                 ;column 1 entry on this row
        imul    dword ptr [bx+coff+16]          ;times row 1 entry in col
if MUL_ROUNDING_ON
        add     eax,8000h                       ;round by adding 2^(-17)
        adc     edx,0                           ;whole part of result is in DX
endif ;MUL_ROUNDING_ON
        shrd    eax,edx,16                      ;shift the result back to 16.16 form
        add     ecx,eax                         ;running total

        mov     eax,[si+roff+8]                 ;column 2 entry on this row
        imul    dword ptr [bx+coff+32]          ;times row 2 entry in col
if MUL_ROUNDING_ON
        add     eax,8000h                       ;round by adding 2^(-17)
        adc     edx,0                           ;whole part of result is in DX
endif ;MUL_ROUNDING_ON
        shrd    eax,edx,16                      ;shift the result back to 16.16 form
        add     ecx,eax                         ;running total

        add     ecx,[si+roff+12]                ;add in translation

        mov     [di+coff+roff],ecx              ;save the result in dest matrix
coff=coff+4                                     ;point to next col in xform2 & dest

roff=roff+16                            ;point to next col in xform2 & dest
        ENDM

else ;!USE386

        mov     di,[bp].SourceXform2            ;DI points to xform2 matrix
        mov     si,[bp].SourceXform1            ;SI points to xform1 matrix
        mov     bx,[bp].DestXform               ;BX points to dest xform matrix
        push    bp                              ;preserve stack frame pointer

roff=0                                          ;row offset
        REPT 3                                  ;once for each row
coff=0                                          ;column offset
        REPT 3                                  ;once for each of the first 3 columns,
                                           ; assuming 0 as the bottom entry (no
                                           ; translation)
     push    bx                            ;remember dest vector pointer
     push    word ptr [si+roff+2]
     push    word ptr [si+roff]
     push    word ptr [di+coff+2]
     push    word ptr [di+coff]
     call    _FixedMul                     ;column 0 entry on this row times row 0
                                           ; entry in column
     add     sp,8                          ;clear parameters from stack
     mov     cx,ax   ;set running total
     mov     bp,dx

     push    cx                            ;preserve low word of running total
     push    word ptr [si+roff+4+2]
     push    word ptr [si+roff+4]
     push    word ptr [di+coff+16+2]
     push    word ptr [di+coff+16]
     call    _FixedMul                     ;column 1 entry on this row times row 1
                                           ; entry in column
     add     sp,8                          ;clear parameters from stack
     pop     cx                            ;restore low word of running total
     add     cx,ax                         ;running total for this row
     adc     bp,dx

     push    cx                            ;preserve low word of running total
     push    word ptr [si+roff+8+2]
     push    word ptr [si+roff+8]
     push    word ptr [di+coff+32+2]
     push    word ptr [di+coff+32]
     call    _FixedMul                     ;column 1 entry on this row times row 1
                                           ; entry in column
     add     sp,8                          ;clear parameters from stack
     pop     cx                            ;restore low word of running total
     add     cx,ax                         ;running total for this row
     adc     bp,dx

     pop     bx                            ;restore DestXForm pointer
     mov     [bx+coff+roff],cx             ;save the result in dest matrix
     mov     [bx+coff+roff+2],bp
coff=coff+4                                ;point to next col in xform2 & dest
     ENDM
                                           ;now do the fourth column, assuming
                                           ; 1 as the bottom entry, causing
                                           ; translation to be performed
     push    bx                            ;remember dest vector pointer
     push    word ptr [si+roff+2]
     push    word ptr [si+roff]
     push    word ptr [di+coff+2]
     push    word ptr [di+coff]
     call    _FixedMul                     ;column 0 entry on this row times row 0
                                           ; entry in column
     add     sp,8                          ;clear parameters from stack
     mov     cx,ax   ;set running total
     mov     bp,dx

     push    cx                            ;preserve low word of running total
     push    word ptr [si+roff+4+2]
     push    word ptr [si+roff+4]
     push    word ptr [di+coff+16+2]
     push    word ptr [di+coff+16]
```

```
      call    _FixedMul                       ;column 1 entry on this row times row 1
                                              ; entry in column
      add     sp,8                            ;clear parameters from stack
      pop     cx                              ;restore low word of running total
      add     cx,ax                           ;running total for this row
      adc     bp,dx

      push    cx                              ;preserve low word of running total
      push    word ptr [si+roff+8+2]
      push    word ptr [si+roff+8]
      push    word ptr [di+coff+32+2]
      push    word ptr [di+coff+32]
      call    _FixedMul                       ;column 1 entry on this row times row 1
                                              ; entry in column
      add     sp,8                            ;clear parameters from stack
      pop     cx                              ;restore low word of running total
      add     cx,ax                           ;running total for this row
      adc     bp,dx

      add     cx,[si+roff+12]                 ;add in translation
      add     bp,[si+roff+12+2]

      pop     bx                              ;restore DestXForm pointer
      mov     [bx+coff+roff],cx               ;save the result in dest matrix
      mov     [bx+coff+roff+2],bp
coff=coff+4                                   ;point to next col in xform2 & dest

roff=roff+16                                  ;point to next col in xform2 & dest
      ENDM

      pop     bp                              ;restore stack frame pointer

endif ;USE386

      pop     di                              ;restore register variables
      pop     si
      pop     bp                              ;restore stack frame
      ret
_ConcatXforms endp
      end
```

Shading

So far, the polygons out of which our animated objects have been built have had colors of fixed intensities. For example, a face of a cube might be blue, or green, or white, but whatever color it is, that color never brightens or dims. Fixed colors are easy to implement, but they don't make for very realistic animation. In the real world, the intensity of the color of a surface varies depending on how brightly it is illuminated. The ability to simulate the illumination of a surface, or shading, is the next feature we'll add to X-Sharp.

The overall shading of an object is the sum of several types of shading components. *Ambient shading* is illumination by what you might think of as background light, light that's coming from all directions; all surfaces are equally illuminated by ambient light, regardless of their orientation. *Directed lighting*, producing diffuse shading, is illumination from one or more specific light sources. Directed light has a specific direction, and the angle at which it strikes a surface determines how brightly it lights that surface.

Specular reflection is the tendency of a surface to reflect light in a mirrorlike fashion. There are other sorts of shading components, including transparency and atmospheric effects, but the ambient and diffuse-shading components are all we're going to deal with in X-Sharp.

Ambient Shading

The basic model for both ambient and diffuse shading is a simple one. Each surface has a reflectivity between 0 and 1, where 0 means all light is absorbed and 1 means all light is reflected. A certain amount of light energy strikes each surface. The energy (intensity) of the light is expressed such that if light of intensity 1 strikes a surface with reflectivity 1, then the brightest possible shading is displayed for that surface. Complicating this somewhat is the need to support color; we do this by separating reflectance and shading into three components each—red, green, and blue—and calculating the shading for each color component separately for each surface.

Given an ambient-light red intensity of IA_{red} and a surface red reflectance R_{red}, the displayed red ambient shading for that surface, as a fraction of the maximum red intensity, is simply $\min(IA_{red} \times R_{red}, 1)$. The green and blue color components are handled similarly. That's really all there is to ambient shading, although of course we must design some way to map displayed color components into the available palette of colors; I'll do that in the next chapter. Ambient shading isn't the whole shading picture, though. In fact, scenes tend to look pretty bland without diffuse shading.

Diffuse Shading

Diffuse shading is more complicated than ambient shading, because the effective intensity of directed light falling on a surface depends on the angle at which it strikes the surface. According to Lambert's law, the light energy from a directed light source striking a surface is proportional to the cosine of the angle at which it strikes the surface, with the angle measured relative to a vector perpendicular to the polygon (a polygon normal), as shown in Figure 39.1. If the red intensity of directed light is ID_{red}, the red

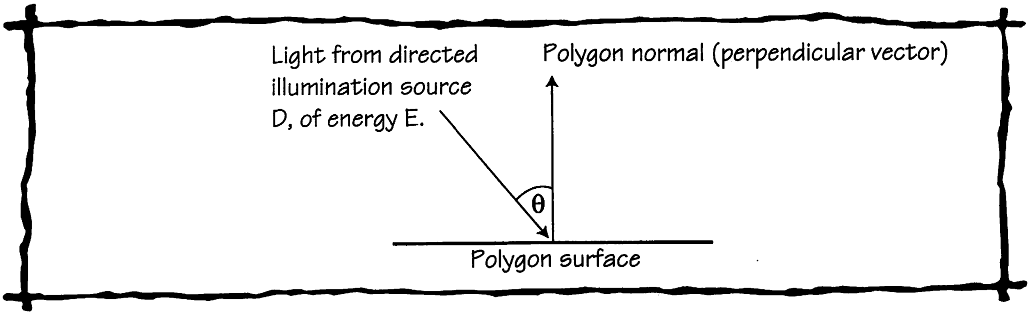

Light from directed illumination source D, of energy E.
Polygon normal (perpendicular vector)
θ
Polygon surface

Figure 39.1 Illumination by a Directed Light Source

reflectance of the surface is R_{red}, and the angle between the incoming directed light and the surface's normal is theta, then the displayed red diffuse shading for that surface, as a fraction of the largest possible red intensity, is min $(ID_{red} \times R_{red} \times \cos(\theta), 1)$.

That's easy enough to calculate—but seemingly slow. Determining the cosine of an angle can be sped up with a table lookup, but there's also the task of figuring out the angle, and, all in all, it doesn't seem that diffuse shading is going to be speedy enough for our purposes. Consider this, however: According to the properties of the dot product (denoted by the operator "•", as shown in Figure 39.2), $\cos(\theta)=(v \bullet w)/ |v| \times |w|$), where v and w are vectors, θ is the angle between v and w, and $|v|$ is the length of v. Suppose, now, that v and w are unit vectors; that is, vectors exactly one unit long. Then the above equation reduces to $\cos(\theta)=v \bullet w$. In other words, we can calculate the cosine between N, the unit-normal vector (one-unit-long perpendicular vector) of a polygon, and L', the reverse of a unit vector describing the direction of a light source, with just three multiplies and two adds. (I'll explain why the light-direction vector must be reversed later.) Once we have that, we can easily calculate the red diffuse shading from a directed light source as $\min(ID_{red} \times R_{red} \times (L' \bullet N), 1)$ and likewise for the green and blue color components.

The overall red shading for each polygon can be calculated by summing the ambient-shading red component with the diffuse-shading component from each light source, as in $\min((IA_{red} \times R_{red}) + (ID_{red0} \times R_{red} \times (L_0' \bullet N)) + (ID_{red1} \times R_{red} \times (L_1' \bullet N)) + \ldots, 1)$ where ID_{red0} and L_0' are the red intensity and the reversed unit-direction vector, respectively, for spotlight 0. Listing 39.2 shows the X-Sharp module DRAWPOBJ.C, which performs ambient and diffuse shading. Toward the bottom, you will find the code that performs shading exactly as described by the above equation, first calculating the ambient red, green, and blue shadings, then summing that with the diffuse red, green, and blue shadings generated by each directed light source.

LISTING 39.2 DRAWPOBJ.C

```
/* Draws all visible faces in the specified polygon-based object. The object
   must have previously been transformed and projected, so that all vertex
   arrays are filled in. Ambient and diffuse shading are supported. */
#include "polygon.h"
```

For two vectors v and w, as follows:

$$v = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} \quad w = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix}$$

the dot product v • w is:

$$v \bullet w = v_1w_1 + v_2w_2 + v_3w_3$$

Figure 39.2 The Dot Product of Two Vectors

```
void DrawPObject(PObject * ObjectToXform)
{
   int i, j, NumFaces = ObjectToXform->NumFaces, NumVertices;
   int * VertNumsPtr, Spot;
   Face * FacePtr = ObjectToXform->FaceList;
   Point * ScreenPoints = ObjectToXform->ScreenVertexList;
   PointListHeader Polygon;
   Fixedpoint Diffusion;
   ModelColor ColorTemp;
   ModelIntensity IntensityTemp;
   Point3 UnitNormal, *NormalStartpoint, *NormalEndpoint;
   long v1, v2, w1, w2;
   Point Vertices[MAX_POLY_LENGTH];

   /* Draw each visible face (polygon) of the object in turn */
   for (i=0; i<NumFaces; i++, FacePtr++) {
      /* Remember where we can find the start and end of the polygon's
         unit normal in view space, and skip over the unit normal endpoint
         entry. The end and start points of the unit normal to the polygon
         must be the first and second entries in the polgyon's vertex list.
         Note that the second point is also an active polygon vertex */
      VertNumsPtr = FacePtr->VertNums;
      NormalEndpoint = &ObjectToXform->XformedVertexList[*VertNumsPtr++];
      NormalStartpoint = &ObjectToXform->XformedVertexList[*VertNumsPtr];
      /* Copy over the face's vertices from the vertex list */
      NumVertices = FacePtr->NumVerts;
      for (j=0; j<NumVertices; j++)
         Vertices[j] = ScreenPoints[*VertNumsPtr++];
      /* Draw only if outside face showing (if the normal to the polygon
         in screen coordinates points toward the viewer; that is, has a
         positive Z component) */
      v1 = Vertices[1].X - Vertices[0].X;
      w1 = Vertices[NumVertices-1].X - Vertices[0].X;
      v2 = Vertices[1].Y - Vertices[0].Y;
      w2 = Vertices[NumVertices-1].Y - Vertices[0].Y;
      if ((v1*w2 - v2*w1) > 0) {
         /* It is facing the screen, so draw */
         /* Appropriately adjust the extent of the rectangle used to
            erase this object later */
         for (j=0; j<NumVertices; j++) {
            if (Vertices[j].X >
                  ObjectToXform->EraseRect[NonDisplayedPage].Right)
               if (Vertices[j].X < SCREEN_WIDTH)
                  ObjectToXform->EraseRect[NonDisplayedPage].Right =
                        Vertices[j].X;
               else ObjectToXform->EraseRect[NonDisplayedPage].Right =
                     SCREEN_WIDTH;
            if (Vertices[j].Y >
                  ObjectToXform->EraseRect[NonDisplayedPage].Bottom)
               if (Vertices[j].Y < SCREEN_HEIGHT)
                  ObjectToXform->EraseRect[NonDisplayedPage].Bottom =
                        Vertices[j].Y;
               else ObjectToXform->EraseRect[NonDisplayedPage].Bottom=
                     SCREEN_HEIGHT;
            if (Vertices[j].X <
                  ObjectToXform->EraseRect[NonDisplayedPage].Left)
               if (Vertices[j].X > 0)
                  ObjectToXform->EraseRect[NonDisplayedPage].Left =
                        Vertices[j].X;
               else ObjectToXform->EraseRect[NonDisplayedPage].Left=0;
            if (Vertices[j].Y <
                  ObjectToXform->EraseRect[NonDisplayedPage].Top)
               if (Vertices[j].Y > 0)
                  ObjectToXform->EraseRect[NonDisplayedPage].Top =
                        Vertices[j].Y;
               else ObjectToXform->EraseRect[NonDisplayedPage].Top=0;
         }
         /* See if there's any shading */
            if (FacePtr->ShadingType == 0) {
            /* No shading in effect, so just draw */
            DRAW_POLYGON(Vertices, NumVertices, FacePtr->ColorIndex, 0, 0);
         } else {
            /* Handle shading */
            /* Do ambient shading, if enabled */
            if (AmbientOn && (FacePtr->ShadingType & AMBIENT_SHADING)) {
               /* Use the ambient shading component */
               IntensityTemp = AmbientIntensity;
            } else {
               SET_INTENSITY(IntensityTemp, 0, 0, 0);
            }
            /* Do diffuse shading, if enabled */
            if (FacePtr->ShadingType & DIFFUSE_SHADING) {
               /* Calculate the unit normal for this polygon, for use in dot
                  products */
               UnitNormal.X = NormalEndpoint->X - NormalStartpoint->X;
               UnitNormal.Y = NormalEndpoint->Y - NormalStartpoint->Y;
               UnitNormal.Z = NormalEndpoint->Z - NormalStartpoint->Z;
               /* Calculate the diffuse shading component for each active
                  spotlight */
               for (Spot=0; Spot<MAX_SPOTS; Spot++) {
                  if (SpotOn[Spot] != 0) {
                     /* Spot is on, so sum, for each color component, the
                        intensity, accounting for the angle of the light rays
                        relative to the orientation of the polygon */
                     /* Calculate cosine of angle between the light and the
                        polygon normal; skip if spot is shining from behind
                        the polygon */
                     if ((Diffusion = DOT_PRODUCT(SpotDirectionView[Spot],
                           UnitNormal)) > 0) {
                        IntensityTemp.Red +=
                              FixedMul(SpotIntensity[Spot].Red, Diffusion);
                        IntensityTemp.Green +=
                              FixedMul(SpotIntensity[Spot].Green, Diffusion);
                        IntensityTemp.Blue +=
                              FixedMul(SpotIntensity[Spot].Blue, Diffusion);
                     }
                  }
               }
            }
            /* Convert the drawing color to the desired fraction of the
               brightest possible color */
            IntensityAdjustColor(&ColorTemp, &FacePtr->FullColor,
                  &IntensityTemp);
            /* Draw with the cumulative shading, converting from the general
               color representation to the best-match color index */
            DRAW_POLYGON(Vertices, NumVertices,
                  ModelColorToColorIndex(&ColorTemp), 0, 0);
         }
      }
   }
}
```

Shading: Implementation Details

In order to calculate the cosine of the angle between an incoming light source and a polygon's unit normal, we must first have the polygon's unit normal. This could be calculated by generating a cross-product on two polygon edges to generate a normal, then calculating the normal's length and scaling to produce a unit normal. Unfortunately, that would require taking a square root, so it's not a desirable course of action. Instead, I've made a change to X-Sharp's polygon format. Now, the first vertex in a shaded polygon's vertex list is the end-point of a unit normal that starts at the second point in the polygon's vertex list, as shown in Figure 39.3. The first point isn't one of the polygon's vertices, but is used only to generate a unit normal. The second point, however, is a polygon vertex. Calculating the difference vector between the first and second points yields the polygon's unit normal. Adding a unit-normal endpoint to each polygon isn't free; each of those end-points has to be transformed, along with the rest of the vertices, and that takes time. Still, it's faster than calculating a unit normal for each polygon from scratch.

We also need a unit vector for each directed light source. The directed light sources I've implemented in X-Sharp are spotlights; that is, they're considered to be point light sources that are infinitely far away. This allows the simplifying assumption that all light rays from a spotlight are parallel and of equal intensity throughout the displayed universe, so each spotlight can be represented with a single unit vector and a single intensity. The only trick is that in order to calculate the desired cos(theta) between the polygon unit normal and a spotlight's unit vector, the direction of the spotlight's unit vector must be reversed, as shown in Figure 39.4. This is necessary because the dot product implicitly places vectors with their start points at the same location when it's used to calculate the cosine of the angle between two vectors. The light vector is incoming to the polygon surface, and the unit normal is outbound, so only by reversing one vector or the other will we get the cosine of the desired angle.

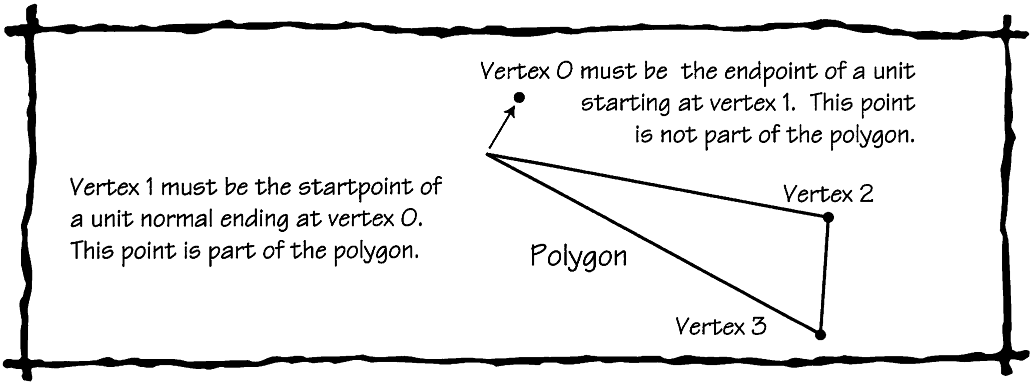

Vertex 0 must be the endpoint of a unit starting at vertex 1. This point is not part of the polygon.
Vertex 1 must be the startpoint of a unit normal ending at vertex 0. This point is part of the polygon.
Vertex 2
Polygon
Vertex 3

Figure 39.3 The Unit Normal in the Polygon Data Structure

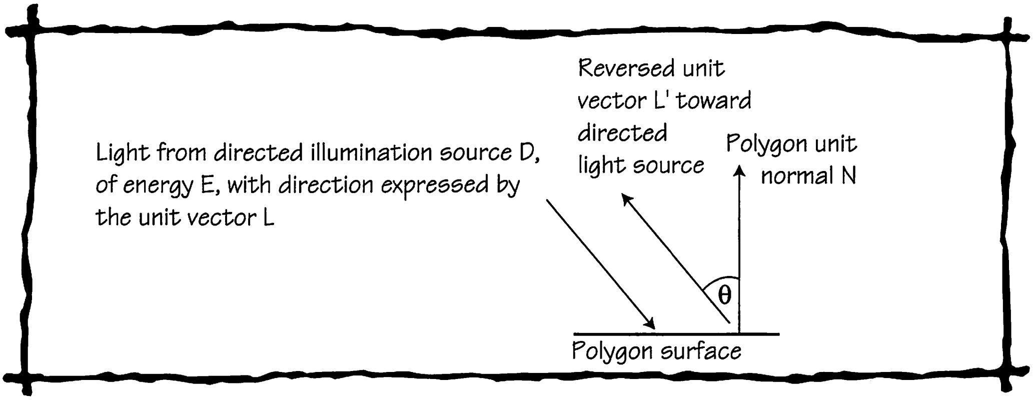

Reversed unit vector L' toward directed light source
Polygon unit normal N
Light from directed illumination source D, of energy E, with direction expressed by the unit vector L
θ
Polygon surface

Figure 39.4 The Reversed Light Source Vector

Given the two unit vectors, it's a piece of cake to calculate intensities, as shown in Listing 39.2. The sample program DEMO1, in the X-Sharp archive on the listings diskette (built by running K1.BAT), puts the shading code to work displaying a rotating ball with ambient lighting and three spot lighting sources that the user can turn on and off. What you'll see when you run DEMO1 is that the shading is very good—face colors change very smoothly indeed—so long as only green lighting sources are on. However, if you combine spotlight two, which is blue, with any other light source, polygon colors will start to shift abruptly and unevenly. As configured in the demo, the palette supports a wide range of shading intensities for a pure version of any one of the three primary colors, but a very limited number of intensity steps (four, in this case) for each color component when two or more primary colors are mixed. While this situation can be improved, it is fundamentally a result of the restricted capabilities of the 256-color palette, and there is only so much that can be done without a larger color set. In the next chapter, I'll talk about some ways to improve the quality of 256-color shading.

Color Modeling in 256-Color Mode

Chapter 40

Pondering X-Sharp's Color Model in an RGB State of Mind

Once she turned six, my daughter wanted some fairly sophisticated books read to her. *Wind in the Willows. Little House on the Prairie.* Pretty heady stuff for one so young, and sometimes I wondered how much of it she really understood. As an experiment, during one reading I stopped whenever I came to a word I thought she might not know, and asked her what it meant. One such word was "mulling."

"Do you know what 'mulling' means?" I asked.

She thought about it for a while, then said, "Pondering."

"Very good!" I said, more than a little surprised.

She smiled and said, "But, Dad, how do you know that I know what 'pondering' means?"

"Okay," I said, "What does 'pondering' mean?"

"Mulling," she said.

What does this anecdote tell us about the universe in which we live? Well, it certainly indicates that this universe is inhabited by at least one comedian and one good straight man. Beyond that, though, it can be construed as a parable about the difficulty of defining things properly; for example, consider the complications inherent in the definition of color on a 256-color display adapter such as the VGA. Coincidentally, VGA color modeling just happens to be this chapter's topic, and the place to start is with color modeling in general.

A Color Model

We've been developing X-Sharp for several chapters now. In the previous chapter, we added illumination sources and shading; that addition makes it necessary for us to have a general-purpose color model, so that we can display the gradations of color intensity necessary to render illuminated surfaces properly. In other words, when a bright light is shining straight at a green surface, we need to be able to display bright green, and as that light dims or tilts to strike the surface at a shallower angle, we need to be able to display progressively dimmer shades of green.

The first thing to do is to select a color model in which to perform our shading calculations. I'll use the dot product-based stuff I discussed in the previous chapter. The approach we'll take is to select an ideal representation of the full color space and do our calculations there, as if we really could display every possible color; only as a final step will we map each desired color into the limited 256-color set of the VGA, or the color range of whatever adapter we happen to be working with. There are a number of color models that we might choose to work with, but I'm going to go with the one that's both most familiar and, in my opinion, simplest: RGB (red, green, blue).

In the RGB model, a given color is modeled as the mix of specific fractions of full intensities of each of the three color primaries. For example, the brightest possible pure blue is 0.0*R, 0.0*G, 1.0*B. Half-bright cyan is 0.0*R, 0.5*G, 0.5*B. Quarter-bright gray is 0.25*R, 0.25*G, 0.25*B. You can think of RGB color space as being a cube, as shown in Figure 40.1, with any particular color lying somewhere inside or on the cube.

RGB is good for modeling colors generated by light sources, because red, green, and blue are the additive primaries; that is, all other colors can be generated by mixing red, green, and blue light sources. They're also the primaries for color computer displays, and the RGB model maps beautifully onto the display capabilities of 15- and 24-bpp display adapters, which tend to represent pixels as RGB combinations in display memory.

How, then, are RGB colors represented in X-Sharp? Each color is represented as an RGB triplet, with eight bits each of red, green, and blue resolution, using the structure shown in Listing 40.1.

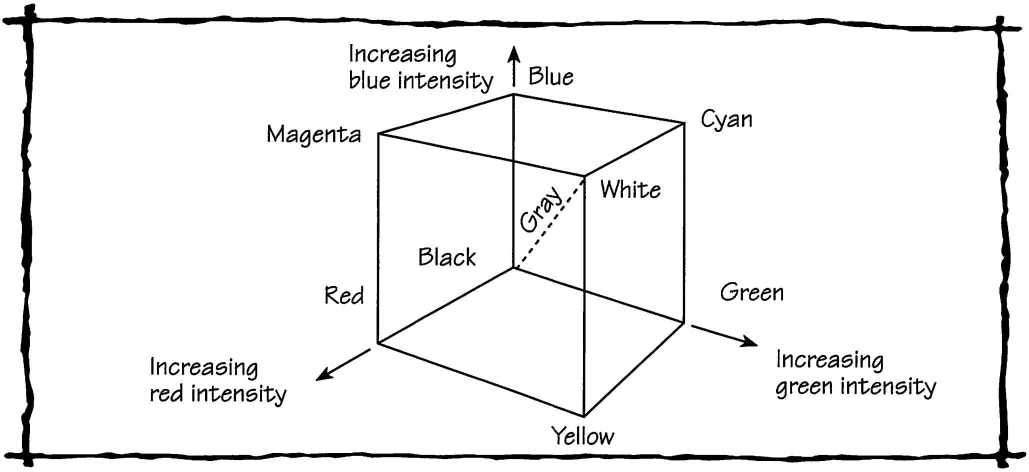


Figure 40.1 The RGB Color Cube

LISTING 40.1 L40-1.C

```
typedef struct _ModelColor {
   unsigned char Red;   /* 255 = max red, 0 = no red */
   unsigned char Green; /* 255 = max green, 0 = no green */
   unsigned char Blue;  /* 255 = max blue, 0 = no blue */
} ModelColor;
```

Here, each color is described by three color components—one each for red, green, and blue—and each primary color component is represented by eight bits. Zero intensity of a color component is represented by the value 0, and full intensity is represented by the value 255. This gives us 256 levels of each primary color component, and a total of 16,772,216 possible colors.

Holy cow! Isn't 16,000,000-plus colors a bit of overkill?

Actually, no, it isn't. At the eighth Annual Computer Graphics Show in New York, Sheldon Linker, of Linker Systems, related an interesting tale about color perception research at the Jet Propulsion Lab back in the '70s. The JPL color research folks had the capability to print more than 50,000,000 distinct and very precise colors on paper. As a test, they tried printing out words in various colors, with each word printed on a background that differed by only one color index from the word's color. No one expected the human eye to be able to differentiate between two colors, out of 50,000,000-plus, that were so similar. It turned out, though, that everyone could read the words with no trouble at all; the human eye is surprisingly sensitive to color gradations, and also happens to be wonderful at detecting edges.

When the JPL team went to test the eye's sensitivity to color on the screen, they found that only about 16,000,000 colors could be distinguished, because the color-sensing mechanism of the human eye is more compatible with reflective sources such as paper and ink than with emissive sources such as CRTs. Still, the human eye can distinguish about 16,000,000 colors on the screen. That's not so hard to believe, if you think about it; the eye senses each primary color separately, so we're really only talking about detecting 256 levels of intensity per primary here. It's the brain that does the amazing part; the 16,000,000-plus color capability actually comes not from extraordinary sensitivity in the eye, but rather from the brain's ability to distinguish between all the mixes of 256 levels of each of three primaries.

So it's perfectly reasonable to maintain 24 bits of color resolution, and X-Sharp represents colors internally as ideal, device-independent 24-bit RGB triplets. All shading calculations are performed on these triplets, with 24-bit color precision. It's only after the final 24-bit RGB drawing color is calculated that the display adapter's color capabilities come into play, as the X-Sharp function **ModelColorToColorIndex()** is called to map the desired RGB color to the closest match the adapter is capable of displaying. Of course, that mapping is adapter-dependent. On a 24-bpp device, it's pretty obvious how the internal RGB color format maps to displayed pixel colors: directly. On VGAs with 15-bpp Sierra Hicolor DACS, the mapping is equally simple, with the five upper bits of each color component mapping straight to display pixels.

But how on earth do we map those 16,000,000-plus RGB colors into the 256-color space of a standard VGA?

This is the "color definition" problem I mentioned at the start of this chapter. The VGA palette is arbitrarily programmable to any set of 256 colors, with each color defined by six bits each of red, green, and blue intensity. In X-Sharp, the function **InitializePalette()** can be customized to set up the palette however we wish; this gives us nearly complete flexibility in defining the working color set. Even with infinite flexibility, however, 256 out of 16,000,000 or so possible colors is a pretty puny selection. It's easy to set up the palette to give yourself a good selection of just blue intensities, or of just greens; but for general color modeling there's simply not enough palette to go around.

One way to deal with the limited simultaneous color capabilities of the VGA is to build an application that uses only a subset of RGB space, then bias the VGA's palette toward that subspace. This is the approach used in the DEMO1 sample program in X-Sharp; Listings 40.2 and 40.3 show the versions of **InitializePalette()** and **ModelColorToColorIndex()** that set up and perform the color mapping for DEMO1.

LISTING 40.2 L40-2.C

```
/* Sets up the palette in mode X, to a 2-2-2 general R-G-B organization, with
   64 separate levels each of pure red, green, and blue. This is very good
   for pure colors, but mediocre at best for mixes.

   ------------------------
   |0  0 | Red|Green| Blue |
   ------------------------
    7  6  5  4  3  2  1  0

   ------------------------
   |0  1 |      Red         |
   ------------------------
    7  6  5  4  3  2  1  0

   ------------------------
   |1  0 |     Green        |
   ------------------------
    7  6  5  4  3  2  1  0

   ------------------------
   |1  1 |      Blue        |
   ------------------------
    7  6  5  4  3  2  1  0

   Colors are gamma corrected for a gamma of 2.3 to provide approximately
   even intensity steps on the screen.
*/

#include <dos.h>
#include "polygon.h"

static unsigned char Gamma4Levels[] = { 0, 39, 53, 63 };
static unsigned char Gamma64Levels[] = {
    0, 10, 14, 17, 19, 21, 23, 24, 26, 27, 28, 29, 31, 32, 33, 34,
   35, 36, 37, 37, 38, 39, 40, 41, 41, 42, 43, 44, 44, 45, 46, 46,
   47, 48, 48, 49, 49, 50, 51, 51, 52, 52, 53, 53, 54, 54, 55, 55,
   56, 56, 57, 57, 58, 58, 59, 59, 60, 60, 61, 61, 62, 62, 63, 63,
};

static unsigned char PaletteBlock[256][3];   /* 256 RGB entries */

void InitializePalette()
{
   int Red, Green, Blue, Index;
   union REGS regset;
   struct SREGS sregset;

   for (Red=0; Red<4; Red++) {
      for (Green=0; Green<4; Green++) {
         for (Blue=0; Blue<4; Blue++) {
            Index = (Red<<4)+(Green<<2)+Blue;
            PaletteBlock[Index][0] = Gamma4Levels[Red];
            PaletteBlock[Index][1] = Gamma4Levels[Green];
            PaletteBlock[Index][2] = Gamma4Levels[Blue];
         }
      }
   }

   for (Red=0; Red<64; Red++) {
      PaletteBlock[64+Red][0] = Gamma64Levels[Red];
      PaletteBlock[64+Red][1] = 0;
      PaletteBlock[64+Red][2] = 0;
   }

   for (Green=0; Green<64; Green++) {
      PaletteBlock[128+Green][0] = 0;
      PaletteBlock[128+Green][1] = Gamma64Levels[Green];
      PaletteBlock[128+Green][2] = 0;
   }

   for (Blue=0; Blue<64; Blue++) {
      PaletteBlock[192+Blue][0] = 0;
      PaletteBlock[192+Blue][1] = 0;
      PaletteBlock[192+Blue][2] = Gamma64Levels[Blue];
   }

   /* Now set up the palette */
   regset.x.ax = 0x1012;   /* set block of DAC registers function */
   regset.x.bx = 0;        /* first DAC location to load */
   regset.x.cx = 256;      /* # of DAC locations to load */
   regset.x.dx = (unsigned int)PaletteBlock; /* offset of array from which
                                                to load RGB settings */
   sregset.es = _DS; /* segment of array from which to load settings */
   int86x(0x10, &regset, &regset, &sregset); /* load the palette block */
}
```

LISTING 40.3 L40-3.C

```
/* Converts a model color (a color in the RGB color cube, in the current
   color model) to a color index for mode X. Pure primary colors are
   special-cased, and everything else is handled by a 2-2-2 model. */
int ModelColorToColorIndex(ModelColor * Color)
{
   if (Color->Red == 0) {
      if (Color->Green == 0) {
         /* Pure blue */
         return(192+(Color->Blue >> 2));
      } else if (Color->Blue == 0) {
         /* Pure green */
         return(128+(Color->Green >> 2));
      }
   } else if ((Color->Green == 0) && (Color->Blue == 0)) {
      /* Pure red */
      return(64+(Color->Red >> 2));
   }
   /* Multi-color mix; look up the index with the two most significant bits
      of each color component */
   return(((Color->Red & 0xC0) >> 2) | ((Color->Green & 0xC0) >> 4) |
        ((Color->Blue & 0xC0) >> 6));
}
```

In DEMO1, three-quarters of the palette is set up with 64 intensity levels of each of the three pure primary colors (red, green, and blue), and then most drawing is done with only pure primary colors. The resulting rendering quality is very good because there are so many levels of each primary.

The downside is that this excellent quality is available for only three colors: red, green, and blue. What about all the other colors that are mixes of the primaries, like cyan or yellow, to say nothing of gray? In the DEMO1 color model, any RGB color that is not a pure primary is mapped into a 2-2-2 RGB space that the remaining quarter of the VGA's palette is set up to display; that is, there are exactly two bits of precision for each color component, or 64 general RGB colors in all. This is genuinely lousy color resolution, being only 1/64th of the resolution we really need for each color component. In this model, a staggering 262,144 colors from the 24-bit RGB cube map to *each* color in the 2-2-2 VGA palette. The results are not impressive; the colors of mixed-primary surfaces jump abruptly, badly damaging the illusion of real illumination. To see how poor a 2-2-2 RGB selection can look, run DEMO1, and press the '2' key to turn on spotlight 2, the blue spotlight. Because the ambient lighting is green, turning on the blue spotlight causes mixed-primary colors to be displayed—and the result looks terrible, because there just isn't enough color resolution. Unfortunately, 2-2-2 RGB is close to the best general color resolution the VGA can display; 3-3-2 is as good as it gets.

Another approach would be to set up the palette with reasonably good mixes of two primaries but no mixes of three primaries, then use only two-primary colors in your applications (no grays or whites or other three-primary mixes). Or you could choose to shade only selected objects, using part of the palette for a good range of the colors of those objects, and reserving the rest of the palette for the fixed colors of the other, nonshaded objects. Jim Kent, author of Autodesk Animator, suggests dynamically adjusting the palette to the needs of each frame, for example by allocating the colors for each frame on a first-come, first-served basis. That wouldn't be trivial to do in real time, but it would make for extremely efficient use of the palette.

Another widely-used solution is to set up a 2-2-2, 3-3-2, or 2.6-2.6-2.6 (6 levels per primary) palette, and dither colors. Dithering is an excellent solution, but outside the scope of this book. Take a look at Chapter 13 of Foley and Van Dam (cited in Further Readings) for an introduction to color perception and approximation.

The sad truth is that the VGA's 256-color palette is an inadequate resource for general RGB shading. The good news is that clever workarounds can make VGA graphics look nearly as good as 24-bpp graphics; but the burden falls on you, the programmer, to design your applications and color mapping to compensate for the VGA's limitations. To experiment with a different 256-color model in X-Sharp, just change **InitializePalette()** to set up the desired palette and **ModelColorToColorIndex()** to map 24-bit RGB triplets into the palette you've set up. It's that simple, and the results can be striking indeed.

A Bonus from the BitMan

Finally, a note on fast VGA text, which came in from a correspondent who asked to be referred to simply as the BitMan. The BitMan passed along a nifty application of the VGA's under-appreciated write mode 3 that is, under the proper circumstances, the fastest possible way to draw text in any 16-color VGA mode.

The task at hand is illustrated by Figure 40.2. We want to draw what's known as solid text, in which the effect is the same as if the cell around each character was drawn in the background color, and then each character was drawn on top of the background box. (This is in contrast to transparent text, where each character is drawn in the foreground color without disturbing the background.) Assume that each character fits in an eight-wide cell (as is the case with the standard VGA fonts), and that we're drawing text at byte-aligned locations in display memory.

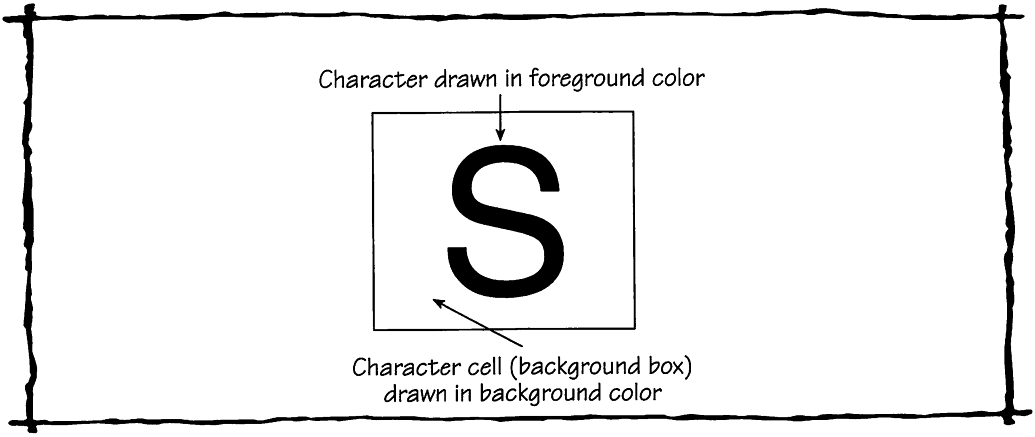

Character drawn in foreground color
S
Character cell (background box) drawn in background color

Figure 40.2 Drawing Solid Text

Solid text is useful for drawing menus, text areas, and the like; basically, it can be used whenever you want to display text on a solid-color background. The obvious way to implement solid text is to fill the rectangle representing the background box, then draw transparent text on top of the background box. However, there are two problems with doing solid text this way. First, there's some flicker, because for a little while the box is there but the text hasn't yet arrived. More important is that the background-followed-by-foreground approach accesses display memory three times for each byte of font data: once to draw the background box, once to read display memory to load the latches, and once to actually draw the font pattern. Display memory is incredibly slow, so we'd like to reduce the number of accesses as much as possible. With the BitMan's approach, we can reduce the number of accesses to just one per font byte, and eliminate flicker, too.

The keys to fast solid text are the latches and write mode 3. The latches, as you may recall from earlier discussions in this book, are four internal VGA registers that hold the last bytes read from the VGA's four planes; every read from VGA memory loads the latches with the values stored at that display memory address across the four planes. Whenever a write is performed to VGA memory, the latches can provide some, none, or all of the bits written to memory, depending on the bit mask, which selects between the latched data and the drawing data on a bit-by-bit basis. The latches solve half our problem; we can fill the latches with the background color, then use them to draw the background box. The trick now is drawing the text pixels in the foreground color at the same time.

This is where it gets a little complicated. In write mode 3 (which incidentally is not available on the EGA), each byte value that the CPU writes to the VGA does not get written to display memory. Instead, it turns into the bit mask. (Actually, it's ANDed with the Bit Mask register, and the result becomes the bit mask, but we'll leave the Bit Mask register set to 0xFF, so the CPU value will become the bit mask.) The bit mask selects, on a bit-by-bit basis, between the data in the latches for each plane (the previously loaded background color, in this case) and the foreground color. Where does the foreground color come from, if not from the CPU? From the Set/Reset register, as shown in Figure 40.3. Thus, each byte written by the CPU (font data, presumably) selects foreground or background color for each of eight pixels, all done with a single write to display memory.

I know this sounds pretty esoteric, but think of it this way: The latches hold the background color in a form suitable for writing eight background pixels (one full byte) at a pop. Write mode 3 allows each CPU byte to punch holes in the background color provided by the latches, holes through which the foreground color from the Set/Reset register can flow. The result is that a single write draws exactly the combination of foreground and background pixels described by each font byte written by the CPU. It may help to look at Listing 40.4, which shows The BitMan's technique in action. And yes, this technique is absolutely worth the trouble; it's about three times faster than the fill-then-draw approach described above, and about twice as fast as transparent text. So far as I know, there is no faster way to draw text on a VGA.

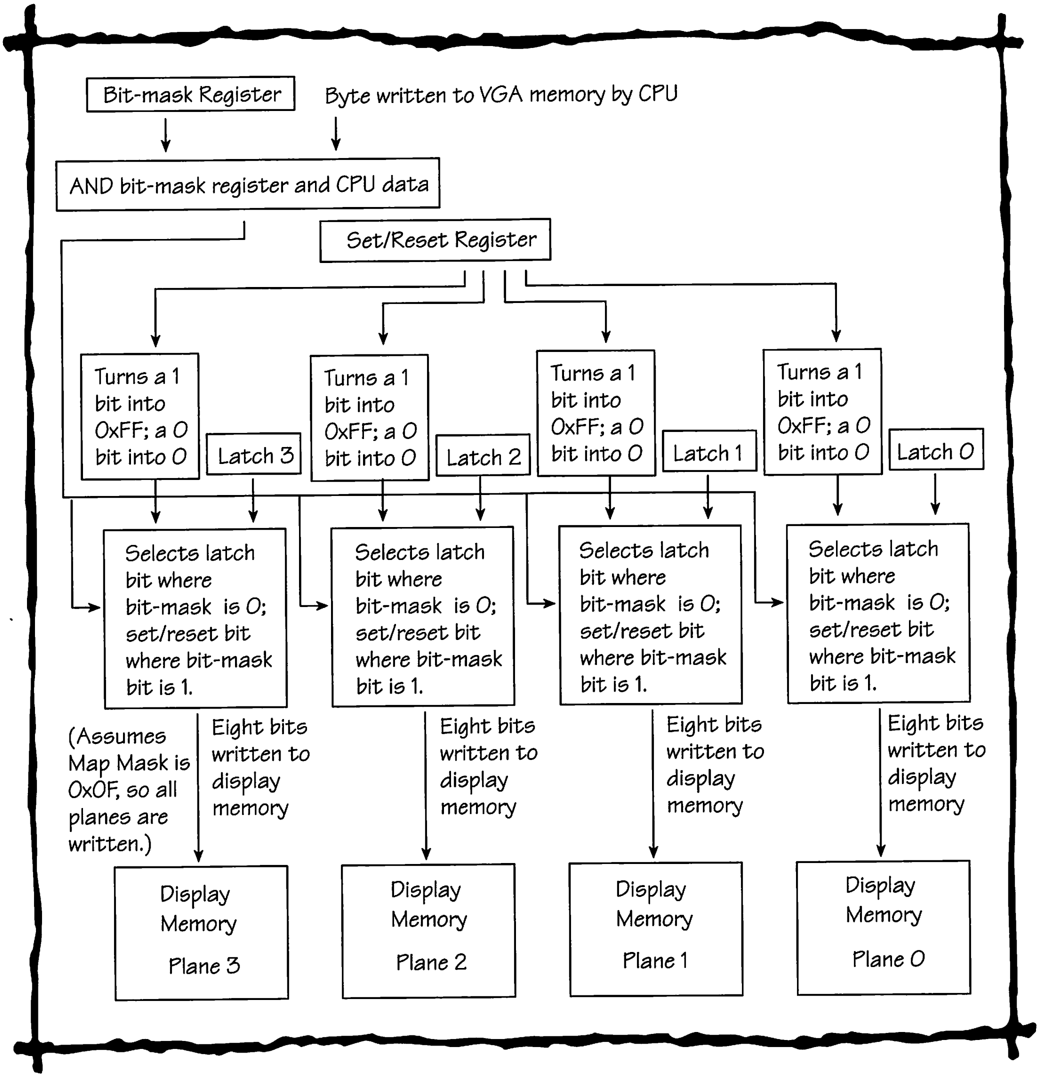

Bit-mask Register
Byte written to VGA memory by CPU
AND bit-mask register and CPU data
Set/Reset Register
Turns a 1 bit into 0xFF; a 0 bit into 0
Latch 3
Turns a 1 bit into 0xFF; a 0 bit into 0
Latch 2
Turns a 1 bit into 0xFF; a 0 bit into 0
Latch 1
Turns a 1 bit into 0xFF; a 0 bit into 0
Latch 0
Selects latch bit where bit-mask is 0; set/reset bit where bit-mask bit is 1.
Selects latch bit where bit-mask is 0; set/reset bit where bit-mask bit is 1.
Selects latch bit where bit-mask is 0; set/reset bit where bit-mask bit is 1.
Selects latch bit where bit-mask is 0; set/reset bit where bit-mask bit is 1.
(Assumes Map Mask is 0x0F, so all planes are written.)
Eight bits written to display memory
Eight bits written to display memory
Eight bits written to display memory
Eight bits written to display memory
Display Memory Plane 3
Display Memory Plane 2
Display Memory Plane 1
Display Memory Plane 0

Figure 40.3 The Data Path in Write Mode 3

It's important to note that the BitMan's technique only works on full bytes of display memory. There's no way to clip to finer precision; the background color will inevitably flood all of the eight destination pixels that aren't selected as foreground pixels. This makes The BitMan's technique most suitable for monospaced fonts with characters that are multiples of eight pixels in width, and for drawing to byte-aligned addresses; the technique can be used in other situations, but is considerably more difficult to apply.

LISTING 40.4 L40-4.ASM

```
; Demonstrates drawing solid text on the VGA, using the BitMan's write mode
; 3-based, one-pass technique.

CHAR_HEIGHT      equ 8           ;# of scan lines per character (must be <256)
SCREEN_HEIGHT    equ 480         ;# of scan lines per screen
SCREEN_SEGMENT   equ 0a000h      ;where screen memory is
FG_COLOR         equ 14          ;text color
BG_COLOR         equ 1           ;background box color
GC_INDEX         equ 3ceh        ;Graphics Controller (GC) Index reg I/O port
SET_RESET        equ 0           ;Set/Reset register index in GC
G_MODE           equ 5           ;Graphics Mode register index in GC
BIT_MASK         equ 8           ;Bit Mask register index in GC

      .model     small
      .stack     200h
      .data
Line             dw ?      ;current line #
CharHeight       dw ?      ;# of scan lines in each character (must be <256)
MaxLines         dw ?      ;max # of scan lines of text that will fit on screen
LineWidthBytes   dw ?            ;offset from one scan line to the next
FontPtr          dd ?            ;pointer to font with which to draw
SampleString     label   byte
      db  'ABCDEFGHIJKLMNOPQRSTUVWXYZ'
      db  'abcdefghijklmnopqrstuvwxyz'
      db  '0123456789!@#$%^&*(),<.>/?;:',0

      .code
start:
      mov   ax,@data
      mov   ds,ax

      mov   ax,12h
      int   10h                         ;select 640x480 16-color mode

      mov   ah,11h                      ;BIOS character generator function
      mov   al,30h                      ;BIOS get font pointer subfunction
      mov   bh,3                        ;get 8x8 ROM font subsubfunction
      int   10h                         ;get the pointer to the BIOS 8x8 font
      mov   word ptr [FontPtr],bp
      mov   word ptr [FontPtr+2],es

      mov   bx,CHAR_HEIGHT
      mov   [CharHeight],bx             ;# of scan lines per character
      mov   ax,SCREEN_HEIGHT
      sub   dx,dx
      div   bx
      mul   bx                          ;max # of full scan lines of text that
      mov   [MaxLines],ax               ; will fit on the screen

      mov   ah,0fh                      ;BIOS video status function
      int   10h                         ;get # of columns (bytes) per row
      mov   al,ah                       ;convert byte columns variable in
      sub   ah,ah                       ; AH to word in AX
      mov   [LineWidthBytes],ax         ;width of scan line in bytes
                                        ;now draw the text
      sub   bx,bx
      mov   [Line],bx                   ;start at scan line 0
```

```
LineLoop:
     sub   ax,ax                     ;start at column 0; must be a multiple of 8
     mov   ch,FG_COLOR               ;color in which to draw text
     mov   cl,BG_COLOR               ;color in which to draw background box
     mov   si,offset SampleString    ;text to draw
     call  DrawTextString            ;draw the sample text
     mov   bx,[Line]
     add   bx,[CharHeight]           ;# of next scan line to draw on
     mov   [Line],bx
     cmp   bx,[MaxLines]             ;done yet?
     jb    LineLoop                  ;not yet

     mov ah,7
     int   21h                       ;wait for a key press, without echo

     mov   ax,03h
     int   10h                       ;back to text mode

     mov   ah,4ch
     int   21h                       ;exit to DOS

; Draws a text string.
; Input: AX = X coordinate at which to draw upper left corner of first char
;    BX = Y coordinate at which to draw upper left corner of first char
;    CH = foreground (text) color
;    CL = background (box) color
;    DS:SI = pointer to string to draw, zero terminated
;    CharHeight must be set to the height of each character
;    FontPtr must be set to the font with which to draw
;        LineWidthBytes must be set to the scan line width in bytes
; Don't count on any registers other than DS, SS, and SP being preserved.
; The X coordinate is truncated to a multiple of 8. Characters are
; assumed to be 8 pixels wide.
     align 2
DrawTextString  proc    near
     cld
     shr   ax,1                      ;byte address of starting X within scan line
     shr   ax,1
     shr   ax,1
     mov   di,ax
     mov   ax,[LineWidthBytes]
     mul   bx                        ;start offset of initial scan line
     add   di,ax                     ;start offset of initial byte
     mov   ax,SCREEN_SEGMENT
     mov   es,ax                     ;ES:DI = offset of initial character's
                                     ; first scan line
                                     ;set up the VGA's hardware so that we can
                                     ; fill the latches with the background color
     mov   dx,GC_INDEX
     mov   ax,(0ffh SHL 8) + BIT_MASK
     out   dx,ax                    ;set Bit Mask register to 0xFF (that's the
                                    ; default, but I'm doing this just to make sure
                                     ; you understand that Bit Mask register and
                                     ; CPU data are ANDed in write mode 3)
     mov   ax,(003h SHL 8) + G_MODE
     out   dx,ax                     ;select write mode 3
     mov   ah,cl                     ;background color
     mov   al,SET_RESET
     out   dx,ax                     ;set the drawing color to background color
     mov   byte ptr es:[0ffffh],0ffh         ;write 8 pixels of the background
                                     ; color to unused offscreen memory
```

```
        mov   cl,es:[0ffffh]             ;read the background color back into the
                                         ; latches; the latches are now filled with
                                         ; the background color. The value in CL
                                         ; doesn't matter, we just needed a target
                                         ; for the read, so we could load the latches
        mov   ah,ch                      ;foreground color
        out   dx,ax                      ;set the Set/Reset (drawing) color to the
                                         ; foreground color
                                         ;we're ready to draw!
    DrawTextLoop:
        lodsb                            ;next character to draw
        and   al,al                      ;end of string?
        jz    DrawTextDone                        ;yes
        push ds                          ;remember string's segment
        push si                          ;remember offset of next character in string
        push di                          ;remember drawing offset
                                         ;load these variables before we wipe out DS
        mov   dx,[LineWidthBytes]        ;offset from one line to next
        dec   dx                         ;compensate for STOSB
        mov   cx,[CharHeight]            ;
        mul   cl                         ;offset of character in font table
        lds   si,[FontPtr]               ;point to font table
        add   si,ax                      ;point to start of character to draw
                                         ;the following loop should be unrolled for
                                         ; maximum performance!
    DrawCharLoop:                        ;draw all lines of the character
        movsb                            ;get the next byte of the character and draw
                                         ; character; data is ANDed with Bit Mask
                                         ; register to become bit mask, and selects
                                         ; between latch (containing the background
                                         ; color) and Set/Reset register (containing
                                         ; foreground color)
        add di,dx                        ;point to next line of destination
        loop DrawCharLoop

        pop   di                         ;retrieve initial drawing offset
        inc   di                         ;drawing offset for next char
        pop   si                         ;retrieve offset of next character in string
        pop   ds                         ;retrieve string's segment
        jmp   DrawTextLoop               ;draw next character, if any

        align 2
    DrawTextDone:                        ;restore the Graphics Mode register to its
                                         ; default state of write mode 0
        mov   dx,GC_INDEX
        mov   ax,(000h SHL 8) + G_MODE
        out   dx,ax                      ;select write mode 0
        ret
    DrawTextString   endp
        end   start
```

Pooh and the Space Station

Chapter 41

Using Fast Texture Mapping to Place Pooh on a Polygon

So, here's where Winnie the Pooh lives: in a space station orbiting Saturn. No, really; I have it straight from my daughter, and an eight-year-old wouldn't make up something that important, would she? One day she wondered aloud, "Where is the Hundred Acre Wood, exactly?" and before I could give one of those boring parental responses about how it was imaginary—but A.A. Milne probably imagined it to be somewhere near London—my daughter announced that the Hundred Acre Wood was in a space station orbiting Saturn, and there you have it.

As it turns out, that's a very good location for the Hundred Acre Wood, leading to many exciting adventures for Pooh and Piglet. Consider the time they went down to the Jupiter gravity level (we're talking centrifugal force here; the station is spinning, of course) and nearly turned into pancakes of the Pooh and Piglet varieties, respectively. Or the time they drifted out into the free-fall area at the core and had to be rescued by humans with wings strapped on (a tip of the hat to Robert Heinlein here). Or the time they were caught up by the current in the river through the Wood and drifted for weeks around the circumference of the station, meeting many cultures and finding many adventures along the way. (Yes, Farmer's Riverworld; no one said the stories you tell your children need to be purely original, just interesting.)

(If you think Pooh and Piglet in a space station is a tad peculiar, then I won't even mention Karla, the woman who invented agriculture, medicine, sanitation, reading and writing, peace, and just about everything else while travelling the length of the Americas with her mountain lion during the last Ice Age; or the Mars Cats and their trip in suspended animation to the Lesser Magellenic Cloud and beyond; or most assuredly Little Whale, the baby Universe Whale that is naughty enough to eat inhabited universes. But I digress.)

Anyway, I bring up Pooh and the space station because the time has come to discuss fast texture mapping. *Texture mapping* is the process of mapping an image (in our case, a bitmap) onto the surface of a polygon that's been transformed in the process of 3-D drawing. Up to this point, each polygon we've drawn in X-Sharp has been a single, solid color. Over the last couple of chapters we added the ability to shade polygons according to lighting, but each polygon was still a single color. Thus, in order to produce any sort of intricate design, a great many tiny polygons would have to be drawn. That would be very slow, so we need another approach. One such approach is texture mapping; that is, mapping the bitmap containing the desired image onto the pixels contained within the transformed polygon. Done properly, this should make it possible to change X-Sharp's output from a bland collection of monocolor facets to a lively, detailed, and much more realistic scene.

"What sort of scene?" you may well ask. This is where Pooh and the space station came in. When I sat down to think of a sample texture-mapping application, it occurred to me that the shaded ball demo we added to X-Sharp recently looked at least a bit like a spinning, spherical space station, and that the single unshaded, yellow polygon looked somewhat like a window in the space station, and it might be a nice example if someone were standing in the window...

The rest is history.

Principles of Quick-and-Dirty Texture Mapping

The key to our texture-mapping approach will be to quickly determine what pixel value to draw for each pixel in the transformed destination polygon. These polygon pixel values will be determined by mapping each destination pixel in the transformed polygon back to the image bitmap, via a reverse transformation, and seeing what color resides at the corresponding location in the image bitmap, as shown in Figure 41.1. It

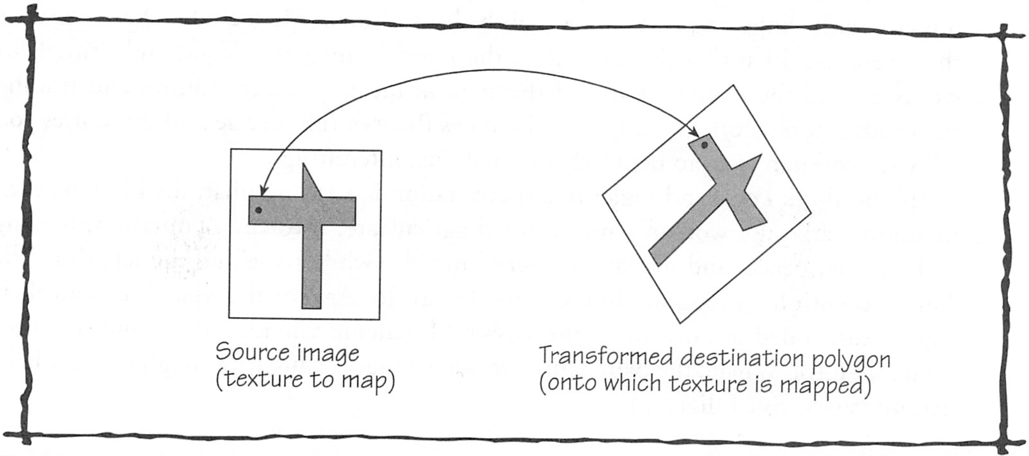

Source image
(texture to map)
Transformed destination polygon
(onto which texture is mapped)

Figure 41.1 Using Reverse Transformation to Find the Source Pixel Color

might seem more intuitive to map pixels the other way, from the image bitmap to the transformed polygon, but in fact it's crucial that the mapping proceed backward from the destination to avoid gaps in the final image. With the approach of finding the right value for each destination pixel in turn, via a backward mapping, there's no way we can miss any destination pixels. On the other hand, with the forward-mapping method, some destination pixels may be skipped or double-drawn, because this is not necessarily a one-to-one or one-to-many mapping. Although we're not going to take advantage of it now, mapping back to the source makes it possible to average several neighboring image pixels together to calculate the value for each destination pixel; that is, to antialias the image. This can greatly improve texture quality, although it is slower.

Mapping Textures Made Easy

To understand how we're going to map textures, consider Figure 41.2, which maps a bitmapped image directly onto an untransformed polygon. Here, we simply map the origin of the polygon's untransformed coordinate system somewhere within the image, then map the vertices to the corresponding image pixels. (For simplicity, I'll assume in this discussion that the polygon's coordinate system is in units of pixels, but scaling images to polygons is eminently doable. This will become clearer when we look at mapping images onto transformed polygons, next.) Mapping the image to the polygon is then a simple matter of stepping one scan line at a time in both the image and the polygon, each time advancing the X coordinates of the edges according to the slopes of the lines, just as is normally done when filling a polygon. Since the polygon is untransformed, the stepping is identical in both the image and the polygon, and the pixel mapping is one-to-one, so the appropriate part of each scan line of the image can simply be block copied to the destination.

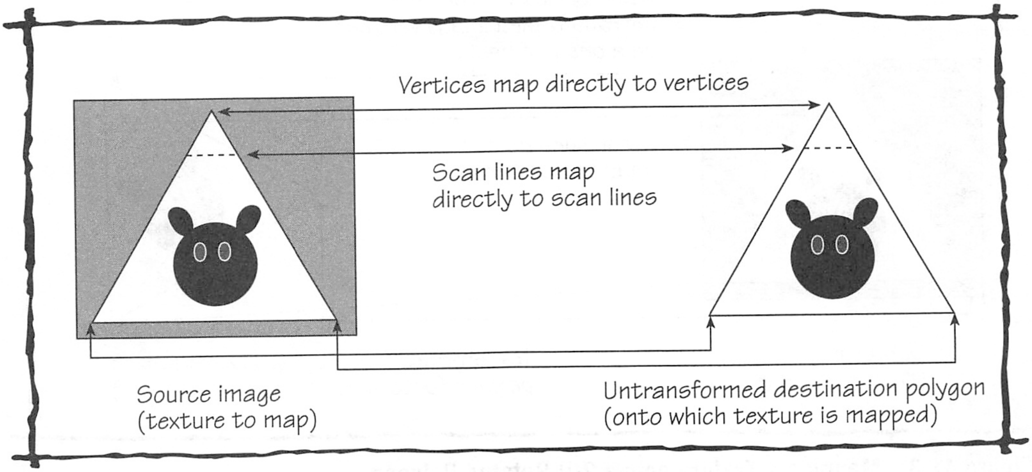

Vertices map directly to vertices
Scan lines map directly to scan lines
Source image (texture to map)
Untransformed destination polygon (onto which texture is mapped)

Figure 41.2 Mapping a Texture onto an Untransformed Polygon

Now, matters get more complicated. What if the destination polygon is rotated in two dimensions? We no longer have a neat direct mapping from image scan lines to destination polygon scan lines. We still want to draw across each destination scan line, but the proper source pixels for each destination scan line may now track across the source bitmap at an angle, as shown in Figure 41.3. What can we do?

The solution is remarkably simple. We'll just map each transformed vertex to the corresponding vertex in the bitmap; this is easy, because the vertices are at the same indices in the original and transformed vertex lists. Each time we select a new edge to scan for the destination polygon, we'll select the corresponding edge in the source bitmap, as well. Then—and this is crucial—each time we step a destination edge one scan line, we'll step the corresponding source image edge an equivalent amount.

Ah, but what is an "equivalent amount?" Think of it this way. If a destination edge is 100 scan lines high, it will be stepped 100 times. Then, we'll divide the **SourceXWidth** and **SourceYHeight** lengths of the source edge by 100, and add those amounts to the source edge's coordinates each time the destination is stepped one scan line. Put another way, we have, as usual, arranged things so that in the destination polygon we step **DestYHeight** times, where **DestYHeight** is the height of the destination edge. The this approach arranges to step the source image edge **DestYHeight** times also, to match what the destination is doing.

Now we're able to track the coordinates of the polygon edges through the source image in tandem with the destination edges. Stepping across each destination scan line uses precisely the same technique, as shown in Figure 41.4. In the destination, we step **DestXWidth** times across each scan line of the polygon, once for each pixel on the scan line. (**DestXWidth** is the horizontal distance between the two edges being scanned on

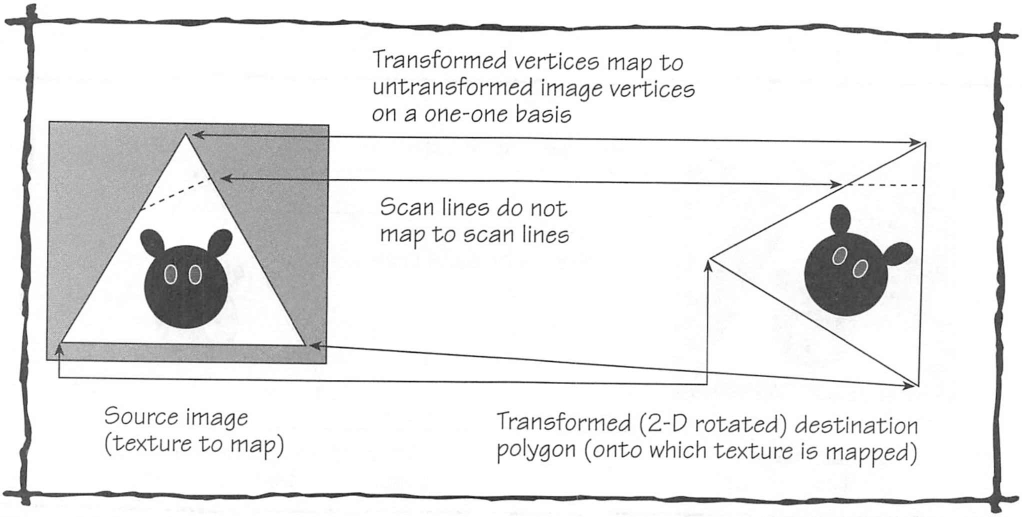

Transformed vertices map to
untransformed image vertices
on a one-one basis
Scan lines do not
map to scan lines
Source image
(texture to map)
Transformed (2-D rotated) destination
polygon (onto which texture is mapped)

Figure 41.3 Mapping a Texture onto a 2-D Rotated Polygon

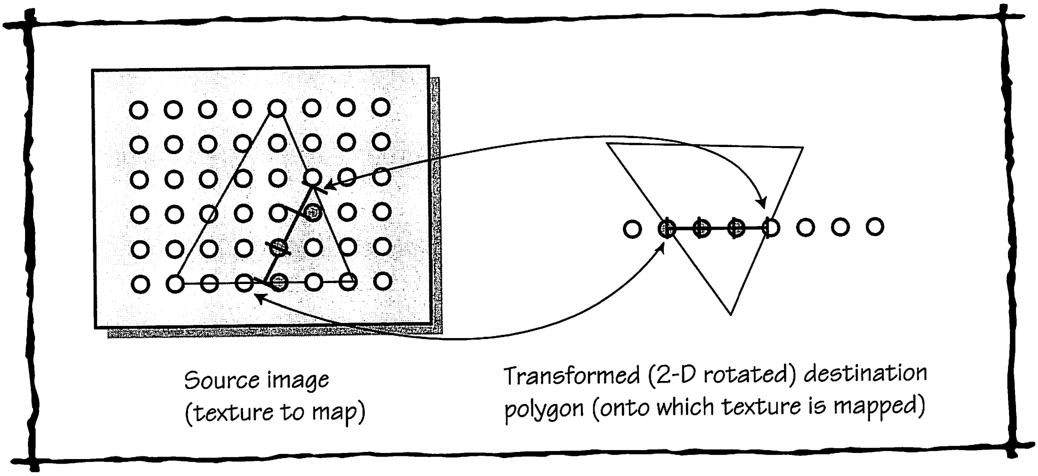

Source image
(texture to map)
Transformed (2-D rotated) destination
polygon (onto which texture is mapped)

Figure 41.4 Mapping a Horizontal Destination Scan Line Back to the Source Image

any given scan line.) To match this, we divide **SourceXWidth** and **SourceYHeight** (the lengths of the scan line in the source image, as determined by the source edge points we've been tracking, as just described) by the width of the destination scan line, **DestXWidth,** to produce **SourceXStep** and **SourceYStep**. Then, we just step **DestXWidth** times, adding **SourceXStep** and **SourceYStep** to **SourceX** and **SourceY** each time, and choose the nearest image pixel to (**SourceX,SourceY**) to copy to (**DestX,DestY**). (Note that the names used above, such as "**SourceXWidth,**" are used for descriptive purposes, and don't necessarily correspond to the actual variable names used in Listing 41.2.)

That's a workable approach for 2-D rotated polygons—but what about 3-D rotated polygons, where the visible dimensions of the polygon can vary with 3-D rotation and perspective projection? First, I'd like to make it clear that texture mapping takes place from the source image to the destination polygon after the destination polygon is projected to the screen. That is, the image will be mapped after the destination polygon is in its final, drawable form. Given that, it should be apparent that the above approach automatically compensates for all changes in the dimensions of a polygon. You see, this approach divides source edges and scan lines into however many steps the destination polygon requires. If the destination polygon is much narrower than the source polygon, as a result of 3-D rotation and perspective projection, we just end up taking bigger steps through the source image and skipping a lot of source image pixels, as shown in Figure 41.5. The upshot is that the above approach handles all transformations and projections effortlessly. It could also be used to scale source images up to fit in larger polygons; all that's needed is a list of where the polygon's vertices map into the source image, and everything else happens automatically. In fact, mapping from any polygonal area of a bitmap to any destination polygon will work, given only that the two polygons have the same number of vertices.

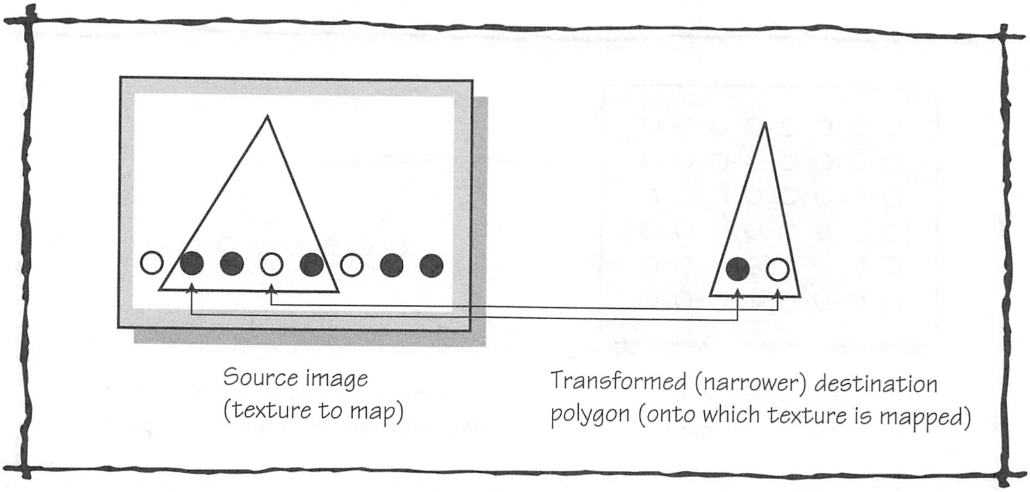

Source image
(texture to map)
Transformed (narrower) destination
polygon (onto which texture is mapped)

Figure 41.5 Mapping a Texture onto a Narrower Polygon

Notes on DDA Texture Mapping

That's all there is to quick-and-dirty texture mapping. This technique basically uses a two-stage digital differential analyzer (DDA) approach to step through the appropriate part of the source image in tandem with the normal scan-line stepping through the destination polygon, so I'll call it "DDA texture mapping." It's worth noting that there is no need for any trigonometric functions at all, and only two divides are required per scan line.

This isn't a perfect approach, of course. For one thing, it isn't anywhere near as fast as drawing solid polygons; the speed is more comparable to drawing each polygon as a series of lines. Also, the DDA approach results in far from perfect image quality, since source pixels may be skipped or selected twice. I trust, however, that you can see how easy it would be to improve image quality by antialiasing with the DDA approach. For example, we could simply average the four surrounding pixels as we did for simple, unweighted antialiasing in Chapters 25 and 26. Or, we could take a Wu antialiasing approach (see Chapter 27) and average the two bracketing pixels along each axis according to proximity. If we had cycles to waste (which, given that this is real-time animation on a PC, we don't), we could improve image quality by putting the source pixels through a low-pass filter sized in X and Y according to the ratio of the source and destination dimensions (that is, how much the destination is scaled up or down from the source).

Even more important is that the sort of texture mapping I'll do in X-Sharp doesn't correct for perspective. That doesn't much matter for small polygons or polygons that are nearly parallel to the screen in 3-space, but it can produce very noticeable bowing of textures on large polygons at an angle to the screen. Perspective texture mapping is a complex subject that's outside the scope of this book, but you should be aware of its existence, because perspective texture mapping is a key element of many games these days.

Finally, I'd like to point out that this sort of DDA texture mapping is display-hardware dependent, because the bitmap for each image must be compatible with the number of bits per pixel in the destination. That's actually a fairly serious issue. One of the nice things about X-Sharp's polygon orientation is that, until now, the only display dependent part of X-Sharp has been the transformation from RGB color space to the adapter's color space. Compensation for aspect ratio, resolution, and the like all happens automatically in the course of projection. Still, we need the ability to display detailed surfaces, and it's hard to conceive of a fast way to do so that's totally hardware independent. (If you know of one, let me know care of the publisher.)

For now, all we need is fast texture mapping of adequate quality, which the straightforward, non-antialiased DDA approach supplies. I'm sure there are many other fast approaches, and, as I've said, there are more accurate approaches, but DDA texture mapping works well, given the constraints of the PC's horsepower. Next, we'll look at code that performs DDA texture mapping. First, though, I'd like to take a moment to thank Jim Kent, author of Autodesk Animator and a frequent correspondent, for getting me started with the DDA approach.

Fast Texture Mapping: An Implementation

As you might expect, I've implemented DDA texture mapping in X-Sharp, and the changes are reflected in the X-Sharp archive in this chapter's subdirectory on the listings diskette. Listing 41.1 shows the new header file entries, and Listing 41.2 shows the actual texture-mapped polygon drawer. The set-pixel routine that Listing 41.2 calls is a slight modification of the Mode X set-pixel routine from Chapter 32. In addition, INITBALL.C has been modified to create three texture-mapped polygons and define the texture bitmaps, and modifications have been made to allow the user to flip the axis of rotation. You will of course need the complete X-Sharp library to see texture mapping in action, but Listings 41.1 and 41.2 are the actual texture mapping code in its entirety.

Here's a major tip: DDA texture mapping looks best on fast-moving surfaces, where the eye doesn't have time to pick nits with the shearing and aliasing that's an inevitable by-product of such a crude approach. Compile DEMO1 from the X-Sharp archive in this chapter's subdirectory of the listings diskette, and run it. The initial display looks okay, but certainly not great, because the rotational speed is so slow. Now press the S key a few times to speed up the rotation and flip between different rotation axes. I think you'll be amazed at how much better DDA texture mapping looks at high speed. This technique would be great for mapping textures onto hurtling asteroids or jets, but would come up short for slow, finely detailed movements.

LISTING 41.1 L41-1.C

```
/* New header file entries related to texture-mapped polygons */

/* Draws the polygon described by the point list PointList with a bitmap
   texture mapped onto it */
#define DRAW_TEXTURED_POLYGON(PointList,NumPoints,TexVerts,TexMap) \
   Polygon.Length = NumPoints; Polygon.PointPtr = PointList;       \
   DrawTexturedPolygon(&Polygon, TexVerts, TexMap);
#define FIXED_TO_INT(FixedVal) ((int) (FixedVal >> 16))
#define ROUND_FIXED_TO_INT(FixedVal) \
   ((int) ((FixedVal + DOUBLE_TO_FIXED(0.5)) >> 16))
/* Retrieves specified pixel from specified image bitmap of specified width. */
#define GET_IMAGE_PIXEL(TexMapBits, TexMapWidth, X, Y) \
   TexMapBits[(Y * TexMapWidth) + X]
/* Masks to mark shading types in Face structure */
#define NO_SHADING      0x0000
#define AMBIENT_SHADING 0x0001
#define DIFFUSE_SHADING 0x0002
#define TEXTURE_MAPPED_SHADING 0x0004
/* Describes a texture map */
typedef struct {
   int TexMapWidth;  /* texture map width in bytes */
   char *TexMapBits; /* pointer to texture bitmap */
} TextureMap;

/* Structure describing one face of an object (one polygon) */
typedef struct {
   int * VertNums;   /* pointer to list of indexes of this polygon's vertices
                        in the object's vertex list. The first two indexes
                        must select end and start points, respectively, of this
                        polygon's unit normal vector. Second point should also
                        be an active polygon vertex */
   int NumVerts;     /* # of verts in face, not including the initial
                        vertex, which must be the end of a unit normal vector
                        that starts at the second index in VertNums */
   int ColorIndex;   /* direct palette index; used only for non-shaded faces */
   ModelColor FullColor; /* polygon's color */
   int ShadingType;  /* none, ambient, diffuse, texture mapped, etc. */
   TextureMap * TexMap; /* pointer to bitmap for texture mapping, if any */
   Point * TexVerts; /* pointer to list of this polygon's vertices, in
                        TextureMap coordinates. Index n must map to index
                        n + 1 in VertNums, (the + 1 is to skip over the unit
                        normal endpoint in VertNums) */
} Face;
extern void DrawTexturedPolygon(PointListHeader *, Point *, TextureMap *);
```

LISTING 41.2 L41-2.C

```
/* Draws a bitmap, mapped to a convex polygon (draws a texture-mapped polygon.)
   "Convex" means that every horizontal line drawn through the polygon at any
   point would cross exactly two active edges (neither horizontal lines nor
   zero-length edges count as active edges; both are acceptable anywhere in
   the polygon), and that the right & left edges never cross. Nonconvex
   polygons won't be drawn properly. Can't fail. */
#include <stdio.h>
#include <math.h>
#include "polygon.h"
/* Describes the current location and stepping, in both the source and
   the destination, of an edge */
```

```
typedef struct {
   int Direction;           /* through edge list; 1 for a right edge (forward
                               through vertex list), -1 for a left edge (backward
                               through vertex list) */
   int RemainingScans;      /* height left to scan out in dest */
   int CurrentEnd;          /* vertex # of end of current edge */
   Fixedpoint SourceX;      /* current X location in source for this edge */
   Fixedpoint SourceY;      /* current Y location in source for this edge */
   Fixedpoint SourceStepX;  /* X step in source for Y step in dest of 1 */
   Fixedpoint SourceStepY;  /* Y step in source for Y step in dest of 1 */
                            /* variables used for all-integer Bresenham's-type
                               X stepping through the dest, needed for precise
                               pixel placement to avoid gaps */
   int DestX;               /* current X location in dest for this edge */
   int DestXIntStep;        /* whole part of dest X step per scan-line Y step */
   int DestXDirection;      /* -1 or 1 to indicate way X steps (left/right) */
   int DestXErrTerm;        /* current error term for dest X stepping */
   int DestXAdjUp;          /* amount to add to error term per scan line move */
   int DestXAdjDown;        /* amount to subtract from error term when the
                               error term turns over */
} EdgeScan;
int StepEdge(EdgeScan *);
int SetUpEdge(EdgeScan *, int);
void ScanOutLine(EdgeScan *, EdgeScan *);
int GetImagePixel(char *, int, int, int);
/* Statics to save time that would otherwise pass them to subroutines. */
static int MaxVert, NumVerts, DestY;
static Point * VertexPtr;
static Point * TexVertsPtr;
static char * TexMapBits;
static int TexMapWidth;
/* Draws a texture-mapped polygon, given a list of destination polygon
   vertices, a list of corresponding source texture polygon vertices, and a
   pointer to the source texture's descriptor. */
void DrawTexturedPolygon(PointListHeader * Polygon, Point * TexVerts,
   TextureMap * TexMap)
{
   int MinY, MaxY, MinVert, i;
   EdgeScan LeftEdge, RightEdge;
   NumVerts = Polygon->Length;
   VertexPtr = Polygon->PointPtr;
   TexVertsPtr = TexVerts;
   TexMapBits = TexMap->TexMapBits;
   TexMapWidth = TexMap->TexMapWidth;
   /* Nothing to draw if less than 3 vertices */
   if (NumVerts < 3) {
      return;
   }
   /* Scan through the destination polygon vertices and find the top of the
      left and right edges, taking advantage of our knowledge that vertices run
      in a clockwise direction (else this polygon wouldn't be visible due to
      backface removal) */
   MinY = 32767;
   MaxY = -32768;
   for (i=0; i<NumVerts; i++) {
      if (VertexPtr[i].Y < MinY) {
         MinY = VertexPtr[i].Y;
         MinVert = i;
      }
      if (VertexPtr[i].Y > MaxY) {
         MaxY = VertexPtr[i].Y;
         MaxVert = i;
      }
   }
   /* Reject flat (0-pixel-high) polygons */
   if (MinY >= MaxY) {
      return;
   }
   /* The destination Y coordinate is not edge specific; it applies to
      both edges, since we always step Y by 1 */
   DestY = MinY;
   /* Set up to scan the initial left and right edges of the source and
      destination polygons. We always step the destination polygon edges
      by one in Y, so calculate the corresponding destination X step for
      each edge, and then the corresponding source image X and Y steps */
   LeftEdge.Direction = -1;   /* set up left edge first */
   SetUpEdge(&LeftEdge, MinVert);
   RightEdge.Direction = 1;   /* set up right edge */
   SetUpEdge(&RightEdge, MinVert);
   /* Step down destination edges one scan line at a time. At each scan
      line, find the corresponding edge points in the source image. Scan
      between the edge points in the source, drawing the corresponding
      pixels across the current scan line in the destination polygon. (We
      know which way the left and right edges run through the vertex list
      because visible (non-backface-culled) polygons always have the vertices
      in clockwise order as seen from the viewpoint) */
   for (;;) {
      /* Done if off bottom of clip rectangle */
      if (DestY >= ClipMaxY) {
         return;
      }
      /* Draw only if inside Y bounds of clip rectangle */
      if (DestY >= ClipMinY) {
         /* Draw the scan line between the two current edges */
         ScanOutLine(&LeftEdge, &RightEdge);
      }
      /* Advance the source and destination polygon edges, ending if we've
         scanned all the way to the bottom of the polygon */
      if (!StepEdge(&LeftEdge)) {
         break;
      }
      if (!StepEdge(&RightEdge)) {
         break;
      }
      DestY++;
   }
}
/* Steps an edge one scan line in the destination, and the corresponding
   distance in the source. If an edge runs out, starts a new edge if there
   is one. Returns 1 for success, or 0 if there are no more edges to scan. */
int StepEdge(EdgeScan * Edge)
{
   /* Count off the scan line we stepped last time; if this edge is
      finished, try to start another one */
   if (--Edge->RemainingScans == 0) {
      /* Set up the next edge; done if there is no next edge */
      if (SetUpEdge(Edge, Edge->CurrentEnd) == 0) {
         return(0);  /* no more edges; done drawing polygon */
      }
      return(1);     /* all set to draw the new edge */
   }
   /* Step the current source edge */
   Edge->SourceX += Edge->SourceStepX;
   Edge->SourceY += Edge->SourceStepY;
   /* Step dest X with Bresenham-style variables, to get precise dest pixel
      placement and avoid gaps */
   Edge->DestX += Edge->DestXIntStep;  /* whole pixel step */
   /* Do error term stuff for fractional pixel X step handling */
   if ((Edge->DestXErrTerm += Edge->DestXAdjUp) > 0) {
      Edge->DestX += Edge->DestXDirection;
      Edge->DestXErrTerm -= Edge->DestXAdjDown;
   }
   return(1);
}
/* Sets up an edge to be scanned; the edge starts at StartVert and proceeds
   in direction Edge->Direction through the vertex list. Edge->Direction must
   be set prior to call; -1 to scan a left edge (backward through the vertex
   list), 1 to scan a right edge (forward through the vertex list).
   Automatically skips over 0-height edges. Returns 1 for success, or 0 if
   there are no more edges to scan. */
int SetUpEdge(EdgeScan * Edge, int StartVert)
{
   int NextVert, DestXWidth;
   Fixedpoint DestYHeight;
   for (;;) {
      /* Done if this edge starts at the bottom vertex */
      if (StartVert == MaxVert) {
         return(0);
      }
      /* Advance to the next vertex, wrapping if we run off the start or end
         of the vertex list */
      NextVert = StartVert + Edge->Direction;
      if (NextVert >= NumVerts) {
         NextVert = 0;
      } else if (NextVert < 0) {
         NextVert = NumVerts - 1;
      }
      /* Calculate the variables for this edge and done if this is not a
         zero-height edge */
      if ((Edge->RemainingScans =
            VertexPtr[NextVert].Y - VertexPtr[StartVert].Y) != 0) {
         DestYHeight = INT_TO_FIXED(Edge->RemainingScans);
         Edge->CurrentEnd = NextVert;
         Edge->SourceX = INT_TO_FIXED(TexVertsPtr[StartVert].X);
         Edge->SourceY = INT_TO_FIXED(TexVertsPtr[StartVert].Y);
         Edge->SourceStepX = FixedDiv(INT_TO_FIXED(TexVertsPtr[NextVert].X) -
               Edge->SourceX, DestYHeight);
         Edge->SourceStepY = FixedDiv(INT_TO_FIXED(TexVertsPtr[NextVert].Y) -
               Edge->SourceY, DestYHeight);
         /* Set up Bresenham-style variables for dest X stepping */
         Edge->DestX = VertexPtr[StartVert].X;
         if ((DestXWidth =
               (VertexPtr[NextVert].X - VertexPtr[StartVert].X)) < 0) {
            /* Set up for drawing right to left */
            Edge->DestXDirection = -1;
            DestXWidth = -DestXWidth;
            Edge->DestXErrTerm = 1 - Edge->RemainingScans;
            Edge->DestXIntStep = -(DestXWidth / Edge->RemainingScans);
         } else {
            /* Set up for drawing left to right */
            Edge->DestXDirection = 1;
            Edge->DestXErrTerm = 0;
            Edge->DestXIntStep = DestXWidth / Edge->RemainingScans;
         }
         Edge->DestXAdjUp = DestXWidth % Edge->RemainingScans;
         Edge->DestXAdjDown = Edge->RemainingScans;
         return(1);  /* success */
      }
      StartVert = NextVert;   /* keep looking for a non-0-height edge */
   }
}
/* Texture-map-draw the scan line between two edges. */
void ScanOutLine(EdgeScan * LeftEdge, EdgeScan * RightEdge)
{
   Fixedpoint SourceX = LeftEdge->SourceX;
   Fixedpoint SourceY = LeftEdge->SourceY;
   int DestX = LeftEdge->DestX;
   int DestXMax = RightEdge->DestX;
   Fixedpoint DestWidth;
   Fixedpoint SourceXStep, SourceYStep;
   /* Nothing to do if fully X clipped */
   if ((DestXMax <= ClipMinX) || (DestX >= ClipMaxX)) {
      return;
   }
   if ((DestXMax - DestX) <= 0) {
      return;  /* nothing to draw */
   }
   /* Width of destination scan line, for scaling. Note: because this is an
      integer-based scaling, it can have a total error of as much as nearly
      one pixel. For more precise scaling, also maintain a fixed-point DestX
      in each edge, and use it for scaling. If this is done, it will also
      be necessary to nudge the source start coordinates to the right by an
      amount corresponding to the distance from the the real (fixed-point)
      DestX and the first pixel (at an integer X) to be drawn) */
   DestWidth = INT_TO_FIXED(DestXMax - DestX);
   /* Calculate source steps that correspond to each dest X step (across
      the scan line) */
   SourceXStep = FixedDiv(RightEdge->SourceX - SourceX, DestWidth);
   SourceYStep = FixedDiv(RightEdge->SourceY - SourceY, DestWidth);
   /* Clip right edge if necessary */
   if (DestXMax > ClipMaxX) {
      DestXMax = ClipMaxX;
   }
   /* Clip left edge if necssary */
   if (DestX < ClipMinX) {
      SourceX += SourceXStep * (ClipMinX - DestX);
      SourceY += SourceYStep * (ClipMinX - DestX);
      DestX = ClipMinX;
   }
   /* Scan across the destination scan line, updating the source image
      position accordingly */
   for (; DestX<DestXMax; DestX++) {
      /* Get currently mapped pixel out of image and draw it to screen */
      WritePixelX(DestX, DestY,
            GET_IMAGE_PIXEL(TexMapBits, TexMapWidth,
            FIXED_TO_INT(SourceX), FIXED_TO_INT(SourceY)) );
      /* Point to the next source pixel */
      SourceX += SourceXStep;
      SourceY += SourceYStep;
   }
}
```

No matter how you slice it, DDA texture mapping beats boring, single-color polygons nine ways to Sunday. The big downside is that it's much slower than a normal polygon fill; move the ball close to the screen in DEMO1, and watch things slow down when one of those big texture maps comes around. Of course, that's partly because the code is all in C; some well-chosen optimizations would work wonders. In the next chapter we'll discuss texture mapping further, crank up the speed of our texture mapper, and attend to some rough spots that remain in the DDA texture mapping implementation, most notably in the area of exactly which texture pixels map to which destination pixels as a polygon rotates.

And, in case you're curious, yes, there is a bear in DEMO1. I wouldn't say he looks much like a Pooh-type bear, but he's a bear nonetheless. He does tend to look a little startled when you flip the ball around so that he's zipping by on his head, but, heck, you would too in the same situation. And remember, when you buy the next VGA megahit, *Bears in Space*, you saw it here first.

10,000 Freshly-Sheared Sheep on the Screen

Chapter 42

The Critical Role of Experience in Implementing Fast, Smooth Texture Mapping

I recently spent an hour or so learning how to shear a sheep. Among other things, I learned—in great detail—about the importance of selecting the proper comb for your shears, heard about the man who holds the world's record for sheep sheared in a day (more than 600, if memory serves), and discovered, Lord help me, the many and varied ways in which the New Zealand Sheep Shearing Board improves the approved sheep-shearing method every year. The fellow giving the presentation did his best, but let's face it, sheep just aren't very interesting. If you have children, you'll know why I was there; if you don't, there's no use explaining.

The chap doing the shearing did say one thing that stuck with me, although it may not sound particularly profound. (Actually, it sounds pretty silly, but bear with me.) He said, "You don't get really good at sheep shearing for ten years, or 10,000 sheep." I'll buy that. In fact, to extend that morsel of wisdom to the greater, non-ovine-centric universe, it actually takes a good chunk of experience before you get good at anything worthwhile—especially graphics, for a couple of reasons. First, performance matters a lot in graphics, and performance programming is largely a matter of experience. You can't speed up PC graphics simply by looking in a book for a better algorithm; you have to understand the code C compilers generate, assembly language optimization, VGA hardware, and the performance implications of various graphics-programming approaches and algorithms. Second, computer graphics is a matter of illusion, of convincing the eye to see what you want it to see, and that's very much a black art based on experience.

Visual Quality: A Black Hole ... Er, Art

Pleasing the eye with real-time computer animation is something less than a science, at least at the PC level, where there's a limited color palette and no time for antialiasing; in fact, sometimes it can be more than a little frustrating. As you may recall, in the previous chapter I implemented texture mapping in X-Sharp. There was plenty of experience involved there, some of which I didn't mention. My first implementation was disappointing; the texture maps shimmied and sheared badly, like a loosely affiliated flock of pixels, each marching to its own drummer. Then, I added a control key to speed up the rotation; what a difference! The aliasing problems were still there, but with the faster rotation, the pixels moved too quickly for the eye to pick up on the aliasing; the rotating texture maps, and the rotating ball as a whole, crossed the threshold into being accepted by the eye as a viewed object, rather than simply a collection of pixels.

The obvious lesson here is that adequate speed is important to convincing animation. There's another, less obvious side to this lesson, though. I'd been running the texture-mapping demo on a 20 MHz 386 with a slow VGA when I discovered the beneficial effects of greater animation speed. When, some time later, I ran the demo on a 33 MHz 486 with a fast VGA, I found that the faster rotation was too fast! The ball spun so rapidly that the eye couldn't blend successive images together into continuous motion, much like watching a badly flickering movie.

So the second lesson is that either too little or too much speed can destroy the illusion. Unless you're antialiasing, you need to tune the shifting of your images so that they're in the "sweet spot" of apparent motion, in which the eye is willing to ignore the jumping and aliasing, and blend the images together into continuous motion. Only experience can give you a feel for that sweet spot.

Fixed-Point Arithmetic, Redux

In the previous chapter I added texture mapping to X-Sharp, but lacked space to explain some of its finer points. I'll pick up the thread now and cover some of those points here, and discuss the visual and performance enhancements that previous chapter's code needed—and which are now present in the version of X-Sharp in this chapter's subdirectory on the listings diskette.

Back in Chapter 21, I spent a good bit of time explaining exactly which pixels were inside a polygon and which were outside, and how to draw those pixels accordingly. This was important, I said, because only with a precise, consistent way of defining inside and outside would it be possible to draw adjacent polygons without either overlap or gaps between them.

As a corollary, I added that only an all-integer, edge-stepping approach would do for polygon filling. Fixed-point arithmetic, although alluring for speed and ease of use, would be unacceptable because round-off error would result in imprecise pixel placement.

More than a year then passed between the time I wrote that statement and the time I implemented X-Sharp's texture mapper, during which time my long-term memory apparently suffered at least partial failure. When I went to implement texture mapping for the previous chapter, I decided that since transformed destination vertices can fall at fractional pixel locations, the cleanest way to do the texture mapping would be to use fixed-point coordinates for both the source texture and the destination screen polygon. That way, there would be a minimum of distortion as the polygon rotated and moved. Theoretically, that made sense; but there was one small problem: gaps between polygons.

Yes, folks, I had ignored the voice of experience (my own voice, at that) at my own peril. You can be assured I will not forget this particular lesson again: Fixed-point arithmetic is not precise. That's not to say that it's impossible to use fixed-point for drawing polygons; if all adjacent edges share common start and end vertices and common edges are always stepped in the same direction, all polygons should share the same fixed-point imprecision, and edges should fit properly (although polygons may not include exactly the right pixels). What you absolutely cannot do is mix fixed-point and all-integer polygon-filling approaches when drawing, as shown in Figure 42.1.

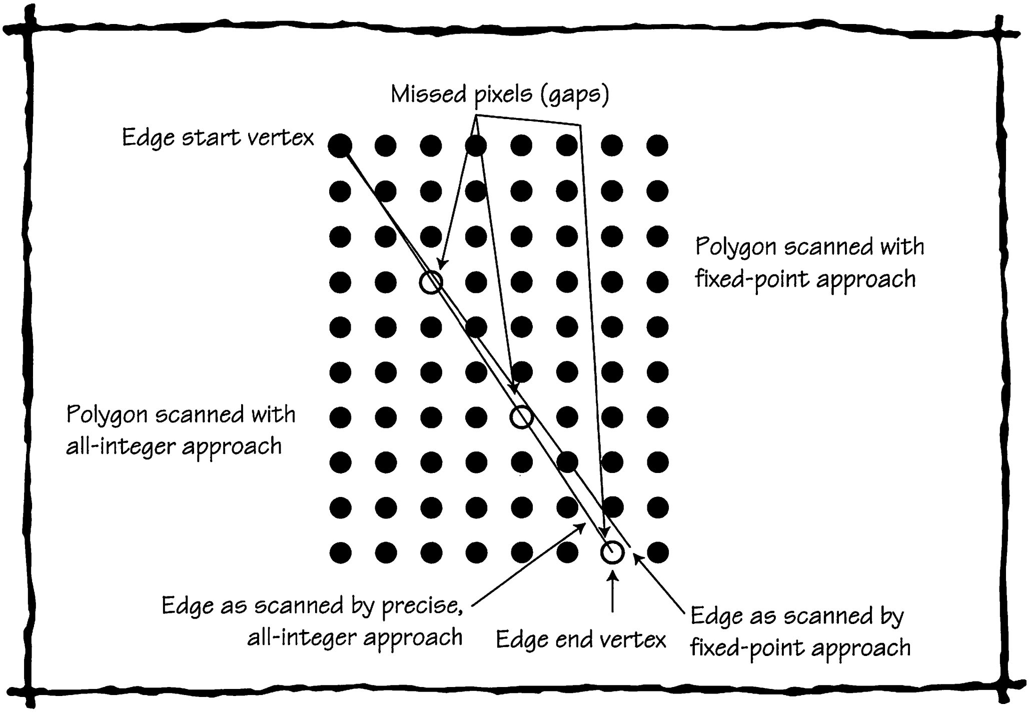

Missed pixels (gaps)
Edge start vertex
Polygon scanned with fixed-point approach
Polygon scanned with all-integer approach
Edge as scanned by precise, all-integer approach
Edge end vertex
Edge as scanned by fixed-point approach

Figure 42.1 Gaps Caused by Mixing Fixed-Point and All-Integer Math

Consequently, I ended up using an all-integer approach in X-Sharp for stepping through the destination polygon. However, I kept the fixed-point approach, which is faster and much simpler, for stepping through the source.

Why was it all right to mix approaches in this case? Precise pixel placement only matters when drawing; otherwise, we can get gaps, which are very visible. When selecting a pixel to copy from the source texture, however, the worst that happens is that we pick the source pixel next to the one we really want, causing the mapped texture to appear to have shifted by one pixel at the corresponding destination pixel; given all the aliasing and shearing already going on in the texture-mapping process, a one-pixel mapping error is insignificant.

Experience again: It's the difference between knowing which flaws (like small texture shifts) can reasonably be ignored, and which (like those that produce gaps between polygons) must be avoided at all costs.

Texture Mapping: Orientation Independence

The double-DDA texture-mapping code presented in the previous chapter worked adequately, but there were two things about it that left me less than satisfied. One flaw was performance; I'll address that shortly. The other flaw was the way textures shifted noticeably as the orientations of the polygons onto which they were mapped changed.

The previous chapter's code followed the standard polygon inside/outside rule for determining which pixels in the source texture map were to be mapped: Pixels that mapped exactly to the left and top destination edges were considered to be inside, and pixels that mapped exactly to the right and bottom destination edges were considered to be outside. That's fine for filling polygons, but when copying texture maps, it causes different edges of the texture map to be omitted, depending on the destination orientation, because different edges of the texture map correspond to the right and bottom destination edges, depending on the current rotation. Also, the previous chapter's code truncated to get integer source coordinates. This, together with the orientation problem, meant that when a texture turned upside down, it slowed one new row and one new column of pixels from the next row and column of the texture map. This asymmetry was quite visible, and not at all the desired effect.

Listing 42.1 is one solution to these problems. This code, which replaces the equivalently named function presented in the previous chapter (and, of course, is present in the X-Sharp archive in this chapter's subdirectory of the listings diskette), makes no attempt to follow the standard polygon inside/outside rules when mapping the source. Instead, it advances a half-step into the texture map before drawing the first pixel, so pixels along all edges are half included. Rounding rather than truncation to texture-map coordinates is also performed. The result is that the texture map stays pretty much centered within the destination polygon as the destination rotates, with a much-reduced level of orientation-dependent asymmetry.

LISTING 42.1 L42-1.C

```
/* Texture-map-draw the scan line between two edges. Uses approach of
   pre-stepping 1/2 pixel into the source image and rounding to the nearest
   source pixel at each step, so that texture maps will appear
   reasonably similar at all angles. */

void ScanOutLine(EdgeScan * LeftEdge, EdgeScan * RightEdge)
{
   Fixedpoint SourceX;
   Fixedpoint SourceY;
   int DestX = LeftEdge->DestX;
   int DestXMax = RightEdge->DestX;
   Fixedpoint DestWidth;
   Fixedpoint SourceStepX, SourceStepY;

   /* Nothing to do if fully X clipped */
   if ((DestXMax <= ClipMinX) || (DestX >= ClipMaxX)) {
      return;
   }

   if ((DestXMax - DestX) <= 0) {
      return;  /* nothing to draw */
   }
   SourceX = LeftEdge->SourceX;
   SourceY = LeftEdge->SourceY;

   /* Width of destination scan line, for scaling. Note: because this is an
      integer-based scaling, it can have a total error of as much as nearly
      one pixel. For more precise scaling, also maintain a fixed-point DestX
      in each edge, and use it for scaling. If this is done, it will also
      be necessary to nudge the source start coordinates to the right by an
      amount corresponding to the distance from the the real (fixed-point)
      DestX and the first pixel (at an integer X) to be drawn). */
   DestWidth = INT_TO_FIXED(DestXMax - DestX);

   /* Calculate source steps that correspond to each dest X step (across
      the scan line) */
   SourceStepX = FixedDiv(RightEdge->SourceX - SourceX, DestWidth);
   SourceStepY = FixedDiv(RightEdge->SourceY - SourceY, DestWidth);

   /* Advance 1/2 step in the stepping direction, to space scanned pixels
      evenly between the left and right edges. (There's a slight inaccuracy
      in dividing negative numbers by 2 by shifting rather than dividing,
      but the inaccuracy is in the least significant bit, and we'll just
      live with it.) */
   SourceX += SourceStepX >> 1;
   SourceY += SourceStepY >> 1;

   /* Clip right edge if necssary */
   if (DestXMax > ClipMaxX)
      DestXMax = ClipMaxX;

   /* Clip left edge if necssary */
   if (DestX < ClipMinX) {
      SourceX += FixedMul(SourceStepX, INT_TO_FIXED(ClipMinX - DestX));
      SourceY += FixedMul(SourceStepY, INT_TO_FIXED(ClipMinX - DestX));
      DestX = ClipMinX;
   }
   /* Scan across the destination scan line, updating the source image
      position accordingly */
   for (; DestX<DestXMax; DestX++) {
      /* Get the currently mapped pixel out of the image and draw it to
         the screen */
      WritePixelX(DestX, DestY,
            GET_IMAGE_PIXEL(TexMapBits, TexMapWidth,
            ROUND_FIXED_TO_INT(SourceX), ROUND_FIXED_TO_INT(SourceY)) );
      /* Point to the next source pixel */
      SourceX += SourceStepX;
      SourceY += SourceStepY;
   }
}
```

Mapping Textures across Multiple Polygons

One of the truly nifty things about double-DDA texture mapping is that it is not limited to mapping a texture onto a single polygon. A single texture can be mapped across any number of adjacent polygons simply by having polygons that share vertices in 3-space also share vertices in the texture map. In fact, the demonstration program DEMO1 in the X-Sharp archive maps a single texture across two polygons; this is the blue-on-green pattern that stretches across two panels of the spinning ball. This capability makes it easy to produce polygon-based objects with complex surfaces (such as banding and insignia on spaceships, or even human figures). Just map the desired texture onto the underlying polygonal framework of an object, and let double-DDA texture mapping do the rest.

Fast Texture Mapping

Of course, there's a problem with mapping a texture across many polygons: Texture mapping is slow. If you run DEMO1 and move the ball up close to the screen, you'll see that the ball slows considerably whenever a texture swings around into view. To some extent that can't be helped, because each pixel of a texture-mapped polygon has to be calculated and drawn independently. Nonetheless, we can certainly improve the performance of texture mapping a good deal over what I presented in the previous chapter.

By and large, there are two keys to improving PC graphics performance. The first —no surprise—is assembly language. The second, without which assembly language is far less effective, is understanding exactly where the cycles go in inner loops. In our case, that means understanding where the bottlenecks are in Listing 42.1.

Listing 42.2 is a high-performance assembly language implementation of Listing 42.1. Apart from the conversion to assembly language, this implementation improves performance by focusing on reducing inner loop bottlenecks. In fact, the whole of Listing 42.2 is nothing more than the inner loop for texture-mapped polygon drawing; Listing 42.2 is only the code to draw a single scan line. Most of the work in drawing a texture-mapped polygon comes in scanning out individual lines, though, so this is the appropriate place to optimize.

LISTING 42.2 L42-2.ASM

```
; Draws all pixels in the specified scan line, with the pixel colors
; taken from the specified texture map.  Uses approach of pre-stepping
; 1/2 pixel into the source image and rounding to the nearest source
; pixel at each step, so that texture maps will appear reasonably similar
; at all angles.  This routine is specific to 320-pixel-wide planar
; (non-Chain4) 256-color modes, such as mode X, which is a planar
; (non-chain4) 256-color mode with a resolution of 320x240.
; C near-callable as:
;   void ScanOutLine(EdgeScan * LeftEdge, EdgeScan * RightEdge);
; Tested with TASM 3.0.

SC_INDEX         equ   03c4h          ;Sequence Controller Index
MAP_MASK         equ   02h            ;index in SC of Map Mask register
SCREEN_SEG       equ   0a000h         ;segment of display memory in mode X
SCREEN_WIDTH     equ   80             ;width of screen in bytes from one scan line
                                      ; to the next

        .model  small
        .data
        extrn   _TexMapBits:word, _TexMapWidth:word, _DestY:word
        extrn   _CurrentPageBase:word, _ClipMinX:word
        extrn   _ClipMinY:word, _ClipMaxX:word, _ClipMaxY:word

; Describes the current location and stepping, in both the source and
; the destination, of an edge. Mirrors structure in DRAWTEXP.C.
EdgeScan struc
Direction        dw    ?    ;through edge list; 1 for a right edge (forward
                            ; through vertex list), -1 for a left edge (backward
                            ; through vertex list)
RemainingScans   dw    ?    ;height left to scan out in dest
CurrentEnd       dw    ?    ;vertex # of end of current edge
SourceX          dd    ?    ;X location in source for this edge
SourceY          dd    ?    ;Y location in source for this edge
SourceStepX      dd    ?    ;X step in source for Y step in dest of 1
SourceStepY      dd    ?    ;Y step in source for Y step in dest of 1
                            ;variables used for all-integer Bresenham's-type
                            ; X stepping through the dest, needed for precise
                            ; pixel placement to avoid gaps
DestX            dw    ?    ;current X location in dest for this edge
DestXIntStep     dw    ?    ;whole part of dest X step per scan-line Y step
DestXDirection   dw    ?    ;-1 or 1 to indicate which way X steps (left/right)
DestXErrTerm     dw    ?    ;current error term for dest X stepping
DestXAdjUp       dw    ?    ;amount to add to error term per scan line move
DestXAdjDown     dw    ?    ;amount to subtract from error term when the
                            ; error term turns over
EdgeScan ends

Parms   struc
                 dw    2 dup(?)   ;return address & pushed BP
LeftEdge         dw    ?          ;pointer to EdgeScan structure for left edge
RightEdge        dw    ?          ;pointer to EdgeScan structure for right edge
Parms   ends

;Offsets from BP in stack frame of local variables.
lSourceX        equ     -4     ;current X coordinate in source image
lSourceY        equ     -8     ;current Y coordinate in source image
lSourceStepX    equ     -12    ;X step in source image for X dest step of 1
lSourceStepY    equ     -16    ;Y step in source image for X dest step of 1
```

```
lXAdvanceByOne  equu    -18     ;used to step source pointer 1 pixel
                                ; incrementally in X
lXBaseAdvance   equ     -20     ;use to step source pointer minimum number of
                                ; pixels incrementally in X
lYAdvanceByOne  equ     -22     ;used to step source pointer 1 pixel
                                ; incrementally in Y
lYBaseAdvance   equ     -24     ;use to step source pointer minimum number of
                                ; pixels incrementally in Y
LOCAL_SIZE      equ     24      ;total size of local variables
        .code
        extrn   _FixedMul:near, _FixedDiv:near
        align   2
ToScanDone:
        jmp     ScanDone
        public  _ScanOutLine
        align   2
_ScanOutLine    proc    near
        push    bp              ;preserve caller's stack frame
        mov     bp,sp           ;point to our stack frame
        sub     sp,LOCAL_SIZE   ;allocate space for local variables
        push    si              ;preserve caller's register variables
        push    di
; Nothing to do if destination is fully X clipped.
        mov     di,[bp].RightEdge
        mov     si,[di].DestX
        cmp     si,[_ClipMinX]
        jle     ToScanDone      ;right edge is to left of clip rect, so done
        mov     bx,[bp].LeftEdge
        mov     dx,[bx].DestX
        cmp     dx,[_ClipMaxX]
        jge     ToScanDone      ;left edge is to right of clip rect, so done
        sub     si,dx           ;destination fill width
        jle     ToScanDone      ;null or negative full width, so done

        mov     ax,word ptr [bx].SourceX        ;initial source X coordinate
        mov     word ptr [bp].lSourceX,ax
        mov     ax,word ptr [bx].SourceX+2
        mov     word ptr [bp].lSourceX+2,ax

        mov     ax,word ptr [bx].SourceY        ;initial source Y coordinate
        mov     word ptr [bp].lSourceY,ax
        mov     ax,word ptr [bx].SourceY+2
        mov     word ptr [bp].lSourceY+2,ax
; Calculate source steps that correspond to each 1-pixel destination X step
; (across the destination scan line).
        push    si                ;push dest X width, in fixedpoint form
        sub     ax,ax
        push    ax                ;push 0 as fractional part of dest X width
        mov     ax,word ptr [di].SourceX
        sub     ax,word ptr [bp].lSourceX    ;low word of source X width
        mov     dx,word ptr [di].SourceX+2
        sbb     dx,word ptr [bp].lSourceX+2  ;high word of source X width
        push    dx                ;push source X width, in fixedpoint form
        push    ax
        call    _FixedDiv         ;scale source X width to dest X width
        add     sp,8              ;clear parameters from stack
        mov     word ptr [bp].lSourceStepX,ax     ;remember source X step for
        mov     word ptr [bp].lSourceStepX+2,dx   ; 1-pixel destination X step
        mov     cx,1              ;assume source X advances non-negative
        and     dx,dx             ;which way does source X advance?
        jns     SourceXNonNeg     ;non-negative
        neg     cx                ;negative
        cmp     ax,0              ;is the whole step exactly an integer?
        jz      SourceXNonNeg     ;yes
        inc     dx                ;no, truncate to integer in the direction of
                                  ; 0, because otherwise we'll end up with a
                                  ; whole step of 1-too-large magnitude
SourceXNonNeg:
        mov     [bp].lXAdvanceByOne,cx       ;amount to add to source pointer to
                                             ; move by one in X
        mov     [bp].lXBaseAdvance,dx        ;minimum amount to add to source
                                             ; pointer to advance in X each time
                                             ; the dest advances one in X
        push    si                           ;push dest Y height, in fixedpoint form
        sub     ax,ax
        push    ax                     ;push 0 as fractional part of dest Y height
        mov     ax,word ptr [di].SourceY
        sub     ax,word ptr [bp].lSourceY    ;low word of source Y height
        mov     dx,word ptr [di].SourceY+2
        sbb     dx,word ptr [bp].lSourceY+2  ;high word of source Y height
        push    dx                     ;push source Y height, in fixedpoint form
        push    ax
        call    _FixedDiv              ;scale source Y height to dest X width
        add     sp,8                   ;clear parameters from stack
        mov     word ptr [bp].lSourceStepY,ax      ;remember source Y step for
        mov     word ptr [bp].lSourceStepY+2,dx    ; 1-pixel destination X step
        mov     cx,[_TexMapWidth]      ;assume source Y advances non-negative
        and     dx,dx                  ;which way does source Y advance?
        jns     SourceYNonNeg          ;non-negative
        neg     cx                     ;negative
        cmp     ax,0                   ;is the whole step exactly an integer?
        jz      SourceYNonNeg          ;yes
        inc     dx                     ;no, truncate to integer in the direction of
                                       ; 0, because otherwise we'll end up with a
                                       ; whole step of 1-too-large magnitude
SourceYNonNeg:
        mov     [bp].lYAdvanceByOne,cx ;amount to add to source pointer to
                                       ; move by one in Y
        mov     ax,[_TexMapWidth]      ;minimum distance skipped in source
        imul    dx                     ; image bitmap when Y steps (ignoring
        mov     [bp].lYBaseAdvance,ax  ; carry from the fractional part)
; Advance 1/2 step in the stepping direction, to space scanned pixels evenly
; between the left and right edges. (There's a slight inaccuracy in dividing
; negative numbers by 2 by shifting rather than dividing, but the inaccuracy
; is in the least significant bit, and we'll just live with it.)
        mov     ax,word ptr [bp].lSourceStepX
        mov     dx,word ptr [bp].lSourceStepX+2
        sar     dx,1
        rcr     ax,1
        add     word ptr [bp].lSourceX,ax
        adc     word ptr [bp].lSourceX+2,dx

        mov     ax,word ptr [bp].lSourceStepY
        mov     dx,word ptr [bp].lSourceStepY+2
        sar     dx,1
        rcr     ax,1
        add     word ptr [bp].lSourceY,ax
        adc     word ptr [bp].lSourceY+2,dx
; Clip right edge if necessary.
        mov     si,[di].DestX
        cmp     si,[_ClipMaxX]
        jl      RightEdgeClipped
        mov     si,[_ClipMaxX]
```

```
RightEdgeClipped:
; Clip left edge if necssary
        mov     bx,[bp].LeftEdge
        mov     di,[bx].DestX
        cmp     di,[_ClipMinX]
        jge     LeftEdgeClipped
; Left clipping is necessary; advance the source accordingly
        neg     di
        add     di,[_ClipMinX]          ;ClipMinX - DestX
                                        ;first, advance the source in X
        push    di                      ;push ClipMinX - DestX, in fixedpoint form
        sub     ax,ax
        push    ax                      ;push 0 as fractional part of ClipMinX-DestX
        push    word ptr [bp].lSourceStepX+2
        push    word ptr [bp].lSourceStepX
        call    _FixedMul               ;total source X stepping in clipped area
        add     sp,8                    ;clear parameters from stack
        add     word ptr [bp].lSourceX,ax    ;step the source X past clipping
        adc     word ptr [bp].lSourceX+2,dx
                                        ;now advance the source in Y
        push    di                      ;push ClipMinX - DestX, in fixedpoint form
        sub     ax,ax
        push    ax                      ;push 0 as fractional part of ClipMinX-DestX
        push    word ptr [bp].lSourceStepY+2
        push    word ptr [bp].lSourceStepY
        call    _FixedMul               ;total source Y stepping in clipped area
        add     sp,8                    ;clear parameters from stack
        add     word ptr [bp].lSourceY,ax    ;step the source Y past clipping
        adc     word ptr [bp].lSourceY+2,dx
        mov     di,[_ClipMinX]          ;start X coordinate in dest after clipping
LeftEdgeClipped:
; Calculate actual clipped destination drawing width.
        sub     si,di
; Scan across the destination scan line, updating the source image position
; accordingly.
; Point to the initial source image pixel, adding 0.5 to both X and Y so that
; we can truncate to integers from now on but effectively get rounding.
        add     word ptr [bp].lSourceY,8000h    ;add 0.5
        mov     ax,word ptr [bp].lSourceY+2
        adc     ax,0
        mul     [_TexMapWidth]          ;initial scan line in source image
        add     word ptr [bp].lSourceX,8000h      ;add 0.5
        mov     bx,word ptr [bp].lSourceX+2       ;offset into source scan line
        adc     bx,ax                   ;initial source offset in source image
        add     bx,[_TexMapBits]        ;DS:BX points to the initial image pixel
; Point to initial destination pixel.
        mov     ax,SCREEN_SEG
        mov     es,ax
        mov     ax,SCREEN_WIDTH
        mul     [_DestY]                ;offset of initial dest scan line
        mov     cx,di                   ;initial destination X
        shr     di,1
        shr     di,1                    ;X/4 = offset of pixel in scan line
        add     di,ax                   ;offset of pixel in page
        add     di,[_CurrentPageBase]   ;offset of pixel in display memory
                                  ;ES:DI now points to the first destination pixel

        and     cl,011b ;CL = pixel's plane
        mov     al,MAP_MASK
        mov     dx,SC_INDEX
        out     dx,al             ;point the SC Index register to the Map Mask
        mov     al,11h          ;one plane bit in each nibble, so we'll get carry
                                ; automatically when going from plane 3 to plane 0
        shl     al,cl           ;set the bit for the first pixel's plane to 1
; If source X step is negative, change over to working with non-negative
; values.
        cmp     word ptr [bp].lXAdvanceByOne,0
        jge     SXStepSet
        neg     word ptr [bp].lSourceStepX
        not     word ptr [bp].lSourceX
SXStepSet:
; If source Y step is negative, change over to working with non-negative
; values.
        cmp     word ptr [bp].lYAdvanceByOne,0
        jge     SYStepSet
        neg     word ptr [bp].lSourceStepY
        not     word ptr [bp].lSourceY
SYStepSet:
; At this point:
;       AL = initial pixel's plane mask
;       BX = pointer to initial image pixel
;       SI = # of pixels to fill
;       DI = pointer to initial destination pixel
        mov     dx,SC_INDEX+1           ;point to SC Data; Index points to Map Mask
TexScanLoop:
; Set the Map Mask for this pixel's plane, then draw the pixel.
        out     dx,al
        mov     ah,[bx]         ;get image pixel
        mov     es:[di],ah      ;set image pixel
; Point to the next source pixel.
        add     bx,[bp].lXBaseAdvance  ;advance the minimum # of pixels in X
        mov     cx,word ptr [bp].lSourceStepX
        add     word ptr [bp].lSourceX,cx    ;step the source X fractional part
        jnc     NoExtraXAdvance              ;didn't turn over; no extra advance
        add     bx,[bp].lXAdvanceByOne       ;did turn over; advance X one extra
NoExtraXAdvance:
        add     bx,[bp].lYBaseAdvance        ;advance the minimum # of pixels in Y
        mov     cx,word ptr [bp].lSourceStepY
        add     word ptr [bp].lSourceY,cx    ;step the source Y fractional part
        jnc     NoExtraYAdvance              ;didn't turn over; no extra advance
        add     bx,[bp].lYAdvanceByOne       ;did turn over; advance Y one extra
NoExtraYAdvance:
; Point to the next destination pixel, by cycling to the next plane, and
; advancing to the next address if the plane wraps from 3 to 0.
        rol     al,1
        adc     di,0
; Continue if there are any more dest pixels to draw.
        dec     si
        jnz     TexScanLoop
ScanDone:
        pop     di                           ;restore caller's register variables
        pop     si
        mov     sp,bp                        ;deallocate local variables
        pop     bp                           ;restore caller's stack frame
        ret
_ScanOutLine    endp
        end
```

Within Listing 42.2, all the important optimization is in the loop that draws across each destination scan line, near the end of the listing. One optimization is elimination of the call to the set-pixel routine used to draw each pixel in Listing 42.1. Function calls are expensive operations, to be avoided when performance matters. Also, although Mode X (the undocumented 320×240 256-color VGA mode X-Sharp runs in) doesn't lend itself well to pixel-oriented operations like line drawing or texture mapping, the inner loop has been set up to minimize Mode X's overhead. A rotating plane mask is maintained in AL, with DX pointing to the Map Mask register; thus, only a rotate and an **OUT** are required to select the plane to which to write, cycling from plane 0 through plane 3 and wrapping back to 0. Better yet, because we know that we're simply stepping horizontally across the destination scan line, we can use a clever optimization to both step the destination and reduce the overhead of maintaining the mask. Two copies of the current plane mask are maintained, one in each nibble of AL. (The Map Mask register pays attention only to the lower nibble.) Then, when one copy rotates out of the lower nibble, the other copy rotates into the lower nibble and is ready to be used. This approach eliminates the need to test for the mask wrapping from plane 3 to plane 0, all the more so because a carry is generated when wrapping occurs, and that carry can be added to DI to advance the screen pointer. (Check out the next chapter, however, to see the best Map Mask optimization of all—setting it once and leaving it unchanged.)

In all, the overhead of drawing each pixel is reduced from a call to the set-pixel routine and full calculation of the screen address and plane mask to five instructions and no branches. This is an excellent example of converting full, from-scratch calculations to incremental processing, whereby only information that has changed since the last operation (the plane mask moving one pixel, for example) is recalculated.

Incremental processing and knowing where the cycles go are both important in the final optimization in Listing 42.2, speeding up the retrieval of pixels from the texture map. This operation looks very efficient in Listing 42.1, consisting of only two adds and the macro **GET_ IMAGE_PIXEL**. However, those adds are fixed-point adds, so they take four instructions apiece, and the macro hides not only conversion from fixed-point to integer, but also a time-consuming multiplication. Incremental approaches are excellent at avoiding multiplication, because cumulative additions can often replace multiplication. That's the case with stepping through the source texture in Listing 42.2; ten instructions, with a maximum of two branches, replace all the texture calculations of Listing 42.1. Listing 42.2 simply detects when the fractional part of the source x or y coordinate turns over and advances the source texture pointer accordingly.

As you might expect, all this optimization is pretty hard to implement, and makes Listing 42.2 much more complicated than Listing 42.1. Is it worth the trouble? Indeed it is. Listing 42.2 is more than twice as fast as Listing 42.1, and the difference is very noticeable when large, texture-mapped areas are animated. Whether more than doubling performance is significant is a matter of opinion, I suppose, but imagine that you're in William Gibson's *Neuromancer*, trying to crack a corporate database. Which texture-mapping routine would you rather have interfacing you to Cyberspace?

I'm always interested in getting your feedback on and hearing about potential improvements to X-Sharp. Contact me through the publisher, or else as mabrash@bix.com. There is no truth to the rumor that I can be reached under the alias "sheep-shearer," at least not for another 9,999 sheep.

Heinlein's Crystal Ball, Spock's Brain, and the 9-Cycle Dare

Chapter 43

Using the Whole-Brain Approach to Accelerate Texture Mapping

I've had the pleasure recently of rereading several of the works of Robert A. Heinlein, and I'm as impressed as I was as a teenager—but in a different way. The first time around, I was wowed by the sheer romance of technology married to powerful stories; this time, I'm struck most of all by The Master's remarkable prescience. "Blowups Happen" is about the risks of nuclear power, and their effects on human psychology—written before a chain reaction had ever happened on this planet. "Solution Unsatisfactory" is about the unsolvable dilemma—ultimate offense, no defense—posed by atomic weapons; this in 1941. And in *Between Planets* (1951), consider this minor bit of action:

> The doctor's phone regretted politely that Dr. Jefferson was not at home and requested him to leave a message. He was dictating it when a warm voice interrupted: 'I'm at home to you, Donald. Where are you, lad?'

Predicting the widespread use of answering machines is perhaps not so remarkable, but foreseeing that they would be used for call screening *is*; technology is much easier to extrapolate than are social patterns.

Even so, Heinlein was no prophet; his crystal ball was just a little less fuzzy than ours. The aforementioned call in *Between Planets* was placed on a viewphone; while that technology has indeed come to pass, its widespread use has not. The ultimate weapon in "Solution Unsatisfactory" was radioactive dust, not nuclear bombs, and we have somehow survived nearly 50 years of nuclear weapons without either acquiring a world dictator or destroying ourselves. Slide rules are all over the place in Heinlein's works, and in one story (the name now lost to memory), an astronaut straps himself into a massive integral calculator; computers are nowhere to be found.

Most telling, I think, is that in "Blowups Happen," the engineers running the nuclear power plant—at considerable risk to both body and sanity—are the best of the best, highly skilled in math and required to ride the nuclear reaction on a second-to-second basis, with the risk of an explosion that might end life on Earth, and would surely kill them, if they slip. Contrast that with our present-day reality of nuclear plants run by generally competent technicians, with the occasional report of shoddy maintenance and bored power-plant employees using drugs, playing games, and falling asleep while on duty. Heinlein's universe makes for a better story, of course, but, more than that, it shows the filters and biases through which he viewed the world. At least in print, Heinlein was an unwavering believer in science, technology, and rationality, and in his stories it is usually the engineers and scientists who are the heroes and push civilization forward, often kicking and screaming. In the real world, I have rarely observed that to be the case.

But of course Heinlein was hardly the only person to have his or her perceptions of the universe, past, present, or future, blurred by his built-in assumptions; you and I, as programmers, are also on that list—and probably pretty near the top, at that. Performance programming is basically a process of going from the general to the specific, special-casing the code so that it does just what it has to, and no more. The greatest impediment to this process is seeing the problem in terms of what the code currently does, or what you already know, thereby ignoring many possible solutions. Put another way, how you look at an optimization problem determines how you'll solve it; your assumptions may speed and simplify the process, but they are also your limitations. Consider, for example, how a seemingly intractable problem becomes eminently tractable the instant you learn that someone else has solved it.

As Exhibit #1, I present my experience with speeding up the texture mapper in X-Sharp.

Texture Mapping Redux

We've spent the previous several chapters exploring the X Sharp graphics library, something I built over time as a serious exercise in 3-D graphics. When X-Sharp reached the point at which we left it at the end of the previous chapter, I was rather pleased with it—with one exception.

My last addition to X-Sharp was a *texture mapper*, a routine that warped and rotated any desired bitmap to map onto an arbitrary convex polygon. Texture mappers are critical to good 3-D games; just a few texture-mapped polygons, backed with well-drawn bitmaps, can represent more detail and look more realistic than dozens or even hundreds of solid-color polygons. My X-Sharp texture mapper was in reasonable assembly—pretty good code, by most standards!—and I felt comfortable with my implementation; but then I got a letter from John Miles, who was at the time getting seriously into 3-D and is now the author of a 3-D game library. (Yes, you can license it from his company, Non-Linear Arts, if you'd like; John can be reached at 70322.2457@compuserve.com.) John wrote me as follows: "Hmm, so *that's* how texture-mapping works. But 3 jumps *per pixel*? Hmph!"

It was the "Hmph" that really got to me.

Left-Brain Optimization

That was the first shot of juice for my optimizer (or at least blow to my ego, which can be just as productive). John went on to say he had gotten texture mapping down to 9 cycles per pixel and one jump per *scanline* on a 486 (all cycle times will be for the 486 unless otherwise noted); given that my code took, on average, about 44 cycles and 2 taken jumps (plus 1 not taken) per pixel, I had a long way to go.

The inner loop of my original texture-mapping code is shown in Listing 43.1. All this code does is draw a single texture-mapped scanline, as shown in Figure 43.1; an outer loop runs through all the scanlines in whatever polygon is being drawn. I immediately saw that I could eliminate nearly 10% of the cycles by unrolling the loop; obviously, John had done that, else there's no way he could branch only once per scanline. (By the way, branching only once per scanline via a fully unrolled loop is not generally recommended. A branch every few pixels costs relatively little, and the cache effects of fully unrolled code are *not* good.) I quickly came up with several other ways to speed up the code, but soon realized that all the clever coding in the world wasn't

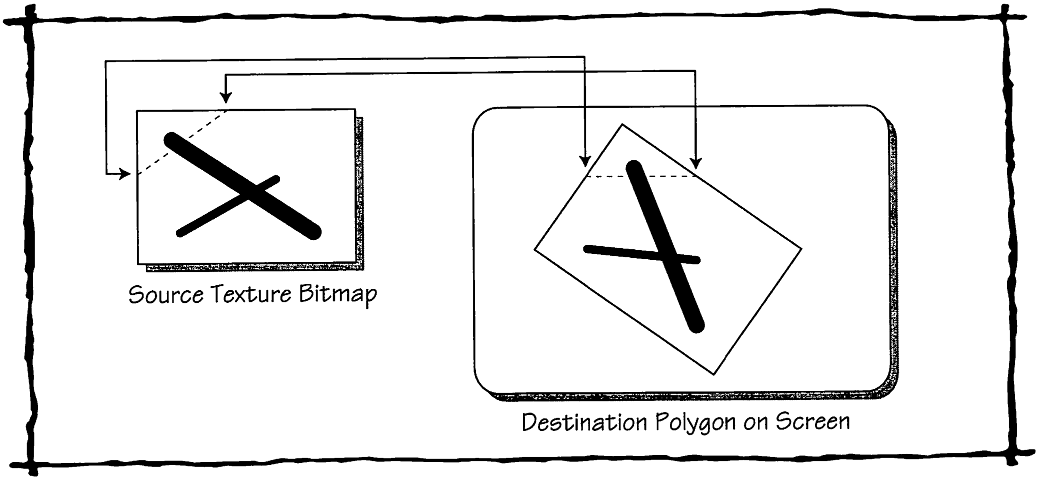


Figure 43.1 Texture Mapping a Single Horizontal Scanline

going to get me within 100% of John's performance so long as I had to cycle from one plane to the next for every pixel.

LISTING 43.1 L43-1.ASM

```
; Inner loop to draw a single texture-mapped horizontal scanline in
; Mode X, the VGA's page-flipped 256-color mode. Because adjacent
; pixels lie in different planes in Mode X, an OUT must be performed
; to select the proper plane before drawing each pixel.
;
; At this point:
;       AL = initial pixel's plane mask
;       DS:BX = initial source texture pointer
;       DX = pointer to VGA's Sequencer Data register
;       SI = # of pixels to fill
;       ES:DI = pointer to initial destination pixel

TexScanLoop:

; Set the Map Mask for this pixel's plane, then draw the pixel.

        out     dx,al
        mov     ah,[bx]         ;get texture pixel
        mov     es:[di],ah      ;set screen pixel

; Point to the next source pixel.

        add     bx,[bp].lXBaseAdvance       ;advance the minimum # of pixels in X
        mov     cx,word ptr [bp].lSourceStepX
        add     word ptr [bp].lSourceX,cx   ;step the source X fractional part
        jnc     NoExtraXAdvance             ;didn't turn over; no extra advance
        add     bx,[bp].lXAdvanceByOne      ;did turn over; advance X one extra
NoExtraXAdvance:

        add     bx,[bp].lYBaseAdvance       ;advance the minimum # of pixels in Y
        mov     cx,word ptr [bp].lSourceStepY
        add     word ptr [bp].lSourceY,cx   ;step the source Y fractional part
        jnc     NoExtraYAdvance             ;didn't turn over; no extra advance
        add     bx,[bp].lYAdvanceByOne      ;did turn over; advance Y one extra
NoExtraYAdvance:

; Point to the next destination pixel, by cycling to the next plane, and
; advancing to the next address if the plane wraps from 3 to 0.

        rol     al,1
        adc     di,0

; Continue if there are any more dest pixels to draw.

        dec     si
        jnz     TexScanLoop
```

Figure 43.2 shows why this cycling is necessary. In Mode X, the page-flipped 256-color mode of the VGA, each successive pixel across a scanline is stored in a different hardware plane, and an OUT to the VGA's hardware is needed to select the plane being drawn to. (See the three chapters of Part VIII for details.) An OUT instruction

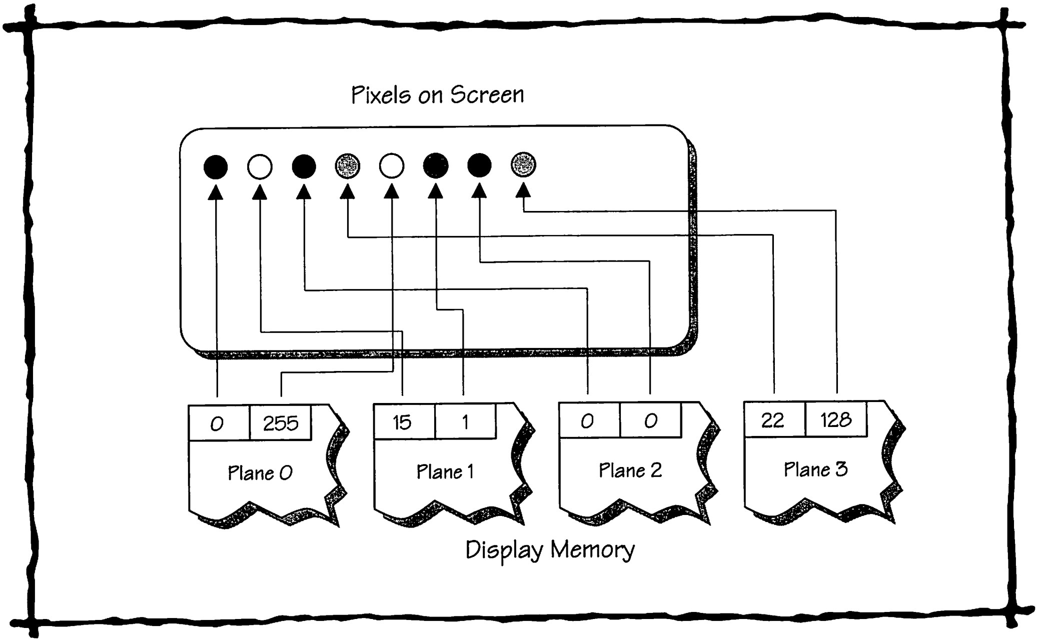


Figure 43.2 Display Memory Organization in Mode X

by itself takes 16 cycles (and in the neighborhood of 30 cycles in virtual-86 or non-privileged protected mode), and an **ROL** takes 2 more, for a total of 18 cycles, double John's 9 cycles, just to handle plane management. Clearly, getting plane control out of the inner loop was absolutely necessary.

I must confess, with some embarrassment, that at this point I threw myself into designing a solution that involved executing the texture mapping code up to four times per scanline, once for the pixels in each plane. It's hard to overstate the complexity of this approach, which involves quadrupling the normal pixel-to-pixel increments, adjusting the start value for each of the passes, and dealing with some nasty boundary cases. Make no mistake, the code was perfectly doable, and would in fact have gotten plane control out of the inner loop, but would have been very difficult to get exactly right, and would have suffered from substantial overhead.

Fortunately, in the last sentence I was able to say "would have," not "was," because my friend Chris Hecker (checker@bix.com) came along to toss a figurative bucket of cold water on my right brain, which was evidently asleep. (Or possibly stolen by scantily-clad, attractive aliens; remember "Spock's Brain"?) Chris is the author of the WinG Windows game graphics package, available from Microsoft via FTP, CompuServe, or MSDN Level 2; if, like me, you were at the Game Developers Conference in April 1994, you, along with everyone else, were stunned to see Id's megahit DOOM running at full speed in a window, thanks to WinG. If you write games for a living, run, don't walk, to check WinG out!

Chris listened to my proposed design for all of maybe thirty seconds, growing visibly more horrified by the moment, before he said, "But why don't you just draw vertical rather than horizontal scanlines?"

Why indeed?

A 90-Degree Shift in Perspective

As I said above, how you look at an optimization problem defines how you'll be able to solve it. In order to boost performance, sometimes it's necessary to look at things from a different angle—and for texture mapping this was literally as well as figuratively true. Chris suggested nothing more nor less than scanning out polygons at a 90-degree angle to normal, starting, say, at the left edge of the polygon, and texture-mapping vertically along each column of pixels, as shown in Figure 43.3. That way, all the pixels in each texture-mapped column would be in the same plane, and I would need to change planes only between columns—outside the inner loop. A trivial change, not fundamental in any sense—and yet just that one change, plus unrolling the loop, reduced the inner loop to the 22-cycles-per-pixel version shown in Listing 43.2. That's exactly twice as fast as Listing 43.1—and given how incredibly slow most VGAs are at completing OUTs, the real-world speedup should be considerably greater still. (The fastest byte OUT I've ever measured for a VGA is 29 cycles, the slowest more than 60 cycles; in the latter case, Listing 43.2 would be on the order of *four* times faster than Listing 43.1.)

LISTING 43.2 L43-2.ASM

```
; Inner loop to draw a single texture-mapped vertical column, rather
; than a horizontal scanline. This allows all pixels handled
; by this code to reside in the same plane, so the time-consuming
; plane switching can be moved out of the inner loop.
;
```

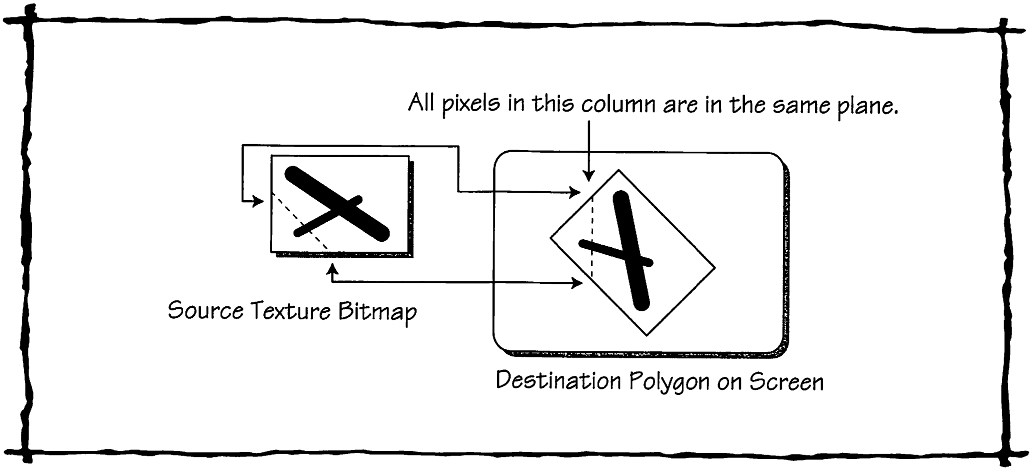

All pixels in this column are in the same plane.
Source Texture Bitmap
Destination Polygon on Screen

Figure 43.3 Texture Mapping a Single Vertical Column

```
; At this point:
;       DS:BX = initial source texture pointer
;       DX = offset to advance to the next pixel in the dest column
;           (either positive or negative scanline width)
;       SI = # of pixels to fill
;       ES:DI = pointer to initial destination pixel
;       VGA set up to draw to the correct plane for this column

     REPT  LOOP_UNROLL

; Set the Map Mask for this pixel's plane, then draw the pixel.

        mov     ah,[bx]                     ;get texture pixel
        mov     es:[di],ah                  ;set screen pixel

; Point to the next source pixel.

        add     bx,[bp].lXBaseAdvance       ;advance the minimum # of pixels in X
        mov     cx,word ptr [bp].lSourceStepX
        add     word ptr [bp].lSourceX,cx   ;step the source X fractional part
        jnc     NoExtraXAdvance             ;didn't turn over; no extra advance
        add     bx,[bp].lXAdvanceByOne      ;did turn over; advance X one extra
NoExtraXAdvance:

        add     bx,[bp].lYBaseAdvance       ;advance the minimum # of pixels in Y
        mov     cx,word ptr [bp].lSourceStepY
        add     word ptr [bp].lSourceY,cx   ;step the source Y fractional part
        jnc     NoExtraYAdvance             ;didn't turn over; no extra advance
        add     bx,[bp].lYAdvanceByOne      ;did turn over; advance Y one extra
NoExtraYAdvance:

; Point to the next destination pixel, which is on the next scan line.

        adc     di,dx

     ENDM
```

I'd like to emphasize that algorithmically and conceptually, there is *no* difference between scanning out a polygon top to bottom and scanning it out left to right; it is only in conjunction with the hardware organization of Mode X that the scanning direction matters in the least.

That's what Zen programming is all about, though; tying together two pieces of seemingly unrelated information to good effect—and that's what I had failed to do. Like Robert Heinlein—like all of us—I had viewed the world through a filter composed of my ingrained assumptions, and one of those assumptions, based on all my past experience, was that pixel processing proceeds left to right. Eventually, I might have come up with Chris's approach; but I would only have come up with it when and if I relaxed and stepped back a little, and allowed myself—almost dared myself—to think of it. When you're optimizing, be sure to leave quiet, nondirected time in which to conjure up those less obvious solutions, and periodically try to figure out what assumptions you're making—and then question them!

There are a few complications with Chris's approach, not least that X-Sharp's polygon-filling convention (top and left edges included, bottom and right edges excluded) is hard to reproduce for column-oriented texture mapping. I solved this in X-Sharp version 22 by tweaking the edge-scanning code to allow column-oriented texture mapping to match the current convention. (You'll find X-Sharp 22 on the listings diskette in the directory for this chapter.)

Chris also illustrated another important principle of optimization: A second pair of eyes is invaluable. Even the best of us have blind spots and get caught up in particular implementations; if you bounce your ideas off someone, you may well find them coming back with an unexpected—and welcome—spin.

That's Nice—But it Sure as Heck Ain't 9 Cycles

Excellent as Chris's suggestion was, I still had work to do: Listing 43.2 is still more than twice as slow as John Miles's code. Traditionally, I start the optimization process with algorithmic optimization, then try to tie the algorithm and the hardware together for maximum efficiency, and finish up with instruction-by-instruction, take-no-prisoners optimization. We've already done the first two steps, so it's time to get down to the bare metal.

Listing 43.2 contains three functional parts: Drawing the pixel, advancing the destination pointer, and advancing the source texture pointer. Each of the three parts is amenable to further acceleration.

Drawing the pixel is difficult to speed up, given that it consists of only two instructions—difficult, but not impossible. True, the instructions themselves are indeed irreducible, but if we can get rid of the ES: prefix (and, as we shall see, we can), we can rearrange the code to make it run faster on the Pentium. Without a prefix, the instructions execute as follows on the Pentium:

```
MOV  AH,[BX]    ;cycle 1 U-pipe
                ;cycle 1 V-pipe idle; reg contention
MOV  [DI],AH    ;cycle 2 U-pipe
```

The second **MOV**, being dependent on the value loaded into AH by the first **MOV**, can't execute until the first **MOV** is finished, so the Pentium's second pipe, the V-pipe, lies idle for a cycle. We can reclaim that cycle simply by shuffling another instruction between the two MOVs.

Advancing the destination pointer is easy to speed up: Just build the offset from one scanline to the next into each pixel-drawing instruction as a constant, as in

```
MOV [EDI+SCANOFFSET],AH
```

and advance EDI only once per unrolled loop iteration.

Advancing the source texture pointer is more complex, but correspondingly more rewarding. Listing 43.2 uses a variant form of 32-bit fixed-point arithmetic to advance the source pointer, with the source texture coordinates and increments stored in 16.16 (16 bits of integer, 16 bits of fraction) format. The source coordinates are stored in a slightly unusual format, whereby the fractional X and Y coordinates are stored and advanced separately, but a single integer value, the source pointer, is used to reflect both the X and Y coordinates. In Listing 43.2, the integer and fractional parts are added into the current coordinates with four separate 16-bit operations, and carries from fractional to integer parts are detected via conditional jumps, as shown in Figure 43.4. There's quite a lot we can do to improve this.

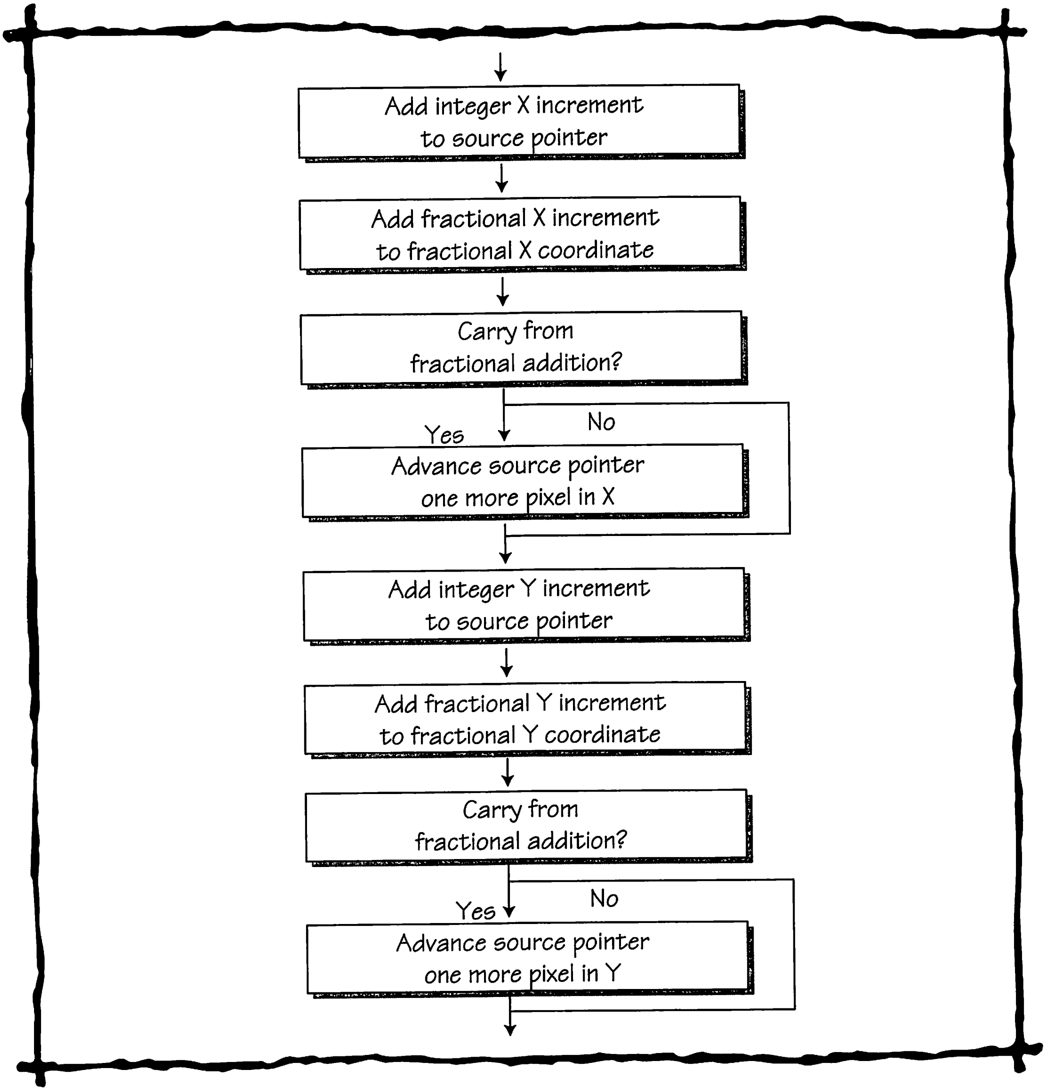

Add integer X increment to source pointer
Add fractional X increment to fractional X coordinate
Carry from fractional addition?
Yes
No
Advance source pointer one more pixel in X
Add integer Y increment to source pointer
Add fractional Y increment to fractional Y coordinate
Carry from fractional addition?
Yes
No
Advance source pointer one more pixel in Y

Figure 43.4 Original Method for Advancing the Source Texture Pointer

First, we can sum the X and Y integer advance amounts outside the loop, then add them both to the source pointer with a single instruction. Second, we can recognize that X advances exactly one extra byte when its fractional part carries, and use ADC to account for X carries, as shown in Figure 43.5. That single ADC can add in not only any X carry, but both the X and Y integer advance amounts as well, thereby eliminating a good chunk of the source-advance code in Listing 43.2. Furthermore, we should somehow be able to use 32-bit registers and instructions to help with the 32-bit fixed-point arithmetic; true, the size override prefix (because we're in a 16-bit segment) will cost a cycle per 32-bit instruction, but that's better than the 3 cycles it takes to do 32-bit arithmetic with 16-bit instructions. It isn't obvious, but there's a nifty trick we can use here, again courtesy of Chris Hecker (who, as you can tell, has done a fair amount of thinking about the complexities of texture mapping).

We can store the current fractional parts of both the X *and* Y source coordinates in a single 32-bit register, EDX, as shown in Figure 43.6. It's important to note that the Y fraction is actually only 15 bits, with bit 15 of EDX always kept at zero; this allows bit 15 to store the carry status from each Y advance. We can similarly store the fractional X and Y advance amounts in ECX, and can store the sum of the integer parts of the X and Y advance amounts in BP. With this arrangement, the single instruction ADD EDX,ECX advances the fractional parts of both X and Y, and the following instruction

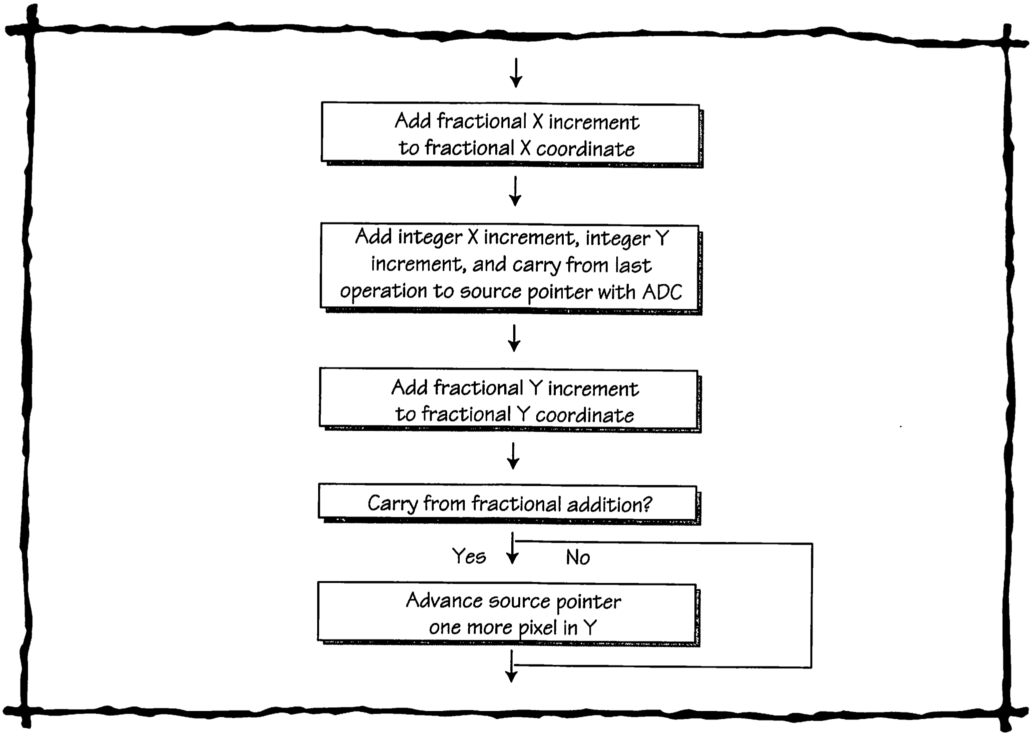

Add fractional X increment to fractional X coordinate
Add integer X increment, integer Y increment, and carry from last operation to source pointer with ADC
Add fractional Y increment to fractional Y coordinate
Carry from fractional addition?
Yes
No
Advance source pointer one more pixel in Y

Figure 43.5 Efficient Method for Advancing Source Texture Pointer

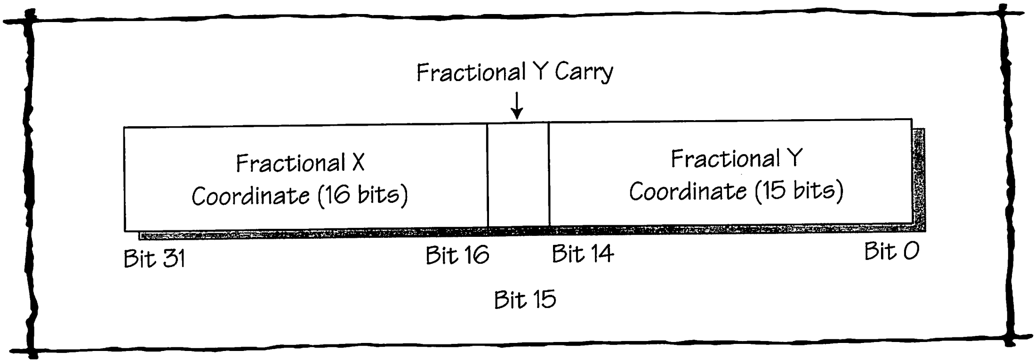

Fractional Y Carry
Fractional X Coordinate (16 bits)
Fractional Y Coordinate (15 bits)
Bit 31
Bit 16
Bit 14
Bit 0
Bit 15

Figure 43.6 Storing Both X and Y Fractional Coordinates in One Register

ADC SI,BP finishes advancing the source pointer in X. That's a mere 3 cycles, and all that remains is to finish advancing the source pointer in Y.

Actually, we also advanced the source pointer by the Y integer amount back when we added BP to SI; all that's left is to detect whether our addition to the Y fractional current coordinate produced a carry. That's easily done by testing bit 15 of EDX; if it's zero, there was no carry and we're done; otherwise, Y carried, so we have to reset bit 15 and advance the source pointer by one scanline. The resulting program flow is shown in Figure 43.7. Note that unlike the X fractional addition, we can't get away with just adding in the carry from the Y fractional addition, because when the Y fraction carries, it indicates a move not from one pixel to the next on a scanline (a single byte), but rather from one scanline to the next (a full scanline width).

All of the above optimizations together get us to 10 cycles—*very* close to John Miles, but not there yet. We have one more trick up our sleeve, though: Suppose we point SS to the segment containing our textures, and point DS to the screen? (This requires either setting up a stack in the texture segment or ensuring that interrupts and other stack activity can't happen while SS points to that segment.) Then, we could swap the functions of SI and BP; that would let us use BP, which accesses SS by default, to get at the textures, and DI to access the screen—all with no segment prefixes at all. By gosh, that would get us exactly one more cycle, and would bring us down to the same 9 cycles John Miles attained; Listing 43.3 shows that code. At long last, the Holy Grail attained and our honor defended, we can rest.

Or can we?

LISTING 43.3 L43-3.ASM

```
; Inner loop to draw a single texture-mapped vertical column,
; rather than a horizontal scanline. Maxed-out 16-bit version.
;
; At this point:
;       AX = source pointer increment to advance one in Y
;       ECX = fractional Y advance in lower 15 bits of CX,
```

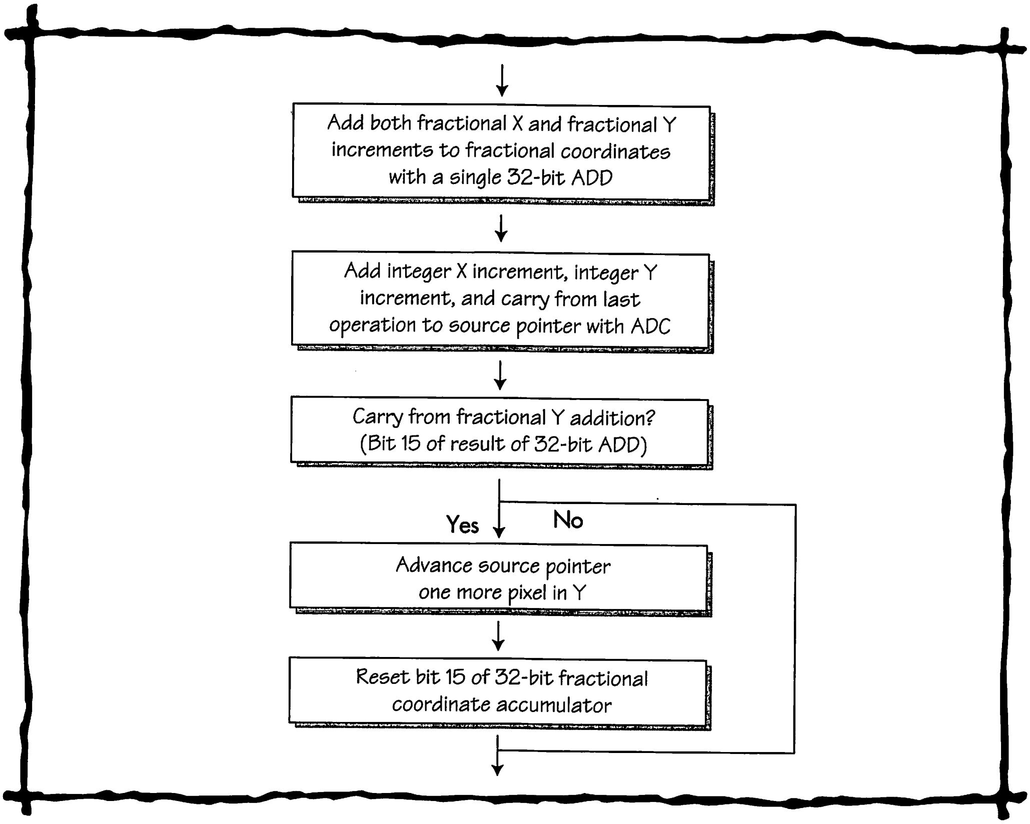

Add both fractional X and fractional Y increments to fractional coordinates with a single 32-bit ADD
Add integer X increment, integer Y increment, and carry from last operation to source pointer with ADC
Carry from fractional Y addition? (Bit 15 of result of 32-bit ADD)
Yes
No
Advance source pointer one more pixel in Y
Reset bit 15 of 32-bit fractional coordinate accumulator

Figure 43.7 Final Method for Advancing Source Texture Pointer

```
;             fractional X advance in high word of ECX, bit
;             15 set to 0
;       EDX = fractional source texture Y coordinate in lower
;             15 bits of CX, fractional source texture X coord
;             in high word of ECX, bit 15 set to 0
;       SI = sum of integral X & Y source pointer advances
;       DS:DI = initial destination pointer
;       SS:BP = initial source texture pointer

SCANOFFSET=0

        REPT LOOP_UNROLL

        mov   bl,[bp]                         ;get texture pixel
        mov   [di+SCANOFFSET],bl              ;set screen pixel

        add   edx,ecx                         ;advance frac Y in DX,
                                              ; frac X in high word of EDX
        adc   bp,si                           ;advance source pointer by integral
                                              ; X & Y amount, also accounting for
                                              ; carry from X fractional addition
        test  dh,80h                          ;carry from Y fractional addition?
        jz    @F                              ;no
        add     bp,ax                           ;yes, advance Y by one
        and     dh,not 80h                      ;reset the Y fractional carry bit
@@:

SCANOFFSET = SCANOFFSET + SCANWIDTH

        ENDM
```

Don't Stop Thinking about Those Cycles

Remember what I said at the outset, that knowing something has been done makes it much easier to do? A corollary is that pushing past that point, once attained, is very difficult. It's only natural to want to relax in the satisfaction of a job well done; then, too, the very nature of the work changes. Getting from 44 cycles down to John's 9 cycles was a huge leap, but we knew it could be done—therefore the nature of the problem was to figure out *how* it was done; in cases like this, if we're sharp enough (and of course we are!), we're guaranteed eventual gratification. Now that we've reached John's level of performance, the problem becomes *whether* the code can be made faster yet, and that's a different kettle of fish altogether, for it may well be that after thinking about it for a while, we'll conclude that it can't. Not only will we have wasted time, but we'll also never be sure we were right; we'll know only that *we* couldn't find a solution. That way lies madness.

And yet—*someone* has to blaze the trail to higher performance, and that someone might as well be us. Let's look for weaknesses in Listing 43.3. None are readily apparent; the only cycle that looks even slightly wasted is the size prefix on ADD EDX,ECX. As it turns out, that cycle really *is* wasted, for there's a way to make the size prefix vanish without losing the benefits of 32-bit instructions: Move the code into a 32-bit segment and make *all* the instructions 32-bit. That's what Listing 43.4 does; this code is similar to Listing 43.3, but runs in 8 cycles per pixel, a 12.5% speedup over Listing 43.3. Whether Listing 43.4 actually draws more pixels per second than Listing 43.3 depends on whether display memory is fast enough to handle pixels as rapidly as Listing 43.4 can deliver them. That speed, one pixel every 122 nanoseconds on a 486/66, is one that ISA adapters can't hope to match, but fast VLB and PCI adapters can handle with ease. Be aware, too, that cache misses when reading the source texture will generally reduce performance below the calculated 8-cycles-per-pixel level, especially because textures, which can be scanned across at any angle, are rarely accessed at consecutive addresses, which is the arrangement that would make for the fewest cache misses.

LISTING 43.4 L43-4.ASM

```
; Inner loop to draw a single texture-mapped vertical column,
; rather than a horizontal scanline. Maxed-out 32-bit version.
;
; At this point:
;       EAX = sum of integral X & Y source pointer advances
;       ECX = source pointer increment to advance one in Y
;       EDX = fractional source texture Y coordinate in lower
;             15 bits of DX, fractional source texture X coord
;             in high word of EDX, bit 15 set to 0
;       ESI = initial source texture pointer
;       EDI = initial destination pointer
;       EBP = fractional Y advance in lower 15 bits of BP,
;             fractional X advance in high word of EBP, bit
;             15 set to 0

SCANOFFSET=0

        REPT LOOP_UNROLL

        mov   bl,[esi]                    ;get image pixel
        add   edx,ebp                     ;advance frac Y in DX,
                                          ; frac X in high word of EDX
        adc   esi,eax                     ;advance source pointer by integral
                                          ; X & Y amount, also accounting for
                                          ; carry from X fractional addition
        mov   [edi+SCANOFFSET],bl         ;set screen pixel
                                          ; (located here to avoid 486
                                          ; AGI from previous byte op)
        test  dh,80h                      ;carry from Y fractional addition?
        jz    short @F                    ;no
        add   esi,ecx                     ;yes, advance Y by one
                                          ; (produces Pentium AGI for MOV BL,[ESI])
        and   dh,not 80h                  ;reset the Y fractional carry bit
@@:

SCANOFFSET = SCANOFFSET + SCANWIDTH

        ENDM
```

And there you have it: A five to ten-times speedup of a decent assembly language texture mapper. All it took was some help from my friends, a good, stiff jolt of right-brain thinking, and some solid left-brain polishing—plus the knowledge that such a speedup was possible. Treat every optimization task as if John Miles has just written to inform you that he's made it faster than your wildest dreams, and you'll be amazed at what you can do!

Texture Mapping Notes

Listing 43.3 contains no 486 pipeline stalls; it has Pentium stalls, but not much can be done for them because of the size prefix on ADD EDX,ECX, which takes 1 cycle to go through the U-pipe, and shuts down the V-pipe for that cycle. Listing 43.4, on the other hand, has been rearranged to eliminate all Pentium stalls save one. When the Y coordinate fractional part carries and ESI advances, the code executes as follows:

```
ADD ESI,ECX     ;cycle 1 U-pipe
AND DH,NOT 80H  ;cycle 1 V-pipe
                ;cycle 2 idle AGI on ESI
```

```
MOV BL,[ESI]      ;cycle 3 U-pipe
ADD EDX,EBP       ;cycle 3 V-pipe
```

However, I don't see any way to eliminate this last AGI, which happens about half the time; even with it, the Pentium execution time for Listing 43.4 is 5.5 cycles. That's 61 nanoseconds—a highly respectable 16 million texture-mapped pixels per second—on a 90 MHz Pentium.

The type of texture mapping discussed in both this and earlier chapters doesn't do perspective correction when mapping textures. Why that is and how to handle perspective correction is a topic for a whole separate book, but be aware that the textures on some large polygons (not the polygon edges themselves) drawn with the code in this chapter will appear to be unnaturally bowed, although small polygons should look fine.

Finally, we never did get rid of the last jump in the texture mapper, yet John Miles claimed no jumps at all. How did he do it? I'm not sure, but I'd guess that he used a two-entry look-up table, based on the Y carry, to decide how much to advance the source pointer in Y. However, I couldn't come up with any implementation of this approach that didn't take 0.5 to 1 cycle more than the test-and-jump approach, so either I didn't come up with an adequately efficient implementation of the table, John saved a cycle somewhere else, or perhaps John implemented his code in a 32-bit segment, but used the less-efficient table in his fervor to get rid of the final jump. The knowledge that I apparently came up with a different solution than John highlights that the technical aspects of John's implementation were, in truth, totally irrelevant to my optimization efforts; the only actual effect John's code had on me was to make me *believe* a texture mapper could run that fast.

Believe it! And while you're at it, give both halves of your brain equal time—and watch out for aliens in short skirts, 60's bouffant hairdos, and an undue interest in either half.

The Idea of BSP Trees

Chapter 44

What BSP Trees Are and How to Walk Them

The answer is: Wendy Tucker.

The question that goes with that answer isn't particularly interesting to anyone but me—but the manner in which I came up with the answer is.

I spent many of my childhood summers at Camp Chingacook, on Lake George in New York. It was a great place to have fun and do some growing up, with swimming and sailing and hiking and lots more.

When I was fourteen, Camp Chingacook had a mixer with a nearby girls' camp. As best I can recall, I had never had any interest in girls before, but after the older kids had paired up, I noticed a pretty girl looking at me and, with considerable trepidation, I crossed the room to talk to her. To my amazement, we hit it off terrifically. We talked non-stop for the rest of the evening, and I walked back to my cabin floating on air. I had taken a first, tentative step into adulthood, and my world would never be quite the same.

That was the only time I ever saw her, although I would occasionally remember that warm glow and call up an image of her smiling face. That happened less frequently as the years passed and I had real girlfriends, and by the time I got married, that particular memory was stashed in some back storeroom of my mind. I didn't think of her again for more than a decade.

A few days ago, for some reason, that mixer popped into my mind as I was trying to fall asleep. And I wondered, for the first time in 20 years, what that girl's name was. The name was there in my mind, somewhere; I could feel the shape of it, in that same back storeroom, if only I could figure out how to retrieve it.

I poked and worried at that memory, trying to get it to come to the surface. I concentrated on it as hard as I could, and even started going through the alphabet one letter at a time, trying to remember if her name started with each letter. After 15 minutes, I was wide awake and totally frustrated. I was also farther than ever from answering the question; all the focusing on the memory was beginning to blur the original imprint.

At this point, I consciously relaxed and made myself think about something completely different. Every time my mind returned to the mystery girl, I gently shifted it to something else. After a while, I began to drift off to sleep, and as I did a connection was made, and a name popped, unbidden, into my mind.

Wendy Tucker.

There are many problems that are amenable to the straight-ahead, purely conscious sort of approach that I first tried to use to retrieve Wendy's name. Writing code (once it's designed) is often like that, as are some sorts of debugging, technical writing, and balancing your checkbook. I personally find these left-brain activities to be very appealing because they're finite and controllable; when I start one, I know I'll be able to deal with whatever comes up and make good progress, just by plowing along. Inspiration and intuitive leaps are sometimes useful, but not required.

The problem is, though, that neither you nor I will ever do anything great without inspiration and intuitive leaps, and especially not without stepping away from what's known and venturing into territories beyond. The way to do that is not by trying harder but, paradoxically, by trying less hard, stepping back, and giving your right brain room to work, then listening for and nurturing whatever comes of that. On a small scale, that's how I remembered Wendy's name, and on a larger scale, that's how programmers come up with products that are more than me-too, checklist-oriented software.

Which, for a couple of reasons, brings us neatly to this chapter's topic, Binary Space Partitioning (BSP) trees. First, games are probably the sort of software in which the right-brain element is most important—blockbuster games are almost always breakthroughs in one way or another—and some very successful games use BSP trees, most notably id Software's megahit DOOM. Second, BSP trees aren't intuitively easy to grasp, and considerable ingenuity and inventiveness is required to get the most from them.

Before we begin, I'd like to thank John Carmack, the technical wizard behind DOOM, for generously sharing his knowledge of BSP trees with me.

BSP Trees

A BSP tree is, at heart, nothing more than a tree that subdivides space in order to isolate features of interest. Each node of a BSP tree splits an area or a volume (in 2-D or 3-D, respectively) into two parts along a line or a plane; thus the name "Binary Space Partitioning." The subdivision is hierarchical; the root node splits the world into two subspaces, then each of the root's two children splits one of those two subspaces into two more parts. This continues with each subspace being further subdivided, until each component of interest (each line segment or polygon, for example) has been assigned its own unique subspace. This is, admittedly, a pretty abstract description, but the workings of BSP trees will become clearer shortly; it may help to glance ahead to this chapter's figures.

Building a tree that subdivides space doesn't sound particularly profound, but there's a lot that can be done with such a structure. BSP trees can be used to represent shapes, and operating on those shapes is a simple matter of combining trees as needed; this makes BSP trees a powerful way to implement Constructive Solid Geometry (CSG). BSP trees can also be used for hit testing, line-of-sight determination, and collision detection.

Visibility Determination

For the time being, I'm going to discuss only one of the many uses of BSP trees: The ability of a BSP tree to allow you to traverse a set of line segments or polygons in back-to-front or front-to-back order as seen from any arbitrary viewpoint. This sort of traversal can be very helpful in determining which parts of each line segment or polygon are visible and which are occluded from the current viewpoint in a 3-D scene. Thus, a BSP tree makes possible an efficient implementation of the painter's algorithm, whereby polygons are drawn in back-to-front order, with closer polygons overwriting more distant ones that overlap, as shown in Figure 44.1. (The line segments in Figure 1(a) and in other figures in this chapter, represent vertical walls, viewed from directly above.) Alternatively, visibility determination can be performed by front-to-back traversal work-

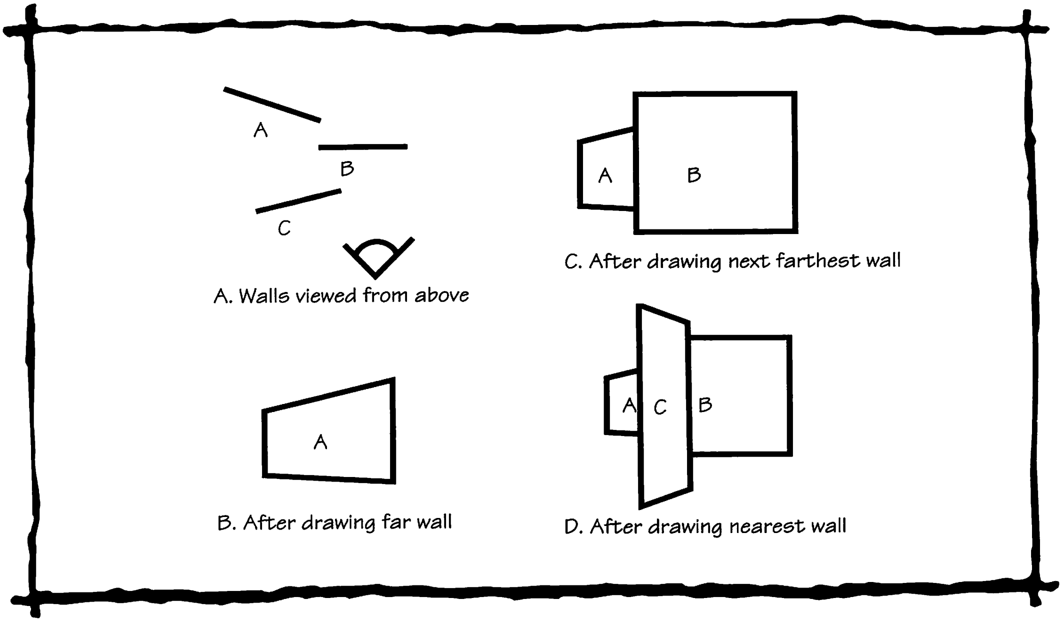

A
B
C
A. Walls viewed from above
A
B
C. After drawing next farthest wall
A
B. After drawing far wall
A
C
B
D. After drawing nearest wall

Figure 44.1 The Painter's Algorithm

ing in conjunction with some method for remembering which pixels have already been drawn. The latter approach is more complex, but has the potential benefit of allowing you to early-out from traversal of the scene database when all the pixels on the screen have been drawn.

Back-to-front or front-to-back traversal in itself wouldn't be so impressive—there are many ways to do that—were it not for one additional detail: The traversal can always be performed in linear time, as we'll see later on. For instance, you can traverse, a polygon list back-to-front from any viewpoint simply by walking through the corresponding BSP tree once, visiting each node one and only one time, and performing only one relatively inexpensive test at each node.

It's hard to get cheaper sorting than linear time, and BSP-based rendering stacks up well against alternatives such as z-buffering, octrees, z-scan sorting, and polygon sorting. Better yet, a scene database represented as a BSP tree can be clipped to the view pyramid very efficiently; huge chunks of a BSP tree can be lopped off when clipping to the view pyramid, because if the entire area or volume of a node lies entirely outside the view volume, then *all* nodes and leaves that are children of that node must likewise be outside the view volume, for reasons that will become clear as we delve into the workings of BSP trees.

Limitations of BSP Trees

Powerful as they are, BSP trees aren't perfect. By far the greatest limitation of BSP trees is that they're time-consuming to build, enough so that, for all practical purposes, BSP trees must be precalculated, and cannot be built dynamically at runtime. In fact, a BSP-tree compiler that attempts to perform some optimization (limiting the number of surfaces that need to be split, for example) can easily take minutes or even hours to process large world databases.

A fixed world database is fine for walkthrough or flythrough applications (where the viewpoint moves through a static scene), but not much use for games or virtual reality, where objects constantly move relative to one another. Consequently, various workarounds have been developed to allow moving objects to appear in BSP tree-based scenes. DOOM, for example, uses 2-D sprites mixed into BSP-based 3-D scenes; note, though, that this approach requires maintaining z information so that sprites can be drawn and occluded properly. Alternatively, movable objects could be represented as separate BSP trees and merged anew into the world BSP tree with each move. Dynamic merging may or may not be fast enough, depending on the scene, but merging BSP trees tends to be quicker than building them, because the BSP trees being merged are already spatially sorted.

Another possibility would be to generate a per-pixel z-buffer for each frame as it's rendered, to allow dynamically-changing objects to be drawn into the BSP-based world. In this scheme, the BSP tree would allow fast traversal and clipping of the complex, static world, and the z-buffer would handle the relatively localized visibility determination involving moving objects. The drawback of this is the need for a memory-hungry z-buffer; a typical 640x480 z-buffer requires a fairly appalling 600K, with equally appalling cache-miss implications for performance.

Yet another possibility would be to build the world so that each dynamic object falls entirely within a single subspace of the static BSP tree, rather than straddling splitting lines or planes. In this case, dynamic objects can be treated as points, which are then just sorted into the BSP tree on the fly as they move.

The only other drawbacks of BSP trees that I know of are the memory required to store the tree, which amounts to a few pointers per node, and the relative complexity of debugging BSP-tree compilation and usage; debugging a large data set being processed by recursive code (which BSP code tends to be) can be quite a challenge. Tools like the BSP compiler I'll present in the next chapter, which visually depicts the process of spatial subdivision as a BSP tree is constructed, help a great deal with BSP debugging.

Building a BSP Tree

Now that we know a good bit about what a BSP tree is, how it helps in visible surface determination, and what its strengths and weaknesses are, let's take a look at how a BSP tree actually works to provide front-to-back or back-to-front ordering. This chapter's discussion will be at a conceptual level, with plenty of figures; in the next chapter we'll get into mechanisms and implementation details.

I'm going to discuss only 2-D BSP trees from here on out, because they're much easier to draw and to grasp than their 3-D counterparts. Don't worry, though; the principles of 2-D BSP trees using line segments generalize directly to 3-D BSP trees using polygons. Also, 2-D BSP trees are quite powerful in their own right, as evidenced by DOOM which is built around 2-D BSP trees.

First, let's construct a simple BSP tree. Figure 44.2 shows a set of four lines that will constitute our sample world. I'll refer to these as walls, because that's one easily-visualized context in which a 2-D BSP tree would be useful in a game. Think of Figure 44.2 as depicting vertical walls viewed from directly above, so they're lines for the purpose of the BSP tree. Note that each wall has a front side, denoted by a normal (perpendicular) vector, and a back side. To make a BSP tree for this sample set, we need to split the world in two, then each part into two again, and so on, until each wall resides in its own unique subspace. An obvious question, then, is how should we carve up the world of Figure 44.2?

There are infinitely valid ways to carve up Figure 44.2, but the simplest is just to carve along the lines of the walls themselves, with each node containing one wall. This is not necessarily optimal, in the sense of producing the smallest tree, but it has the virtue of generating the splitting lines without expensive analysis. It also saves on data storage, because the data for the walls can do double duty in describing the splitting lines as well. (Putting one wall on each splitting line doesn't actually create a unique subspace for each wall, but it does create a unique subspace *boundary* for each wall; as we'll see, that spatial organization provides for the same unambiguous visibility ordering as a unique subspace would.)

Creating a BSP tree is a recursive process, so we'll perform the first split and go from there. Figure 44.3 shows the world carved along the line of wall C into two parts: walls that are in front of wall C, and walls that are behind. (Any of the walls would have been an equally valid choice for the initial split; we'll return to the issue of choosing splitting walls in the next chapter.) This splitting into front and back is the essential dualism of BSP trees.

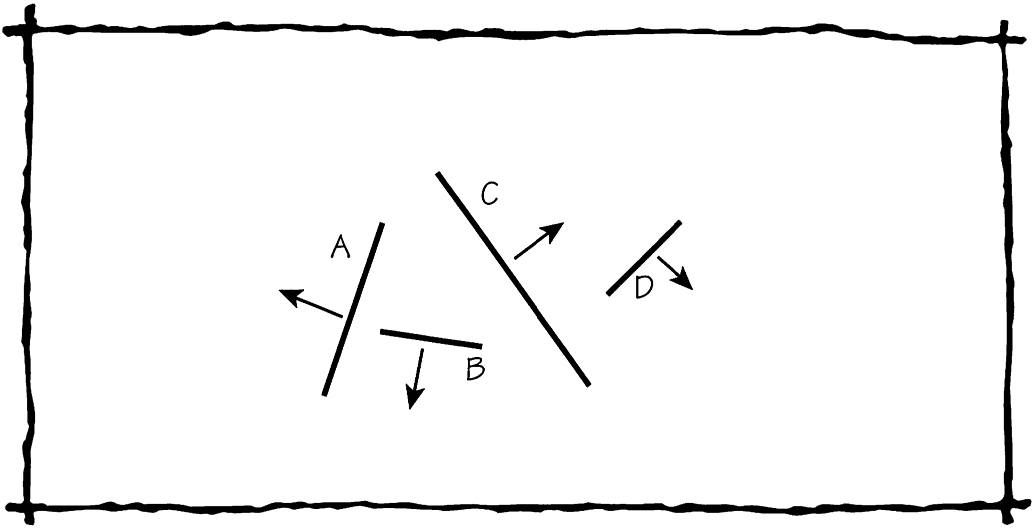


Figure 44.2 A sample set of walls, viewed from above.

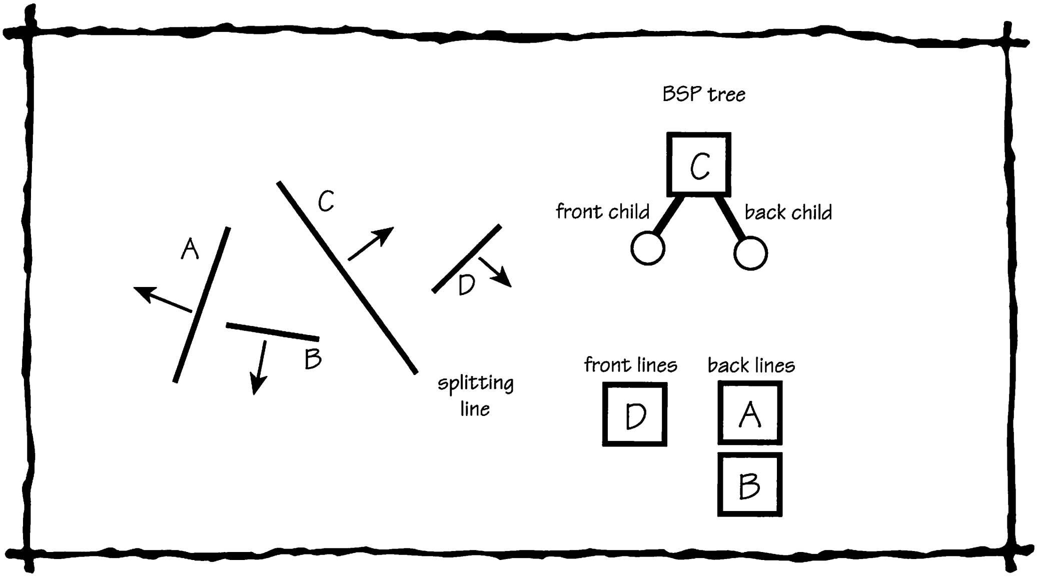


Figure 44.3 Initial split along the line of wall C.

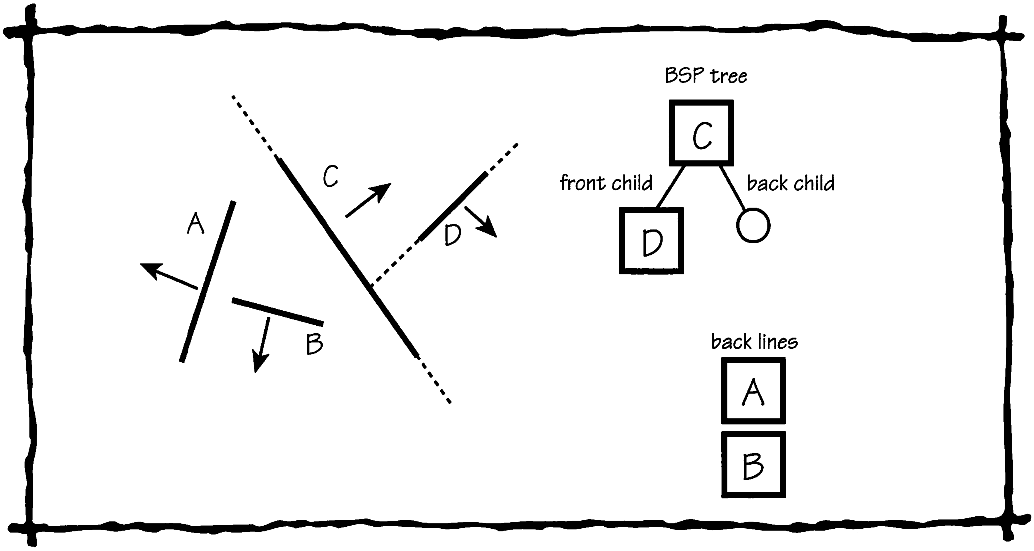


Figure 44.4 Split of wall C's front subspace along the line of wall D.

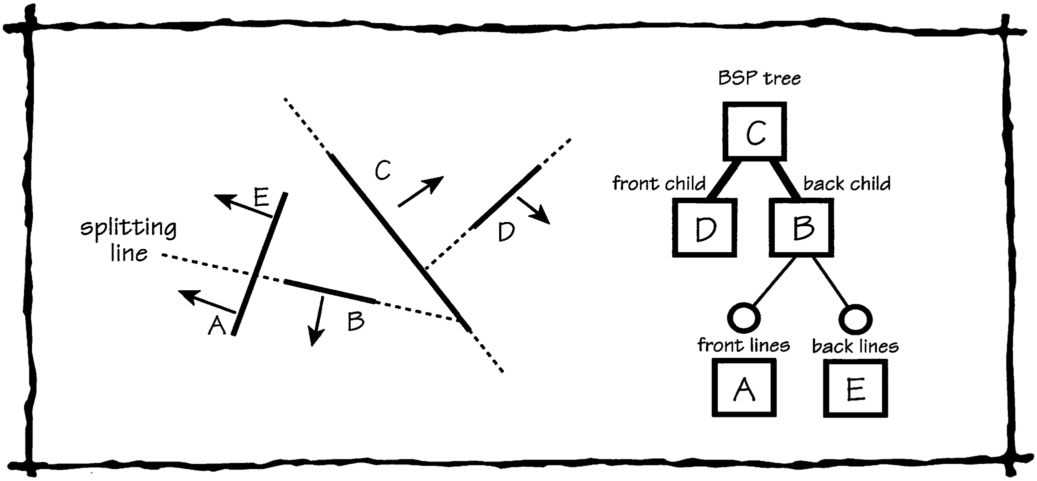


Figure 44.5 Split of wall C's back subspace along the line of wall B.

Next, in Figure 44.4, the front subspace of wall C is split by wall D. This is the only wall in that subspace, so we're done with wall C's front subspace.

Figure 44.5 shows the back subspace of wall C being split by wall B. There's a difference here, though: Wall A straddles the splitting line generated from wall B. Does wall A belong in the front or back subspace of wall B?

Both, actually. Wall A gets split into two pieces, which I'll call wall A and wall E; each piece is assigned to the appropriate subspace and treated as a separate wall. As

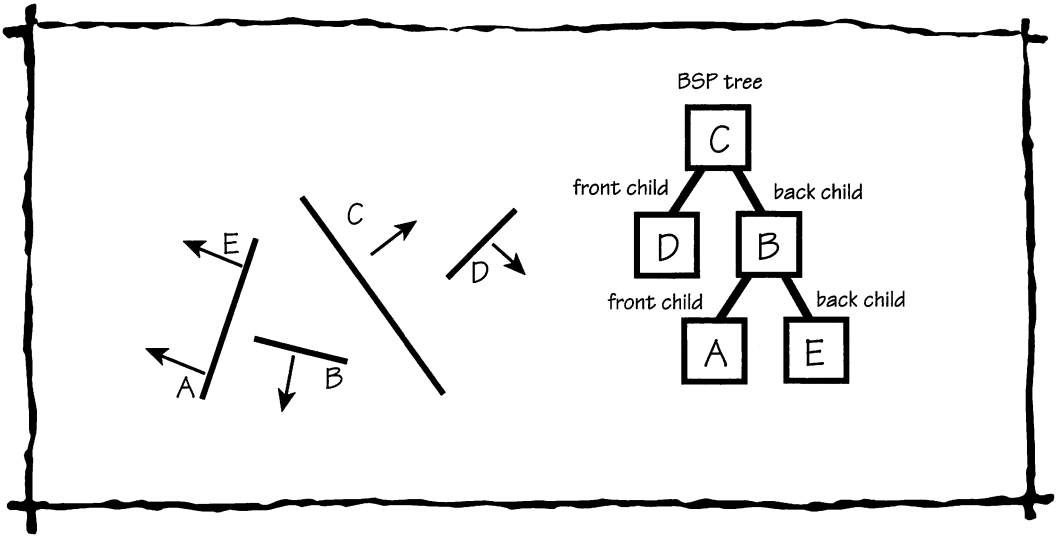


Figure 44.6 The final BSP tree.

shown in Figure 44.6, each of the split pieces then has a subspace to itself, and each becomes a leaf of the tree. The BSP tree is now complete.

Visibility Ordering

Now that we've successfully built a BSP tree, you might justifiably be a little puzzled as to how any of this helps with visibility ordering. The answer is that each BSP node can definitively determine which of its child trees is nearer and which is farther from any and all viewpoints; applied throughout the tree, this principle makes it possible to establish visibility ordering for all the line segments or planes in a BSP tree, no matter what the viewing angle.

Consider the world of Figure 44.2 viewed from an arbitrary angle, as shown in Figure 44.7. The viewpoint is in front of wall C; this tells us that all walls belonging to the front tree that descends from wall C are nearer along every ray from the viewpoint than wall C is (that is, they can't be occluded by wall C). All the walls in wall C's back tree are likewise farther away than wall C along any ray. Thus, for this viewpoint, we know for sure that if we're using the painter's algorithm, we want to draw all the walls in the back tree first, then wall C, and then the walls in the front tree. If the viewpoint had been on the back side of wall C, this order would have been reversed.

Of course, we need more ordering information than wall C alone can give us, but we get that by traversing the tree recursively, making the same far-near decision at each node. Figure 44.8 shows the painter's algorithm (back-to-front) traversal order of the tree for the viewpoint of Figure 44.7. At each node, we decide whether we're seeing the front or back side of that node's wall, then visit whichever of the wall's children is on

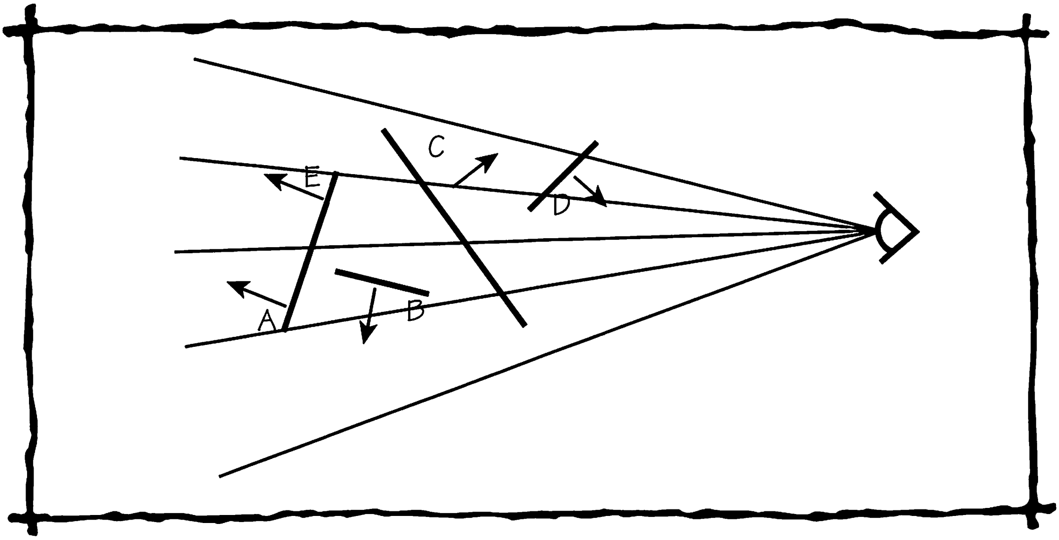
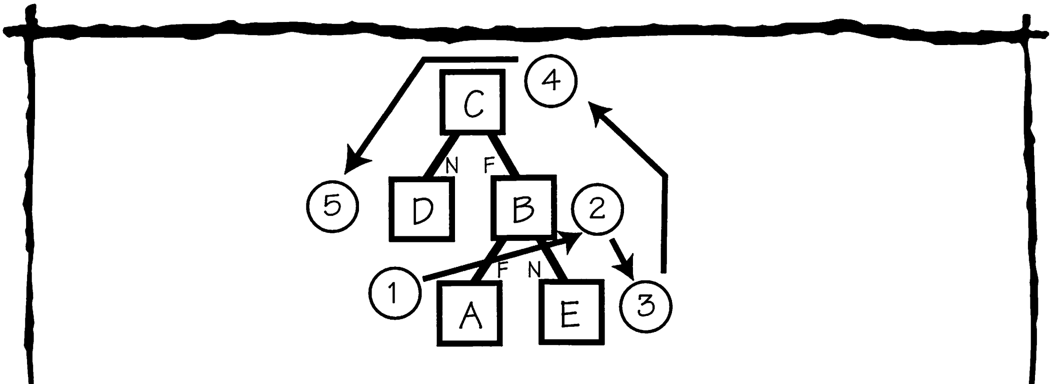


Figure 44.7 Viewing the BSP tree from an arbitrary angle.

the far side from the viewpoint, draw the wall, and then visit the node's nearer child, in that order. Visiting a child is recursive, involving the same far-near visiting order.

The key is that each BSP splitting line separates all the walls in the current subspace into two groups relative to the viewpoint, and every single member of the farther group is guaranteed not to occlude every single member of the nearer. By applying this ordering recursively, the BSP tree can be traversed to provide back-to-front or front-to-back ordering, with each node being visited only once.



Note: 'F' and 'N' indicate the far and near children, respectively, of each node from the viewpoint of figure 44.7.

FIGURE 44.8 Back-to-front traversal of the BSP tree as viewed in Figure 44.7.

The type of tree walk used to produce front-to-back or back-to-front BSP traversal is known as an *inorder* walk. More on this very shortly; you're also likely to find a discussion of inorder walking in any good data structures book. The only special aspect of BSP walks is that a decision has to be made at each node about which way the node's wall is facing relative to the viewpoint, so we know which child tree is nearer and which is farther.

Listing 44.1 shows a function that draws a BSP tree back-to-front. The decision whether a node's wall is facing forward, made by **WallFacingForward()** in Listing 44.1, can, in general, be made by generating a normal to the node's wall in screenspace (perspective-corrected space as seen from the viewpoint) and checking whether the z component of the normal is positive or negative, or by checking the sign of the dot product of a viewspace (non-perspective corrected space as seen from the viewpoint) normal and a ray from the viewpoint to the wall. In 2-D, the decision can be made by enforcing the convention that when a wall is viewed from the front, the start vertex is leftmost; then a simple screenspace comparison of the x coordinates of the left and right vertices indicates which way the wall is facing.

Listing 44.1. L44_1.C

```
void WalkBSPTree(NODE *pNode)
{
   if (WallFacingForward(pNode) {
      if (pNode->BackChild) {
         WalkBSPTree(pNode->BackChild);
      }
      Draw(pNode);
      if (pNode->FrontChild) {
         WalkBSPTree(pNode->FrontChild);
      }
   } else {
      if (pNode->FrontChild) {
         WalkBSPTree(pNode->FrontChild);
      }
      Draw(pNode);
      if (pNode->BackChild) {
         WalkBSPTree(pNode->BackChild);
      }
   }
}
```

Be aware that BSP trees can often be made smaller and more efficient by detecting collinear surfaces (like aligned wall segments) and generating only one BSP node for each collinear set, with the collinear surfaces stored in, say, a linked list attached to that node. Collinear surfaces partition space identically and can't occlude one another, so it suffices to generate one splitting node for each collinear set.

Inorder Walks of BSP Trees

It was implementing BSP trees that got me to thinking about inorder tree traversal. In inorder traversal, the left subtree of each node gets visited first, then the node, and then the right subtree. You apply this sequence recursively to each node and its children until the entire tree has been visited, as shown in Figure 44.9. Walking a BSP tree is basically an inorder tree walk; the only difference is that with a BSP tree a decision is made before each descent as to which subtree to visit first, rather than simply visiting whatever's pointed to by the left-subtree pointer. Conceptually, however, an inorder walk is what's used to traverse a BSP tree; from now on I'll discuss normal inorder walking, with the understanding that the same principles apply to BSP trees.

As I've said again and again in my printed works over the years, you have to dig deep below the surface to *really* understand something if you want to get it right, and inorder walking turns out to be an excellent example of this. In fact, it's such a good example that I routinely use it as an interview question for programmer candidates, and, to my astonishment, not one interviewee has done a good job with this one yet. I ask the question in two stages, and I get remarkably consistent results.

First, I ask for an implementation of a function **WalkTree()** that visits each node in a passed-in tree in inorder sequence. Each candidate unhesitatingly writes something like the perfectly good code in Listings 44.2 and 44.3 shown below.

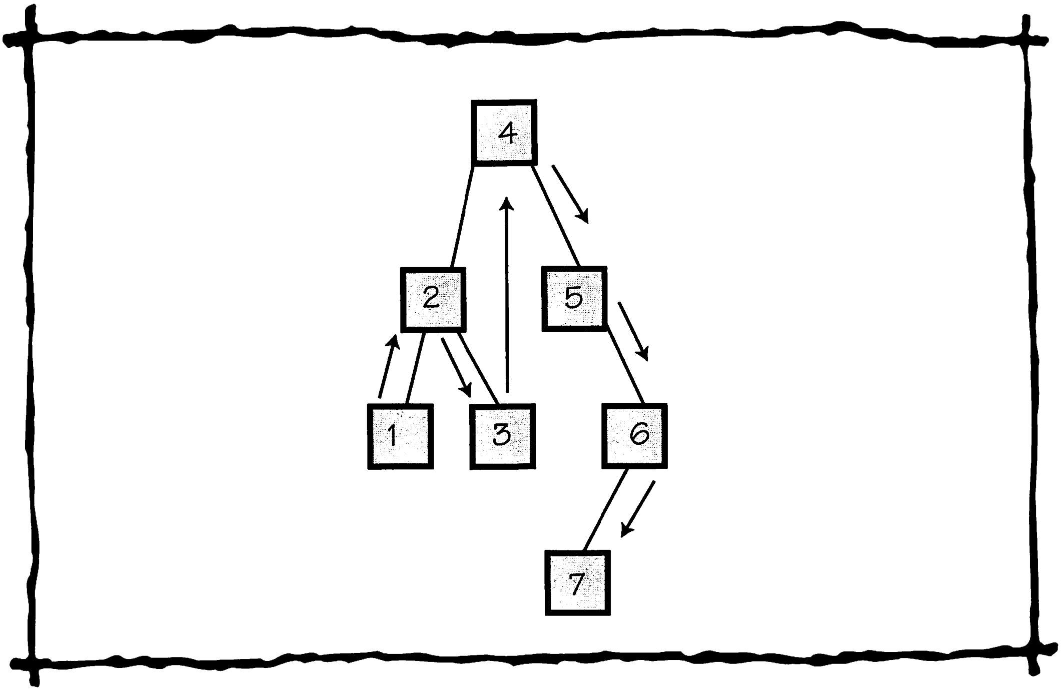


Figure 44.9 An inorder walk of a BSP tree.

Listing 44.2. L44_2.C

```
// Function to inorder walk a tree, using code recursion.
// Tested with 32-bit Visual C++ 1.10.
#include <stdlib.h>
#include "tree.h"
extern void Visit(NODE *pNode);
void WalkTree(NODE *pNode)
{
   // Make sure the tree isn't empty
   if (pNode != NULL)
   {
      // Traverse the left subtree, if there is one
      if (pNode->pLeftChild != NULL)
      {
         WalkTree(pNode->pLeftChild);
      }
      // Visit this node
      Visit(pNode);
      // Traverse the right subtree, if there is one
      if (pNode->pRightChild != NULL)
      {
         WalkTree(pNode->pRightChild);
      }
   }
}
```

Listing 44.3. L44_3.H

```
// Header file TREE.H for tree-walking code.
typedef struct _NODE {
      struct _NODE *pLeftChild;
      struct _NODE *pRightChild;
} NODE;
```

Then I ask if they have any idea how to make the code faster; some don't, but most point out that function calls are pretty expensive. Either way, I then ask them to rewrite the function without code recursion.

And then I sit back and squirm for a minimum of 15 minutes.

I have never had *anyone* write a functional data-recursion inorder walk function in less time than that, and several people have simply never gotten the code to work at all. Even the best of them have fumbled their way through the code, sticking in a push here or a pop there, then working through sample scenarios in their head to see what's broken, programming by trial and error until the errors seem to be gone. No one is ever sure they have it right; instead, when they can't find any more bugs, they look at me hopefully to see if it's thumbs-up or thumbs-down.

And yet, a data-recursive inorder walk implementation has *exactly* the same flowchart and exactly the same functionality as the code-recursive version they've already written. They already have a fully functional model to follow, with all the problems solved, but they can't make the connection between that model and the code they're trying to implement. Why is this?

Know It Cold

The problem is that these people don't understand inorder walking through and through. They understand the concepts of visiting left and right subtrees, and they have a general picture of how traversal moves about the tree, but they do not understand exactly what the code-recursive version does. If they really comprehended everything that happens in each iteration of **WalkTree()**—how each call saves the state, and what that implies for the order in which operations are performed—they would simply and without fuss implement code like that in Listing 44.4, working with the code-recursive version as a model.

Listing 44.4. L44_4.C

```
// Function to inorder walk a tree, using data recursion.
// No stack overflow testing is performed.
// Tested with 32-bit Visual C++ 1.10.
#include <stdlib.h>
#include "tree.h"
#define MAX_PUSHED_NODES   100
extern void Visit(NODE *pNode);
void WalkTree(NODE *pNode)
{
   NODE *NodeStack[MAX_PUSHED_NODES];
   NODE **pNodeStack;
   // Make sure the tree isn't empty
   if (pNode != NULL)
   {
      NodeStack[0] = NULL;  // push "stack empty" value
      pNodeStack = NodeStack + 1;
      for (;;)
      {
         // If the current node has a left child, push
         // the current node and descend to the left
         // child to start traversing the left subtree.
         // Keep doing this until we come to a node
         // with no left child; that's the next node to
         // visit in inorder sequence
         while (pNode->pLeftChild != NULL)
         {
            *pNodeStack++ = pNode;
            pNode = pNode->pLeftChild;
         }
         // We're at a node that has no left child, so
         // visit the node, then visit the right
         // subtree if there is one, or the last-
         // pushed node otherwise; repeat for each
         // popped node until one with a right
         // subtree is found or we run out of pushed
         // nodes (note that the left subtrees of
         // pushed nodes have already been visited, so
         // they're equivalent at this point to nodes
         // with no left children)
         for (;;)
         {
            Visit(pNode);
            // If the node has a right child, make
            // the child the current node and start
            // traversing that subtree; otherwise, pop
            // back up the tree, visiting nodes we
            // passed on the way down, until we find a
            // node with a right subtree to traverse
            // or run out of pushed nodes and are done
            if (pNode->pRightChild != NULL)
            {
               // Current node has a right child;
               // traverse the right subtree
               pNode = pNode->pRightChild;
               break;
            }
            // Pop the next node from the stack so
            // we can visit it and see if it has a
            // right subtree to be traversed
            if ((pNode = *–pNodeStack) == NULL)
            {
               // Stack is empty and the current node
               // has no right child; we're done
               return;
            }
         }
      }
   }
}
```

Take a few minutes to look over Listing 44.4 and relate it to Listing 44.2. The structure is different, but upon examination it becomes clear that both listings reflect the same underlying model: For each node, visit the left subtree, visit the node, visit the right subtree. And although Listing 44.4 is longer, that's mostly because I commented it heavily to make sure its workings are understood; there are only 13 lines that actually do anything in Listing 44.4.

Let's look at it another way. All the code in Listing 44.2 does is say: "Here I am at a node. First I'll visit the left subtree if there is one, then I'll visit this node, then I'll visit the right subtree if there is one. While I'm visiting the left subtree, I'll just push a marker on a stack that tells me to come back here when the left subtree is done. If, after visiting a node, there are no right children to visit and nothing left on the stack, I'm finished. The code does this at each node—and that's *all* it does. That's all Listing 44.4 does, too, but people tend to get tangled up in pushes and pops and **while** loops when they use data recursion. When the implementation model changes to one with which they are unfamiliar, they abandon the perfectly good model they used before and try to rederive it in the new context by the seat of their pants.

Here's a secret when you're faced with a situation like this: Step back and get a clear picture of what your code has to do. Omit no steps. You should build a model that is so consistent and solid that you can instantly answer any question about how the code should behave in any situation. For example, my interviewees often decide, *by trial and error, that there are two distinct types of right children: Right children visited after popping back to visit a node after the left subtree has been visited, and right children visited after descending to a node that has no left child. This makes the traversal code a mass of special cases, each of which has to be detected by the programmer by trying out scenarios. Worse, you can never be sure with this approach that you've caught all the special cases.*

The alternative is to develop and apply a unifying model. There aren't really two types of right children; the rule is that all right children are visited after their parents are visited, period. The presence or absence of a left child is irrelevant. The possibility that a right child may be reached via different code paths depending on the presence of a left child does not affect the overall model. While this distinction may seem trivial it is in fact crucial, because if you have the model down cold, you can always tell if the implementation is correct by comparing it with the model.

Measure and Learn

How much difference does all this fuss make, anyway? Listing 44.5 is a sample program that builds a tree, then calls **WalkTree** () to walk it 1,000 times, and times how long this takes. Using 32-bit Visual C++ 1.10 running on Windows NT, with default optimization selected, Listing 44.5 reports that Listing 44.4 is about 20 percent faster than Listing 44.2 on a 486/33, a reasonable return for a little code rearrangement, especially when you consider that the speedup is diluted by calling the **Visit**() function and by the cache miss that happens on virtually every node access. (Listing 44.5 builds a rather unique tree, one in which every node has exactly two children. Different sorts of trees can and do produce different performance results. Always know what you're measuring!)

Listing 44.5. L55_5.C

```
// Sample program to exercise and time the performance of
// implementations of WalkTree().
// Tested with 32-bit Visual C++ 1.10 under Windows NT.
#include <stdio.h>
#include <conio.h>
#include <stdlib.h>
#include <time.h>
#include "tree.h"
long VisitCount = 0;
void main(void);
void BuildTree(NODE *pNode, int RemainingDepth);
extern void WalkTree(NODE *pRootNode);
void main()
{
   NODE RootNode;
   int i;
   long StartTime;
   // Build a sample tree
   BuildTree(&RootNode, 14);
   // Walk the tree 1000 times and see how long it takes
   StartTime = time(NULL);
   for (i=0; i<1000; i++)
   {
      WalkTree(&RootNode);
   }
   printf("Seconds elapsed: %ld\n",
           time(NULL) - StartTime);
   getch();
}
//
// Function to add right and left subtrees of the
// specified depth off the passed-in node.
//
void BuildTree(NODE *pNode, int RemainingDepth)
{
   if (RemainingDepth == 0)
   {
      pNode->pLeftChild = NULL;
      pNode->pRightChild = NULL;
   }
   else
   {
      pNode->pLeftChild = malloc(sizeof(NODE));
      if (pNode->pLeftChild == NULL)
      {
         printf("Out of memory\n");
         exit(1);
      }
      pNode->pRightChild = malloc(sizeof(NODE));
      if (pNode->pRightChild == NULL)
      {
         printf("Out of memory\n");
         exit(1);
      }
      BuildTree(pNode->pLeftChild, RemainingDepth - 1);
      BuildTree(pNode->pRightChild, RemainingDepth - 1);
   }
}
//
// Node-visiting function so WalkTree() has something to
// call.
//
void Visit(NODE *pNode)
{
   VisitCount++;
}
```

Things change when maximum optimization is selected, however: The performance of the two implementations becomes virtually identical! How can this be? Part of the answer is that the compiler does an amazingly good job with Listing 44.2. Most impressively, when compiling Listing 44.2, the compiler actually converts all right-subtree descents from code recursion to data recursion, by simply jumping back to the left-subtree handling code instead of recursively calling **WalkTree()**. This means that half the time Listing 44.4 has no advantage over Listing 44.2; in fact, it's at a disadvantage because the code that the compiler generates for handling right-subtree descent in Listing 44.4 is somewhat inefficient, but the right-subtree code in Listing 44.2 is a marvel of code generation, at just 3 instructions.

What's more, although left-subtree traversal is more efficient with data recursion than with code recursion, the advantage is only four instructions, because only one parameter is passed and because the compiler doesn't bother setting up an EBP-based stack frame, instead it uses ESP to address the stack. (And, in fact, this cost could be reduced still further by eliminating the check for a NULL **pNode** at all but the top level.) There are other interesting aspects to what the compiler does with Listings 44.2 and 44.4 but that's enough to give you the idea. It's worth noting that the compiler might not do as well with code recursion in a more complex function, and that a good assembly language implementation could probably speed up Listing 44.4 enough to make it measurably faster than Listing 44.2, but not even close to being *enough* faster to be worth the effort.

The moral of this story (apart from it being a good idea to enable compiler optimization) is:

1) Understand what you're doing, through and through.
2) Build a complete and consistent model in your head.
3) Design from the principles that the model provides.
4) Implement the design.
5) Measure to learn what you've wrought.
6) Go back to step 1 and apply what you've just learned.

With each iteration you'll dig deeper, learn more, and improve your ability to know where and how to focus your design and programming efforts. For example, with the C compilers I used five to ten years ago, back when I learned about the relative strengths and weaknesses of code and data recursion, and with the processors then in use, Listing 44.4 would have blown away Listing 44.2. While doing this chapter, I've learned that given current processors and compiler technology, data recursion isn't going to get me any big wins; and yes, that was news to me. That's *good*; this information saves me from wasted effort in the future and tells me what to concentrate on when I use recursion.

Assume nothing, keep digging deeper, and never stop learning and growing. The world won't hold still for you, but fortunately you *can* run fast enough to keep up if you just keep at it.

Depths within depths indeed!

Surfing Amidst the Trees

In the next chapter we'll build a BSP-tree compiler, and after that, we'll put together a rendering system built around the BSP trees the compiler generates. If the subject of BSP trees really grabs your fancy (as it should if you care at all about performance graphics) there is at this writing (February 1996) a World Wide Web page on BSP trees that you must investigate at http://www.qualia.com/bspfaq/. It's set up in the familiar Internet Frequently Asked Questions (FAQ) style, and is very good stuff.

Related Reading

Foley, J., A. van Dam, S. Feiner, and J. Hughes, *Computer Graphics: Principles and Practice (Second Edition)*, Addison Wesley, 1990, pp. 555-557, 675-680.

Fuchs, H., Z. Kedem, and B. Naylor, "On Visible Surface Generation by A Priori Tree Structures," *Computer Graphics* Vol. 17(3), June 1980, pp. 124-133.

Gordon, D., and S. Chen, "Front-to-Back Display of BSP Trees," *IEEE Computer Graphics and Applications*, September 1991, pp. 79-85.

Naylor, B., "Binary Space Partitioning Trees as an Alternative Representation of Polytopes," *Computer Aided Design*, Vol. 22(4), May 1990, pp. 250-253.

Compiling BSP Trees

Chapter 45

Taking BSP Trees from Concept to Reality

As long-time readers of my columns know, I tend to move my family around the country quite a bit. Change doesn't come out of the blue, so there's some interesting history to every move, but the roots of the latest move go back even farther than usual. To wit:

In 1986, just after we moved from Pennsylvania to California, I started writing a column for *Programmer's Journal.* I was paid peanuts for writing it, and I doubt if even 5000 people saw some of the first issues the columns appeared in, but I had a lot of fun exploring fast graphics for the EGA and VGA.

By 1991, we were in Vermont, and I was writing the *Graphics Programming* column for *Dr. Dobb's Journal* (and having a great time doing it, even though it took all my spare nights and weekends to stay ahead of the deadlines). In those days I received a lot of unsolicited evaluation software, including a PC shareware game called *Commander Keen*, a side-scrolling game that was every bit as good as the hot Nintendo games of the day. I loved the way the game looked, and actually drafted a column opening about how for years I'd been claiming that the PC could be a great game machine in the hands of great programmers, and here, finally, was the proof, in the form of *Commander Keen.* In the end, though, I decided that would be too close to a product review, an area that I've observed inflames passions in nonconstructive ways, so I went with a different opening.

In 1992, I did a series of columns about my X-Sharp 3D library, and hung out on *DDJ*'s bulletin board. There was another guy who hung out there who knew a lot about 3-D, a fellow named John Carmack who was surely the only game programmer I'd ever heard of who developed under NEXTSTEP. When we moved to Redmond, I didn't have time for BBSs anymore, though.

In early 1993, I hired Chris Hecker. Later that year, Chris showed me an alpha copy of *DOOM*, and I nearly fell out of my chair. About a year later, Chris forwarded me a newsgroup post about NEXTSTEP, and said, "Isn't this the guy you used to know on the *DDJ* bulletin board?" Indeed it was John Carmack; what's more, it turned out that John was the guy who had written *DOOM*. I sent him a congratulatory piece of mail, and he sent back some thoughts about what he was working on, and somewhere in there I asked if he ever came up my way. It turned out he had family in Seattle, so he stopped in and visited, and we had a great time.

Over the next year, we exchanged some fascinating mail, and I became steadily more impressed with John's company, id Software. Eventually, John asked if I'd be interested in joining id, and after a good bit of consideration I couldn't think of anything else that would be as much fun or teach me as much. The upshot is that here we all are in Dallas, our fourth move of 2000 miles or more since I've starting writing in the computer field, and now I'm writing some seriously cool 3-D software.

Now that I'm here, it's an eye-opener to look back and see how events fit together over the last decade. You see, when John started doing PC game programming he learned fast graphics programming from those early *Programmer's Journal* articles of mine. The copy of *Commander Keen* that validated my faith in the PC as a game machine was the fruit of those articles, for that was an id game (although I didn't know that then). When John was hanging out on the *DDJ* BBS, he had just done *Castle Wolfenstein 3-D*, the first great indoor 3-D game, and was thinking about how to do *DOOM*. (If only I'd known that then!) And had I not hired Chris, or had he not somehow remembered me talking about that guy who used NEXTSTEP, I'd never have gotten back in touch with John, and things would surely be different. (At the very least, I wouldn't be hearing jokes about how my daughter's going to grow up saying "y'all".)

I think there's a worthwhile lesson to be learned from all this, a lesson that I've seen hold true for many other people, as well. If you do what you love, and do it as well as you can, good things will eventually come of it. Not necessarily quickly or easily, but if you stick with it, they will come. There are threads that run through our lives, and by the time we've been adults for a while, practically everything that happens has roots that run far back in time. The implication should be clear: If you want good things to happen in your future, stretch yourself and put in the extra effort now at whatever you care passionately about, so those roots will have plenty to work with down the road.

All this is surprisingly closely related to this Chapter's topic, BSP trees, because John is the fellow who brought BSP trees into the spotlight by building DOOM around them. He also got me started with BSP trees by explaining how DOOM worked and getting me interested enough to want to experiment; the BSP compiler in this article is the direct result. Finally, John has been an invaluable help to me as I've learned about BSP trees, as will become evident when we discuss BSP optimization.

Onward to compiling BSP trees.

Compiling BSP Trees

As you'll recall from the previous chapter, a BSP tree is nothing more than a series of binary subdivisions that partion space into ever-smaller pieces. That's a simple data structure, and a BSP compiler is a correspondingly simple tool. First, it groups all the surfaces (lines in 2-D, or polygons in 3-D) together into a single subspace that encompasses the entire world of the database. Then, it chooses one of the surfaces as the root node, and uses its line or plane to divide the remaining surfaces into two subspaces, splitting surfaces into two parts if they cross the line or plane of the root. Each of the two resultant subspaces is then processed in the same fashion, and so on, recursively, until the point is reached where all surfaces have been assigned to nodes, and each leaf surface subdivides a subspace that is empty except for that surface. Put another way, the root node carves space into two parts, and the root's children carve each of those parts into two more parts, and so on, with each surface carving ever smaller subspaces, until all surfaces have been used. (Actually, there are many other lines or planes that a BSP tree can use to carve up space, but this is the approach we'll use in the current discussion.)

If you find any of the above confusing (and it would be understandable if that were the case; BSP trees are not easy to get the hang of), you might want to refer back to the previous chapter. It would also be a good idea to get hold of the visual BSP compiler I'll discuss shortly; when it comes to understanding BSP trees, there's nothing quite like seeing one being built.

So there are really only two interesting operations in building a BSP tree: choosing a root node for the current subspace (a "splitter") and assigning surfaces to one side or another of the current root node, splitting any that straddle the splitter. We'll get to the issue of choosing splitters shortly, but first let's look at the process of splitting and assigning. To do that, we need to understand parametric lines.

Parametric Lines

We're all familiar with lines described in slope-intercept form, with y as a function of x:

$$y = mx + b,$$

but there's another sort of line description that's very useful for clipping (and for a variety of 3-D purposes, such as curved surfaces and texture mapping): *parametric lines.* In parametric lines, x and y are decoupled from one another, and are instead described as a function of the parameter t:

$$x = x_{start} + t(x_{end} - x_{start})$$
$$y = y_{start} + t(y_{end} - y_{start}).$$

This can be summarized as:

$$L = L_{start} + t(L_{end} - L_{start})$$

where L = (x, y).

Figure 45.1 shows how a parametric line works. The t parameter describes how far along a line segment the current x and y coordinates are. Note that this description is valid not only for the line segment, but also for the entire infinite line; however, only points with t values between 0 and 1 are actually on the line segment.

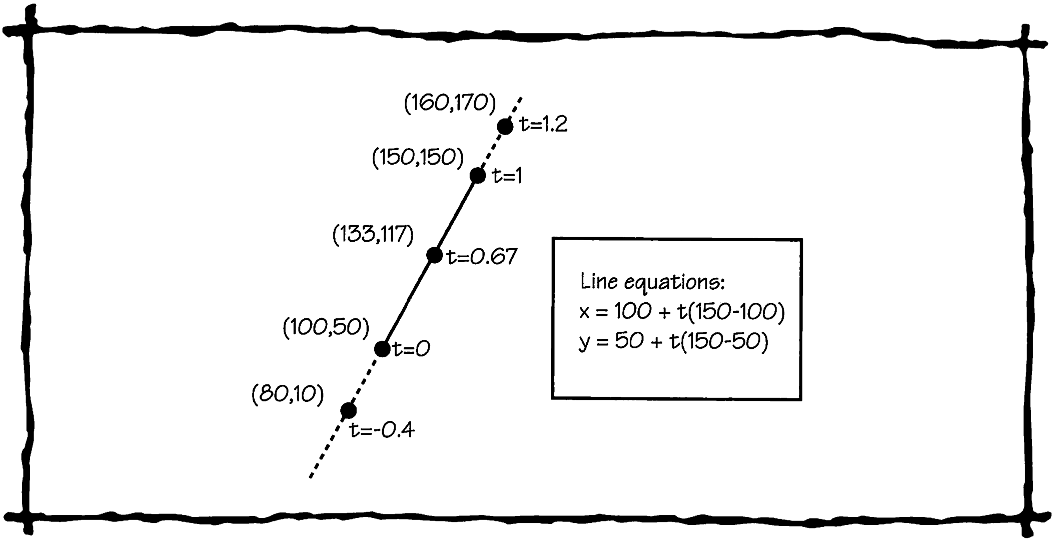


Figure 45.1 A sample parametric line.

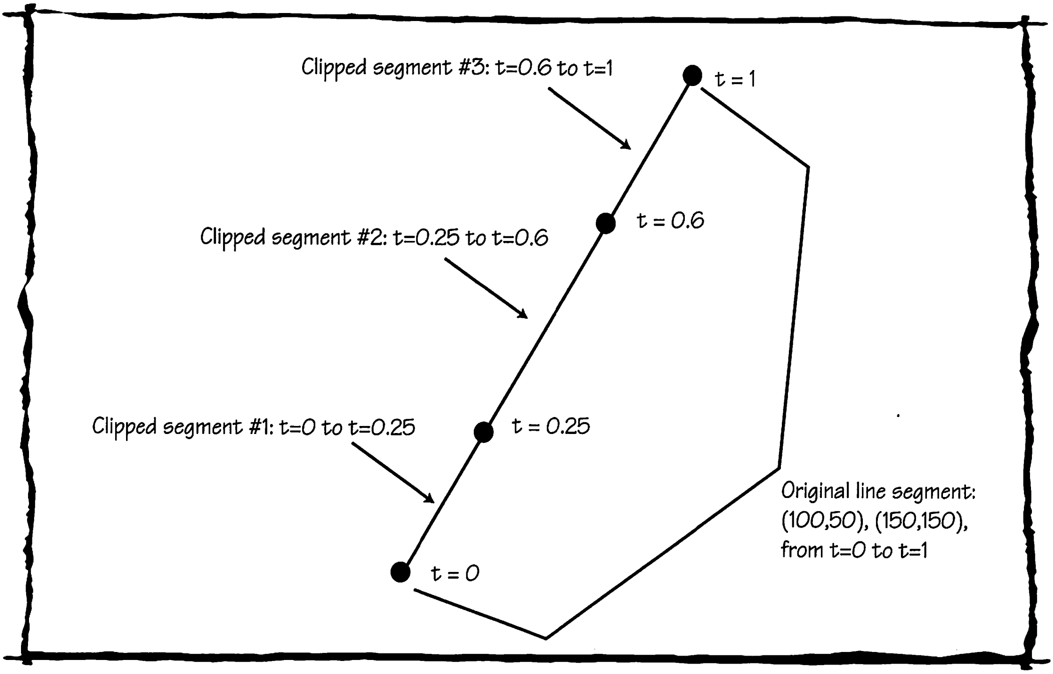

Clipped segment #3: t=0.6 to t=1
t = 1
Clipped segment #2: t=0.25 to t=0.6
t = 0.6
Clipped segment #1: t=0 to t=0.25
t = 0.25
t = 0
Original line segment:
(100,50), (150,150),
from t=0 to t=1

Figure 45.2 Line segment storage in the BSP compiler.

In our 2-D BSP compiler (as you'll recall from the previous chapter, we're working with 2-D trees for simplicity, but the principles generalize to 3-D), we'll represent our walls (all vertical) as line segments viewed from above. The segments will be stored in parametric form, with the endpoints of the original line segment and two t values describing the endpoints of the current (possibly clipped) segment providing a complete specification for each segment, as shown in Figure 45.2.

What does that do for us? For one thing, it keeps clipping errors from creeping in, because clipped line segments are always based on the original line segment, not derived from clipped versions. Also, it's potentially a more compact format, because we need to store the endpoints only for the original line segments; for clipped line segments, we can just store pairs of t values, along with a pointer to the original line segment. The biggest win, however, is that it allows us to use parametric line clipping, a very clean form of clipping, indeed.

Parametric Line Clipping

In order to assign a line segment to one subspace or the other of a splitter, we must somehow figure out whether the line segment straddles the splitter or falls on one side or the other. In order to determine that, we first plug the line segment and splitter into the following parametric line intersection equation:

$$\text{numer} = N\ (L_{start} - S_{start})\quad\text{(Equation 1)}$$
$$\text{denom} = -N\ (L_{end} - L_{start})\quad\text{(Equation 2)}$$
$$t_{intersect} = \text{numer} / \text{denom}\quad\text{(Equation 3)}$$

where N is the normal of the splitter, S_{start} is the start point of the splitting line segment in standard (x,y) form, and L_{start} and L_{end} are the endpoints of the line segment being split, again in (x,y) form. Figure 45.3 illustrates the intersection calculation. Due to lack of space, I'm just going to present this equation and its implications as fact, rather than deriving them; if you want to know more, there's an excellent explanation on page 117 of *Computer Graphics: Principles and Practice*, by Foley and van Dam (Addison Wesley, ISBN 0-201-12110-7), a book that you should certainly have in your library.

If the denominator is zero, we know that the lines are parallel and don't intersect, so we don't divide, but rather check the sign of the numerator, which tells us which side of the splitter the line segment is on. Otherwise, we do the division, and the result is the t value for the intersection point, as shown in Figure 45.3. We then simply compare the t value to the t values of the endpoints of the line segment being split. If it's between them, that's where we split the line segment, otherwise, we can tell which side of the splitter the line segment is on by which side of the line segment's t range it's on. Simple comparisons do all the work, and there's no need to do the work of generating actual x and y values. If you look closely at Listing 45.1, the core of the BSP compiler, you'll see that the parametric clipping code itself is exceedingly short and simple.

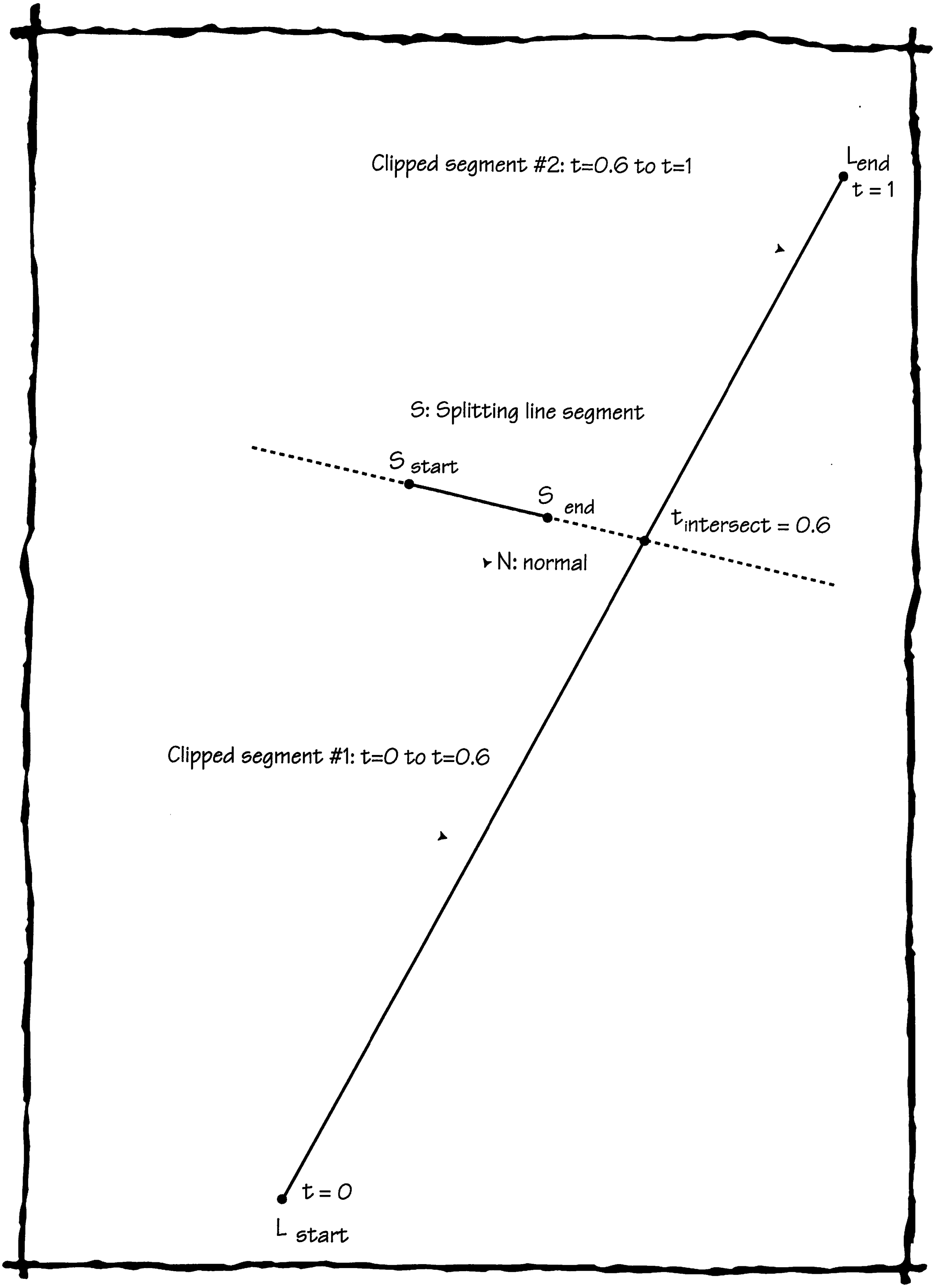

Clipped segment #2: t=0.6 to t=1
L_{end}
t = 1
S: Splitting line segment
S start
S end
$t_{intersect}$ = 0.6
N: normal
Clipped segment #1: t=0 to t=0.6
t = 0
L start

Figure 45.3 How line intersection is calculated.

One interesting point about Listing 45.1 is that it generates normals to splitting surfaces simply by exchanging the x and y lengths of the splitting line segment and negating the resultant y value, thereby rotating the line 90 degrees. In 3-D, it's not that simple to come by a normal; you could calculate the normal as the cross-product of two of the polygon's edges, or precalculate it when you build the world database.

The BSP Compiler

Listing 45.1 shows the core of a BSP compiler—the code that actually builds the BSP tree. (Note that Listing 45.1 is excerpted from a C++ .CPP file, but in fact what I show here is very close to straight C. It may even compile as a .C file, though I haven't checked.) The compiler begins by setting up an empty tree, then passes that tree and the complete set of line segments from which a BSP tree is to be generated to **SelectBSPTree()**, which chooses a root node and calls **BuildBSPTree()** to add that node to the tree and generate child trees for each of the node's two subspaces. **BuildBSPTree()** calls **SelectBSPTree()** recursively to select a root node for each of those child trees, and this continues until all lines have been assigned nodes. **SelectBSP()** uses parametric clipping to decide on the splitter, as described below, and **BuildBSPTree()** uses parametric clipping to decide which subspace of the splitter each line belongs in, and to split lines, if necessary.

Listing 45.1. L45_1.CPP

```
#define MAX_NUM_LINESEGS 1000
#define MAX_INT          0x7FFFFFFF
#define MATCH_TOLERANCE  0.00001
// A vertex
typedef struct _VERTEX
{
   double x;
   double y;
} VERTEX;
// A potentially split piece of a line segment, as processed from the
// base line in the original list
typedef struct _LINESEG
{
   _LINESEG *pnextlineseg;
    int startvertex;
    int endvertex;
    double walltop;
    double wallbottom;
    double tstart;
    double tend;
    int color;
    _LINESEG *pfronttree;
    _LINESEG *pbacktree;
} LINESEG, *PLINESEG;
static VERTEX *pvertexlist;
static int NumCompiledLinesegs = 0;
static LINESEG *pCompiledLinesegs;
// Builds a BSP tree from the specified line list. List must contain
// at least one entry. If pCurrentTree is NULL, then this is the root
// node, otherwise pCurrentTree is the tree that's been build so far.
// Returns NULL for errors.
LINESEG * SelectBSPTree(LINESEG * plineseghead,
    LINESEG * pCurrentTree, LINESEG ** pParentsChildPointer)
{
    LINESEG *pminsplit;
    int minsplits;
    int tempsplitcount;
    LINESEG *prootline;
    LINESEG *pcurrentline;
    double nx, ny, numer, denom, t;
    // Pick a line as the root, and remove it from the list of lines
    // to be categorized. The line we'll select is the one of those in
    // the list that splits the fewest of the other lines in the list
    minsplits = MAX_INT;
    prootline = plineseghead;
    while (prootline != NULL) {
        pcurrentline = plineseghead;
        tempsplitcount = 0;
        while (pcurrentline != NULL) {
            // See how many other lines the current line splits
            nx = pvertexlist[prootline->startvertex].y -
                    pvertexlist[prootline->endvertex].y;
            ny = -(pvertexlist[prootline->startvertex].x -
                    pvertexlist[prootline->endvertex].x);
            // Calculate the dot products we'll need for line
            // intersection and spatial relationship
            numer = (nx * (pvertexlist[pcurrentline->startvertex].x -
                    pvertexlist[prootline->startvertex].x)) +
                    (ny * (pvertexlist[pcurrentline->startvertex].y -
                    pvertexlist[prootline->startvertex].y));
            denom = ((-nx) * (pvertexlist[pcurrentline->endvertex].x -
                    pvertexlist[pcurrentline->startvertex].x)) +
                    ((-ny) * (pvertexlist[pcurrentline->endvertex].y -
                    pvertexlist[pcurrentline->startvertex].y));
            // Figure out if the infinite lines of the current line
            // and the root intersect; if so, figure out if the
            // current line segment is actually split, split if so,
            // and add front/back polygons as appropriate
            if (denom == 0.0) {
                // No intersection, because lines are parallel; no
                // split, so nothing to do
            } else {
                // Infinite lines intersect; figure out whether the
                // actual line segment intersects the infinite line
                // of the root, and split if so
                t =  numer / denom;
                if ((t > pcurrentline->tstart) &&
                        (t < pcurrentline->tend)) {
                    // The root splits the current line
                    tempsplitcount++;
                } else {
                    // Intersection outside segment limits, so no
                    // split, nothing to do
                }
            }
            pcurrentline = pcurrentline->pnextlineseg;
        }
        if (tempsplitcount < minsplits) {
            pminsplit = prootline;
            minsplits = tempsplitcount;
        }
        prootline = prootline->pnextlineseg;
    }
    // For now, make this a leaf node so we can traverse the tree
    // as it is at this point. BuildBSPTree() will add children as
    // appropriate
    pminsplit->pfronttree = NULL;
    pminsplit->pbacktree = NULL;
    // Point the parent's child pointer to this node, so we can
    // track the currently-build tree
    *pParentsChildPointer = pminsplit;
    return BuildBSPTree(plineseghead, pminsplit, pCurrentTree);
}
// Builds a BSP tree given the specified root, by creating front and
// back lists from the remaining lines, and calling itself recursively
LINESEG * BuildBSPTree(LINESEG * plineseghead, LINESEG * prootline,
    LINESEG * pCurrentTree)
{
    LINESEG *pfrontlines;
    LINESEG *pbacklines;
    LINESEG *pcurrentline;
    LINESEG *pnextlineseg;
    LINESEG *psplitline;
    double nx, ny, numer, denom, t;
    int Done;
    // Categorize all non-root lines as either in front of the root's
    // infinite line, behind the root's infinite line, or split by the
    // root's infinite line, in which case we split it into two lines
    pfrontlines = NULL;
    pbacklines = NULL;
    pcurrentline = plineseghead;
    while (pcurrentline != NULL)
    {
      // Skip the root line when encountered
      if (pcurrentline == prootline) {
        pcurrentline = pcurrentline->pnextlineseg;
      } else  {
        nx = pvertexlist[prootline->startvertex].y -
                pvertexlist[prootline->endvertex].y;
        ny = -(pvertexlist[prootline->startvertex].x -
                pvertexlist[prootline->endvertex].x);
        // Calculate the dot products we'll need for line intersection
        // and spatial relationship
        numer = (nx * (pvertexlist[pcurrentline->startvertex].x -
                 pvertexlist[prootline->startvertex].x)) +
                (ny * (pvertexlist[pcurrentline->startvertex].y -
                 pvertexlist[prootline->startvertex].y));
        denom = ((-nx) * (pvertexlist[pcurrentline->endvertex].x -
                 pvertexlist[pcurrentline->startvertex].x)) +
                (-(ny) * (pvertexlist[pcurrentline->endvertex].y -
                 pvertexlist[pcurrentline->startvertex].y));
        // Figure out if the infinite lines of the current line and
        // the root intersect; if so, figure out if the current line
        // segment is actually split, split if so, and add front/back
        // polygons as appropriate
        if (denom == 0.0) {
            // No intersection, because lines are parallel; just add
            // to appropriate list
            pnextlineseg = pcurrentline->pnextlineseg;
            if (numer < 0.0) {
```

```
        // Current line is in front of root line; link into
        // front list
        pcurrentline->pnextlineseg = pfrontlines;
        pfrontlines = pcurrentline;
    } else {
        // Current line behind root line; link into back list
        pcurrentline->pnextlineseg = pbacklines;
        pbacklines = pcurrentline;
    }
    pcurrentline = pnextlineseg;
} else {
    // Infinite lines intersect; figure out whether the actual
    // line segment intersects the infinite line of the root,
    // and split if so
    t =  numer / denom;
    if ((t > pcurrentline->tstart) &&
            (t < pcurrentline->tend)) {
        // The line segment must be split; add one split
        // segment to each list
        if (NumCompiledLinesegs > (MAX_NUM_LINESEGS - 1)) {
            DisplayMessageBox("Out of space for line segs; "
                         "increase MAX_NUM_LINESEGS");
            return NULL;
        }
        // Make a new line entry for the split part of line
        psplitline = &pCompiledLinesegs[NumCompiledLinesegs];
        NumCompiledLinesegs++;
        *psplitline = *pcurrentline;
        psplitline->tstart = t;
        pcurrentline->tend = t;

        pnextlineseg = pcurrentline->pnextlineseg;
        if (numer < 0.0) {
            // Presplit part is in front of root line; link
            // into front list and put postsplit part in back
            // list
            pcurrentline->pnextlineseg = pfrontlines;
            pfrontlines = pcurrentline;
            psplitline->pnextlineseg = pbacklines;
            pbacklines = psplitline;
        } else {
            // Presplit part is in back of root line; link
            // into back list and put postsplit part in front
            // list
            psplitline->pnextlineseg = pfrontlines;
            pfrontlines = psplitline;
            pcurrentline->pnextlineseg = pbacklines;
            pbacklines = pcurrentline;
        }
        pcurrentline = pnextlineseg;
    } else {
        // Intersection outside segment limits, so no need to
        // split; just add to proper list
        pnextlineseg = pcurrentline->pnextlineseg;
        Done = 0;
        while (!Done) {
            if (numer < -MATCH_TOLERANCE) {
                // Current line is in front of root line;
                // link into front list
                pcurrentline->pnextlineseg = pfrontlines;
                pfrontlines = pcurrentline;
                Done = 1;
```

```
                    } else if (numer > MATCH_TOLERANCE) {
                        // Current line is behind root line; link
                        // into back list
                        pcurrentline->pnextlineseg = pbacklines;
                        pbacklines = pcurrentline;
                        Done = 1;
                    } else {
                        // The point on the current line we picked to
                        // do front/back evaluation happens to be
                        // collinear with the root, so use the other
                        // end of the current line and try again
                        numer =
                            (nx *
                             (pvertexlist[pcurrentline->endvertex].x -
                              pvertexlist[prootline->startvertex].x))+
                            (ny *
                             (pvertexlist[pcurrentline->endvertex].y -
                              pvertexlist[prootline->startvertex].y));
                    }
                }
                pcurrentline = pnextlineseg;
            }
        }
      }
    }
    // Make a node out of the root line, with the front and back trees
    // attached
    if (pfrontlines == NULL) {
        prootline->pfronttree = NULL;
    } else {
        if (!SelectBSPTree(pfrontlines, pCurrentTree,
                          &prootline->pfronttree)) {
            return NULL;
        }
    }
    if (pbacklines == NULL) {
        prootline->pbacktree = NULL;
    } else {
        if (!SelectBSPTree(pbacklines, pCurrentTree,
                          &prootline->pbacktree)) {
            return NULL;
        }
    }
    return(prootline);
}
```

Listing 45.1 isn't very long or complex, but it's somewhat more complicated than it could be because it's structured to allow visual display of the ongoing compilation process. That's because Listing 45.1 is actually just a part of a BSP compiler for Win32 that visually depicts the progressive subdivision of space as the BSP tree is built. (Note that Listing 45.1 might not compile as printed; I may have missed copying some global variables that it uses.) The complete code is too large to print here in its entirety, but it's on the CD-ROM in file DDJBSP.ZIP.

Optimizing the BSP Tree

In the previous chapter, I promised that I'd discuss how to go about deciding which wall to use as the splitter at each node in constructing a BSP tree. That turns out to be a far more difficult problem than one might think, but we can't ignore it, because the choice of splitter can make a huge difference.

Consider, for example, a BSP in which the line or plane of the splitter at the root node splits every single other surface in the world, doubling the total number of surfaces to be dealt with. Contrast that with a BSP built from the same surface set in which the initial splitter doesn't split anything. Both trees provide a valid ordering, but one tree is much larger than the other, with twice as many polygons after the selection of just one node. Apply the same difference again to each node, and the relative difference in size (and, correspondingly, in traversal and rendering time) soon balloons astronomically. So we need to do *something* to optimize the BSP tree—but what? Before we can try to answer that, we need to know exactly what we'd like to optimize.

There are several possible optimization objectives in BSP compilation. We might choose to balance the tree as evenly as possible, thereby reducing the average depth to which the tree must be traversed. Alternatively, we might try to approximately balance the area or volume on either side of each splitter. That way we don't end up with huge chunks of space in some tree branches and tiny slivers in others, and the overall processing time will be more consistent. Or, we might choose to select planes aligned with the major axes, because such planes can help speed up our BSP traversal.

The BSP metric that seems most useful to me, however, is the number of polygons that are split into two polygons in the course of building a BSP tree. Fewer splits is better; the tree is smaller with fewer polygons, and drawing will go faster with fewer polygons to draw, due to per-polygon overhead. There's a problem with the fewest-splits metric, though: There's no sure way to achieve it.

The obvious approach to minimizing polygon splits would be to try all possible trees to find the best one. Unfortunately, the order of that particular problem is N!, as I found to my dismay when I implemented brute-force optimization in the first version of my BSP compiler. Take a moment to calculate the number of operations for the 20-polygon set I originally tried brute-force optimization on. I'll give you a hint: There are 19 digits in 20!, and if each operation takes only one microsecond, that's over 70,000 years (or, if you prefer, over 500,000 dog years.) Now consider that a single game level might have 5000 to 10,000 polygons; there aren't anywhere near enough dog years in the lifetime of the universe to handle that. We're going to have to give up on optimal compilation and come up with a decent heuristic approach, no matter what optimization objective we select.

In Listing 45.1, I've applied the popular heuristic of choosing as the splitter at each node the surface that splits the fewest of the other surfaces that are being considered for that node. In other words, I choose the wall that splits the fewest of the walls in the subspace it's subdividing.

BSP Optimization: an Undiscovered Country

Although BSP trees have been around for at least 15 years now, they're still only partially understood and are a ripe area for applied research and general ingenuity. You might want to try your hand at inventing new BSP optimization approaches; it's an interesting problem, and you might strike paydirt. There are many things that BSP trees can't do well, because it takes so long to build them—but what they do, they do exceedingly well, so a better compilation approach that allowed BSP trees to be used for more purposes would be valuable, indeed.

Frames of Reference

Chapter 46

The Fundamentals of the Math behind 3-D Graphics

Several years ago, I opened a column in *Dr. Dobb's Journal* with a story about singing my daughter to sleep with Beatles' songs. Beatles' songs, at least the earlier ones, tend to be bouncy and pleasant, which makes them suitable goodnight fodder—and there are a *lot* of them, a useful hedge against terminal boredom. So for many good reasons, "Can't Buy Me Love "and "A Hard Day's Night" and "Help!" and the rest were evening staples for years.

No longer, though. You see, I got my wife some Beatles tapes for Christmas, and we've all been listening to them in the car, and now that my daughter has heard the real thing, she can barely stand to be in the same room, much less fall asleep, when I sing those songs.

What's noteworthy is that the only variable involved in this change was my daughter's frame of reference. My singing hasn't gotten any worse over the last four years. (I'm not sure it's *possible* for my singing to get worse.) All that changed was my daughter's frame of reference for those songs. The rest of the universe stayed the same; the change was in her mind, lock, stock, and barrel.

Often, the key to solving a problem, or to working on a problem efficiently, is having a proper frame of reference. The model you have of a problem you're tackling often determines how deeply you can understand the problem, and how flexible and innovative you'll be able to be in solving it.

An excellent example of this, and one that I'll discuss toward the end of this chapter, is that of *3-D transformation*—the process of converting coordinates from one coordinate space to another, for example from worldspace to viewspace. The way this is traditionally explained is functional, but not particularly intuitive, and fairly hard to visualize. Recently, I've come across another way of looking at transforms that seems to me to be far easier to grasp. The two approaches are technically equivalent, so the difference is purely a matter of how we choose to view things—but sometimes that's the most important sort of difference.

Before we can talk about transforming between coordinate spaces, however, we need two building blocks: dot products and cross products.

3-D Math

At this point in the book I was originally going to present a BSP-based renderer, to complement the BSP compiler I presented in the previous chapter. What changed my plans was the considerable amount of mail about 3-D math that I've gotten in recent months. In every case, the writer has bemoaned their lack of expertise with 3-D math, and has asked what books about 3-D math I'd recommend, and how else they could learn more.

That's a commendable attitude, but the truth is, there's not all that much to 3-D math, at least not when it comes to the sort of polygon-based, realtime 3-D that's done on PCs. You really need only two basic math tools beyond simple arithmetic: dot products and cross products, and really mostly just the former. My friend Chris Hecker points out that this is an oversimplification; he notes that lots more math-related stuff, like BSP trees, graphs, discrete math for edge stepping, and affine and perspective texture mappings, goes into a production-quality game. While that's surely true, dot and cross products, together with matrix math and perspective projection, constitute the bulk of what most people are asking about when they inquire about "3-D math," and, as we'll see, are key tools for a lot of useful 3-D operations.

The other thing the mail made clear was that there are a lot of people out there who don't understand either type of product, at least insofar as they apply to 3-D. Since much or even most advanced 3-D graphics machinery relies to a greater or lesser extent on dot products and cross products (even the line intersection formula I discussed in the last chapter is actually a quotient of dot products), I'm going to spend this chapter examining these basic tools and some of their 3-D applications. If this is old hat to you, my apologies, and I'll return to BSP-based rendering in the next chapter.

Foundation Definitions

The dot and cross products themselves are straightforward and require almost no context to understand, but I need to define some terms I'll use when describing applications of the products, so I'll do that now, and then get started with dot products.

I'm going to have to assume you have *some* math backgroun, or we'll never get to the good stuff. So, I'm just going to quickly define a *vector* as a direction and a magnitude, represented as a coordinate pair (in 2-D) or triplet (in 3-D), relative to the origin. That's a pretty sloppy definition, but it'll do for our purposes; if you want the Real McCoy, I suggest you check out *Calculus and Analytic Geometry*, by Thomas and Finney (Addison-Wesley: ISBN 0-201-52929-7).

So, for example, in 3-D, the vector V = [5 0 5] has a length, or magnitude, by the Pythagorean theorem, of

$$\|\mathbf{V}\| = \sqrt{v_1^2 + v_2^2 + v_3^2} = \sqrt{5^2 + 0^2 + 5^2} = 5\sqrt{2}, \qquad \text{(eq. 1)}$$

(where vertical double bars denote vector length), and a direction in the plane of the x and z axes, exactly halfway between those two axes.

I'll be working in a left-handed coordinate system, whereby if you wrap the fingers of your left hand around the z axis with your thumb pointing in the positive z direction, your fingers will curl from the positive x axis to the positive y axis. The positive x axis runs left to right across the screen, the positive y axis runs bottom to top across the screen, and the positive z axis runs into the screen.

For our purposes, *projection* is the process of mapping coordinates onto a line or surface. *Perspective projection* projects 3-D coordinates onto a viewplane, scaling coordinates according to their z distance from the viewpoint in order to provide proper perspective. *Objectspace* is the coordinate space in which an object is defined, independent of other objects and the world itself. *Worldspace* is the absolute frame of reference for a 3-D world; all objects' locations and orientations are with respect to worldspace, and this is the frame of reference around which the viewpoint and view direction move. *Viewspace* is worldspace as seen from the viewpoint, looking in the view direction. *Screenspace* is viewspace after perspective projection and scaling to the screen.

Finally, *transformation* is the process of converting points from one coordinate space into another; in our case, that'll mean rotating and translating (moving) points from objectspace or worldspace to viewspace.

For additional information, you might want to check out Foley & van Dam's *Computer Graphics* (ISBN 0-201-12110-7), or the chapters in Part IX of this book, dealing with my X-Sharp 3-D graphics library.

The Dot Product

Now we're ready to move on to the dot product. Given two vectors U = [u_1 u_2 u_3] and V = [v_1 v_2 v_3], their dot product, denoted by the symbol •, is calculated as:

$$\mathbf{U} \bullet \mathbf{V} = u_1 v_1 + u_2 v_2 + u_3 v_3. \qquad \text{(eq. 2)}$$

As you can see, the result is a scalar value (a single real-valued number), *not* another vector.

Now that we know how to calculate a dot product, what does that get us? Not much. The dot product isn't of much use for graphics until you start thinking of it this way:

$$\mathbf{U} \bullet \mathbf{V} = \cos(\theta)\, \|\mathbf{U}\|\, \|\mathbf{V}\|, \qquad \text{(eq. 3)}$$

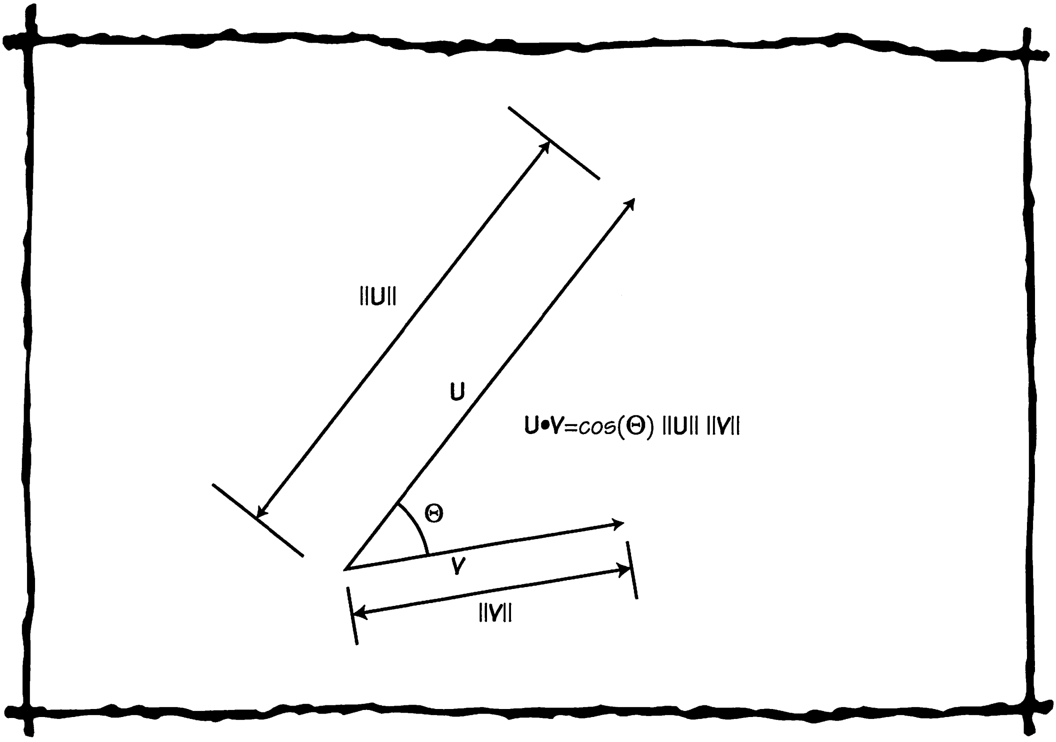


Figure 46.1 The dot product.

where θ is the angle between the two vectors, and the other two terms are the lengths of the vectors, as shown in Figure 46.1. Although it's not immediately obvious, equation 3 has a wide variety of applications in 3-D graphics.

Dot Products of Unit Vectors

The simplest case of the dot product is when both vectors are *unit vectors*; that is, when their lengths are both one, as calculated as in Equation 1. In this case, equation 3 simplifies to

$$\mathbf{U} \bullet \mathbf{V} = \cos(\theta). \qquad \text{(eq. 4)}$$

In other words, the dot product of two unit vectors is the cosine of the angle between them.

One obvious use of this is to find angles between unit vectors, in conjunction with an inverse cosine function or lookup table. A more useful application in 3-D graphics lies in lighting surfaces, where the cosine of the angle between incident light and the normal (perpendicular vector) of a surface determines the fraction of the light's full intensity at which the surface is illuminated, as in:

$$I_s = I_l\cos(\theta). \qquad \text{(eq. 5)}$$

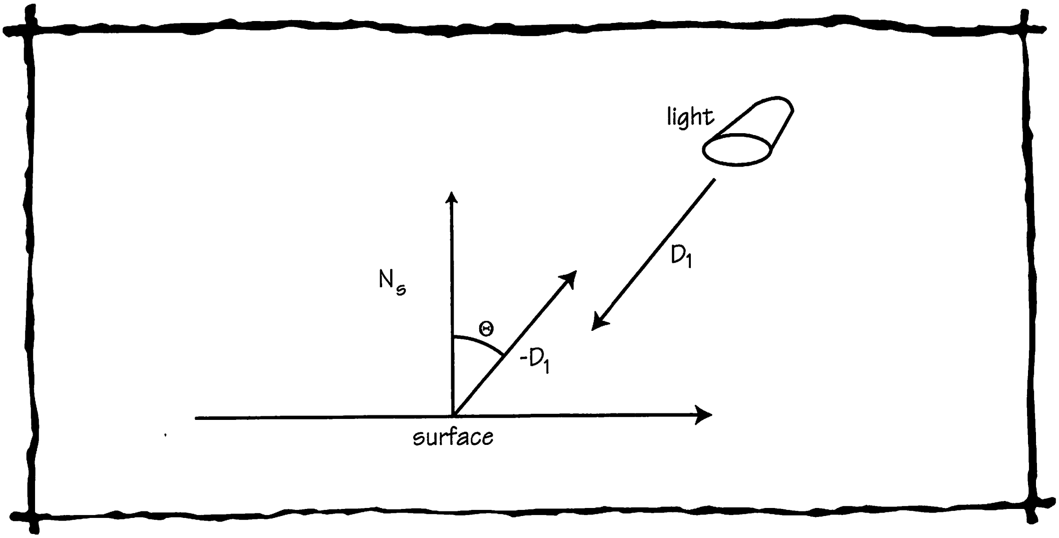


Figure 46.2 The dot product as used in calculating lighting intensity.

where I_s is the intensity of illumination of the surface, I_l is the intensity of the light, and θ is the angle between $-D_l$ (where D_l is the light direction vector) and the surface normal. If the inverse light vector and the surface normal are both unit vectors, then this calculation can be performed with four multiplies and three additions—and no explicit cosine calculations—as:

$$I_s = I_l\left(\mathbf{N}_s \bullet -\mathbf{D}_l\right), \qquad \text{(eq. 6)}$$

where N_s is the surface unit normal and D_l is the light unit direction vector, as shown in Figure 46.2.

Cross Products and the Generation of Polygon Normals

One question Equation 6 begs is where the surface unit normal comes from. One approach is to store the end of a surface normal as an extra data point with each polygon (with the start being some point that's already in the polygon), and transform it along with the rest of the points. This has the advantage that if the normal starts out as a unit normal, it will end up that way too, if only rotations and translations (but not scaling and shears) are performed.

The problem with having an explicit normal is that it will remain a normal—that is, perpendicular to the surface- -only through viewspace. Rotation, translation, and scaling preserve right angles, which is why normals are still normals in viewspace, but perspective projection does not preserve angles, so vectors that were surface normals in viewspace are no longer normals in screenspace.

Why does this matter? It matters because, on average, half the polygons in any scene are facing away from the viewer, and hence shouldn't be drawn. One way to identify such polygons is to see whether they're facing toward or away from the viewer; that is, whether their normals have negative z values (so they're visible) or positive z values (so they should be culled). However, we're talking about screenspace normals here, because the perspective projection can shift a polygon relative to the viewpoint so that although its viewspace normal has a negative z, its screenspace normal has a positive z, and vice-versa, as shown in Figure 46.3. So we need screenspace normals, but those can't readily be generated by transformation from worldspace.

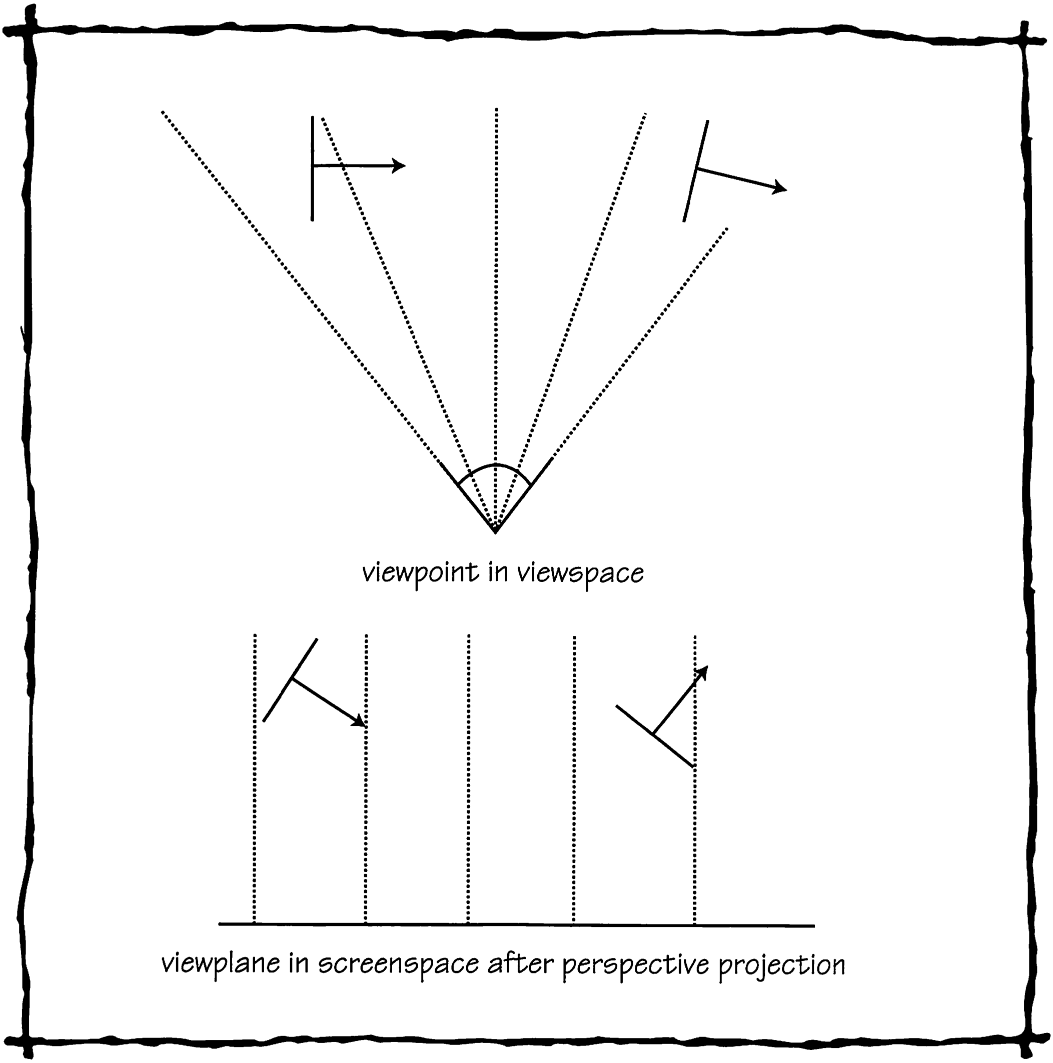


Figure 46.3 A problem with determining front/back visibility.

The solution is to use the cross product of two of the polygon's edges to generate a normal. The formula for the cross product is:

$$\mathbf{U} \times \mathbf{V} = \begin{bmatrix} u_2 v_3 - u_3 v_2 & u_3 v_1 - u_1 v_3 & u_1 v_2 - u_2 v_1 \end{bmatrix} \qquad \text{(eq. 7)}$$

(Note that the cross product operation is denoted by an X.) Unlike the dot product, the result of the cross product is a vector. Not just any vector, either; the vector generated by the cross product is perpendicular to both of the original vectors. Thus, the cross product can be used to generate a normal to any surface for which you have two vectors that lie within the surface. This means that we can generate the screenspace normals we need by taking the cross product of two adjacent polygon edges, as shown in Figure 46.4.

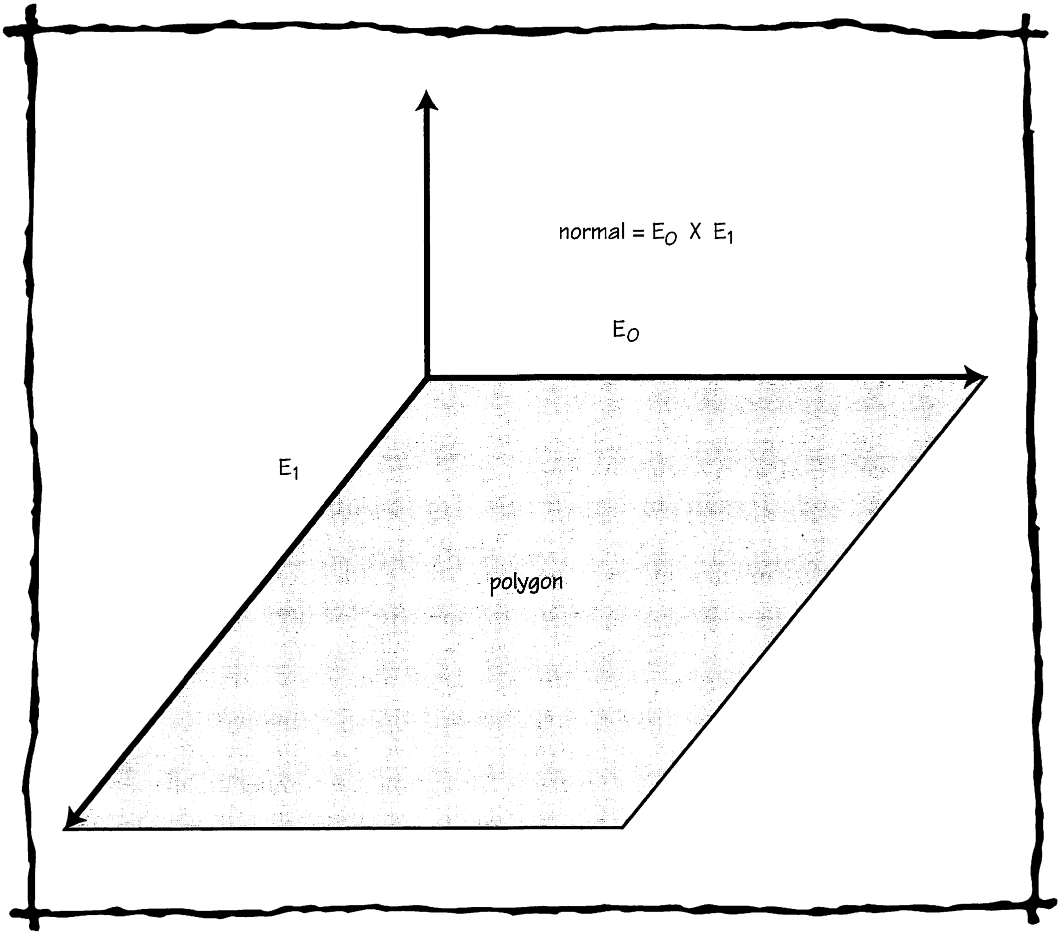


Figure 46.4 How the cross product of polygon edge vectors generates a polygon normal.

In fact, we can cull with only one-third the work needed to generate a full cross product; because we're interested only in the sign of the z component of the normal, we can skip entirely calculating the x and y components. The only caveat is to be careful that neither edge you choose is zero-length and that the edges aren't collinear, because the dot product can't produce a normal in those cases.

Perhaps the most often asked question about cross products is "Which way do normals generated by cross products go?" In a left-handed coordinate system, curl the fingers of your left hand so the fingers curl through an angle of less than 180 degrees from the first vector in the cross product to the second vector. Your thumb now points in the direction of the normal.

If you take the cross product of two orthogonal (right-angle) unit vectors, the result will be a unit vector that's orthogonal to both of them. This means that if you're generating a new coordinate space—such as a new viewing frame of reference—you only need to come up with unit vectors for two of the axes for the new coordinate space, and can then use their cross product to generate the unit vector for the third axis. If you need unit normals, and the two vectors being crossed aren't orthogonal unit vectors, you'll have to normalize the resulting vector; that is, divide each of the vector's components by the length of the vector, to make it a unit long.

Using the Sign of the Dot Product

The dot product is the cosine of the angle between two vectors, scaled by the magnitudes of the vectors. Magnitudes are always positive, so the sign of the cosine determines the sign of the result. The dot product is positive if the angle between the vectors is less than 90 degrees, negative if it's greater than 90 degrees, and zero if the angle is exactly 90 degrees. This means that just the sign of the dot product suffices for tests involving comparisons of angles to 90 degrees, and there are more of those than you'd think.

Consider, for example, the process of backface culling, which we discussed above in the context of using screenspace normals to determine polygon orientation relative to the viewer. The problem with that approach is that it requires each polygon to be transformed into viewspace, then perspective projected into screenspace, before the test can be performed, and that involves a lot of time-consuming calculation. Instead, we can perform culling way back in worldspace (or even earlier, in objectspace, if we transform the viewpoint into that frame of reference), given only a vertex and a normal for each polygon and a location for the viewer.

Here's the trick: Calculate the vector from the viewpoint to any vertex in the polygon and take its dot product with the polygon's normal, as shown in Figure 46.5. If the polygon is facing the viewpoint, the result is negative, because the angle between the two vectors is greater than 90 degrees. If the polygon is facing away, the result is posi-

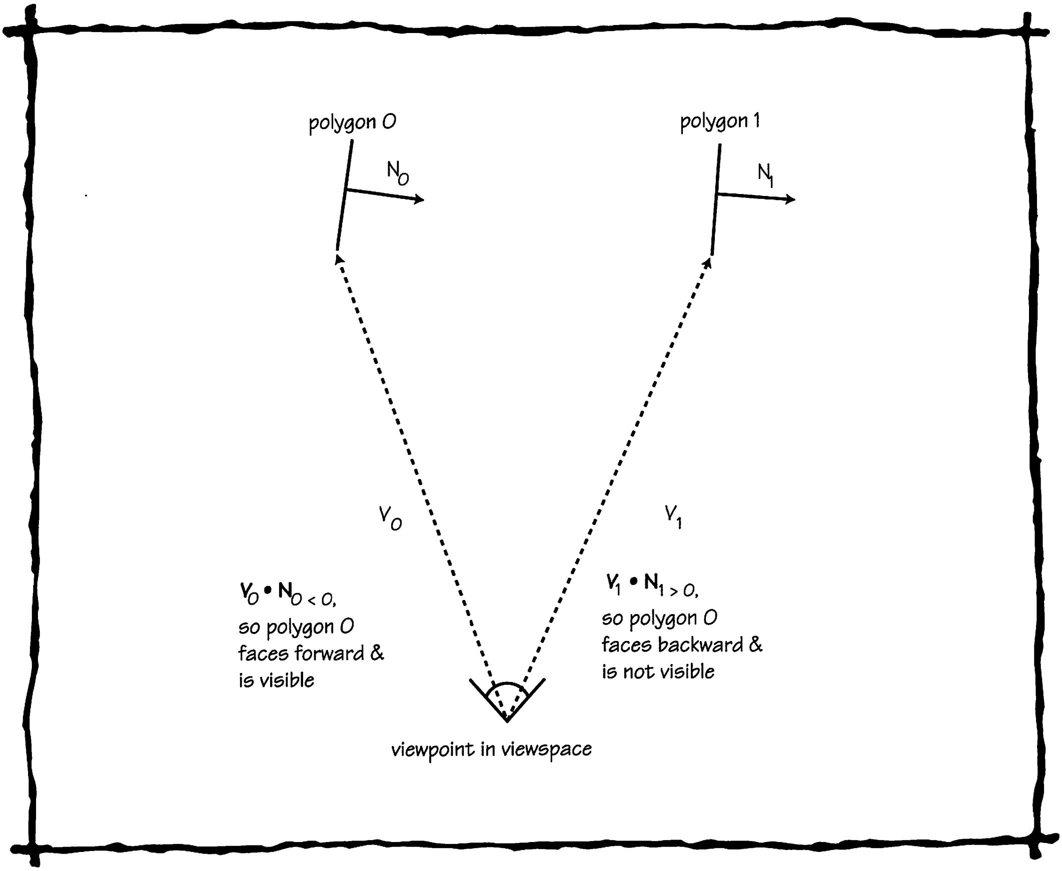


Figure 46.5 Backface culling with the dot product.

tive, and if the polygon is edge-on, the result is 0. That's all there is to it—and this sort of backface culling happens before any transformation or projection at all is performed, saving a great deal of work for the half of all polygons, on average, that are culled.

Backface culling with the dot product is just a special case of determining which side of a plane any point (in this case, the viewpoint) is on. The same trick can be applied whenever you want to determine whether a point is in front of or behind a plane, where a plane is described by any point that's on the plane (which I'll call the plane origin), plus a plane normal. One such application is in clipping a line (such as a polygon edge) to a plane. Just do a dot product between the plane normal and the vector from one line endpoint to the plane origin, and repeat for the other line endpoint. If the signs of the dot products are the same, no clipping is needed; if they differ, clipping is needed. And yes, the dot product is also the way to do the actual clipping; but before we can talk about that, we need to understand the use of the dot product for projection.

Using the Dot Product for Projection

Consider Equation 3 again, but this time make one of the vectors, say V, a unit vector. Now the equation reduces to:

$$\mathbf{U} \bullet \mathbf{V} = \cos(\theta)\|\mathbf{U}\|. \qquad \text{(eq. 8)}$$

In other words, the result is the cosine of the angle between the two vectors, scaled by the magnitude of the non-unit vector. Now, consider that cosine is really just the length of the adjacent leg of a right triangle, and think of the non-unit vector as the hypotenuse of a right triangle, and remember that all sides of similar triangles scale equally. What it all works out to is that the value of the dot product of any vector with a unit vector is the length of the first vector projected onto the unit vector, as shown in Figure 46.6.

This unlocks all sorts of neat stuff. Want to know the distance from a point to a plane? Just dot the vector from the point P to the plane origin O_P with the plane unit normal N_P, to project the vector onto the normal, then take the absolute value:

$$\text{distance} = |(\mathbf{P} - \mathbf{O}_P) \bullet \mathbf{N}_P|,$$

as shown in Figure 46.7.

Want to clip a line to a plane? Calculate the distance from one endpoint to the plane, as just described, and dot the whole line segment with the plane normal, to get the full length of the line along the plane normal. The ratio of the two dot products is then how far along the line from the endpoint the intersection point is; just move

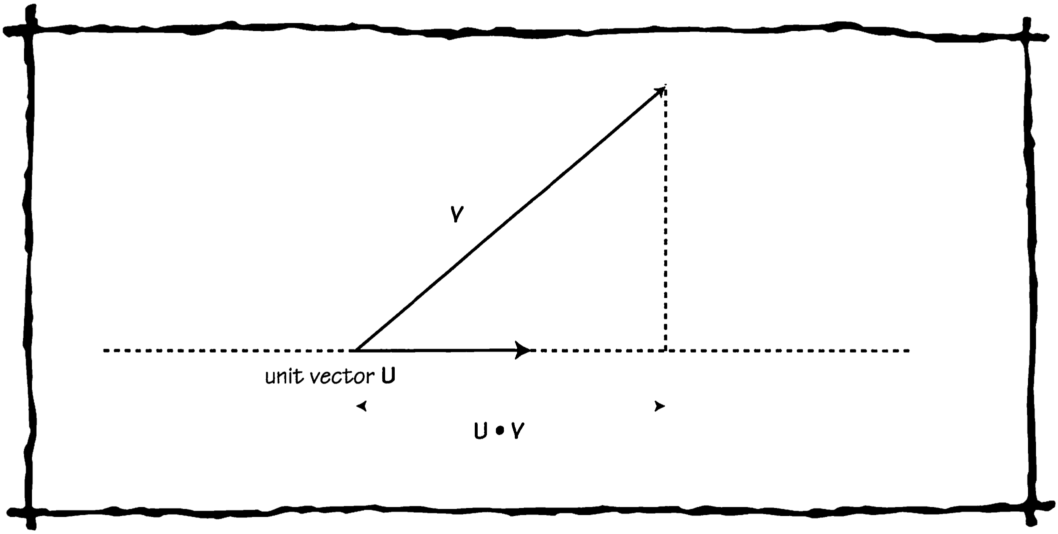


Figure 46.6 How the dot product with a unit vector performs a projection.

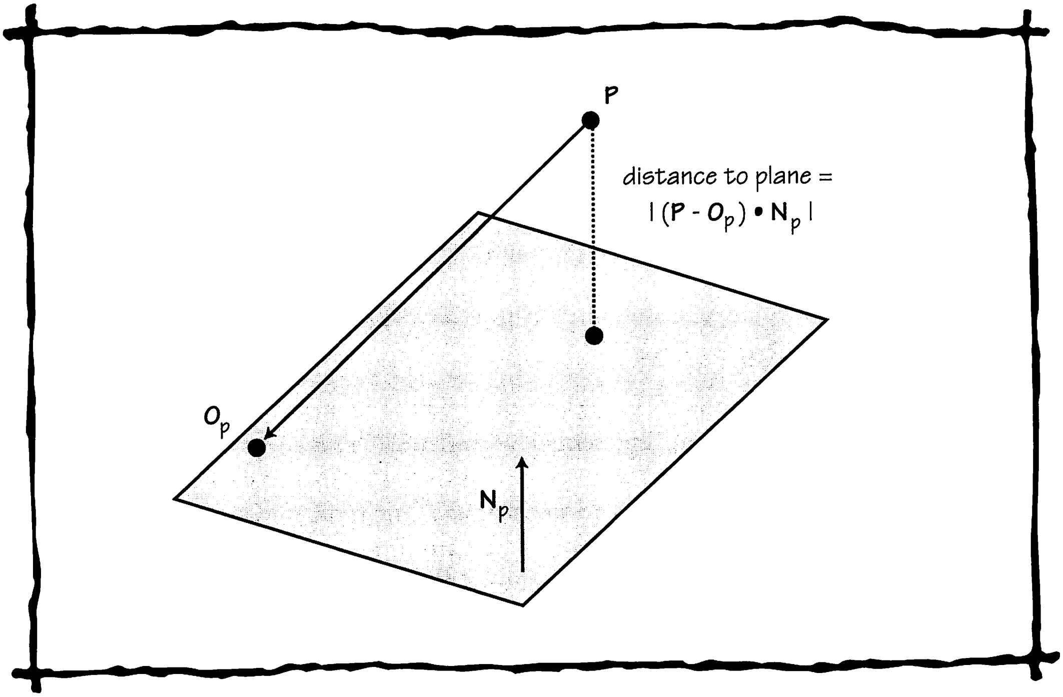


Figure 46.7 Using the dot product to get the distance from a point to a plane.

along the line segment by that distance from the endpoint, and you're at the intersection point, as shown in Listing 46.1.

Listing 46.1. L46_1.C

```
// Given two line endpoints, a point on a plane, and a unit normal
// for the plane, returns the point of intersection of the line
// and the plane in intersectpoint.
#define DOT_PRODUCT(x,y)   (x[0]*y[0]+x[1]*y[1]+x[2]*y[2])
void LineIntersectPlane (float *linestart, float *lineend,
   float *planeorigin, float *planenormal, float *intersectpoint)
{
   float vec1[3], projectedlinelength, startdistfromplane, scale;
   vec1[0] = linestart[0] - planeorigin[0];
   vec1[1] = linestart[1] - planeorigin[1];
   vec1[2] = linestart[2] - planeorigin[2];
   startdistfromplane = DOT_PRODUCT(vec1, planenormal);
   if (startdistfromplane == 0)
   {
        // point is in plane
        intersectpoint[0] = linestart[0];
        intersectpoint[1] = linestart[1];
        intersectpoint[2] = linestart[1];
        return;
    }
    vec1[0] = linestart[0] - lineend[0];
    vec1[1] = linestart[1] - lineend[1];
    vec1[2] = linestart[2] - lineend[2];
    projectedlinelength = DOT_PRODUCT(vec1, planenormal);
    scale = startdistfromplane / projectedlinelength;
    intersectpoint[0] = linestart[0] - vec1[0] * scale;
    intersectpoint[1] = linestart[1] - vec1[1] * scale;
    intersectpoint[2] = linestart[1] - vec1[2] * scale;
}
```

Rotation by Projection

We can use the dot product's projection capability to look at rotation in an interesting way. Typically, rotations are represented by matrices. This is certainly a workable representation that encapsulates all aspects of transformation in a single object, and is ideal for concatenations of rotations and translations. One problem with matrices, though, is that many people, myself included, have a hard time looking at a matrix of sines and cosines and visualizing what's actually going on. So when two 3-D experts, John Carmack and Billy Zelsnack, mentioned that they think of rotation differently, in a way that seemed more intuitive to me, I thought it was worth passing on.

Their approach is this: Think of rotation as projecting coordinates onto new axes. That is, given that you have points in, say, worldspace, define the new coordinate space (viewspace, for example) you want to rotate to by a set of three orthogonal unit vectors

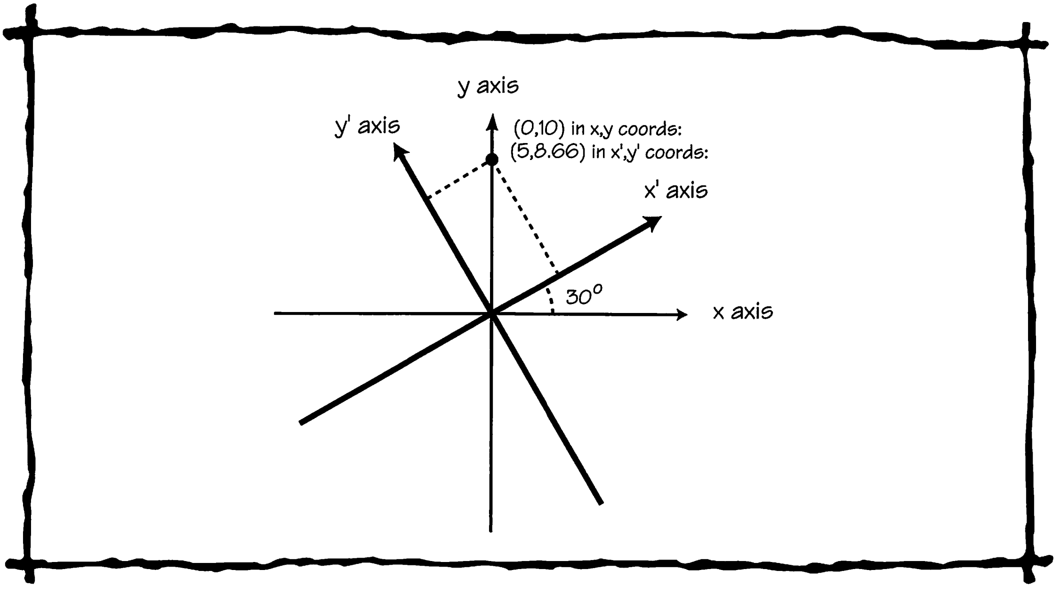


Figure 46.8 Rotation to a new coordinate space by projection onto new axes.

defining the new axes, and then project each point onto each of the three axes to get the coordinates in the new coordinate space, as shown for the 2-D case in Figure 46.8. In 3-D, this involves three dot products per point, one to project the point onto each axis. Translation can be done separately from rotation by simple addition.

Rotation by projection is exactly the same as rotation via matrix multiplication; in fact, the rows of a rotation matrix are the orthogonal unit vectors pointing along the new axes. Rotation by projection buys us no technical advantages, so that's not what's important here; the key is that the concept of rotation by projection, together with a separate translation step, gives us a new way to look at transformation that I, for one, find easier to visualize and experiment with. A new frame of reference for how we think about 3-D frames of reference, if you will.

Three things I've learned over the years are that it never hurts to learn a new way of looking at things, that it helps to have a clearer, more intuitive model in your head of whatever it is you're working on, and that new tools, or new ways to use old tools, are Good Things. My experience has been that rotation by projection, and dot product tricks in general, offer those sorts of benefits for 3-D.

One Story, Two Rules, and a BSP Renderer

Chapter 47

Taking a Compiled BSP Tree from Logical to Visual Reality

As I've noted before, I'm working on Quake, id Software's follow-up to DOOM. A month or so back, we added page flipping to Quake, and made the startling discovery that the program ran nearly twice as fast with page flipping as it did with the alternative method of drawing the whole frame to system memory, then copying it to the screen. We were delighted by this, but baffled. I did a few tests and came up with several possible explanations, including slow writes through the external cache, poor main memory performance, and cache misses when copying the frame from system memory to video memory. Although each of these can indeed affect performance, none seemed to account for the magnitude of the speedup, so I assumed there was some hidden hardware interaction at work. Anyway, "why" was secondary; what really mattered was that we had a way to double performance, which meant I had a lot of work to do to support page flipping as widely as possible.

A few days ago, I was using the Pentium's built-in performance counters to seek out areas for improvement in Quake and, for no particular reason, checked the number of writes performed while copying the frame to the screen in non-page-flipped mode. The answer was 64,000. That seemed odd, since there were 64,000 byte-sized pixels to copy, and I was calling **memcpy()**, which of course performs copies a dword at a time whenever possible. I thought maybe the Pentium counters report the number of bytes written rather than the number of writes performed, but fortunately, this time I tested my assumptions by writing an ASM routine to copy the frame a dword at a time, without the help of **memcpy()**. This time the Pentium counters reported 16,000 writes.

Whoops.

As it turns out, the **memcpy()** routine in the DOS version of our compiler (gcc) inexplicably copies memory a byte at a time. With my new routine, the non-page-flipped approach suddenly became slightly *faster* than page flipping.

The first relevant rule is pretty obvious: *Assume nothing.* Measure early and often. Know what's really going on when your program runs, if you catch my drift. To do otherwise is to risk looking mighty foolish.

The second rule: When you do look foolish (and trust me, it *will* happen if you do challenging work) have a good laugh at yourself, and use it as a reminder of Rule #1. I hadn't done any extra page-flipping work yet, so I didn't waste any time due to my faulty assumption that **memcpy()** performed a maximum-speed copy, but that was just luck. I should have done experiments until I was sure I knew what was going on before drawing any conclusions and acting on them.

In general, make it a point not to fall into a tightly focused rut; stay loose and think of alternative possibilities and new approaches, and always, always, always keep asking questions. It'll pay off big in the long run. If I hadn't indulged my curiosity by running the Pentium counter test on the copy to the screen, even though there was no specific reason to do so, I would never have discovered the ***memcpy()*** *problem—and by so doing I doubled the performance of the entire program in five minutes, a rare accomplishment indeed.*

By the way, I have found the Pentium's performance counters to be very useful in figuring out what my code really does and where the cycles are going. One useful source of information on the performance counters and other aspects of the Pentium is Mike Schmit's book, *Pentium Processor Optimization Tools*, AP Professional, ISBN 0-12-627230-1.

Onward to rendering from a BSP tree.

BSP-based Rendering

For the last several chapters I've been discussing the nature of BSP (Binary Space Partitioning) trees, and in Chapter 45 I presented a compiler for 2-D BSP trees. Now we're ready to use those compiled BSP trees to do realtime rendering.

As you'll recall, the BSP compiler took a list of vertical walls and built a 2-D BSP tree from the walls, as viewed from above. The result is shown in Figure 47.1. The world is split into two pieces by the line of the root wall, and each half of the world is then split again by the root's children, and so on, until the world is carved into subspaces along the lines of all the walls.

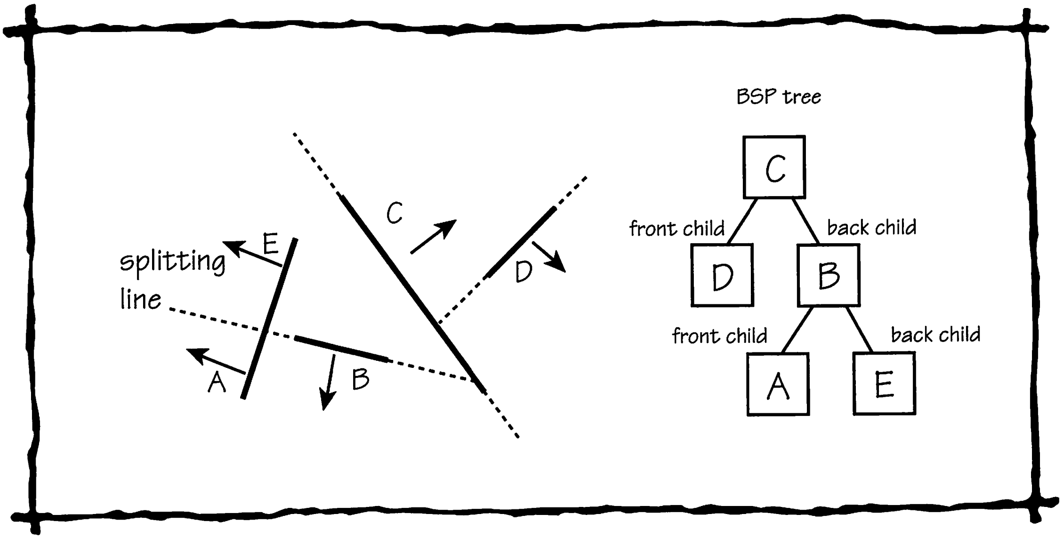


Figure 47.1 Vertical walls and a BSP tree to represent them.

Our objective is to draw the world so that whenever walls overlap we see the nearer wall at each overlapped pixel. The simplest way to do that is with the painter's algorithm; that is, drawing the walls in back-to-front order, assuming no polygons interpenetrate or form cycles. BSP trees guarantee that no polygons interpenetrate (such polygons are automatically split), and make it easy to walk the polygons in back-to-front (or front-to-back) order.

Given a BSP tree, in order to render a view of that tree, all we have to do is descend the tree, deciding at each node whether we're seeing the front or back of the wall at that node from the current viewpoint. We use that knowledge to first recursively descend and draw the farther subtree of that node, then draw that node, and finally draw the nearer subtree of that node. Applied recursively from the root of our BSP trees, this approach guarantees that overlapping polygons will always be drawn in back-to-front order. Listing 47.1 draws a BSP-based world in this fashion. (Because of the constraints of the printed page, Listing 47.1 is only the core of the BSP renderer, without the program framework, some math routines, and the polygon rasterizer; but, the entire program is on the CD-ROM as DDJBSP2.ZIP. Listing 47.1 is in a compressed format, with relatively little whitespace; the full version on the CD-ROM is formatted normally.)

Listing 47.1. L47_1.C

```
/* Core renderer for Win32 program to demonstrate drawing from a 2D
   BSP tree; illustrate the use of BSP trees for surface visibility.
   UpdateWorld() is the top-level function in this module.
   Full source code for the BSP-based renderer, and for the
   accompanying BSP compiler, may be downloaded from
   ftp.idsoftware.com/mikeab, in the file ddjbsp2.zip.
   Tested with VC++ 2.0 running on Windows NT 3.5. */
#define FIXEDPOINT(x)   ((FIXEDPOINT)(((long)x)*((long)0x10000)))
#define FIXTOINT(x)     ((int)(x >> 16))
#define ANGLE(x)        ((long)x)
#define STANDARD_SPEED  (FIXEDPOINT(20))
#define STANDARD_ROTATION (ANGLE(4))
#define MAX_NUM_NODES   2000
#define MAX_NUM_EXTRA_VERTICES   2000
#define WORLD_MIN_X  (FIXEDPOINT(-16000))
#define WORLD_MAX_X  (FIXEDPOINT(16000))
#define WORLD_MIN_Y  (FIXEDPOINT(-16000))
#define WORLD_MAX_Y  (FIXEDPOINT(16000))
#define WORLD_MIN_Z  (FIXEDPOINT(-16000))
#define WORLD_MAX_Z  (FIXEDPOINT(16000))
#define PROJECTION_RATIO (2.0/1.0)  // controls field of view; the
                 // bigger this is, the narrower the field of view
typedef long FIXEDPOINT;
typedef struct _VERTEX {
   FIXEDPOINT x, z, viewx, viewz;
} VERTEX, *PVERTEX;
typedef struct _POINT2 { FIXEDPOINT x, z; } POINT2, *PPOINT2;
typedef struct _POINT2INT { int  x; int y; } POINT2INT, *PPOINT2INT;
typedef long ANGLE;     // angles are stored in degrees
typedef struct _NODE {
   VERTEX *pstartvertex, *pendvertex;
   FIXEDPOINT  walltop, wallbottom, tstart, tend;
   FIXEDPOINT  clippedtstart, clippedtend;
   struct _NODE *fronttree, *backtree;
   int         color, isVisible;
   FIXEDPOINT  screenxstart, screenxend;
   FIXEDPOINT  screenytopstart, screenybottomstart;
   FIXEDPOINT  screenytopend, screenybottomend;
} NODE, *PNODE;
char * pDIB;            // pointer to DIB section we'll draw into
HBITMAP hDIBSection;    // handle of DIB section
HPALETTE hpalDIB;
int iteration = 0, WorldIsRunning = 1;
HWND hwndOutput;
int DIBWidth, DIBHeight, DIBPitch, numvertices, numnodes;
FIXEDPOINT fxHalfDIBWidth, fxHalfDIBHeight;
VERTEX *pvertexlist, *pextravertexlist;
NODE *pnodelist;
POINT2 currentlocation, currentdirection, currentorientation;
ANGLE currentangle;
FIXEDPOINT currentspeed, fxViewerY, currentYSpeed;
FIXEDPOINT FrontClipPlane = FIXEDPOINT(10);
FIXEDPOINT FixedMul(FIXEDPOINT x, FIXEDPOINT y);
FIXEDPOINT FixedDiv(FIXEDPOINT x, FIXEDPOINT y);
FIXEDPOINT FixedSin(ANGLE angle), FixedCos(ANGLE angle);
extern int FillConvexPolygon(POINT2INT * VertexPtr, int Color);
// Returns nonzero if a wall is facing the viewer, 0 else.
int WallFacingViewer(NODE * pwall)
{
   FIXEDPOINT viewxstart = pwall->pstartvertex->viewx;
   FIXEDPOINT viewzstart = pwall->pstartvertex->viewz;
   FIXEDPOINT viewxend = pwall->pendvertex->viewx;
   FIXEDPOINT viewzend = pwall->pendvertex->viewz;
   int Temp;
```

```
/*  // equivalent C code
   if (( ((pwall->pstartvertex->viewx >> 16) *
         ((pwall->pendvertex->viewz -
          pwall->pstartvertex->viewz) >> 16)) +
         ((pwall->pstartvertex->viewz >> 16) *
          ((pwall->pstartvertex->viewx -
            pwall->pendvertex->viewx) >> 16)) )
               < 0)
      return(1);
   else
      return(0);
*/
   _asm {
      mov   eax,viewzend
      sub   eax,viewzstart
      imul  viewxstart
      mov   ecx,edx
      mov   ebx,eax
      mov   eax,viewxstart
      sub   eax,viewxend
      imul  viewzstart
      add   eax,ebx
      adc   edx,ecx
      mov   eax,0
      jns   short WFVDone
      inc   eax
WFVDone:
      mov   Temp,eax
   }
   return(Temp);
}
// Update the viewpoint position as needed.
void UpdateViewPos()
{
   if (currentspeed != 0) {
      currentlocation.x += FixedMul(currentdirection.x,
                                    currentspeed);
      if (currentlocation.x <= WORLD_MIN_X)
         currentlocation.x = WORLD_MIN_X;
      if (currentlocation.x >= WORLD_MAX_X)
         currentlocation.x = WORLD_MAX_X - 1;
      currentlocation.z += FixedMul(currentdirection.z,
                                    currentspeed);
      if (currentlocation.z <= WORLD_MIN_Z)
         currentlocation.z = WORLD_MIN_Z;
      if (currentlocation.z >= WORLD_MAX_Z)
         currentlocation.z = WORLD_MAX_Z - 1;
   }
   if (currentYSpeed != 0) {
      fxViewerY += currentYSpeed;
      if (fxViewerY <= WORLD_MIN_Y)
         fxViewerY = WORLD_MIN_Y;
      if (fxViewerY >= WORLD_MAX_Y)
         fxViewerY = WORLD_MAX_Y - 1;
   }
}
// Transform all vertices into viewspace.
void TransformVertices()
{
   VERTEX *pvertex;
   FIXEDPOINT tempx, tempz;
   int vertex;
   pvertex = pvertexlist;
   for (vertex = 0; vertex < numvertices; vertex++) {
      // Translate the vertex according to the viewpoint
      tempx = pvertex->x - currentlocation.x;
      tempz = pvertex->z - currentlocation.z;
      // Rotate the vertex so viewpoint is looking down z axis
      pvertex->viewx = FixedMul(FixedMul(tempx,
                                    currentorientation.z) +
                 FixedMul(tempz, -currentorientation.x),
                 FIXEDPOINT(PROJECTION_RATIO));
      pvertex->viewz = FixedMul(tempx, currentorientation.x) +
                 FixedMul(tempz, currentorientation.z);
      pvertex++;
   }
}
// 3D clip all walls. If any part of each wall is still visible,
// transform to perspective viewspace.
void ClipWalls()
{
   NODE *pwall;
   int wall;
   FIXEDPOINT tempstartx, tempendx, tempstartz, tempendz;
   FIXEDPOINT tempstartwalltop, tempstartwallbottom;
   FIXEDPOINT tempendwalltop, tempendwallbottom;
   VERTEX *pstartvertex, *pendvertex;
   VERTEX *pextravertex = pextravertexlist;
   pwall = pnodelist;
   for (wall = 0; wall < numnodes; wall++) {
      // Assume the wall won't be visible
      pwall->isVisible = 0;
      // Generate the wall endpoints, accounting for t values and
      // clipping
      // Calculate the viewspace coordinates for this wall
      pstartvertex = pwall->pstartvertex;
      pendvertex = pwall->pendvertex;
      // Look for z clipping first
      // Calculate start and end z coordinates for this wall
      if (pwall->tstart == FIXEDPOINT(0))
         tempstartz = pstartvertex->viewz;
      else
         tempstartz = pstartvertex->viewz +
               FixedMul((pendvertex->viewz-pstartvertex->viewz),
               pwall->tstart);
      if (pwall->tend == FIXEDPOINT(1))
         tempendz = pendvertex->viewz;
      else
         tempendz = pstartvertex->viewz +
               FixedMul((pendvertex->viewz-pstartvertex->viewz),
               pwall->tend);
      // Clip to the front plane
      if (tempendz < FrontClipPlane) {
         if (tempstartz < FrontClipPlane) {
            // Fully front-clipped
            goto NextWall;
         } else {
            pwall->clippedtstart = pwall->tstart;
            // Clip the end point to the front clip plane
            pwall->clippedtend =
            FixedDiv(pstartvertex->viewz - FrontClipPlane,
                  pstartvertex->viewz-pendvertex->viewz);
      tempendz = pstartvertex->viewz +
         FixedMul((pendvertex->viewz-pstartvertex->viewz),
         pwall->clippedtend);
   }
} else {
   pwall->clippedtend = pwall->tend;
   if (tempstartz < FrontClipPlane) {
      // Clip the start point to the front clip plane
      pwall->clippedtstart =
            FixedDiv(FrontClipPlane - pstartvertex->viewz,
                  pendvertex->viewz-pstartvertex->viewz);
      tempstartz = pstartvertex->viewz +
         FixedMul((pendvertex->viewz-pstartvertex->viewz),
         pwall->clippedtstart);
   } else {
      pwall->clippedtstart = pwall->tstart;
   }
}
// Calculate x coordinates
if (pwall->clippedtstart == FIXEDPOINT(0))
   tempstartx = pstartvertex->viewx;
else
   tempstartx = pstartvertex->viewx +
         FixedMul((pendvertex->viewx-pstartvertex->viewx),
         pwall->clippedtstart);
if (pwall->clippedtend == FIXEDPOINT(1))
   tempendx = pendvertex->viewx;
else
   tempendx = pstartvertex->viewx +
         FixedMul((pendvertex->viewx-pstartvertex->viewx),
         pwall->clippedtend);
// Clip in x as needed
if ((tempstartx > tempstartz) || (tempstartx < -tempstartz)) {
   // The start point is outside the view triangle in x;
   // perform a quick test for trivial rejection by seeing if
   // the end point is outside the view triangle on the same
   // side as the start point
   if (((tempstartx>tempstartz) && (tempendx>tempendz)) ||
      ((tempstartx<-tempstartz) && (tempendx<-tempendz)))
      // Fully clipped—trivially reject
      goto NextWall;
   // Clip the start point
   if (tempstartx > tempstartz) {
      // Clip the start point on the right side
      pwall->clippedtstart =
         FixedDiv(pstartvertex->viewx-pstartvertex->viewz,
                pendvertex->viewz-pstartvertex->viewz -
                pendvertex->viewx+pstartvertex->viewx);
      tempstartx = pstartvertex->viewx +
         FixedMul((pendvertex->viewx-pstartvertex->viewx),
                 pwall->clippedtstart);
      tempstartz = tempstartx;
   } else {
      // Clip the start point on the left side
      pwall->clippedtstart =
         FixedDiv(-pstartvertex->viewx-pstartvertex->viewz,
                pendvertex->viewx+pendvertex->viewz -
                pstartvertex->viewz-pstartvertex->viewx);
      tempstartx = pstartvertex->viewx +
         FixedMul((pendvertex->viewx-pstartvertex->viewx),
                 pwall->clippedtstart);
      tempstartz = -tempstartx;
   }
}
// See if the end point needs clipping
if ((tempendx > tempendz) || (tempendx < -tempendz)) {
   // Clip the end point
   if (tempendx > tempendz) {
      // Clip the end point on the right side
      pwall->clippedtend =
         FixedDiv(pstartvertex->viewx-pstartvertex->viewz,
                pendvertex->viewz-pstartvertex->viewz -
                pendvertex->viewx+pstartvertex->viewx);
      tempendx = pstartvertex->viewx +
         FixedMul((pendvertex->viewx-pstartvertex->viewx),
                 pwall->clippedtend);
      tempendz = tempendx;
   } else {
      // Clip the end point on the left side
      pwall->clippedtend =
         FixedDiv(-pstartvertex->viewx-pstartvertex->viewz,
                pendvertex->viewx+pendvertex->viewz -
                pstartvertex->viewz-pstartvertex->viewx);
      tempendx = pstartvertex->viewx +
         FixedMul((pendvertex->viewx-pstartvertex->viewx),
                 pwall->clippedtend);
      tempendz = -tempendx;
   }
}
tempstartwalltop = FixedMul((pwall->walltop - fxViewerY),
      FIXEDPOINT(PROJECTION_RATIO));
tempendwalltop = tempstartwalltop;
tempstartwallbottom = FixedMul((pwall->wallbottom-fxViewerY),
      FIXEDPOINT(PROJECTION_RATIO));
tempendwallbottom = tempstartwallbottom;
// Partially clip in y (the rest is done later in 2D)
// Check for trivial accept
if ((tempstartwalltop > tempstartz) ||
   (tempstartwallbottom < -tempstartz) ||
   (tempendwalltop > tempendz) ||
   (tempendwallbottom < -tempendz)) {
   // Not trivially unclipped; check for fully clipped
   if ((tempstartwallbottom > tempstartz) &&
      (tempstartwalltop < -tempstartz) &&
      (tempendwallbottom > tempendz) &&
      (tempendwalltop < -tempendz)) {
      // Outside view triangle, trivially clipped
      goto NextWall;
   }
   // Partially clipped in Y; we'll do Y clipping at
   // drawing time
}
// The wall is visible; mark it as such and project it.
// +1 on scaling because of bottom/right exclusive polygon
// filling
pwall->isVisible = 1;
pwall->screenxstart =
   (FixedMulDiv(tempstartx, fxHalfDIBWidth+FIXEDPOINT(0.5),
            tempstartz) + fxHalfDIBWidth + FIXEDPOINT(0.5));
      pwall->screenytopstart =
            (FixedMulDiv(tempstartwalltop,
            fxHalfDIBHeight + FIXEDPOINT(0.5), tempstartz) +
            fxHalfDIBHeight + FIXEDPOINT(0.5));
      pwall->screenybottomstart =
            (FixedMulDiv(tempstartwallbottom,
            fxHalfDIBHeight + FIXEDPOINT(0.5), tempstartz) +
            fxHalfDIBHeight + FIXEDPOINT(0.5));
      pwall->screenxend =
            (FixedMulDiv(tempendx, fxHalfDIBWidth+FIXEDPOINT(0.5),
            tempendz) + fxHalfDIBWidth + FIXEDPOINT(0.5));
      pwall->screenytopend =
            (FixedMulDiv(tempendwalltop,
            fxHalfDIBHeight + FIXEDPOINT(0.5), tempendz) +
            fxHalfDIBHeight + FIXEDPOINT(0.5));
      pwall->screenybottomend =
            (FixedMulDiv(tempendwallbottom,
            fxHalfDIBHeight + FIXEDPOINT(0.5), tempendz) +
            fxHalfDIBHeight + FIXEDPOINT(0.5));
NextWall:
      pwall++;
   }
}
// Walk the tree back to front; backface cull whenever possible,
// and draw front-facing walls in back-to-front order.
void DrawWallsBackToFront()
{
   NODE *pFarChildren, *pNearChildren, *pwall;
   NODE *pendingnodes[MAX_NUM_NODES];
   NODE **pendingstackptr;
   POINT2INT apoint[4];
   pwall = pnodelist;
   pendingnodes[0] = (NODE *)NULL;
   pendingstackptr = pendingnodes + 1;
   for (;;) {
      for (;;) {
         // Descend as far as possible toward the back,
         // remembering the nodes we pass through on the way.
         // Figure whether this wall is facing frontward or
         // backward; do in viewspace because non-visible walls
         // aren't projected into screenspace, and we need to
         // traverse all walls in the BSP tree, visible or not,
         // in order to find all the visible walls
         if (WallFacingViewer(pwall)) {
            // We're on the forward side of this wall, do the back
            // children first
            pFarChildren = pwall->backtree;
         } else {
            // We're on the back side of this wall, do the front
            // children first
            pFarChildren = pwall->fronttree;
         }
         if (pFarChildren == NULL)
            break;
         *pendingstackptr = pwall;
         pendingstackptr++;
         pwall = pFarChildren;
      }
      for (;;) {
         // See if the wall is even visible
         if (pwall->isVisible) {
            // See if we can backface cull this wall
            if (pwall->screenxstart < pwall->screenxend) {
               // Draw the wall
               apoint[0].x = FIXTOINT(pwall->screenxstart);
               apoint[1].x = FIXTOINT(pwall->screenxstart);
               apoint[2].x = FIXTOINT(pwall->screenxend);
               apoint[3].x = FIXTOINT(pwall->screenxend);
               apoint[0].y = FIXTOINT(pwall->screenytopstart);
               apoint[1].y = FIXTOINT(pwall->screenybottomstart);
               apoint[2].y = FIXTOINT(pwall->screenybottomend);
               apoint[3].y = FIXTOINT(pwall->screenytopend);
               FillConvexPolygon(apoint, pwall->color);
            }
         }
         // If there's a near tree from this node, draw it;
         // otherwise, work back up to the last-pushed parent
         // node of the branch we just finished; we're done if
         // there are no pending parent nodes.
         // Figure whether this wall is facing frontward or
         // backward; do in viewspace because non-visible walls
         // aren't projected into screenspace, and we need to
            // traverse all walls in the BSP tree, visible or not,
            // in order to find all the visible walls
         if (WallFacingViewer(pwall)) {
            // We're on the forward side of this wall, do the
            // front children now
            pNearChildren = pwall->fronttree;
         } else {
            // We're on the back side of this wall, do the back
            // children now
            pNearChildren = pwall->backtree;
         }
         // Walk the near subtree of this wall
         if (pNearChildren != NULL)
            goto WalkNearTree;
         // Pop the last-pushed wall
         pendingstackptr–;
         pwall = *pendingstackptr;
         if (pwall == NULL)
            goto NodesDone;
      }
WalkNearTree:
      pwall = pNearChildren;
   }
NodesDone:
;
}
// Render the current state of the world to the screen.
void UpdateWorld()
{
   HPALETTE holdpal;
   HDC hdcScreen, hdcDIBSection;
   HBITMAP holdbitmap;
   // Draw the frame
   UpdateViewPos();
   memset(pDIB, 0, DIBPitch*DIBHeight);    // clear frame
   TransformVertices();
   ClipWalls();
```

```
    DrawWallsBackToFront();
    // We've drawn the frame; copy it to the screen
    hdcScreen = GetDC(hwndOutput);
    holdpal = SelectPalette(hdcScreen, hpalDIB, FALSE);
    RealizePalette(hdcScreen);
    hdcDIBSection = CreateCompatibleDC(hdcScreen);
    holdbitmap = SelectObject(hdcDIBSection, hDIBSection);
    BitBlt(hdcScreen, 0, 0, DIBWidth, DIBHeight, hdcDIBSection,
           0, 0, SRCCOPY);
    SelectPalette(hdcScreen, holdpal, FALSE);
    ReleaseDC(hwndOutput, hdcScreen);
    SelectObject(hdcDIBSection, holdbitmap);
    ReleaseDC(hwndOutput, hdcDIBSection);
    iteration++;
}
```

The Rendering Pipeline

Conceptually rendering from a BSP tree really is that simple, but the implementation is a bit more complicated. The full rendering pipeline, as coordinated by **UpdateWorld()**, is this:

- Update the current location.
- Transform all wall endpoints into viewspace (the world as seen from the current location with the current viewing angle).
- Clip all walls to the view pyramid.
- Project wall vertices to screen coordinates.
- Walk the walls back to front, and for each wall that lies at least partially in the view pyramid, perform backface culling (skip walls facing away from the viewer), and draw the wall if it's not culled.

Next, we'll look at each part of the pipeline more closely. The pipeline is too complex for me to be able to discuss each part in complete detail. Some sources for further reading are *Computer Graphics*, by Foley and van Dam (ISBN 0-201-12110-7), and the *DDJ Essential Books on Graphics Programming* CD.

Moving the Viewer

The sample BSP program performs first-person rendering; that is, it renders the world as seen from your eyes as you move about. The rate of movement is controlled by key-handling code that's not shown in Listing 47.1; however, the variables set by the key-handling code are used in **UpdateViewPos()** to bring the current location up to date.

Note that the view position can change not only in x and z (movement around the plane upon which the walls are set), but also in y (vertically). However, the view direction is always horizontal; that is, the code in Listing 47.1 supports moving to any 3-D point, but only viewing horizontally. Although the BSP tree is only 2-D, it is quite possible to support looking up and down to at least some extent, particularly if the world dataset is restricted so that, for example, there are never two rooms stacked on top of each other, or any tilted walls. For simplicity's sake, I have chosen not to implement this in Listing 47.1, but you may find it educational to add it to the program yourself.

Transformation into Viewspace

The viewing angle (which controls direction of movement as well as view direction) can sweep through the full 360 degrees around the viewpoint, so long as it remains horizontal. The viewing angle is controlled by the key handler, and is used to define a unit vector stored in **currentorientation** that explicitly defines the view direction (the z axis of viewspace), and implicitly defines the x axis of viewspace, because that axis is at right angles to the z axis, where x increases to the right of the viewer.

As I discussed in the previous chapter, rotation to a new coordinate system can be performed by using the dot product to project points onto the axes of the new coordinate system, and that's what **TransformVertices()** does, after first translating (moving) the coordinate system to have its origin at the viewpoint. (It's necessary to perform the translation first so that the viewing rotation is around the viewpoint.) Note that this operation can equivalently be viewed as a matrix math operation, and that this is in fact the more common way to handle transformations.

At the same time, the points are scaled in x according to **PROJECTION_RATIO** to provide the desired field of view. Larger scale values result in narrower fields of view.

When this is done the walls are in viewspace, ready to be clipped.

Clipping

In viewspace, the walls may be anywhere relative to the viewpoint: in front, behind, off to the side. We only want to draw those parts of walls that properly belong on the screen; that is, those parts that lie in the view pyramid (view frustum), as shown in Figure 47.2. Unclipped walls—walls that lie entirely in the frustum—should be drawn in their entirety, fully clipped walls should not be drawn, and partially clipped walls must be trimmed before being drawn.

In Listing 47.1, **ClipWalls()** does this in three steps for each wall in turn. First, the z coordinates of the two ends of the wall are calculated. (Remember, walls are vertical and their ends go straight up and down, so the top and bottom of each end have the same x and z coordinates.) If both ends are on the near side of the front clip plane, then the polygon is fully clipped, and we're done with it. If both ends are on the far side, then the polygon isn't z-clipped, and we leave it unchanged. If the polygon straddles the near clip plane, then the wall is trimmed to stop at the near clip plane by adjusting the t value of the nearest endpoint appropriately; this calculation is a simple matter of scaling by z, because the near clip plane is at a constant z distance. (The use of t values

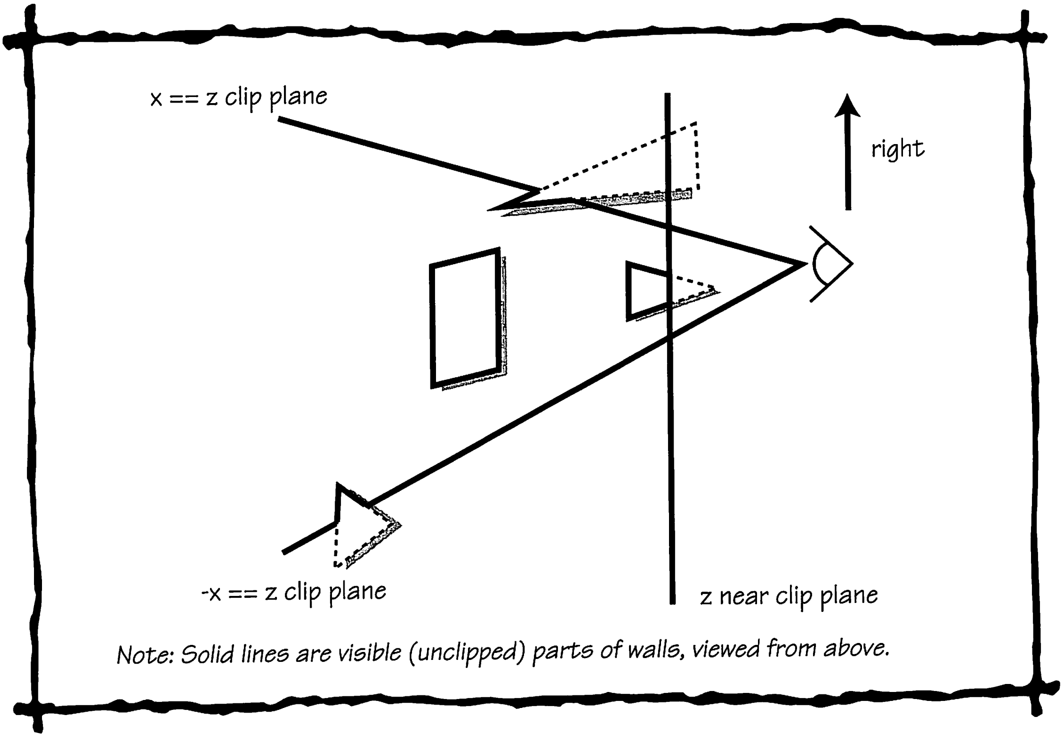

x == z clip plane
right
-x == z clip plane
z near clip plane
Note: Solid lines are visible (unclipped) parts of walls, viewed from above.

Figure 47.2 Clipping to the view pyramid.

for parametric lines was discussed in Chapter 45.) The process is further simplified because the walls can be treated as lines viewed from above, so we can perform 2-D clipping in z; this would not be the case if walls sloped or had sloping edges.

After clipping in z, we clip by viewspace x coordinate, to ensure that we draw only wall portions that lie between the left and right edges of the screen. Like z-clipping, x-clipping can be done as a 2-D clip, because the walls and the left and right sides of the frustum are all vertical. We compare both the start and endpoint of each wall to the left and right sides of the frustum, and reject, accept, or clip each wall's t values accordingly. The test for x clipping is very simple, because the edges of the frustum are defined as the planes where x==z and -x==z.

The final clip stage is clipping by y coordinate, and this is the most complicated, because vertical walls can be clipped at an angle in y, as shown in Figure 47.3, so true 3-D clipping of all four wall vertices is involved. We handle this in **ClipWalls()** by detecting trivial rejection in y, using y==z and -y==z as the y boundaries of the frustum. However, we leave partial clipping to be handled as a 2-D clipping problem; we are able to do this only because our earlier z-clip to the near clip plane guarantees that no remaining polygon point can have z<=0, ensuring that when we project we'll always pass valid, y-clippable screenspace vertices to the polygon filler.

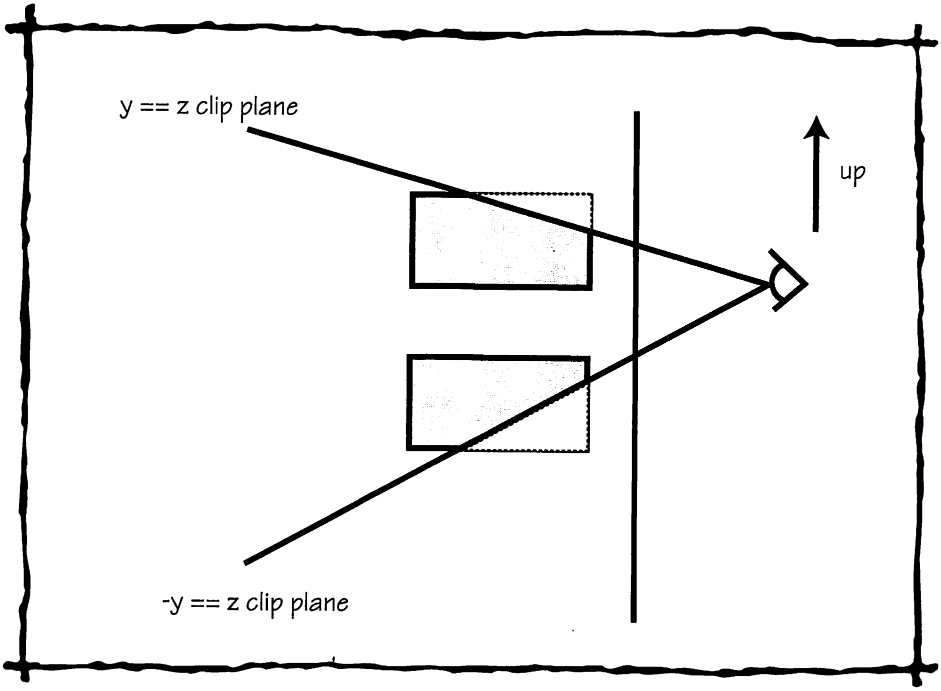


Figure 47.3 Why Y clipping is more complex than X or Z clipping.

Projection to Screenspace

At this point, we have viewspace vertices for each wall that's at least partially visible. All we have to do is project these vertices according to z distance—that is, perform perspective projection—and scale the results to the width of the screen, then we'll be ready to draw. Although this step is logically separate from clipping, it is performed as the last step for visible walls in **ClipWalls()**.

Walking the Tree, Backface Culling and Drawing

Now that we have all the walls clipped to the frustum, with vertices projected into screen coordinates, all we have to do is draw them back to front; that's the job of **DrawWallsBackToFront()**. Basically, this routine walks the BSP tree, descending recursively from each node to draw the farther children of each node first, then the wall at the node, then the nearer children. In the interests of efficiency, this particular implementation performs a data-recursive walk of the tree, rather than the more familiar code recursion. Interestingly, the performance speedup from data recursion turned out to be more modest than I had expected, based on past experience; see Chapter 44 for further details.

As it comes to each wall, **DrawWallsBackToFront()** first descends to draw the farther subtree. Next, if the wall is both visible and pointing toward the viewer, it is drawn as a solid polygon. The polygon filler (not shown in Listing 47.1) is a modification of the polygon filler I presented in Chapters 21 and 22.

It's worth noting how backface culling and front/back wall orientation testing are performed. (Note that walls are always one-sided, visible only from the front.) I discussed backface culling in general in the previous chapter, and mentioned two possible approaches: generating a screenspace normal (perpendicular vector) to the polygon and seeing which way that points, or taking the world or screenspace dot product between the vector from the viewpoint to any polygon point and the polygon's normal and checking the sign. Listing 47.1 does both, but because our BSP tree is 2-D and the viewer is always upright, we can save some work.

Consider this: Walls are stored so that the left end, as viewed from the front side of the wall, is the start vertex, and the right end is the end vertex. There are only two possible ways that a wall can be positioned in screenspace, then: viewed from the front, in which case the start vertex is to the left of the end vertex, or viewed from the back, in which case the start vertex is to the right of the end vertex, as shown in Figure 47.4. So we can tell which side of a wall we're seeing, and thus backface cull, simply by comparing the screenspace x coordinates of the start and end vertices, a simple 2-D version of checking the direction of the screenspace normal.

The wall orientation test used for walking the BSP tree, performed in **WallFacingViewer()**, takes the other approach, and checks the viewspace sign of the dot product of the wall's normal with a vector from the viewpoint to the wall. Again, this code takes advantage of the 2-D nature of the tree to generate the wall normal by swapping x and z and altering signs. We can't use the quicker screenspace x test here

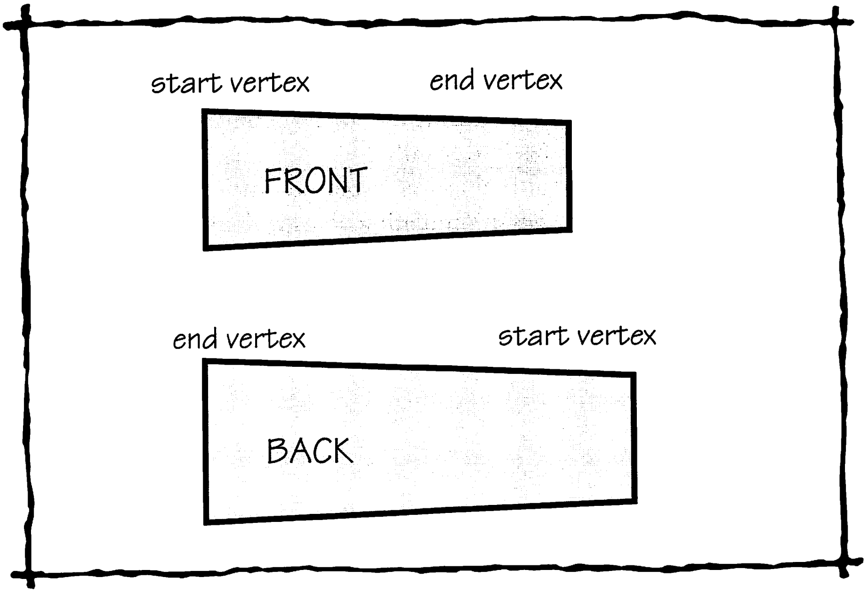


Figure 47.4 Fast backspace culling test in screenspace.

that we used for backface culling, because not all walls can be projected into screenspace; for example, trying to project a wall at z==0 would result in division by zero.

All the visible, front-facing walls are drawn into a buffer by **DrawWallsBackToFront()**, then **UpdateWorld()** calls Win32 to copy the new frame to the screen. The frame of animation is complete.

Notes on the BSP Renderer

Listing 47.1 is far from complete or optimal. There is no such thing as a tiny BSP rendering demo, because 3D rendering, even when based on a 2-D BSP tree, requires a substantial amount of code and complexity. Listing 47.1 is reasonably close to a minimum rendering engine, and is specifically intended to illuminate basic BSP principles, given the space limitations of one chapter in a book that's already larger than it should be. Think of Listing 47.1 as a learning tool and a starting point.

The most obvious lack in Listing 47.1 is that there is no support for floors and ceilings; the walls float in space, unsupported. Is it necessary to go to 3-D BSP trees to get a normal-looking world?

No. Although 3-D BSP trees offer many advantages in that they allow arbitrary datasets with viewing in any arbitrary direction and, in truth, aren't much more complicated than 2-D BSP trees for back-to-front drawing, they do tend to be larger and more difficult to debug, and they aren't necessary for floors and ceilings. One way to get floors and ceilings out of a 2-D BSP tree is to change the nature of the BSP tree so that polygons are no longer stored in the splitting nodes. Instead, each leaf of the tree—that is, each subspace carved out by the tree—would store the polygons for the walls, floors, and ceilings that lie on the boundaries of that space and face into that space. The subspace would be convex, because all BSP subspaces are automatically convex, so the polygons in that subspace can be drawn in any order. Thus, the subspaces in the BSP tree would each be drawn in turn as convex sets, back to front, just as Listing 47.1 draws polygons back to front.

This sort of BSP tree, organized around volumes rather than polygons, has some additional interesting advantages in simulating physics, detecting collisions, doing line-of-sight determination, and performing volume-based operations such as dynamic illumination and event triggering. However, that discussion will have to wait until another day.

Quake's Visible-Surface Determination

Chapter 48

The Challenge of Separating All Things Seen from All Things Unseen

Years ago, I was working at Video Seven, a now-vanished video adapter manufacturer, helping to develop a VGA clone. The fellow who was designing Video Seven's VGA chip, Tom Wilson, had worked around the clock for months to make his VGA run as fast as possible, and was confident he had pretty much maxed out its performance. As Tom was putting the finishing touches on his chip design, however, news came fourth-hand that a competitor, Paradise, had juiced up the performance of the clone they were developing by putting in a FIFO.

That was all he knew; there was no information about what sort of FIFO, or how much it helped, or anything else. Nonetheless, Tom, normally an affable, laid-back sort, took on the wide-awake, haunted look of a man with too much caffeine in him and no answers to show for it, as he tried to figure out, from hopelessly thin information, what Paradise had done. Finally, he concluded that Paradise must have put a write FIFO between the system bus and the VGA, so that when the CPU wrote to video memory, the write immediately went into the FIFO, allowing the CPU to keep on processing instead of stalling each time it wrote to display memory.

Tom couldn't spare the gates or the time to do a full FIFO, but he could implement a one-deep FIFO, allowing the CPU to get one write ahead of the VGA. He wasn't sure how well it would work, but it was all he could do, so he put it in and taped out the chip.

The one-deep FIFO turned out to work astonishingly well; for a time, Video Seven's VGAs were the fastest around, a testament to Tom's ingenuity and creativity under pressure. However, the truly remarkable part of this story is that Paradise's FIFO design turned out to bear not the slightest resemblance to Tom's, and *didn't work as well.* Paradise had stuck a *read* FIFO between display memory and the video output stage of the VGA, allowing the video output to read ahead, so that when the CPU wanted to access display memory, pixels could come from the FIFO while the CPU was serviced immediately. That did indeed help performance—but not as much as Tom's write FIFO.

What we have here is as neat a parable about the nature of creative design as one could hope to find. The scrap of news about Paradise's chip contained almost no actual information, but it forced Tom to push past the limits he had unconsciously set in coming up with his original design. And, in the end, I think that the single most important element of great design, whether it be hardware, software, or any creative endeavor, is precisely what the Paradise news triggered in Tom: The ability to detect the limits you have built into the way you think about your design, and then transcend those limits.

The problem, of course, is how to go about transcending limits you don't even know you've imposed. There's no formula for success, but two principles can stand you in good stead: simplify and keep on trying new things.

Generally, if you find your code getting more complex, you're fine-tuning a frozen design, and it's likely you can get more of a speed-up, with less code, by rethinking the design. A really good design should bring with it a moment of immense satisfaction in which everything falls into place, and you're amazed at how little code is needed and how all the boundary cases just work properly.

As for how to rethink the design, do it by pursuing whatever ideas occur to you, no matter how off-the-wall they seem. Many of the truly brilliant design ideas I've heard of over the years sounded like nonsense at first, because they didn't fit my preconceived view of the world. Often, such ideas are in fact off-the-wall, but just as the news about Paradise's chip sparked Tom's imagination, aggressively pursuing seemingly outlandish ideas can open up new design possibilities for you.

Case in point: The evolution of Quake's 3-D graphics engine.

VSD: The Toughest 3-D Challenge of All

I've spent most of my waking hours for the last several months working on Quake, id Software's successor to DOOM, and I suspect I have a few more months to go. The very best things don't happen easily, nor quickly—but when they happen, all the sweat becomes worthwhile.

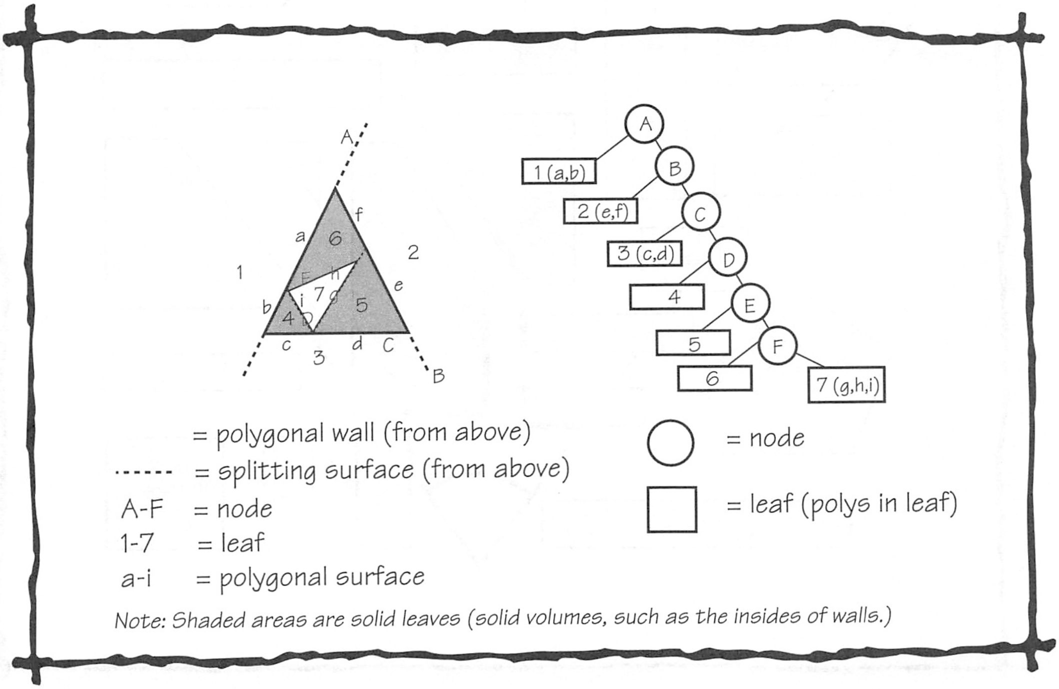
In terms of graphics, Quake is to DOOM as DOOM was to its predecessor, Wolfenstein 3D. Quake adds true, arbitrary 3-D (you can look up and down, lean, and even fall on your side), detailed lighting and shadows, and 3-D monsters and players in place of DOOM's sprites. Someday I hope to talk about how all that works, but for the here and now I want to talk about what is, in my opinion, the toughest 3-D problem of all: visible surface determination (drawing the proper surface at each pixel), and its close relative, culling (discarding non-visible polygons as quickly as possible, a way of accelerating visible surface determination). In the interests of brevity, I'll use the abbreviation VSD to mean both visible surface determination and culling from now on.

Why do I think VSD is the toughest 3-D challenge? Although rasterization issues such as texture mapping are fascinating and important, they are tasks of relatively finite scope, and are being moved into hardware as 3-D accelerators appear; also, they only scale with increases in screen resolution, which are relatively modest.

In contrast, VSD is an open-ended problem, and there are dozens of approaches currently in use. Even more significantly, the performance of VSD, done in an unsophisticated fashion, scales directly with scene complexity, which tends to increase as a square or cube function, so this very rapidly becomes the limiting factor in rendering realistic worlds. I expect VSD to be the increasingly dominant issue in realtime PC 3-D over the next few years, as 3-D worlds become increasingly detailed. Already, a good-sized Quake level contains on the order of 10,000 polygons, about three times as many polygons as a comparable DOOM level.

The Structure of Quake Levels

Before diving into VSD, let me note that each Quake level is stored as a single huge 3-D BSP tree. This BSP tree, like any BSP, subdivides space, in this case along the planes of the polygons. However, unlike the BSP tree I presented in the last chapter, Quake's BSP tree



Note: Shaded areas are solid leaves (solid volumes, such as the insides of walls.)

Figure 48.1 Quake's polygons are stored as empty leaves.

does not store polygons in the tree nodes, as part of the splitting planes, but rather in the empty (non-solid) leaves, as shown in overhead view in Figure 48.1.

Correct drawing order can be obtained by drawing the leaves in front-to-back or back-to-front BSP order, again as discussed in the previous chapter. Also, because BSP leaves are always convex and the polygons are on the boundaries of the BSP leaves, facing inward, the polygons in a given leaf can never obscure one another and can be drawn in any order. (This is a general property of convex polyhedra.)

Culling and Visible Surface Determination

The process of VSD would ideally work as follows: First, you would cull all polygons that are completely outside the view frustum (view pyramid), and would clip away the irrelevant portions of any polygons that are partially outside. Then, you would draw only those pixels of each polygon that are actually visible from the current viewpoint, as shown in overhead view in Figure 48.2, wasting no time overdrawing pixels multiple times; note how little of the polygon sets in Figure 48.2 actually need to be drawn. Finally, in a perfect world, the

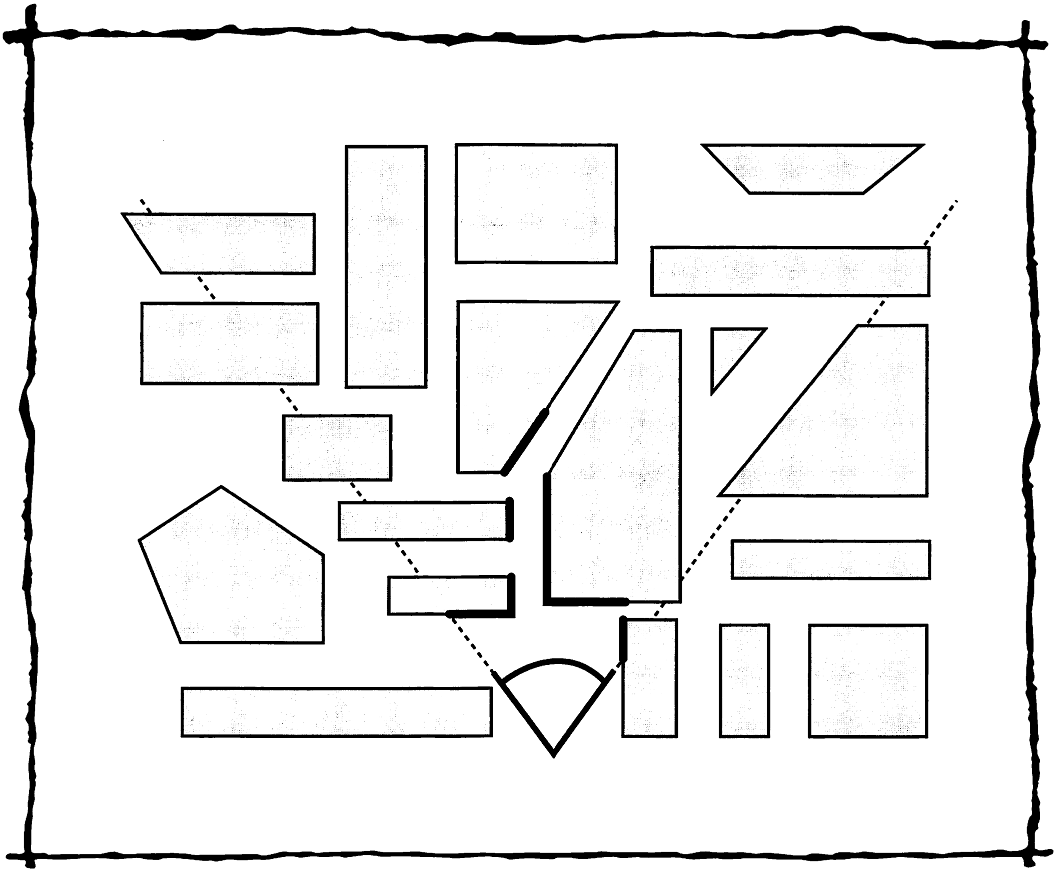


Figure 48.2 Pixels visible from the current viewpoint.

tests to figure out what parts of which polygons are visible would be free, and the processing time would be the same for all possible viewpoints, giving the game a smooth visual flow.

As it happens, it is easy to determine which polygons are outside the frustum or partially clipped, and it's quite possible to figure out precisely which pixels need to be drawn. Alas, the world is far from perfect, and those tests are far from free, so the real trick is how to accelerate or skip various tests and still produce the desired result.

As I discussed at length in the last chapter, given a BSP, it's easy and inexpensive to walk the world in front-to-back or back-to-front order. The simplest VSD solution, which I in fact demonstrated earlier, is to simply walk the tree back-to-front, clip each polygon to the frustum, and draw it if it's facing forward and not entirely clipped (the painter's algorithm). Is that an adequate solution?

For relatively simple worlds, it is perfectly acceptable. It doesn't scale very well, though. One problem is that as you add more polygons in the world, more transformations and tests have to be performed to cull polygons that aren't visible; at some point, that will bog considerably performance down.

Nodes Inside and Outside the View Frustum

Happily, there's a good workaround for this particular problem. As discussed earlier, each leaf of a BSP tree represents a convex subspace, with the nodes that bound the leaf

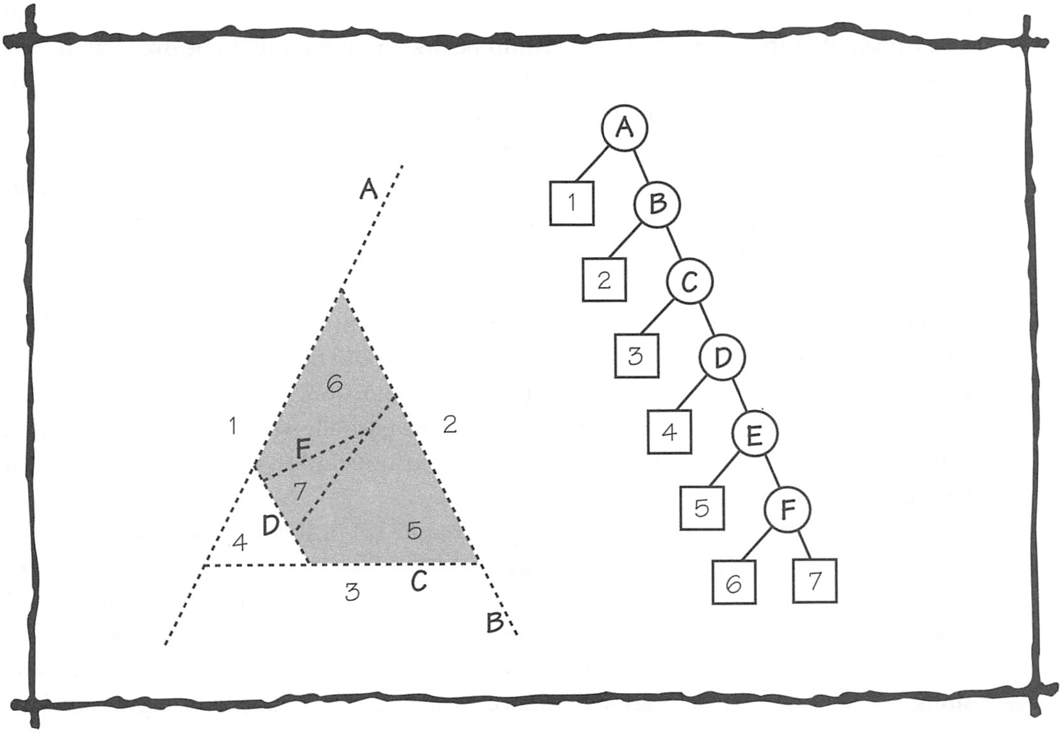


Figure 48.3 The substance described by node E.

delimiting the space. Perhaps less obvious is that each node in a BSP tree also describes a subspace—the subspace composed of all the node's children, as shown in Figure 48.3. Another way of thinking of this is that each node splits the subspace into two pieces created by the nodes above it in the tree, and the node's children then further carve that subspace into all the leaves that descend from the node.

Since a node's subspace is bounded and convex, it is possible to test whether it is entirely outside the frustum. If it is, *all* of the node's children are certain to be fully clipped and can be rejected without any additional processing. Since most of the world is typically outside the frustum, many of the polygons in the world can be culled almost for free, in huge, node-subspace chunks. It's relatively expensive to perform a perfect test for subspace clipping, so instead bounding spheres or boxes are often maintained for each node, specifically for culling tests.

So culling to the frustum isn't a problem, and the BSP can be used to draw back-to-front. What, then, *is* the problem?

Overdraw

The problem John Carmack, the driving technical force behind DOOM and Quake, faced when he designed Quake was that in a complex world, many scenes have an awful lot of polygons in the frustum. Most of those polygons are partially or entirely obscured by other polygons, but the painter's algorithm described earlier requires that every pixel of every polygon in the frustum be drawn, often only to be overdrawn. In a 10,000-polygon Quake level, it would be easy to get a worst-case overdraw level of 10 times or more; that is, in some frames each pixel could be drawn 10 times or more, on average. No rasterizer is fast enough to compensate for an order of such magnitude and more work than is actually necessary to show a scene; worse still, the painter's algorithm will cause a vast difference between best-case and worst-case performance, so the frame rate can vary wildly as the viewer moves around.

So the problem John faced was how to keep overdraw down to a manageable level, preferably drawing each pixel exactly once, but certainly no more than two or three times in the worst case. As with frustum culling, it would be ideal if he could eliminate all invisible polygons in the frustum with virtually no work. It would also be a plus if he could manage to draw only the visible parts of partially-visible polygons, but that was a balancing act in that it had to be a lower-cost operation than the overdraw that would otherwise result.

When I arrived at id at the beginning of March 1995, John already had an engine prototyped and a plan in mind, and I assumed that our work was a simple matter of finishing and optimizing that engine. If I had been aware of id's history, however, I would have known better. John had done not only DOOM, but also the engines for Wolfenstein 3D and several earlier games, and had actually done several different versions of each engine in the course of development (once doing four engines in four weeks), for a total of perhaps 20 distinct engines over a four-year period. John's tireless pursuit of new and better designs for Quake's engine, from every angle he could think of, would end only when we shipped the product.

By three months after I arrived, only one element of the original VSD design was anywhere in sight, and John had taken the dictum of "try new things" farther than I'd ever seen it taken.

The Beam Tree

John's original Quake design was to draw front-to-back, using a second BSP tree to keep track of what parts of the screen were already drawn and which were still empty and therefore drawable by the remaining polygons. Logically, you can think of this BSP tree as being a 2-D region describing solid and empty areas of the screen, as shown in Figure 48.4, but in fact it is a 3-D tree, of the sort known as a *beam tree*. A beam tree is a collection of 3-D wedges (beams), bounded by planes, projecting out from some center point, in this case the viewpoint, as shown in Figure 48.5.

In John's design, the beam tree started out consisting of a single beam describing the frustum; everything outside that beam was marked solid (so nothing would draw there), and the inside of the beam was marked empty. As each new polygon was reached while walking the world BSP tree front-to-back, that polygon was converted to a beam by running planes from its edges through the viewpoint, and any part of

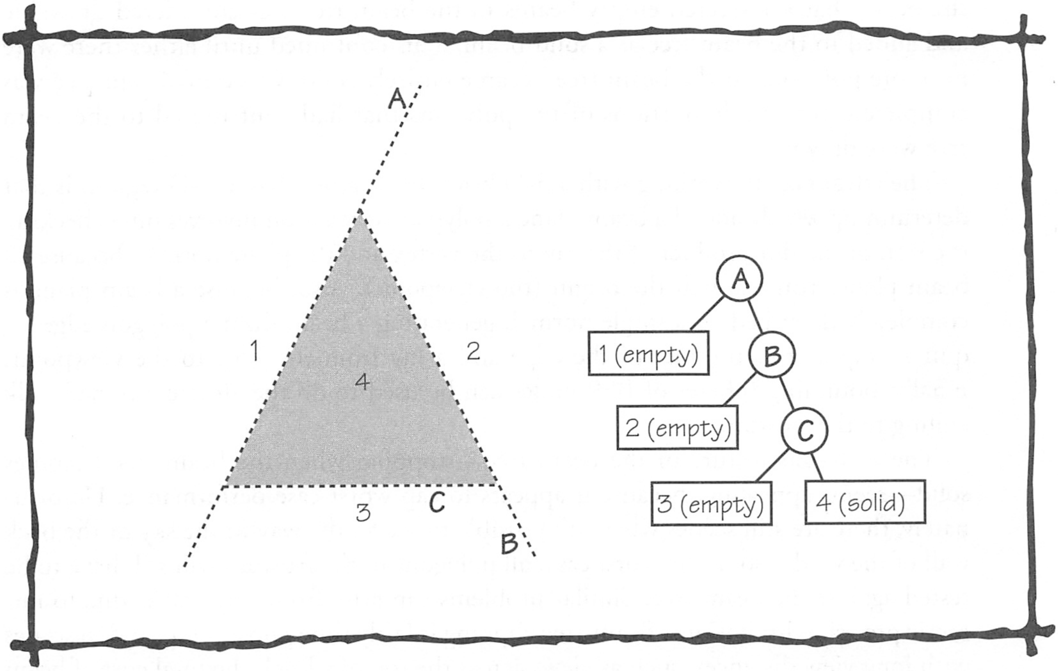


Figure 48.4 Partitioning the screen into 2-D regions.

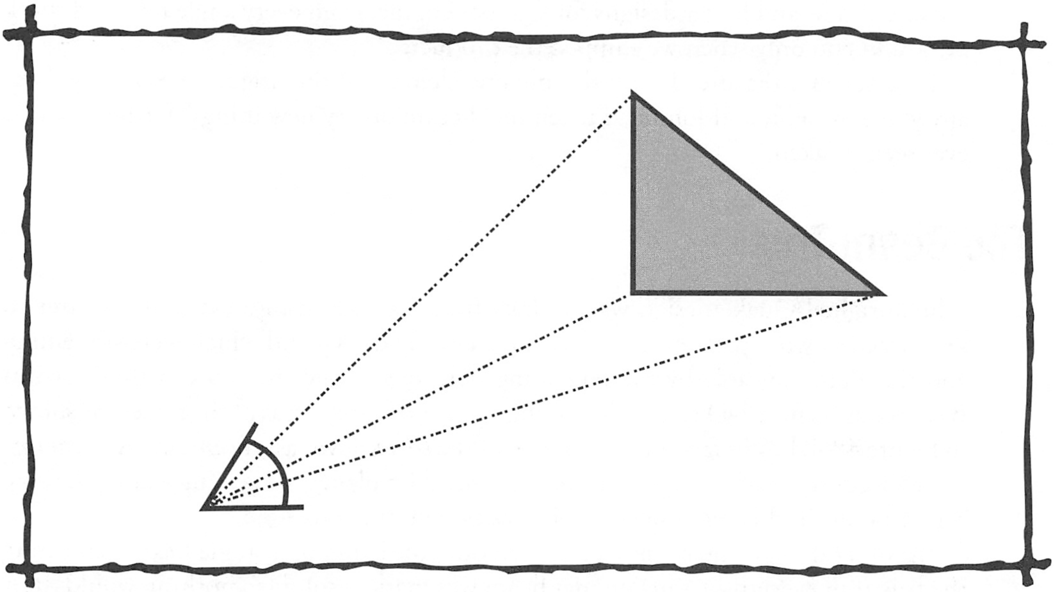


Figure 48.5 Beams as wedges projecting from the viewpoint to polygon edges.

the beam that intersected empty beams in the beam tree was considered drawable and added to the beam tree as a solid beam. This continued until either there were no more polygons or the beam tree became entirely solid. Once the beam tree was completed, the visible portions of the polygons that had contributed to the beam tree were drawn.

The advantage to working with a 3-D beam tree, rather than a 2-D region, is that determining which side of a beam plane a polygon vertex is on involves only checking the sign of the dot product of the ray to the vertex and the plane normal, because all beam planes run through the origin (the viewpoint). Also, because a beam plane is completely described by a single normal, generating a beam from a polygon edge requires only a cross-product of the edge and a ray from the edge to the viewpoint. Finally, bounding spheres of BSP nodes can be used to do the aforementioned bulk culling to the frustum.

The early-out feature of the beam tree—stopping when the beam tree becomes solid—seems appealing, because it appears to cap worst-case performance. Unfortunately, there are still scenes where it's possible to see all the way to the sky or the back wall of the world, so in the worst case, all polygons in the frustum will still have to be tested against the beam tree. Similar problems can arise from tiny cracks due to numeric precision limitations. Beam-tree clipping is fairly time-consuming, and in scenes with long view distances, such as views across the top of a level, the total cost of beam processing slowed Quake's frame rate to a crawl. So, in the end, the beam-tree approach proved to suffer from much the same malady as the painter's algorithm: The worst case was much worse than the average case, and it didn't scale well with increasing level complexity.

3-D Engine *du Jour*

Once the beam tree was working, John relentlessly worked at speeding up the 3-D engine, always trying to improve the design, rather than tweaking the implementation. At least once a week, and often every day, he would walk into my office and say "Last night I couldn't get to sleep, so I was thinking..." and I'd know that I was about to get my mind stretched yet again. John tried many ways to improve the beam tree, with some success, but more interesting was the profusion of wildly different approaches that he generated, some of which were merely discussed, others of which were implemented in overnight or weekend-long bursts of coding, in both cases ultimately discarded or further evolved when they turned out not to meet the design criteria well enough. Here are some of those approaches, presented in minimal detail in the hopes that, like Tom Wilson with the Paradise FIFO, your imagination will be sparked.

Subdividing Raycast

Rays are cast in an 8x8 screen-pixel grid; this is a highly efficient operation because the first intersection with a surface can be found by simply clipping the ray into the BSP tree, starting at the viewpoint, until a solid leaf is reached. If adjacent rays don't hit the same surface, then a ray is cast halfway between, and so on until all adjacent rays either hit the same surface or are on adjacent pixels; then the block around each ray is drawn from the polygon that was hit. This scales very well, being limited by the number of pixels, with no overdraw. The problem is dropouts; it's quite possible for small polygons to fall between rays and vanish.

Vertex-Free Surfaces

The world is represented by a set of surface planes. The polygons are implicit in the plane intersections, and are extracted from the planes as a final step before drawing. This makes for fast clipping and a very small data set (planes are far more compact than polygons), but it's time-consuming to extract polygons from planes.

The Draw-Buffer

Like a z-buffer, but with 1 bit per pixel, indicating whether the pixel has been drawn yet. This eliminates overdraw, but at the cost of an inner-loop buffer test, extra writes and cache misses, and, worst of all, considerable complexity. Variations include testing the draw-buffer a byte at a time and completely skipping fully-occluded bytes, or branching off each draw-buffer byte to one of 256 unrolled inner loops for drawing 0-8 pixels, in the process possibly taking advantage of the ability of the x86 to do the perspective floating-point divide in parallel while 8 pixels are processed.

Span-Based Drawing

Polygons are rasterized into spans, which are added to a global span list and clipped against that list so that only the nearest span at each pixel remains. Little sorting is needed with front-to-back walking, because if there's any overlap, the span already in the list is nearer. This eliminates overdraw, but at the cost of a lot of span arithmetic; also, every polygon still has to be turned into spans.

Portals

The holes where polygons are missing on surfaces are tracked, because it's only through such portals that line-of-sight can extend. Drawing goes front-to-back, and when a portal is encountered, polygons and portals behind it are clipped to its limits, until no polygons or portals remain visible. Applied recursively, this allows drawing only the visible portions of visible polygons, but at the cost of a considerable amount of portal clipping.

Breakthrough!

In the end, John decided that the beam tree was a sort of second-order structure, reflecting information already implicitly contained in the world BSP tree, so he tackled the problem of extracting visibility information directly from the world BSP tree. He spent a week on this, as a byproduct devising a perfect DOOM (2-D) visibility architecture, whereby a single, linear walk of a DOOM BSP tree produces zero-overdraw 2-D visibility. Doing the same in 3-D turned out to be a much more complex problem, though, and by the end of the week John was frustrated by the increasing complexity and persistent glitches in the visibility code. Although the direct-BSP approach was getting closer to working, it was taking more and more tweaking, and a simple, clean design didn't seem to be falling out. When I left work one Friday, John was preparing to try to get the direct-BSP approach working properly over the weekend.

When I came in on Monday, John had the look of a man who had broken through to the other side—and also the look of a man who hadn't had much sleep. He had worked all weekend on the direct-BSP approach, and had gotten it working reasonably well, with insights into how to finish it off. At 3:30 a.m. Monday morning, as he lay in bed, thinking about portals, he thought of precalculating and storing in each leaf a list of all leaves visible from that leaf, and then at runtime just drawing the visible leaves back-to-front for whatever leaf the viewpoint happens to be in, ignoring all other leaves entirely.

Size was a concern; initially, a raw, uncompressed potentially visible set (PVS) was several megabytes in size. However, the PVS could be stored as a bit vector, with 1 bit per leaf, a structure that shrunk a great deal with simple zero-byte compression. Those steps, along with changing the BSP heuristic to generate fewer leaves (choosing as the next splitter the polygon that splits the fewest other polygons appears to be the best heuristic) and sealing the outside of the levels so the BSPer can remove the outside surfaces, which can never be seen, eventually brought the PVS down to about 20 Kb for a good-size level.

In exchange for that 20 Kb, culling leaves outside the frustum is speeded up (because only leaves in the PVS are considered), and culling inside the frustum costs nothing more than a little overdraw (the PVS for a leaf includes all leaves visible from anywhere in the leaf, so some overdraw, typically on the order of 50% but ranging up to 150%, generally occurs). Better yet, precalculating the PVS results in a leveling of performance; worst case is no longer much worse than best case, because there's no longer extra VSD processing—just more polygons and perhaps some extra overdraw—associated with complex scenes. The first time John showed me his working prototype, I went to the most complex scene I knew of, a place where the frame rate used to grind down into the single digits, and spun around smoothly, with no perceptible slowdown.

John says precalculating the PVS was a logical evolution of the approaches he had been considering, that there was no moment when he said "Eureka!" Nonetheless, it was clearly a breakthrough to a brand-new, superior design, a design that, together with a still-in-development sorted-edge rasterizer that completely eliminates overdraw, comes remarkably close to meeting the "perfect-world" specifications we laid out at the start.

Simplify, and Keep on Trying New Things

What does it all mean? Exactly what I said up front: Simplify, and keep trying new things. The precalculated PVS is simpler than any of the other schemes that had been considered (although precalculating the PVS is an interesting task that I'll discuss another time). In fact, at runtime the precalculated PVS is just a constrained version of the painter's algorithm. Does that mean it's not particularly profound?

Not at all. All really great designs seem simple and even obvious—once they've been designed. But the process of getting there requires incredible persistence and a willingness to try lots of different ideas until the right one falls into place, as happened here.

My friend Chris Hecker has a theory that all approaches work out to the same thing in the end, since they all reflect the same underlying state and functionality. In terms of underlying theory, I've found that to be true; whether you do perspective texture mapping with a divide or with incremental hyperbolic calculations, the numbers do exactly the same thing. When it comes to implementation, however, my experience is that simply time-shifting an approach, or matching hardware capabilities better, or caching can make an astonishing difference.

My friend Terje Mathisen likes to say that "almost all programming can be viewed as an exercise in caching," and that's exactly what John did. No matter how fast he made his VSD calculations, they could never be as fast as precalculating and looking up the visibility, and his most inspired move was to yank himself out of the "faster code" mindset and realize that it was in fact possible to precalculate (in effect, cache) and look up the PVS.

The hardest thing in the world is to step outside a familiar, pretty good solution to a difficult problem and look for a different, better solution. The best ways I know to do that are to keep trying new, wacky things, and always, always, always try to simplify. One of John's goals is to have fewer lines of code in each 3-D game than in the previous game, on the assumption that as he learns more, he should be able to do things better with less code.

So far, it seems to have worked out pretty well for him.

Learn Now, Pay Forward

There's one other thing I'd like to mention before I close this chapter. Much of what I've learned, and a great deal of what I've written, has been in the pages of *Dr. Dobb's Journal.* As far back as I can remember, *DDJ* has epitomized the attitude that sharing programming information is A Good Thing. I know a lot of programmers who were able to leap ahead in their development because of Hendrix's Tiny C, or Stevens' D-Flat, or simply by browsing through *DDJ*'s annual collections. (Me, for one.) Understandably, most companies understandably view sharing information in a very different way, as potential profit lost—but that's what makes *DDJ* so valuable to the programming community.

It is in that spirit that id Software is allowing me to describe in these pages (which also appeared in one of the *DDJ* special issues) how Quake works, even before Quake has shipped. That's also why id has placed the full source code for Wolfenstein 3D on ftp.idsoftware.com/idstuff/source; and although you can't just recompile the code and sell it, you can learn how a full-blown, successful game works. Check wolfsrc.txt in the above-mentioned directory for details on how the code may be used.

So remember, when it's legally possible, sharing information benefits us all in the long run. You can pay forward the debt for the information you gain here and elsewhere by sharing what you know whenever you can, by writing an article or book or posting on the Net. None of us learns in a vacuum; we all stand on the shoulders of giants such as Wirth and Knuth and thousands of others. Lend your shoulders to building the future!

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Teller, Seth, *Visibility Preprocessing for Interactive Walkthroughs,* SIGGRAPH 91 proceedings, pp. 61-69.

3-D Clipping and Other Thoughts

Chapter 49

Determining What's Inside Your Field of View

Our part of the world is changing, and I'm concerned. By way of explanation, three anecdotes.

Anecdote the first: In the introduction to one of his books, Frank Herbert, author of *Dune*, told how he had once been approached by a friend who claimed he (the friend) had a killer idea for an SF story, and offered to tell it to Herbert. In return, Herbert had to agree that if he used the idea in a story, he'd split the money from the story with this fellow. Herbert's response was that ideas were a dime a dozen; he had more story ideas than he could ever write in a lifetime. The hard part was the writing, not the ideas.

Anecdote the second: I've been programming micros for 15 years, and writing about them for more than a decade and, until about a year ago, I had never—not once!—had anyone offer to sell me a technical idea. In the last year, it's happened multiple times, generally via unsolicited email along the lines of Herbert's tale.

This trend toward selling ideas is one symptom of an attitude that I've noticed more and more among programmers over the past few years—an attitude of which software patents are the most obvious manifestation—a desire to think something up without breaking a sweat, then let someone else's hard work make you money. It's an attitude that says, "I'm so smart that my ideas alone set me apart." Sorry, it doesn't work that way in the real world. Ideas are a dime a dozen in programming, too; I have a lifetime's worth of article and software ideas written neatly in a notebook, and I know several truly original thinkers who have far more yet. Folks, it's not the ideas; it's design, implementation, and especially hard work that make the difference.

Virtually every idea I've encountered in 3-D graphics was invented decades ago. You think you have a clever graphics idea? Sutherland, Sproull, Schumacker, Catmull, Smith, Blinn, Glassner, Kajiya, Heckbert or Teller probably thought of your idea years ago. (I'm serious—spend a few weeks reading through the literature on 3-D graphics, and you'll be amazed at what's already been invented and published.) If they thought it was important enough, they wrote a paper about it, or tried to commercialize it, but what they didn't do was try to charge people for the idea itself.

A closely related point is the astonishing lack of gratitude some programmers show for the hard work and sense of community that went into building the knowledge base with which they work. How about this? Anyone who thinks they have a unique idea that they want to "own" and milk for money can do so—but first they have to track down and appropriately compensate all the people who made possible the compilers, algorithms, programming courses, books, hardware, and so forth that put them in a position to have their brainstorm.

Put that way, it sounds like a silly idea, but the idea behind software patents is precisely that eventually everyone will own parts of our communal knowledge base, and that programming will become in large part a process of properly identifying and compensating each and every owner of the techniques you use. All I can say is that if we do go down that path, I guarantee that it will be a poorer profession for all of us—except the patent attorneys, I guess.

Anecdote the third: A while back, I had the good fortune to have lunch down by Seattle's waterfront with Neal Stephenson, the author of *Snow Crash* and *The Diamond Age* (one of the best SF books I've come across in a long time). As he talked about the nature of networked technology and what he hoped to see emerge, he mentioned that a couple of blocks down the street was the pawn shop where Jimi Hendrix bought his first guitar. His point was that if a cheap guitar hadn't been available, Hendrix's unique talent would never have emerged. Similarly, he views the networking of society as a way to get affordable creative tools to many people, so as much talent as possible can be unearthed and developed.

Extend that to programming. The way it should work is that a steady flow of information circulates, so that everyone can do the best work they're capable of. The idea is that I don't gain by intellectually impoverishing you, and vice-versa; as we both compete and (intentionally or otherwise) share ideas, both our products become better, so the market grows larger and everyone benefits.

That's the way things have worked with programming for a long time. So far as I can see it has worked remarkably well, and the recent signs of change make me concerned about the future of our profession.

Things aren't changing *everywhere,* though; over the past year, I've circulated a good bit of info about 3-D graphics, and plan to keep on doing it as long as I can. Next, we're going to take a look at 3-D clipping.

3-D Clipping Basics

Before I got deeply into 3-D, I kept hearing how difficult 3-D clipping was, so I was pleasantly surprised when I actually got around to doing it and found that it was quite straightforward, after all. At heart, 3-D clipping is nothing more than evaluating whether and where a line intersects a plane; in this context, the plane is considered to have an "inside" (a side on which points are to be kept) and an "outside" (a side on which points are to be removed or clipped). We can easily extend this single operation to polygon clipping, working with the line segments that form the edges of a polygon.

The most common application of 3-D clipping is as part of the process of hidden surface removal. In this application, the four planes that make up the view volume, or view frustum, are used to clip away parts of polygons that aren't visible. Sometimes this process includes clipping to near and far plane, to restrict the depth of the scene. Other applications include clipping to splitting planes while building BSP trees, and clipping moving objects to convex sectors such as BSP leaves. The clipping principles I'll cover apply to any sort of 3-D clipping task, but clipping to the frustum is the specific context in which I'll discuss clipping below.

In a commercial application, you wouldn't want to clip every single polygon in the scene database individually. As I mentioned in the last chapter, the use of bounding volumes to cull chunks of the scene database that fall entirely outside the frustum, without having to consider each polygon separately, is an important performance aspect of scene rendering. Once that's done, however, you're still left with a set of polygons that may be entirely inside, or partially or completely outside, the frustum. In this chapter, I'm going to talk about how to clip those remaining polygons. I'll focus on the basics of 3-D clipping, the stuff I wish I'd known when I started doing 3-D. There are plenty of ways to speed up clipping under various circumstances, some of which I'll mention, but the material covered below will give you the tools you need to implement functional 3-D clipping.

Intersecting a Line Segment with a Plane

The fundamental 3-D clipping operation is clipping a line segment to a plane. There are two parts to this operation: determining if the line is clipped by (intersects) the plane at all and, if it is clipped, calculating the point of intersection.

Before we can intersect a line segment with a plane, we must first define how we'll represent the line segment and the plane. The segment will be represented in the obvious way by the (x,y,z) coordinates of its two endpoints; this extends well to polygons, where each vertex is an (x,y,z) point. Planes can be described in many ways, among them are three points on the plane, a point on the plane and a unit normal, or a unit normal and a distance from the origin along the normal; we'll use the latter definition. Further, we'll define the normal to point to the inside (unclipped side) of the plane. The structures for points, polygons, and planes are shown in Listing 49.1.

Listing 49.1

```
typedef struct {
    double v[3];
} point_t;
```

```
typedef struct {
    double   x, y;
} point2D_t;

typedef struct {
    int         color;
    int         numverts;
    point_t     verts[MAX_POLY_VERTS];
} polygon_t;

typedef struct {
    int         color;
    int         numverts;
    point2D_t   verts[MAX_POLY_VERTS];
} polygon2D_t;

typedef struct convexobject_s {
    struct convexobject_s   *pnext;
    point_t                 center;
    double                  vdist;
    int                     numpolys;
    polygon_t               *ppoly;
} convexobject_t;

typedef struct {
    double  distance;
    point_t normal;
} plane_t;
```

Given a line segment, and a plane to which to clip the segment, the first question is whether the segment is entirely on the inside or the outside of the plane, or intersects the plane. If the segment is on the inside, then the segment is not clipped by the plane, and we're done. If it's on the outside, then it's entirely clipped, and we're likewise done. If it intersects the plane, then we have to remove the clipped portion of the line by replacing the endpoint on the outside of the plane with the point of intersection between the line and the plane.

The way to answer this question is to find out which side of the plane each endpoint is on, and the dot product is the right tool for the job. As you may recall from Chapter 46, dotting any vector with a unit normal returns the length of the projection of that vector onto the normal. Therefore, if we take any point and dot it with the plane normal we'll find out how far from the origin the point is, as measured along the plane normal. Another way to think of this is to say that the dot product of a point and the plane normal returns how far from the origin along the normal the plane would have to be in order to have the point lie within the plane, as if we slid the plane along the normal until it touched the point.

Now, remember that our definition of a plane is a unit normal and a distance along the normal. That means that we have a distance for the plane as part of the plane structure, and we can get the distance at which the plane would have to be to touch the point from the dot product of the point and the normal; a simple comparison of the two values suffices to tell us which side of the plane the point is on. If the dot product of the point and the plane normal is greater than the plane distance, then the point is in front of the plane (inside the volume being clipped to); if it's less, then the point is outside the volume and should be clipped.

After we do this twice, once for each line endpoint, we know everything necessary to categorize our line segment. If both endpoints are on the same side of the plane, there's nothing more to do, because the line is either completely inside or completely outside; otherwise, it's on to the next step, clipping the line to the plane by replacing the outside vertex with the point of intersection of the line and the plane. Happily, it turns out that we already have all of the information we need to do this.

From our earlier tests, we already know the length from the plane, measured along the normal, to the inside endpoint; that's just the distance, along the normal, of the inside endpoint from the origin (the dot product of the endpoint with the normal), minus the plane distance, as shown in Figure 49.1. We also know the length of the line segment, again measured as projected onto the normal; that's the difference between the distances along the normal of the inside and outside endpoints from the origin. The ratio of these two lengths is the fraction of the segment that remains after

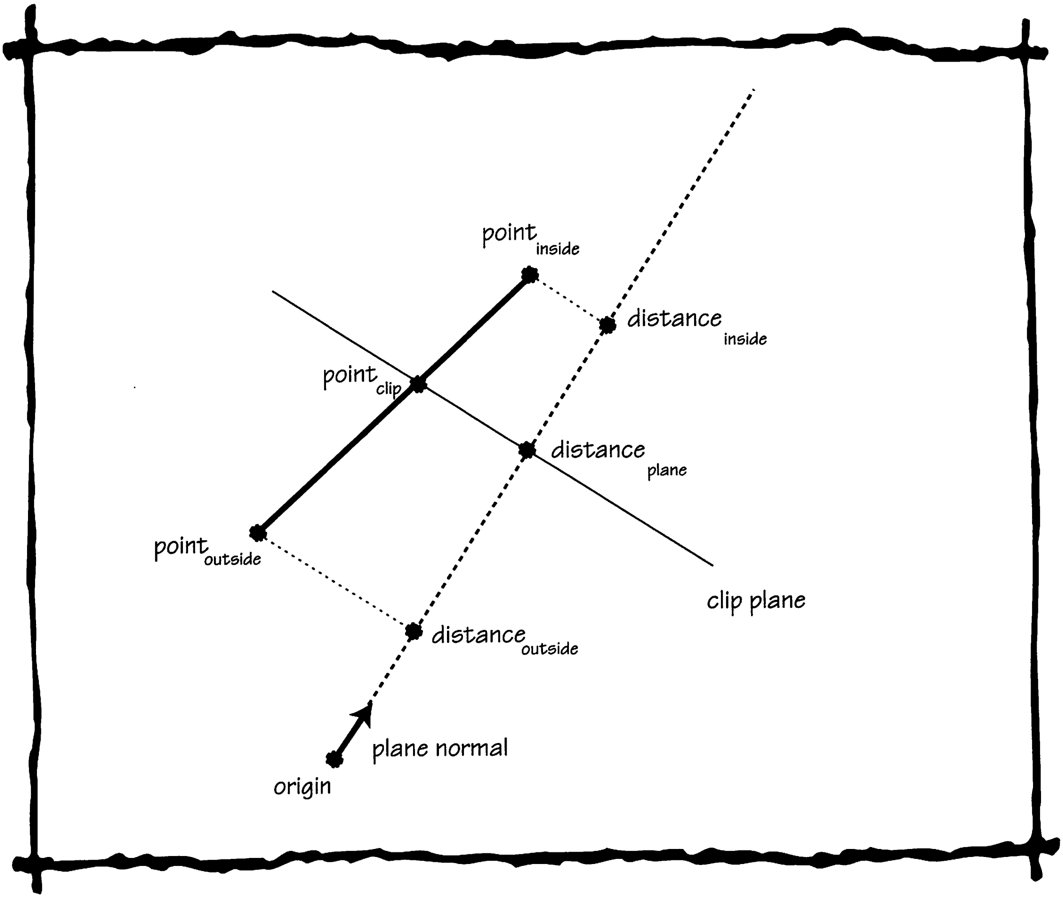


Figure 49.1 The distance from the plane to the inside endpoint, measured along the normal.

clipping. If we scale the x, y, and z lengths of the line segment by that fraction, and add the results to the inside endpoint, we get a new, clipped endpoint at the point of intersection.

Polygon Clipping

Line clipping is fine for wireframe rendering, but what we really want to do is polygon rendering of solid models, which requires polygon clipping. As with line segments, the clipping process with polygons is to determine if they're inside, outside, or partially inside the clip volume, lopping off any vertices that are outside the clip volume and substituting vertices at the intersection between the polygon and the clip plane, as shown in Figure 49.2.

An easy way to clip a polygon is to decompose it into a set of edges, and clip each edge separately as a line segment. Let's define a polygon as a set of vertices that wind clockwise around the outside of the polygonal area, as viewed from the front side of the polygon; the edges are implicitly defined by the order of the vertices. Thus, an edge is the line segment described by the two adjacent vertices that form its endpoints. We'll clip a polygon by clipping each edge individually, emitting vertices for the resulting polygon as appropriate, depending on the clipping state of the edge. If the start point of the edge is inside, that point is added to the output polygon. Then, if the start and end points are in different states (one inside and one outside), we clip the edge to the plane, as described above, and add the point at which the line intersects the clip plane as the next polygon vertex, as shown in Figure 49.3. Listing 49.2 shows a polygon-clipping function.

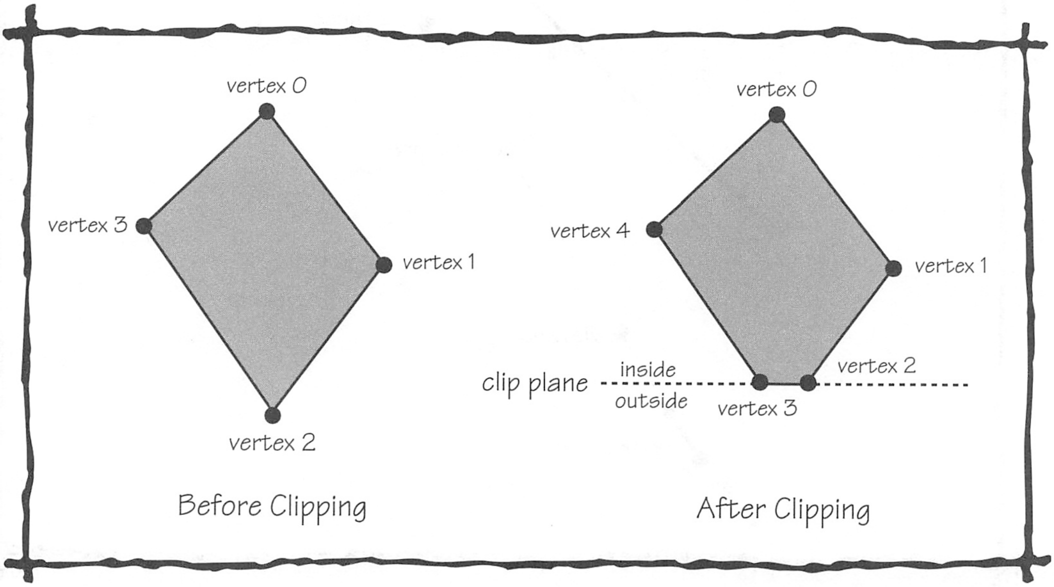


Figure 49.2 Clipping a polygon.

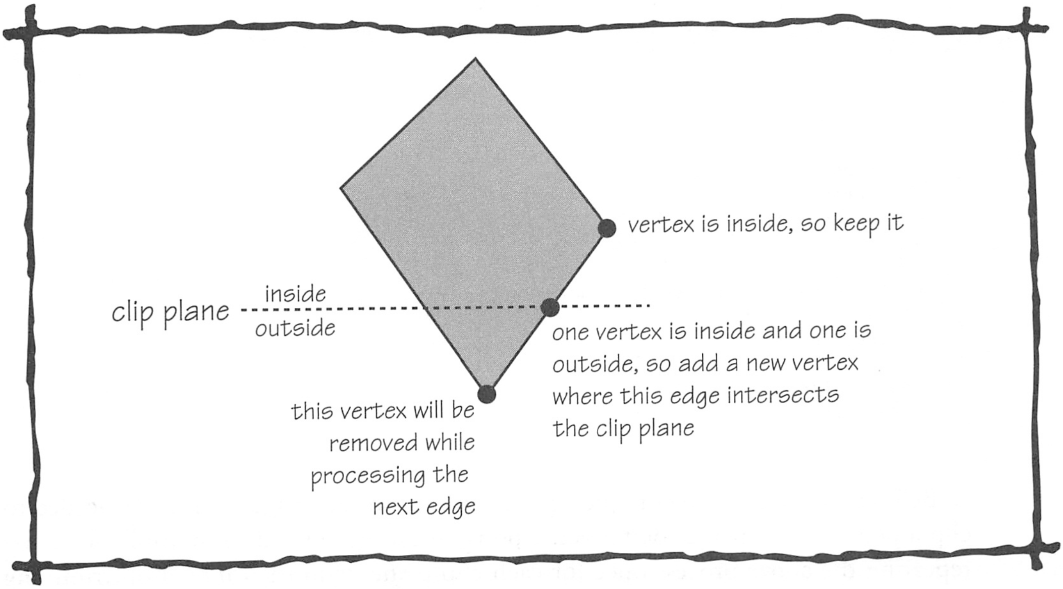

vertex is inside, so keep it
clip plane
inside
outside
one vertex is inside and one is outside, so add a new vertex where this edge intersects the clip plane
this vertex will be removed while processing the next edge

Figure 49.3 "Clipping a polygon edge."

Listing 49.2

```
int ClipToPlane(polygon_t *pin, plane_t *pplane, polygon_t *pout)
{
    int     i, j, nextvert, curin, nextin;
    double  curdot, nextdot, scale;
    point_t *pinvert, *poutvert;

    pinvert = pin->verts;
    poutvert = pout->verts;

    curdot = DotProduct(pinvert, &pplane->normal);
    curin = (curdot >= pplane->distance);

    for (i=0 ; i<pin->numverts ; i++)
    {
        nextvert = (i + 1) % pin->numverts;

        // Keep the current vertex if it's inside the plane
        if (curin)
            *poutvert++ = *pinvert;

        nextdot = DotProduct(&pin->verts[nextvert], &pplane->normal);
        nextin = (nextdot >= pplane->distance);

        // Add a clipped vertex if one end of the current edge is
        // inside the plane and the other is outside
        if (curin != nextin)
        {
            scale = (pplane->distance - curdot) /
                    (nextdot - curdot);
            for (j=0 ; j<3 ; j++)
            {
                poutvert->v[j] = pinvert->v[j] +
                    ((pin->verts[nextvert].v[j] - pinvert->v[j]) *
                     scale);
            }
            poutvert++;
        }

        curdot = nextdot;
        curin = nextin;
        pinvert++;
    }

    pout->numverts = poutvert - pout->verts;
    if (pout->numverts < 3)
        return 0;

    pout->color = pin->color;
    return 1;
}
```

Believe it or not, this technique, applied in turn to each edge, is all that's needed to clip a polygon to a plane. Better yet, a polygon can be clipped to multiple planes by repeating the above process once for each clip plane, with each interation trimming away any part of the polygon that's clipped by that particular plane.

One particularly useful aspect of 3-D clipping is that if you're drawing texture mapped polygons, texture coordinates can be clipped in exactly the same way as (x,y,z) coordinates. In fact, the very same fraction that's used to advance x, y, and z from the inside point to the point of intersection with the clip plane can be used to advance the texture coordinates as well, so only one extra multiply and one extra add are required for each texture coordinate.

Clipping to the Frustum

Given a polygon-clipping function, it's easy to clip to the frustum: set up the four planes for the sides of the frustum, with another one or two planes for near and far clipping, if desired; next, clip each potentially visible polygon to each plane in turn; then draw whatever polygons emerge from the clipping process. Listing 49.3 is the core code for a simple 3-D clipping example that allows you to move around and look at polygonal models from any angle. The full code for this program is available on the CD-ROM in the file DDJCLIP.ZIP.

Listing 49.3

```
int DIBWidth, DIBHeight;
int DIBPitch;
double  roll, pitch, yaw;
double  currentspeed;
point_t currentpos;
double  fieldofview, xcenter, ycenter;
double  xscreenscale, yscreenscale, maxscale;
```

```
int     numobjects;
double  speedscale = 1.0;
plane_t frustumplanes[NUM_FRUSTUM_PLANES];
double  mroll[3][3] = {{1, 0, 0}, {0, 1, 0}, {0, 0, 1}};
double  mpitch[3][3] = {{1, 0, 0}, {0, 1, 0}, {0, 0, 1}};
double  myaw[3][3] =  {{1, 0, 0}, {0, 1, 0}, {0, 0, 1}};
point_t vpn, vright, vup;
point_t xaxis = {1, 0, 0};
point_t zaxis = {0, 0, 1};
convexobject_t objecthead = {NULL, {0,0,0}, -999999.0};

// Project viewspace polygon vertices into screen coordinates.
// Note that the y axis goes up in worldspace and viewspace, but
// goes down in screenspace.
void ProjectPolygon (polygon_t *ppoly, polygon2D_t *ppoly2D)
{
    int     i;
    double  zrecip;

    for (i=0 ; i<ppoly->numverts ; i++)
    {
        zrecip = 1.0 / ppoly->verts[i].v[2];
        ppoly2D->verts[i].x =
               ppoly->verts[i].v[0] * zrecip * maxscale + xcenter;
        ppoly2D->verts[i].y = DIBHeight -
             (ppoly->verts[i].v[1] * zrecip * maxscale + ycenter);
    }
    ppoly2D->color = ppoly->color;
    ppoly2D->numverts = ppoly->numverts;
}

// Sort the objects according to z distance from viewpoint.
void ZSortObjects(void)
{
    int             i, j;
    double          vdist;
    convexobject_t  *pobject;
    point_t         dist;

    objecthead.pnext = &objecthead;
    for (i=0 ; i<numobjects ; i++)
    {
        for (j=0 ; j<3 ; j++)
            dist.v[j] = objects[i].center.v[j] - currentpos.v[j];
        objects[i].vdist = sqrt(dist.v[0] * dist.v[0] +
                                dist.v[1] * dist.v[1] +
                                dist.v[2] * dist.v[2]);
        pobject = &objecthead;
        vdist = objects[i].vdist;
        // Viewspace-distance-sort this object into the others.
        // Guaranteed to terminate because of sentinel
        while (vdist < pobject->pnext->vdist)
            pobject = pobject->pnext;
        objects[i].pnext = pobject->pnext;
        pobject->pnext = &objects[i];
    }
}

// Move the view position and set the world->view transform.
void UpdateViewPos()
{
    int      i;
    point_t motionvec;
    double  s, c, mtemp1[3][3], mtemp2[3][3];

    // Move in the view direction, across the x-y plane, as if
    // walking. This approach moves slower when looking up or
    // down at more of an angle
    motionvec.v[0] = DotProduct(&vpn, &xaxis);
    motionvec.v[1] = 0.0;
    motionvec.v[2] = DotProduct(&vpn, &zaxis);
    for (i=0 ; i<3 ; i++)
    {
        currentpos.v[i] += motionvec.v[i] * currentspeed;
        if (currentpos.v[i] > MAX_COORD)
            currentpos.v[i] = MAX_COORD;
        if (currentpos.v[i] < -MAX_COORD)
            currentpos.v[i] = -MAX_COORD;
    }
    // Set up the world-to-view rotation.
    // Note: much of the work done in concatenating these matrices
    // can be factored out, since it contributes nothing to the
    // final result; multiply the three matrices together on paper
    // to generate a minimum equation for each of the 9 final elements
    s = sin(roll);
    c = cos(roll);
    mroll[0][0] = c;
    mroll[0][1] = s;
    mroll[1][0] = -s;
    mroll[1][1] = c;
    s = sin(pitch);
    c = cos(pitch);
    mpitch[1][1] = c;
    mpitch[1][2] = s;
    mpitch[2][1] = -s;
    mpitch[2][2] = c;
    s = sin(yaw);
    c = cos(yaw);
    myaw[0][0] = c;
    myaw[0][2] = -s;
    myaw[2][0] = s;
    myaw[2][2] = c;
    MConcat(mroll, myaw, mtemp1);
    MConcat(mpitch, mtemp1, mtemp2);
    // Break out the rotation matrix into vright, vup, and vpn.
    // We could work directly with the matrix; breaking it out
    // into three vectors is just to make things clearer
    for (i=0 ; i<3 ; i++)
    {
        vright.v[i] = mtemp2[0][i];
        vup.v[i] = mtemp2[1][i];
        vpn.v[i] = mtemp2[2][i];
    }
    // Simulate crude friction
    if (currentspeed > (MOVEMENT_SPEED * speedscale / 2.0))
        currentspeed -= MOVEMENT_SPEED * speedscale / 2.0;
    else if (currentspeed < -(MOVEMENT_SPEED * speedscale / 2.0))
        currentspeed += MOVEMENT_SPEED * speedscale / 2.0;
    else
        currentspeed = 0.0;
}
```

```
// Rotate a vector from viewspace to worldspace.
void BackRotateVector(point_t *pin, point_t *pout)
{
    int     i;

    // Rotate into the world orientation
    for (i=0 ; i<3 ; i++)
        pout->v[i] = pin->v[0] * vright.v[i] +
                     pin->v[1] * vup.v[i] +
                     pin->v[2] * vpn.v[i];
}

// Transform a point from worldspace to viewspace.
void TransformPoint(point_t *pin, point_t *pout)
{
    int     i;
    point_t tvert;

    // Translate into a viewpoint-relative coordinate
    for (i=0 ; i<3 ; i++)
        tvert.v[i] = pin->v[i] - currentpos.v[i];
    // Rotate into the view orientation
    pout->v[0] = DotProduct(&tvert, &vright);
    pout->v[1] = DotProduct(&tvert, &vup);
    pout->v[2] = DotProduct(&tvert, &vpn);
}

// Transform a polygon from worldspace to viewspace.
void TransformPolygon(polygon_t *pinpoly, polygon_t *poutpoly)
{
    int         i;

    for (i=0 ; i<pinpoly->numverts ; i++)
        TransformPoint(&pinpoly->verts[i], &poutpoly->verts[i]);
    poutpoly->color = pinpoly->color;
    poutpoly->numverts = pinpoly->numverts;
}

// Returns true if polygon faces the viewpoint, assuming a clockwise
// winding of vertices as seen from the front.
int PolyFacesViewer(polygon_t *ppoly)
{
    int     i;
    point_t viewvec, edge1, edge2, normal;

    for (i=0 ; i<3 ; i++)
    {
        viewvec.v[i] = ppoly->verts[0].v[i] - currentpos.v[i];
        edge1.v[i] = ppoly->verts[0].v[i] - ppoly->verts[1].v[i];
        edge2.v[i] = ppoly->verts[2].v[i] - ppoly->verts[1].v[i];
    }
    CrossProduct(&edge1, &edge2, &normal);
    if (DotProduct(&viewvec, &normal) > 0)
        return 1;
    else
        return 0;
}

// Set up a clip plane with the specified normal.
void SetWorldspaceClipPlane(point_t *normal, plane_t *plane)
{
    // Rotate the plane normal into worldspace
    BackRotateVector(normal, &plane->normal);
    plane->distance = DotProduct(&currentpos, &plane->normal) +
            CLIP_PLANE_EPSILON;
}

// Set up the planes of the frustum, in worldspace coordinates.
void SetUpFrustum(void)
{
    double  angle, s, c;
    point_t normal;

    angle = atan(2.0 / fieldofview * maxscale / xscreenscale);
    s = sin(angle);
    c = cos(angle);
    // Left clip plane
    normal.v[0] = s;
    normal.v[1] = 0;
    normal.v[2] = c;
    SetWorldspaceClipPlane(&normal, &frustumplanes[0]);
    // Right clip plane
    normal.v[0] = -s;
    SetWorldspaceClipPlane(&normal, &frustumplanes[1]);
    angle = atan(2.0 / fieldofview * maxscale / yscreenscale);
    s = sin(angle);
    c = cos(angle);
    // Bottom clip plane
    normal.v[0] = 0;
    normal.v[1] = s;
    normal.v[2] = c;
    SetWorldspaceClipPlane(&normal, &frustumplanes[2]);
    // Top clip plane
    normal.v[1] = -s;
    SetWorldspaceClipPlane(&normal, &frustumplanes[3]);
}

// Clip a polygon to the frustum.
int ClipToFrustum(polygon_t *pin, polygon_t *pout)
{
    int         i, curpoly;
    polygon_t   tpoly[2], *ppoly;

    curpoly = 0;
    ppoly = pin;
    for (i=0 ; i<(NUM_FRUSTUM_PLANES-1); i++)
    {
        if (!ClipToPlane(ppoly,
                        &frustumplanes[i],
                        &tpoly[curpoly]))
            return 0;
        ppoly = &tpoly[curpoly];
        curpoly ^= 1;
    }
    return ClipToPlane(ppoly,
                    &frustumplanes[NUM_FRUSTUM_PLANES-1],
                    pout);
}
```

```
// Render the current state of the world to the screen.
void UpdateWorld()
{
    HPALETTE        holdpal;
    HDC             hdcScreen, hdcDIBSection;
    HBITMAP         holdbitmap;
    polygon2D_t     screenpoly;
    polygon_t       *ppoly, tpoly0, tpoly1, tpoly2;
    convexobject_t  *pobject;
    int             i, j, k;

    UpdateViewPos();
    memset(pDIBBase, 0, DIBWidth*DIBHeight);    // clear frame
    SetUpFrustum();
    ZSortObjects();
    // Draw all visible faces in all objects
    pobject = objecthead.pnext;
    while (pobject != &objecthead)
    {
        ppoly = pobject->ppoly;
        for (i=0 ; i<pobject->numpolys ; i++)
        {
            // Move the polygon relative to the object center
            tpoly0.color = ppoly->color;
            tpoly0.numverts = ppoly->numverts;
            for (j=0 ; j<tpoly0.numverts ; j++)
            {
                for (k=0 ; k<3 ; k++)
                    tpoly0.verts[j].v[k] = ppoly->verts[j].v[k] +
                            pobject->center.v[k];
            }
            if (PolyFacesViewer(&tpoly0))
            {
                if (ClipToFrustum(&tpoly0, &tpoly1))
                {
                    TransformPolygon (&tpoly1, &tpoly2);
                    ProjectPolygon (&tpoly2, &screenpoly);
                    FillPolygon2D (&screenpoly);
                }
            }
            ppoly++;
        }
        pobject = pobject->pnext;
    }
    // We've drawn the frame; copy it to the screen
    hdcScreen = GetDC(hwndOutput);
    holdpal = SelectPalette(hdcScreen, hpalDIB, FALSE);
    RealizePalette(hdcScreen);
    hdcDIBSection = CreateCompatibleDC(hdcScreen);
    holdbitmap = SelectObject(hdcDIBSection, hDIBSection);
    BitBlt(hdcScreen, 0, 0, DIBWidth, DIBHeight, hdcDIBSection,
           0, 0, SRCCOPY);
    SelectPalette(hdcScreen, holdpal, FALSE);
    ReleaseDC(hwndOutput, hdcScreen);
    SelectObject(hdcDIBSection, holdbitmap);
    ReleaseDC(hwndOutput, hdcDIBSection);
}
```

The Lessons of Listing 49.3

There are several interesting points to Listing 49.3. First, floating-point arithmetic is used throughout the clipping process. While it is possible to use fixed-point, doing so requires considerable care regarding range and precision. Floating-point is much easier—and, with the Pentium generation of processors, is generally comparable in speed. In fact, for some operations, such as multiplication in general and division when the floating-point unit is in single-precision mode, floating-point is much faster. Check out Chris Hecker's column in the February 1996 *Game Developer* for an interesting discussion along these lines.

Second, the planes that form the frustum are shifted ever so slightly inward from their proper positions at the edge of the field of view. This guarantees that it's never possible to generate a visible vertex exactly at the eyepoint, averting the divide-by-zero error that such a vertex would cause when projected and at no performance cost.

Third, the orientation of the viewer relative to the world is specified via yaw, pitch, and roll angles, successively applied in that order. These angles are accumulated from frame to frame according to user input, and for each frame are used to rotate the view up, view right, and viewplane normal vectors, which define the world coordinate system, into the viewspace coordinate system; those transformed vectors in turn define the rotation from worldspace to viewspace. (See Chapter 46 for a discussion of coordinate systems and rotation, and take a look at Chapters 5 and 6 of *Computer Graphics*, by Foley & van Dam, for a broader overview.) One attractive aspect of accumulating angular rotations that are then applied to the coordinate system vectors is that there is no deterioration of the rotation matrix over time. This is in contrast to my X-Sharp package, (developed in Part IX of this book) in which I accumulated rotations by keeping a cumulative matrix of all the rotations ever performed; unfortunately, that approach caused roundoff error to accumulate, so objects began to warp visibly after many rotations.

Fourth, Listing 49.3 processes each input polygon into a clipped polygon, one line segment at a time. It would be more efficient to process all the vertices, categorizing whether and how they're clipped, and then perform a test such as the Cohen-Sutherland outcode test to detect trivial acceptance (the polygon is entirely inside) and sometimes trivial rejection (the polygon is fully outside) without ever dealing with the edges, and to identify which planes actually need to be clipped against, as discussed in "Line-Segment Clipping Revisited," *Dr. Dobb's Journal*, January 1996. Some clipping approaches also minimize the number of intersection calculations when a segment is clipped by multiple planes. Further, Listing 49.3 clips a polygon against each plane in turn, generating a new output polygon for each plane; it is possible and can be more efficient to generate the final, clipped polygon without any intermediate representations. For further reading on advanced clipping techniques, see the discussion starting on page 271 of Foley & van Dam.

Finally, clipping in Listing 49.3 is performed in worldspace, rather than in viewspace. The frustum is backtransformed from viewspace (where it is defined, since it exists relative to the viewer) to worldspace for this purpose. Worldspace clipping allows us to transform only those vertices that are visible, rather than transforming all vertices into viewspace, then clipping them. However, the decision whether to clip in worldspace or viewspace is not clear-cut and is affected by several factors.

Advantages of Viewspace Clipping

Although viewspace clipping requires transforming vertices that may not be drawn, it has potential performance advantages. For example, in worldspace, near and far clip planes are just additional planes that have to be tested and clipped to, using dot products. In viewspace, near and far clip planes are typically planes with constant z coordinates, so testing whether a vertex is near or far-clipped can be performed with a single z compare, and the fractional distance along a line segment to a near or far clip intersection can be calculated with a couple of z subtractions and a divide; no dot products are needed.

Similarly, if the field of view is exactly 90 degrees, so the frustum planes go out at 45 degree angles relative to the viewplane, then x==z and y==z along the clip planes. This means that the clipping status of a vertex can be determined with a simple comparison, far more quickly than the standard dot-product test. This lends itself particularly well to outcode-based clipping algorithms, since each compare can set one outcode bit.

For a game, 90 degrees is a pretty good field of view, but can we get the same sort of efficient clipping if we need some other field of view? Sure. All we have to do is scale the x and y results of the world-to-view transformation to account for the field of view, so that the coordinates lie in a viewspace that's normalized such that the frustum planes extend along lines of x==z and y==z. The resulting visible projected points span the range -1 to 1 (before scaling up to get pixel coordinates), just as with a 90-degree field of view, so the rest of the drawing pipeline remains unchanged. Better yet, there is no cost in performance because the adjustment can be added to the transformation matrix.

I didn't implement normalized clipping in Listing 49.3 because I wanted to illustrate the general 3-D clipping mechanism without additional complications, and because for many applications the dot product (which, after all, takes only 10-20 cycles on a Pentium) is sufficient. However, the more frustum clipping you're doing, especially if most of the polygons are trivially visible, the more attractive the performance advantages of normalized clipping become.

Further Reading

You now have the basics of 3-D clipping, but because fast clipping is central to high-performance 3-D, there's a lot more to be learned. One good place for further reading is Foley & van Dam; another is *Procedural Elements of Computer Graphics*, by David F. Rogers. Read and understand either of these books, and you'll know everything you need for world-class clipping.

And, as you read, you might take a moment to consider how wonderful it is that anyone who's interested can tap into so much expert knowledge for the price of a book—or, on the Internet, for free—with no strings attached. Our part of the world is a pretty good place right now, isn't it?

Quake's Hidden-Surface Removal

Chapter 50

Struggling with Z-Order Solutions to the Hidden Surface Problem

Okay, I admit it: I'm sick and tired of classic rock. Admittedly, it's been a while, about 20 years, since I was last excited to hear anything by the Cars or Boston, and I was never particularly excited in the first place about Bob Seger or Queen, to say nothing of Elvis, so some things haven't changed. But I knew something was up when I found myself changing the station on the Allman Brothers and Steely Dan and Pink Floyd and, God help me, the Beatles (just stuff like "Hello Goodbye" and "I'll Cry Instead," though, not "Ticket to Ride" or "A Day in the Life"; I'm not *that* far gone). It didn't take long to figure out what the problem was; I'd been hearing the same songs for a quarter-century, and I was bored.

I tell you this by way of explaining why it was that when my daughter and I drove back from dinner the other night, the radio in my car was tuned, for the first time ever, to a station whose slogan is "There is no alternative."

Now, we're talking here about a ten-year-old who worships the Beatles and has been raised on a steady diet of oldies. She loves melodies, catchy songs, and good singers, none of which you're likely to find on an alternative rock station. So it's no surprise that when I turned on the radio, the first word out of her mouth was "Yuck!"

What did surprise me was that after listening for a while, she said, "You know, Dad, it's actually kind of interesting."

Apart from giving me a clue as to what sort of music I can expect to hear blasting through our house when she's a teenager, her quick uptake on alternative rock (versus my decades-long devotion to the music of my youth) reminded me of something that it's easy to forget as we become older and more set in our ways. It reminded me that it's essential to keep an open mind, and to be willing, better yet, eager, to try new things.

Programmers tend to become attached to familiar approaches, and are inclined to stick with whatever is currently doing the job adequately well, but in programming there are always alternatives, and I've found that they're often worth considering.

Not that I should have needed any reminding, considering the ever-evolving nature of Quake.

Creative Flux and Hidden Surfaces

Back in Chapter 48, I described the creative flux that led to John Carmack's decision to use a precalculated potentially visible set (PVS) of polygons for each possible viewpoint in Quake, the game we're developing here at id Software. The precalculated PVS meant that instead of having to spend a lot of time searching through the world database to find out which polygons were visible from the current viewpoint, we could simply draw all the polygons in the PVS from back-to-front (getting the ordering courtesy of the world BSP tree) and get the correct scene drawn with no searching at all; letting the back-to-front drawing perform the final stage of hidden-surface removal (HSR). This was a terrific idea, but it was far from the end of the road for Quake's design.

Drawing Moving Objects

For one thing, there was still the question of how to sort and draw moving objects properly; in fact, this is the single technical question I've been asked most often in recent months, so I'll take a moment to address it here. The primary problem is that a moving model can span multiple BSP leaves, with the leaves that are touched varying as the model moves; that, together with the possibility of multiple models in one leaf, means there's no easy way to use BSP order to draw the models in correctly sorted order. When I wrote Chapter 48, we were drawing sprites (such as explosions), moveable BSP models (such as doors), and polygon models (such as monsters) by clipping each into all the leaves it touched, then drawing the appropriate parts as each BSP leaf was reached in back-to-front traversal. However, this didn't solve the issue of sorting multiple moving models in a single leaf against each other, and also left some ugly sorting problems with complex polygon models.

John solved the sorting issue for sprites and polygon models in a startlingly low-tech way: We now z-buffer them. (That is, before we draw each pixel, we compare its distance, or z, value with the z value of the pixel currently on the screen, drawing only if the new pixel is nearer than the current one.) First, we draw the basic world, walls, ceilings, and the like. No z-buffer *testing* is involved at this point (the world visible surface determination is done in a different way, as we'll see soon); however, we do *fill* the z-buffer with the z values (actually, 1/z values, as discussed below) for all the world pixels. Z-filling is a much faster process than z-buffering the entire world would be, because no reads or compares are involved, just writes of z values. Once the drawing and z-filling of the world is done, we can simply draw the sprites and polygon models with z-buffering and get perfect sorting all around.

Performance Impact

Whenever a z-buffer is involved, the questions inevitably are: What's the memory footprint and what's the performance impact? Well, the memory footprint at 320x200 is 128K, not trivial but not a big deal for a game that requires 8 MB to run. The performance impact is about 10% for z-filling the world, and roughly 20% (with lots of variation) for drawing sprites and polygon models. In return, we get a perfectly sorted world, and also the ability to do additional effects, such as particle explosions and smoke, because the z-buffer lets us flawlessly sort such effects into the world. All in all, the use of the z-buffer vastly improved the visual quality and flexibility of the Quake engine, and also simplified the code quite a bit, at an acceptable memory and performance cost.

Leveling and Improving Performance

As I said above, in the Quake architecture, the world itself is drawn first, without z-buffer reads or compares, but filling the z-buffer with the world polygons' z values, and then the moving objects are drawn atop the world, using full z-buffering. Thus far, I've discussed how to draw moving objects. For the rest of this chapter, I'm going to talk about the other part of the drawing equation; that is, how to draw the world itself, where the entire world is stored as a single BSP tree and never moves.

As you may recall from Chapter 48, we're concerned with both raw performance and level performance. That is, we want the drawing code to run as fast as possible, but we also want the difference in drawing speed between the average scene and the slowest-drawing scene to be as small as possible.

It does little good to average 30 frames per second if 10% of the scenes draw at 5 fps, because the jerkiness in those scenes will be extremely obvious by comparison with the average scene, and highly objectionable. It would be better to average 15 fps 100% of the time, even though the average drawing speed is only half as much.

The precalculated PVS was an important step toward both faster and more level performance, because it eliminated the need to identify visible polygons, a relatively slow step that tended to be at its worst in the most complex scenes. Nonetheless, in some spots in real game levels the precalculated PVS contains five times more polygons than are actually visible; together with the back-to-front HSR approach, this created hot spots in which the frame rate bogged down visibly as hundreds of polygons are drawn back-to-front, most of those immediately getting overdrawn by nearer polygons. Raw performance in general was also reduced by the typical 50% overdraw resulting from drawing everything in the PVS. So, although drawing the PVS back-to-front as the final HSR stage worked and was an improvement over previous designs, it was not ideal. Surely, John thought, there's a better way to leverage the PVS than back-to-front drawing.

And indeed there is.

Sorted Spans

The ideal final HSR stage for Quake would reject all the polygons in the PVS that are actually invisible, and draw only the visible pixels of the remaining polygons, with no overdraw, that is, with every pixel drawn exactly once, all at no performance cost, of course. One way to do that (although certainly not at zero cost) would be to draw the polygons from front-to-back, maintaining a region describing the currently occluded portions of the screen and clipping each polygon to that region before drawing it. That sounds promising, but it is in fact nothing more or less than the beam tree approach I described in Chapter 48, an approach that we found to have considerable overhead and serious leveling problems.

We can do much better if we move the final HSR stage from the polygon level to the span level and use a sorted-spans approach. In essence, this approach consists of turning each polygon into a set of spans, as shown in Figure 50.1, and then sorting and clipping the spans against each other until only the visible portions of visible spans are left to be drawn, as shown in Figure 50.2. This may sound a lot like z-buffering (which is simply too slow for use in drawing the world, although it's fine for smaller moving objects, as described earlier), but there are crucial differences.

By contrast with z-buffering, only visible portions of visible spans are scanned out pixel by pixel (although all polygon edges must still be rasterized). Better yet, the sorting that z-buffering does at each pixel becomes a per-span operation with sorted spans, and because of the coherence implicit in a span list, each edge is sorted only against some of the spans on the same line and is clipped only to the few spans that it

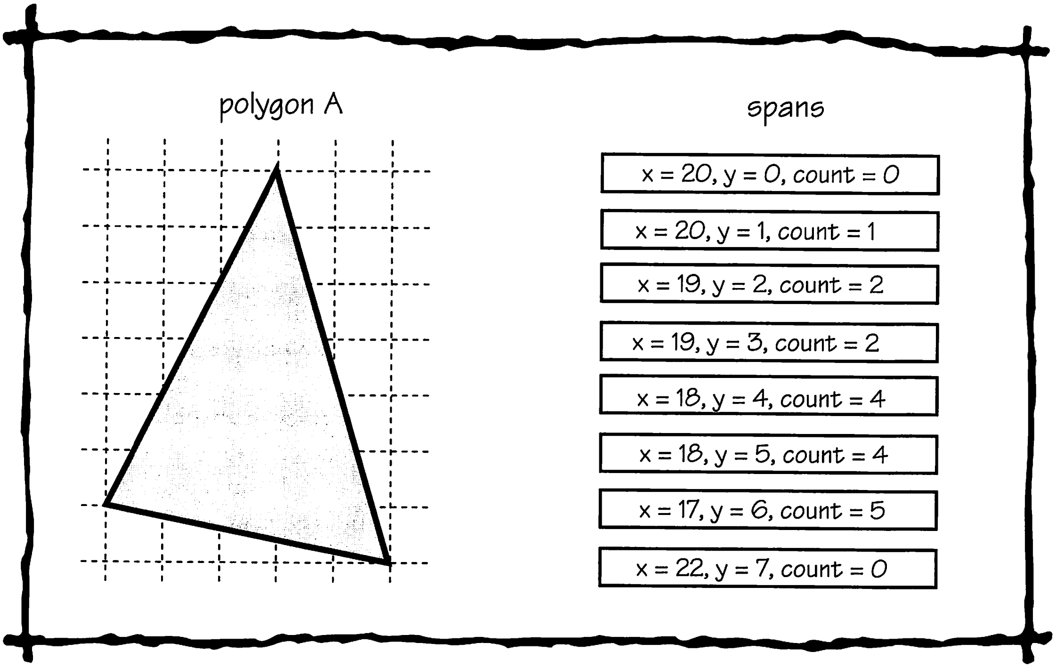


Figure 50.1 Span generation.

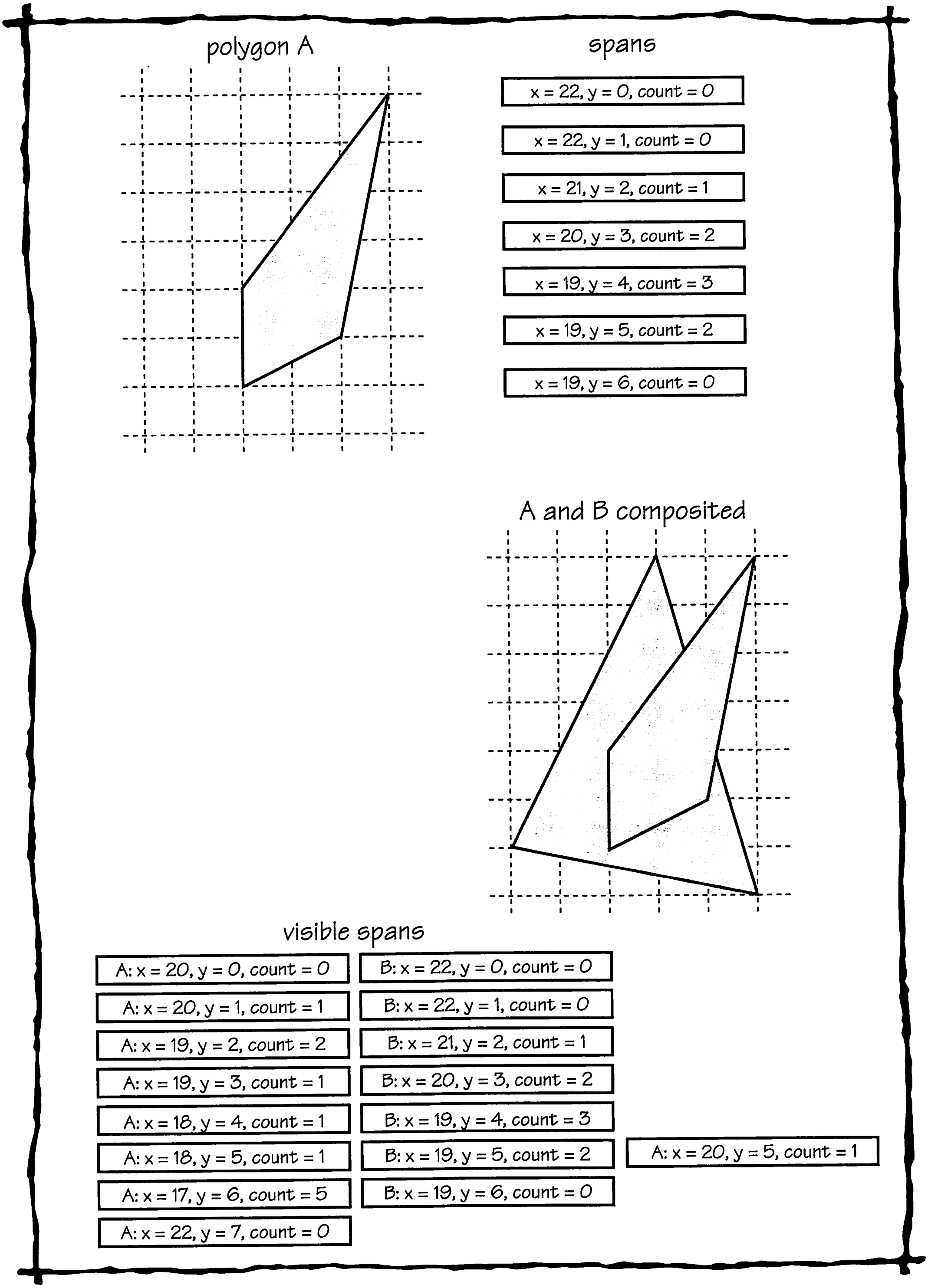

polygon A
spans
x = 22, y = 0, count = 0
x = 22, y = 1, count = 0
x = 21, y = 2, count = 1
x = 20, y = 3, count = 2
x = 19, y = 4, count = 3
x = 19, y = 5, count = 2
x = 19, y = 6, count = 0
A and B composited
visible spans
A: x = 20, y = 0, count = 0
A: x = 20, y = 1, count = 1
A: x = 19, y = 2, count = 2
A: x = 19, y = 3, count = 1
A: x = 18, y = 4, count = 1
A: x = 18, y = 5, count = 1
A: x = 17, y = 6, count = 5
A: x = 22, y = 7, count = 0
B: x = 22, y = 0, count = 0
B: x = 22, y = 1, count = 0
B: x = 21, y = 2, count = 1
B: x = 20, y = 3, count = 2
B: x = 19, y = 4, count = 3
B: x = 19, y = 5, count = 2
B: x = 19, y = 6, count = 0
A: x = 20, y = 5, count = 1

Figure 50.2 Two sets of spans sorted and clipped against one another.

overlaps horizontally. Although complex scenes still take longer to process than simple scenes, the worst case isn't as bad as with the beam tree or back-to-front approaches, because there's no overdraw or scanning of hidden pixels, because complexity is limited to pixel resolution and because span coherence tends to limit the worst-case sorting in any one area of the screen. As a bonus, the output of sorted spans is in precisely the form that a low-level rasterizer needs, a set of span descriptors, each consisting of a start coordinate and a length.

In short, the sorted spans approach meets our original criteria pretty well; although it isn't zero-cost, it's not horribly expensive, it completely eliminates both overdraw and pixel scanning of obscured portions of polygons and it tends to level worst-case performance. We wouldn't want to rely on sorted spans alone as our hidden-surface mechanism, but the precalculated PVS reduces the number of polygons to a level that sorted spans can handle quite nicely.

So we've found the approach we need; now it's just a matter of writing some code and we're on our way, right? Well, yes and no. Conceptually, the sorted-spans approach is simple, but it's surprisingly difficult to implement, with a couple of major design choices to be made, a subtle mathematical element, and some tricky gotchas that I'll have to defer until Chapter 51. Let's look at the design choices first.

Edges Versus Spans

The first design choice is whether to sort spans or edges (both of which fall into the general category of "sorted spans"). Although the results are the same both ways, a list of spans to be drawn, with no overdraw, the implementations and performance implications are quite different, because the sorting and clipping are performed using very different data structures.

With span-sorting, spans are stored in x-sorted, linked list buckets, typically with one bucket per scan line. Each polygon in turn is rasterized into spans, as shown in Figure 50.1, and each span is sorted and clipped into the bucket for the scan line the span is on, as shown in Figure 50.2, so that at any time each bucket contains the nearest spans encountered thus far, always with no overlap. This approach involves generating all spans for each polygon in turn, with each span immediately being sorted, clipped, and added to the appropriate bucket.

With edge-sorting, edges are stored in x-sorted, linked list buckets according to their start scan line. Each polygon in turn is decomposed into edges, cumulatively building a list of all the edges in the scene. Once all edges for all polygons in the view frustum have been added to the edge list, the whole list is scanned out in a single top-to-bottom, left-to-right pass. An active edge list (AEL) is maintained. With each step to a new scan line, edges that end on that scan line are removed from the AEL, active edges are stepped to their new x coordinates, edges starting on the new scan line are added to the AEL, and the edges are sorted by current x coordinate.

For each scan line, a z-sorted active polygon list (APL) is maintained. The x-sorted AEL is stepped through in order. As each new edge is encountered (that is, as each polygon starts or ends as we move left to right), the associated polygon is activated and sorted into the APL, as shown in Figure 50.3, or deactivated and removed from the APL, as shown in Figure 50.4, for a leading or trailing edge, respectively. If the nearest polygon has changed (that is, if the new polygon is nearest, or if the nearest polygon just ended), a span is emitted for the polygon that just stopped being the nearest,

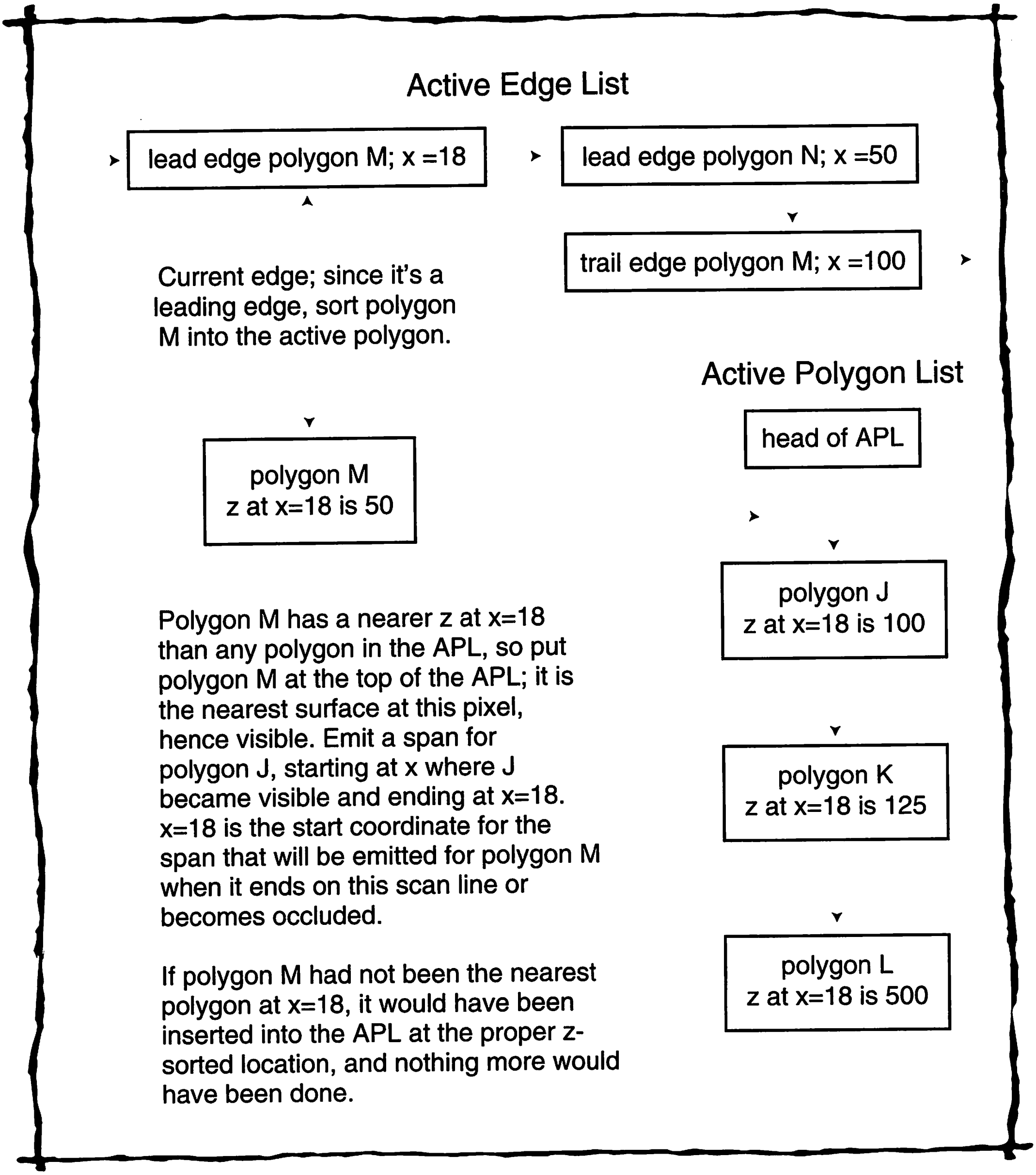
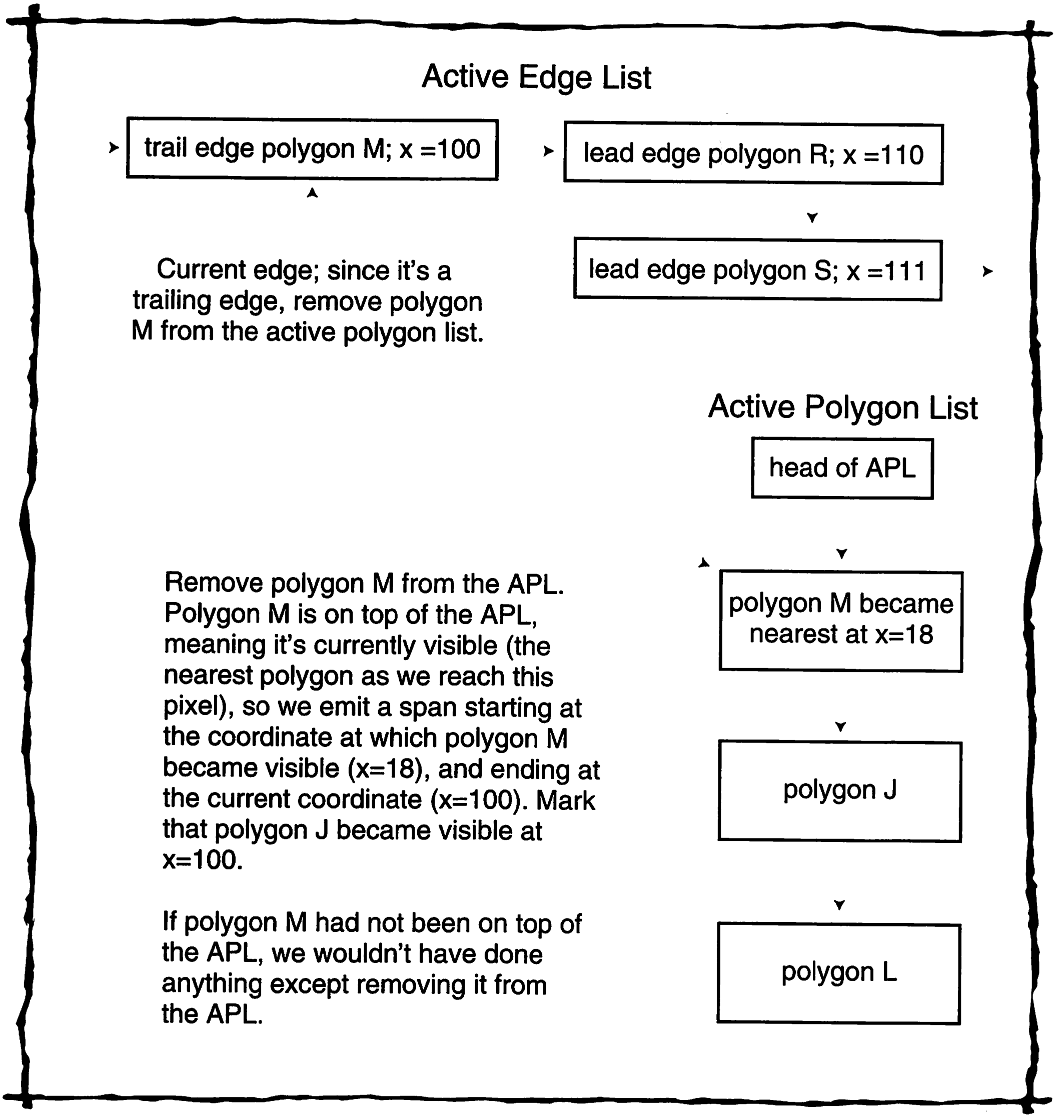

Active Edge List
lead edge polygon M; x =18
lead edge polygon N; x =50
trail edge polygon M; x =100
Current edge; since it's a leading edge, sort polygon M into the active polygon.
Active Polygon List
head of APL
polygon M
z at x=18 is 50
polygon J
z at x=18 is 100
polygon K
z at x=18 is 125
polygon L
z at x=18 is 500
Polygon M has a nearer z at x=18 than any polygon in the APL, so put polygon M at the top of the APL; it is the nearest surface at this pixel, hence visible. Emit a span for polygon J, starting at x where J became visible and ending at x=18. x=18 is the start coordinate for the span that will be emitted for polygon M when it ends on this scan line or becomes occluded.
If polygon M had not been the nearest polygon at x=18, it would have been inserted into the APL at the proper z-sorted location, and nothing more would have been done.

Figure 50.3 Activating a polygon when a leading edge is encountered in the AEL.



Active Edge List
trail edge polygon M; x =100
lead edge polygon R; x =110
lead edge polygon S; x =111
Active Polygon List
head of APL
polygon M became nearest at x=18
polygon J
polygon L

Current edge; since it's a trailing edge, remove polygon M from the active polygon list.

Remove polygon M from the APL. Polygon M is on top of the APL, meaning it's currently visible (the nearest polygon as we reach this pixel), so we emit a span starting at the coordinate at which polygon M became visible (x=18), and ending at the current coordinate (x=100). Mark that polygon J became visible at x=100.

If polygon M had not been on top of the APL, we wouldn't have done anything except removing it from the APL.

Figure 50.4 Deactivating a polygon when a trailing edge is encountered in the AEL.

starting at the point where the polygon first because nearest and ending at the x coordinate of the current edge, and the current x coordinate is recorded in the polygon that is now the nearest. This saved coordinate later serves as the start of the span emitted when the new nearest polygon ceases to be in front.

Don't worry if you didn't follow all of that; the above is just a quick overview of edge-sorting to help make the rest of this chapter a little clearer. My thorough discussion of the topic will be in Chapter 51.

The spans that are generated with edge-sorting are exactly the same spans that ultimately emerge from span-sorting; the difference lies in the intermediate data structures that are used to sort the spans in the scene. With edge-sorting, the spans are kept implicit in the edges until the final set of visible spans is generated, so the sorting, clipping, and span emission is done as each edge adds or removes a polygon, based on the span state implied by the edge and the set of active polygons. With span-sorting, spans are immediately made explicit when each polygon is rasterized, and those intermediate spans are then sorted and clipped against other the spans on the scan line to generate the final spans, so the states of the spans are explicit at all times, and all work is done directly with spans.

Both span-sorting and edge-sorting work well, and both have been employed successfully in commercial projects. We've chosen to use edge-sorting in Quake partly because it seems inherently more efficient, with excellent horizontal coherence that makes for minimal time spent sorting, in contrast with the potentially costly sorting into linked lists that span-sorting can involve. A more important reason, though, is that with edge-sorting we're able to share edges between adjacent polygons, and that cuts the work involved in sorting, clipping, and rasterizing edges nearly in half, while also shrinking the world database quite a bit due to the sharing.

One final advantage of edge-sorting is that it makes no distinction between convex and concave polygons. That's not an important consideration for most graphics engines, but in Quake, edge clipping, transformation, projection, and sorting have become a major bottleneck, so we're doing everything we can to get the polygon and edge counts down, and concave polygons help a lot in that regard. While it's possible to handle concave polygons with span-sorting, that can involve significant performance penalties.

Nonetheless, there's no cut-and-dried answer as to which approach is better. In the end, span-sorting and edge-sorting amount to the same functionality, and the choice between them is a matter of whatever you feel most comfortable with. In Chapter 51, I'll go into considerable detail about edge-sorting, complete with a full implementation. I'm going the spend the rest of this chapter laying the foundation for Chapter 51 by discussing sorting keys and 1/z calculation. In the process, I'm going to have to make a few forward references to aspects of edge-sorting that I haven't yet covered in detail; my apologies, but it's unavoidable, and all should become clear by the end of Chapter 51.

Edge-Sorting Keys

Now that we know we're going to sort edges, using them to emit spans for the polygons nearest the viewer, the question becomes: How can we tell which polygons are nearest? Ideally, we'd just store a sorting key in each polygon, and whenever a new edge came along, we'd compare its surface's key to the keys of other currently active polygons, and could easily tell which polygon was nearest.

That sounds too good to be true, but it is possible. If, for example, your world database is stored as a BSP tree, with all polygons clipped into the BSP leaves, then BSP walk order is a valid drawing order. So, for example, if you walk the BSP back-to-front, assigning each polygon an incrementally higher key as you reach it, polygons with higher keys are guaranteed to be in front of polygons with lower keys. This is the approach Quake used for a while, although a different approach is now being used, for reasons I'll explain shortly.

If you don't happen to have a BSP or similar data structure handy, or if you have lots of moving polygons (BSPs don't handle moving polygons very efficiently), another way to accomplish your objectives would be to sort all the polygons against one another before drawing the scene, assigning appropriate keys based on their spatial relationships in viewspace. Unfortunately, this is generally an extremely slow task, because every polygon must be compared to every other polygon. There are techniques to improve the performance of polygon sorts, but I don't know of anyone who's doing general polygon sorts of complex scenes in realtime on a PC.

An alternative is to sort by z distance from the viewer in screenspace, an approach that dovetails nicely with the excellent spatial coherence of edge-sorting. As each new edge is encountered on a scan line, the corresponding polygon's z distance can be calculated and compared to the other polygons' distances, and the polygon can be sorted into the APL accordingly.

Getting z distances can be tricky, however. Remember that we need to be able to calculate z at any arbitrary point on a polygon, because an edge may occur and cause its polygon to be sorted into the APL at any point on the screen. We could calculate z directly from the screen x and y coordinates and the polygon's plane equation, but unfortunately this can't be done very quickly, because the z for a plane doesn't vary linearly in screenspace; however, 1/z *does* vary linearly, so we'll use that instead. (See Chris Hecker's 1995 series of columns on texture mapping in *Game Developer* magazine for a discussion of screenspace linearity and gradients for 1/z.) Another advantage of using 1/z is that its resolution increases with decreasing distance, meaning that by using 1/z, we'll have better depth resolution for nearby features, where it matters most.

The obvious way to get a 1/z value at any arbitrary point on a polygon is to calculate 1/z at the vertices, interpolate it down both edges of the polygon, and interpolate between the edges to get the value at the point of interest. Unfortunately, that requires doing a lot of work along each edge, and worse, requires division to calculate the 1/z step per pixel across each span.

A better solution is to calculate 1/z directly from the plane equation and the screen x and y of the pixel of interest. The equation is:

$$1/z = (a/d)x' - (b/d)y' + c/d$$

where z is the viewspace z coordinate of the point on the plane that projects to screen coordinate (x',y') (the origin for this calculation is the center of projection, the point on the screen straight ahead of the viewpoint), [a b c] is the plane normal in viewspace, and d is the distance from the viewspace origin to the plane along the normal. Division is done only once per plane, because a, b, c, and d are per-plane constants.

The full 1/z calculation requires two multiplies and two adds, all of which should be floating-point to avoid range errors. That much floating-point math sounds expensive but really isn't, especially on a Pentium, where a plane's 1/z value at any point can be calculated in as little as six cycles in assembly language.

Where That 1/Z Equation Comes From

For those who are interested, here's a quick derivation of the 1/z equation. The plane equation for a plane is:

$ax + by + cz - d = 0,$

where x and y are viewspace coordinates, and a, b, c, d, and z are defined above. If we substitute x=x'z and y=-y'z (from the definition of the perspective projection, with y inverted because y increases upward in viewspace but downward in screenspace), and do some rearrangement, we get:

$z = d / (ax' - by' + c).$

Inverting and distributing yields:

$1/z = ax'/d - by'/d + c/d.$

We'll see 1/z sorting in action in Chapter 51.

Quake and Z-Sorting

I mentioned above that Quake no longer uses BSP order as the sorting key; in fact, it uses 1/z as the key now. Elegant as the gradients are, calculating 1/z from them is clearly slower than just doing a compare on a BSP-ordered key, so why have we switched Quake to 1/z?

The primary reason is to reduce the number of polygons. Drawing in BSP order means following certain rules, including the rule that polygons must be split if they cross BSP planes. This splitting increases the numbers of polygons and edges considerably. By sorting on 1/z, we're able to leave polygons unsplit but still get correct drawing order, so we have far fewer edges to process and faster drawing overall, despite the added cost of 1/z sorting.

Another advantage of 1/z sorting is that it solves the sorting issues I mentioned at the start involving moving models that are themselves small BSP trees. Sorting in world BSP order wouldn't work here, because these models are separate BSPs, and there's no easy way to work them into the world BSP's sequence order. We don't want to use z-buffering for these models because they're often large objects such as doors, and we don't want to lose the overdraw-reduction benefits that closed doors provide when drawn through the edge list. With sorted spans, the edges of moving BSP models are simply placed in the edge list (first clipping polygons so they don't cross any solid world surfaces, to avoid complications associated with interpenetration), along with all the world edges, and 1/z sorting takes care of the rest.

Decisions Deferred

There is, without a doubt, an awful lot of information in the preceding pages, and it may not all connect together yet in your mind. The code and accompanying explanation in the next chapter should help; if you want to peek ahead, the code is available on the CD-ROM as DDJZSORT.ZIP in the directory for Chapter 51. You may also want to take a look at Foley & van Dam's *Computer Graphics* or Rogers' *Procedural Elements for Computer Graphics.*

As I write this, it's unclear whether Quake will end up sorting edges by BSP order or 1/z. Actually, there's no guarantee that sorted spans in any form will be the final design. Sometimes it seems like we change graphics engines as often as they play Elvis on the '50s oldies stations (but, one would hope, with more aesthetically pleasing results!) and no doubt we'll be considering the alternatives right up until the day we ship.

Sorted Spans in Action

Chapter 51

Implementing Independent Span Sorting for Rendering without Overdraw

In Chapter 50, we dove headlong into the intricacies of hidden surface removal by way of z-sorted (actually, 1/z-sorted) spans. At the end of that chapter, I noted that we were currently using 1/z-sorted spans in Quake, but it was unclear whether we'd switch back to BSP order. Well, some time after that writing, it's become clear: We're back to sorting spans by BSP order.

In Robert A. Heinlein's wonderful story "The Man Who Sold the Moon," the chief engineer of the Moon rocket project tries to figure out how to get a payload of three astronauts to the Moon and back. He starts out with a four-stage rocket design, but finds that it won't do the job, so he adds a fifth stage. The fifth stage helps, but not quite enough, "Because," he explains, "I've had to add in too much dead weight, that's why." (The dead weight is the control and safety equipment that goes with the fifth stage.) He then tries adding yet another stage, only to find that the sixth stage actually results in a net slowdown. In the end, he has to give up on the three-person design and build a one-person spacecraft instead.

1/z-sorted spans in Quake turned out pretty much the same way, as we'll see in a moment. First, though, I'd like to note up front that this chapter is very technical and builds heavily on material I covered earlier in this section of the book; if you haven't already read the other chapters in Part X (Chapters 44 through 50) you really should. Make no mistake about it, this is commercial-quality stuff; in fact, the code in this chapter uses the same sorting technique as the test version of Quake, QTEST1.ZIP, that id Software placed on the Internet in early March 1996. The material in Part X is the Real McCoy, true reports from the leading edge, and I trust that you'll be patient if careful rereading and some occasional catch-up reading of earlier chapters are required to absorb everything contained herein. Besides, the ultimate reference for any design is working code, which you'll find, in part, in Listing 51.1, and in its entirety in the file DDJZSORT.ZIP on the CD-ROM.

Quake and Sorted Spans

As you'll recall from Chapter 50, Quake uses sorted spans to get zero overdraw while rendering the world, thereby both improving overall performance and leveling frame rates by speeding up scenes that would otherwise experience heavy overdraw. Our original design used spans sorted by BSP order; because we traverse the world BSP tree from front-to-back relative to the viewpoint, the order in which BSP nodes are visited is a guaranteed front-to-back sorting order. We simply gave each node an increasing BSP sequence number as it was visited, set each polygon's sort key to the BSP sequence number of the node (BSP splitting plane) it lay on, and used those sort keys when generating spans.

(In a change from earlier designs, polygons now are stored on nodes, rather than leaves, which are the convex subspaces carved out by the BSP tree. Visits to potentially visible leaves are used only to mark that the polygons that touch those leaves are visible and need to be drawn, and each marked-visible polygon is then drawn after everything in front of its node has been drawn. This results in less BSP splitting of polygons, which is A Good Thing, as explained below.)

This worked flawlessly for the world, but had a couple of downsides. First, it didn't address the issue of sorting small, moving BSP models such as doors; those models could be clipped into the world BSP tree's leaves and assigned sort keys corresponding to the leaves into which they fell, but there was still the question of how to sort multiple BSP models in the same world leaf against each other. Second, strict BSP order requires that polygons be split so that every polygon falls entirely within a single leaf. This can be stretched by putting polygons on nodes, allowing for larger polygons on average, but even then, polygons still need to be split so that every polygon falls within the bounding volume for the node on which it lies. The end result, in either case, is more and smaller polygons than if BSP order weren't used—and that, in turn, means lower performance, because more polygons must be clipped, transformed, and projected, more sorting must be done, and more spans must be drawn.

We figured that if only we could avoid those BSP splits, Quake would get a lot faster. Accordingly, we switched from sorting on BSP order to sorting on 1/z, and left our polygons unsplit. Things did get faster at first, but not as much as we had expected, for two reasons.

First, as the world BSP tree is descended, we clip each node's bounding box in turn to see if it's inside or outside each plane of the view frustum. The clipping results can be remembered, and often allow the avoidance of some or all clipping for the node's polygons. For example, all polygons in a node that has a trivially accepted bounding box are likewise guaranteed to be unclipped and in the frustum, since they all lie within the node's volume and need no further clipping. This efficient clipping mechanism vanished as soon as we stepped out of BSP order, because a polygon was no longer necessarily confined to its node's volume.

Second, sorting on 1/z isn't as cheap as sorting on BSP order, because floating-point calculations and comparisons are involved, rather than integer compares. So Quake got faster but, like Heinlein's fifth rocket stage, there was clear evidence of diminishing returns.

That wasn't the bad part; after all, even a small speed increase is A Good Thing. The real problem was that our initial 1/z sorting proved to be unreliable. We first ran into problems when two forward-facing polygons started at a common edge, because it was hard to tell which one was really in front (as discussed below), and we had to do additional floating-point calculations to resolve these cases. This fixed the problems for a while, but then odd cases started popping up where just the right combination of polygon alignments caused new sorting errors. We tinkered with those too, adding more code and incurring additional slowdowns in the process. Finally, we had everything working smoothly again, although by this point Quake was back to pretty much the same speed it had been with BSP sorting.

And then yet another crop of sorting errors popped up.

We could have fixed those errors too; we'll take a quick look at how to deal with such cases shortly. However, like the sixth rocket stage, the fixes would have made Quake *slower* than it had been with BSP sorting. So we gave up and went back to BSP order, and now the code is simpler and sorting works reliably. It's too bad our experiment didn't work out, but it wasn't wasted time because in trying what we did we learned quite a bit. In particular, we learned that the information provided by a simple, reliable world ordering mechanism, such as a BSP tree, can do more good than is immediately apparent, in terms of both performance and solid code.

Nonetheless, sorting on 1/z can be a valuable tool, used in the right context; drawing a Quake world just doesn't happen to be such a case. In fact, sorting on 1/z is how we're now handling the sorting of multiple BSP models that lie within the same world leaf in Quake. In this case, we don't have the option of using BSP order (because we're drawing multiple independent trees), so we've set restrictions on the BSP models to avoid running into the types of 1/z sorting errors we encountered drawing the Quake world. Below, we'll look at another application in which sorting on 1/z is quite useful, one where objects move freely through space. As is so often the case in 3-D, there is no one "right" technique, but rather a great many different techniques, each one handy in the right situations. Often, a combination of techniques is beneficial; for example, the combination in Quake of BSP sorting for the world and 1/z sorting for BSP models in the same world leaf.

For the remainder of this chapter, I'm going to look at the three main types of 1/z span sorting, then discuss a sample 3-D app built around 1/z span sorting.

Types of 1/z Span Sorting

As a quick refresher: With 1/z span sorting, all the polygons in a scene are treated as sets of screenspace pixel spans, and 1/z (where z is distance from the viewpoint in viewspace, as measured along the viewplane normal) is used to sort the spans so that the nearest span overlapping each pixel is drawn. As I discussed in Chapter 50, in the sample program we're actually going to do all our sorting with polygon edges, which represent spans in an implicit form.

There are three types of 1/z span sorting, each requiring a different implementation. In order of increasing speed and decreasing complexity, they are: intersecting, abutting, and independent. (These are names of my own devising; I haven't come across any standard nomenclature in the literature.)

Intersecting Span Sorting

Intersecting span sorting occurs when polygons can interpenetrate. Thus, two spans may cross such that part of each span is visible, in which case the spans have to be split and drawn appropriately, as shown in Figure 51.1.

Intersecting is the slowest and most complicated type of span sorting, because it is necessary to compare 1/z values at two points in order to detect interpenetration, and additional work must be done to split the spans as necessary. Thus, although intersecting span sorting certainly works, it's not the first choice for performance.

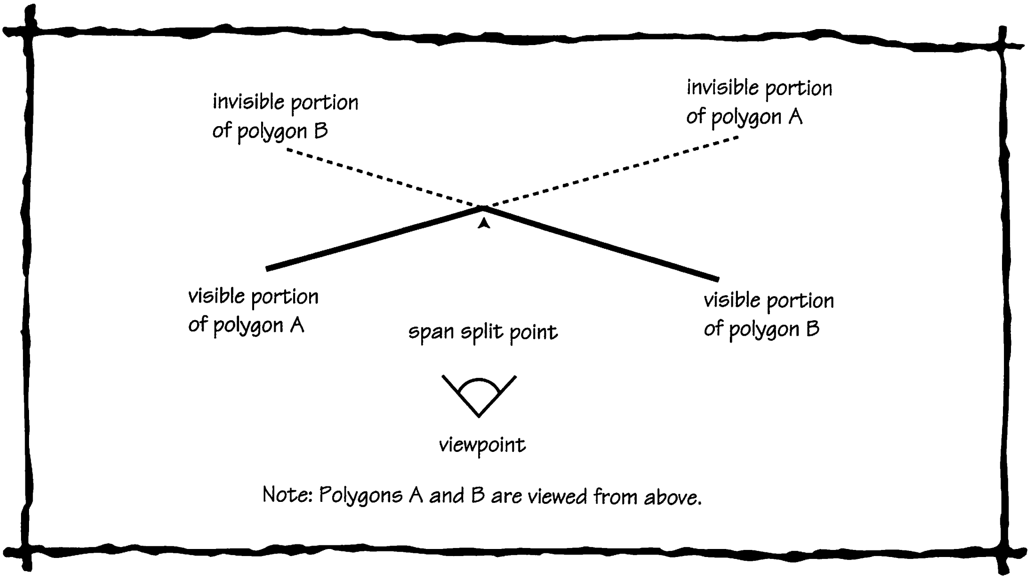

invisible portion of polygon B
invisible portion of polygon A
visible portion of polygon A
span split point
visible portion of polygon B
viewpoint
Note: Polygons A and B are viewed from above.

Figure 51.1 Intersecting span sorting.

Abutting Span Sorting

Abutting span sorting occurs when polygons that are not part of a continuous surface can butt up against one another, but don't interpenetrate, as shown in Figure 51.2. This is the sorting used in Quake, where objects like doors often abut walls and floors, and turns out to be more complicated than you might think. The problem is that when an abutting polygon starts on a given scan line, as with polygon B in Figure 51.2, it starts at exactly the same 1/z value as the polygon it abuts, in this case, polygon A, so additional sorting is needed when these ties happen. Of course, the two-point sorting used for intersecting polygons would work, but we'd like to find something faster.

As it turns out, the additional sorting for abutting polygons is actually quite simple; whichever polygon has a greater 1/z gradient with respect to screen x (that is, whichever polygon is heading fastest toward the viewer along the scan line) is the front one. The hard part is identifying *when* ties—that is, abutting polygons—occur; due to floating-point imprecision, as well as fixed-point edge-stepping imprecision that can move an edge slightly on the screen, calculations of 1/z from the combination of screen coordinates and 1/z gradients (as discussed last time) can be slightly off, so most tie cases will show up as near matches, not exact matches. This imprecision makes it necessary to perform two comparisons, one with an adjust-up by a small epsilon and one with an adjust-down, creating a range in which near-matches are considered matches. Fine-tuning this epsilon to catch all ties, without falsely reporting close-but-not-abutting edges as ties, proved to be troublesome in Quake, and the epsilon calculations and extra comparisons slowed things down.

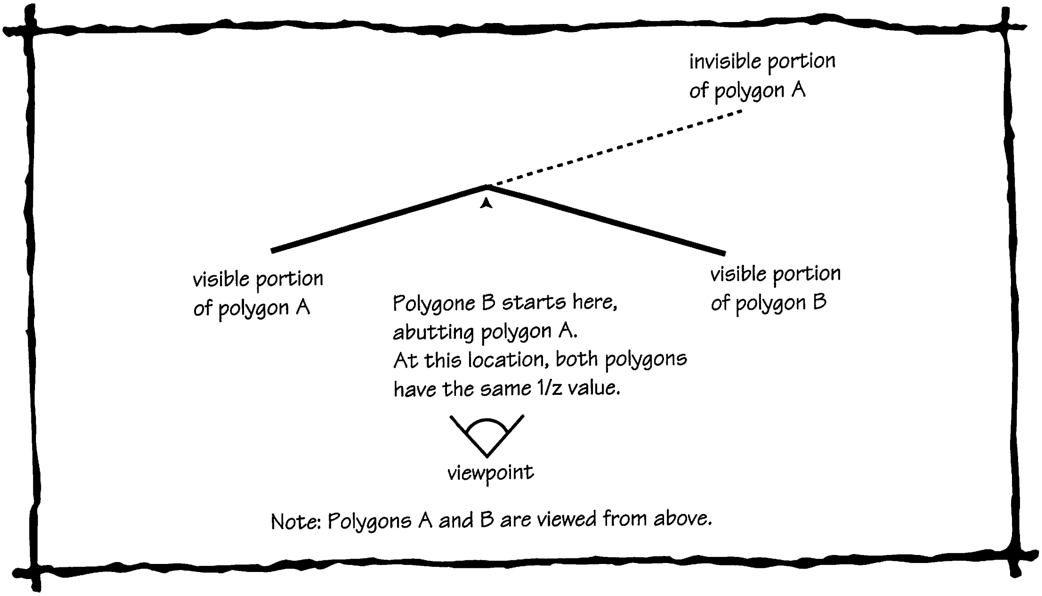

invisible portion of polygon A
visible portion of polygon A
Polygone B starts here, abutting polygon A. At this location, both polygons have the same 1/z value.
visible portion of polygon B
viewpoint
Note: Polygons A and B are viewed from above.

Figure 51.2 Abutting span sorting.

I do think that abutting 1/z span sorting could have been made reliable enough for production use in *Quake*, were it not that we share edges between adjacent polygons in *Quake*, so that the world is a large polygon mesh. When a polygon ends and is followed by an adjacent polygon that shares the edge that just ended, we simply assume that the adjacent polygon sorts relative to other active polygons in the same place as the one that ended (because the mesh is continuous and there's no interpenetration), rather than doing a 1/z sort from scratch. This speeds things up by saving a lot of sorting, but it means that if there is a sorting error, a whole string of adjacent polygons can be sorted incorrectly, pulled in by the one missorted polygon. Missorting is a very real hazard when a polygon is very nearly perpendicular to the screen, so that the 1/z calculations push the limits of numeric precision, especially in single-precision floating point.

Many caching schemes are possible with abutting span sorting, because any given pair of polygons, being noninterpenetrating, will sort in the same order throughout a scene. However, in *Quake* at least, the benefits of caching sort results were outweighed by the additional overhead of maintaining the caching information, and every caching variant we tried actually slowed *Quake* down.

Independent Span Sorting

Finally, we come to independent span sorting, the simplest and fastest of the three, and the type the sample code in Listing 51.1 uses. Here, polygons never intersect or touch any other polygons except adjacent polygons with which they form a continuous mesh. This means that when a polygon starts on a scan line, a single 1/z comparison between that polygon and the polygons it overlaps on the screen is guaranteed to produce correct sorting, with no extra calculations or tricky cases to worry about.

Independent span sorting is ideal for scenes with lots of moving objects that never actually touch each other, such as a space battle. Next, we'll look at an implementation of independent 1/z span sorting.

1/z Span Sorting in Action

Listing 51.1 is a portion of a program that demonstrates independent 1/z span sorting. This program is based on the sample 3-D clipping program from Chapter 49; however, the earlier program did hidden surface removal (HSR) by simply z-sorting whole objects and drawing them back-to-front, while Listing 51.1 draws all polygons by way of a 1/z-sorted edge list. Consequently, where the earlier program worked only so long as object centers correctly described sorting order, Listing 51.1 works properly for all combinations of non-intersecting and non-abutting polygons. In particular, Listing 51.1 correctly handles concave polyhedra; a new L-shaped object (the data for which is not included in Listing 51.1) has been added to the sample program to illustrate this capability. The ability to handle complex shapes makes Listing 51.1 vastly more useful for real-world applications than the 3-D clipping demo from Chapter 49.

Listing 51.1 L51_1.C

```
// Part of Win32 program to demonstrate z-sorted spans. Whitespace
// removed for space reasons. Full source code, with whitespace,
// available from ftp.idsoftware.com/mikeab/ddjzsort.zip.

#define MAX_SPANS         10000
#define MAX_SURFS         1000
#define MAX_EDGES         5000

typedef struct surf_s {
    struct surf_s    *pnext, *pprev;
    int              color, visxstart, state;
    double           zinv00, zinvstepx, zinvstepy;
} surf_t;

typedef struct edge_s {
    int              x, xstep, leading;
    surf_t           *psurf;
    struct edge_s    *pnext, *pprev, *pnextremove;
} edge_t;

// Span, edge, and surface lists
span_t  spans[MAX_SPANS];
edge_t  edges[MAX_EDGES];
surf_t  surfs[MAX_SURFS];

// Bucket list of new edges to add on each scan line
edge_t  newedges[MAX_SCREEN_HEIGHT];

// Bucket list of edges to remove on each scan line
edge_t  *removeedges[MAX_SCREEN_HEIGHT];

// Head and tail for the active edge list
edge_t  edgehead, edgetail;

// Edge used as sentinel of new edge lists
edge_t  maxedge = {0x7FFFFFFF};

// Head/tail/sentinel/background surface of active surface stack
surf_t  surfstack;

// pointers to next available surface and edge
surf_t  *pavailsurf;
edge_t  *pavailedge;


// Returns true if polygon faces the viewpoint, assuming a clockwise
// winding of vertices as seen from the front.
int PolyFacesViewer(polygon_t *ppoly, plane_t *pplane)
{
    int     i;
    point_t viewvec;

    for (i=0 ; i<3 ; i++)
        viewvec.v[i] = ppoly->verts[0].v[i] - currentpos.v[i];
    // Use an epsilon here so we don't get polygons tilted so
    // sharply that the gradients are unusable or invalid
    if (DotProduct (&viewvec, &pplane->normal) < -0.01)
        return 1;
    return 0;
}
```

```
// Add the polygon's edges to the global edge table.
void AddPolygonEdges (plane_t *plane, polygon2D_t *screenpoly)
{
    double  distinv, deltax, deltay, slope;
    int     i, nextvert, numverts, temp, topy, bottomy, height;
    edge_t  *pedge;

    numverts = screenpoly->numverts;

    // Clamp the polygon's vertices just in case some very near
    // points have wandered out of range due to floating-point
    // imprecision
    for (i=0 ; i<numverts ; i++) {
        if (screenpoly->verts[i].x < -0.5)
            screenpoly->verts[i].x = -0.5;
        if (screenpoly->verts[i].x > ((double)DIBWidth - 0.5))
            screenpoly->verts[i].x = (double)DIBWidth - 0.5;
        if (screenpoly->verts[i].y < -0.5)
            screenpoly->verts[i].y = -0.5;
        if (screenpoly->verts[i].y > ((double)DIBHeight - 0.5))
            screenpoly->verts[i].y = (double)DIBHeight - 0.5;
    }

    // Add each edge in turn
    for (i=0 ; i<numverts ; i++) {
        nextvert = i + 1;
        if (nextvert >= numverts)
            nextvert = 0;
        topy = (int)ceil(screenpoly->verts[i].y);
        bottomy = (int)ceil(screenpoly->verts[nextvert].y);
        height = bottomy - topy;
        if (height == 0)
            continue;       // doesn't cross any scan lines
        if (height < 0) {
            // Leading edge
            temp = topy;
            topy = bottomy;
            bottomy = temp;
            pavailedge->leading = 1;
            deltax = screenpoly->verts[i].x -
                     screenpoly->verts[nextvert].x;
            deltay = screenpoly->verts[i].y -
                     screenpoly->verts[nextvert].y;
            slope = deltax / deltay;
            // Edge coordinates are in 16.16 fixed point
            pavailedge->xstep = (int)(slope * (float)0x10000);
            pavailedge->x = (int)((screenpoly->verts[nextvert].x +
                ((float)topy - screenpoly->verts[nextvert].y) *
                slope) * (float)0x10000);
        } else {
            // Trailing edge
            pavailedge->leading = 0;
            deltax = screenpoly->verts[nextvert].x -
                     screenpoly->verts[i].x;
            deltay = screenpoly->verts[nextvert].y -
                     screenpoly->verts[i].y;
            slope = deltax / deltay;
            // Edge coordinates are in 16.16 fixed point
            pavailedge->xstep = (int)(slope * (float)0x10000);
            pavailedge->x = (int)((screenpoly->verts[i].x +
                ((float)topy - screenpoly->verts[i].y) * slope) *
                (float)0x10000);
        }

        // Put the edge on the list to be added on top scan
        pedge = &newedges[topy];
        while (pedge->pnext->x < pavailedge->x)
            pedge = pedge->pnext;
        pavailedge->pnext = pedge->pnext;
        pedge->pnext = pavailedge;

        // Put the edge on the list to be removed after final scan
        pavailedge->pnextremove = removeedges[bottomy - 1];
        removeedges[bottomy - 1] = pavailedge;

        // Associate the edge with the surface we'll create for
        // this polygon
        pavailedge->psurf = pavailsurf;

        // Make sure we don't overflow the edge array
        if (pavailedge < &edges[MAX_EDGES])
            pavailedge++;
    }

    // Create the surface, so we'll know how to sort and draw from
    // the edges
    pavailsurf->state = 0;
    pavailsurf->color = currentcolor;

    // Set up the 1/z gradients from the polygon, calculating the
    // base value at screen coordinate 0,0 so we can use screen
    // coordinates directly when calculating 1/z from the gradients
    distinv = 1.0 / plane->distance;
    pavailsurf->zinvstepx = plane->normal.v[0] * distinv *
            maxscreenscaleinv * (fieldofview / 2.0);
    pavailsurf->zinvstepy = -plane->normal.v[1] * distinv *
            maxscreenscaleinv * (fieldofview / 2.0);
    pavailsurf->zinv00 = plane->normal.v[2] * distinv -
            xcenter * pavailsurf->zinvstepx -
            ycenter * pavailsurf->zinvstepy;

    // Make sure we don't overflow the surface array
    if (pavailsurf < &surfs[MAX_SURFS])
        pavailsurf++;
}


// Scan all the edges in the global edge table into spans.
void ScanEdges (void)
{
    int     x, y;
    double  fx, fy, zinv, zinv2;
    edge_t  *pedge, *pedge2, *ptemp;
    span_t  *pspan;
    surf_t  *psurf, *psurf2;

    pspan = spans;

    // Set up the active edge list as initially empty, containing
    // only the sentinels (which are also the background fill). Most
    // of these fields could be set up just once at start-up
    edgehead.pnext = &edgetail;
edgehead.pprev = NULL;
edgehead.x = -0xFFFF;           // left edge of screen
edgehead.leading = 1;
edgehead.psurf = &surfstack;
edgetail.pnext = NULL;          // mark edge of list
edgetail.pprev = &edgehead;
edgetail.x = DIBWidth << 16;    // right edge of screen
edgetail.leading = 0;
edgetail.psurf = &surfstack;

// The background surface is the entire stack initially, and
// is infinitely far away, so everything sorts in front of it.
// This could be set just once at start-up
surfstack.pnext = surfstack.pprev = &surfstack;
surfstack.color = 0;
surfstack.zinv00 = -999999.0;
surfstack.zinvstepx = surfstack.zinvstepy = 0.0;
for (y=0 ; y<DIBHeight ; y++) {
    fy = (double)y;
    // Sort in any edges that start on this scan
    pedge = newedges[y].pnext;
    pedge2 = &edgehead;
    while (pedge != &maxedge) {
        while (pedge->x > pedge2->pnext->x)
            pedge2 = pedge2->pnext;
        ptemp = pedge->pnext;
        pedge->pnext = pedge2->pnext;
        pedge->pprev = pedge2;
        pedge2->pnext->pprev = pedge;
        pedge2->pnext = pedge;
        pedge2 = pedge;
        pedge = ptemp;
    }

    // Scan out the active edges into spans
    // Start out with the left background edge already inserted,
    // and the surface stack containing only the background
    surfstack.state = 1;
    surfstack.visxstart = 0;
    for (pedge=edgehead.pnext ; pedge ; pedge=pedge->pnext) {
        psurf = pedge->psurf;
        if (pedge->leading) {
            // It's a leading edge. Figure out where it is
            // relative to the current surfaces and insert in
            // the surface stack; if it's on top, emit the span
            // for the current top.
            // First, make sure the edges don't cross
            if (++psurf->state == 1) {
                fx = (double)pedge->x * (1.0 / (double)0x10000);
                // Calculate the surface's 1/z value at this pixel
                zinv = psurf->zinv00 + psurf->zinvstepx * fx +
                        psurf->zinvstepy * fy;
                // See if that makes it a new top surface
                psurf2 = surfstack.pnext;
                zinv2 = psurf2->zinv00 + psurf2->zinvstepx * fx +
                        psurf2->zinvstepy * fy;
                if (zinv >= zinv2) {
                    // It's a new top surface
                    // emit the span for the current top
                    x = (pedge->x + 0xFFFF) >> 16;
                    pspan->count = x - psurf2->visxstart;
                if (pspan->count > 0) {
                    pspan->y = y;
                    pspan->x = psurf2->visxstart;
                    pspan->color = psurf2->color;
                    // Make sure we don't overflow
                    // the span array
                    if (pspan < &spans[MAX_SPANS])
                        pspan++;
                }
                psurf->visxstart = x;
                // Add the edge to the stack
                psurf->pnext = psurf2;
                psurf2->pprev = psurf;
                surfstack.pnext = psurf;
                psurf->pprev = &surfstack;
            } else {
                // Not a new top; sort into the surface stack.
                // Guaranteed to terminate due to sentinel
                // background surface
                do {
                    psurf2 = psurf2->pnext;
                    zinv2 = psurf2->zinv00 +
                            psurf2->zinvstepx * fx +
                            psurf2->zinvstepy * fy;
                } while (zinv < zinv2);
                // Insert the surface into the stack
                psurf->pnext = psurf2;
                psurf->pprev = psurf2->pprev;
                psurf2->pprev->pnext = psurf;
                psurf2->pprev = psurf;
            }
        }
    } else {
        // It's a trailing edge; if this was the top surface,
        // emit the span and remove it.
        // First, make sure the edges didn't cross
        if (-psurf->state == 0) {
            if (surfstack.pnext == psurf) {
                // It's on top, emit the span
                x = ((pedge->x + 0xFFFF) >> 16);
                pspan->count = x - psurf->visxstart;
                if (pspan->count > 0) {
                    pspan->y = y;
                    pspan->x = psurf->visxstart;
                    pspan->color = psurf->color;
                    // Make sure we don't overflow
                    // the span array
                    if (pspan < &spans[MAX_SPANS])
                        pspan++;
                }
                psurf->pnext->visxstart = x;
            }
            // Remove the surface from the stack
            psurf->pnext->pprev = psurf->pprev;
            psurf->pprev->pnext = psurf->pnext;
        }
    }
}

// Remove edges that are done
pedge = removeedges[y];
```

```
        while (pedge) {
            pedge->pprev->pnext = pedge->pnext;
            pedge->pnext->pprev = pedge->pprev;
            pedge = pedge->pnextremove;
        }

        // Step the remaining edges one scan line, and re-sort
        for (pedge=edgehead.pnext ; pedge != &edgetail ; ) {
            ptemp = pedge->pnext;
            // Step the edge
            pedge->x += pedge->xstep;
            // Move the edge back to the proper sorted location,
            // if necessary
            while (pedge->x < pedge->pprev->x) {
                pedge2 = pedge->pprev;
                pedge2->pnext = pedge->pnext;
                pedge->pnext->pprev = pedge2;
                pedge2->pprev->pnext = pedge;
                pedge->pprev = pedge2->pprev;
                pedge->pnext = pedge2;
                pedge2->pprev = pedge;
            }
            pedge = ptemp;
        }
    }
    pspan->x = -1;  // mark the end of the list
}


// Draw all the spans that were scanned out.
void DrawSpans (void)
{
    span_t  *pspan;
    for (pspan=spans ; pspan->x != -1 ; pspan++)
        memset (pDIB + (DIBPitch * pspan->y) + pspan->x,
                pspan->color,
                pspan->count);
}


// Clear the lists of edges to add and remove on each scan line.
void ClearEdgeLists(void)
{
    int i;
    for (i=0 ; i<DIBHeight ; i++) {
        newedges[i].pnext = &maxedge;
        removeedges[i] = NULL;
    }
}


// Render the current state of the world to the screen.
void UpdateWorld()
{
    HPALETTE        holdpal;
    HDC             hdcScreen, hdcDIBSection;
    HBITMAP         holdbitmap;
    polygon2D_t     screenpoly;
    polygon_t       *ppoly, tpoly0, tpoly1, tpoly2;
    convexobject_t  *pobject;
    int             i, j, k;
```

```
plane_t         plane;
point_t         tnormal;

UpdateViewPos();
SetUpFrustum();
ClearEdgeLists();
pavailsurf = surfs;
pavailedge = edges;

// Draw all visible faces in all objects
pobject = objecthead.pnext;
while (pobject != &objecthead) {
    ppoly = pobject->ppoly;
    for (i=0 ; i<pobject->numpolys ; i++) {
        // Move the polygon relative to the object center
        tpoly0.numverts = ppoly[i].numverts;
        for (j=0 ; j<tpoly0.numverts ; j++) {
            for (k=0 ; k<3 ; k++)
                tpoly0.verts[j].v[k] = ppoly[i].verts[j].v[k] +
                        pobject->center.v[k];
        }
        if (PolyFacesViewer(&tpoly0, &ppoly[i].plane)) {
            if (ClipToFrustum(&tpoly0, &tpoly1)) {
                currentcolor = ppoly[i].color;
                TransformPolygon (&tpoly1, &tpoly2);
                ProjectPolygon (&tpoly2, &screenpoly);

                // Move the polygon's plane into viewspace
                // First move it into worldspace (object relative)
                tnormal = ppoly[i].plane.normal;
                plane.distance = ppoly[i].plane.distance +
                    DotProduct (&pobject->center, &tnormal);

                // Now transform it into viewspace
                // Determine the distance from the viewpont
                plane.distance -=
                      DotProduct (&currentpos, &tnormal);

                // Rotate the normal into view orientation
                plane.normal.v[0] =
                        DotProduct (&tnormal, &vright);
                plane.normal.v[1] =
                        DotProduct (&tnormal, &vup);
                plane.normal.v[2] =
                        DotProduct (&tnormal, &vpn);
                AddPolygonEdges (&plane, &screenpoly);
            }
        }
    }
    pobject = pobject->pnext;
}
ScanEdges ();
DrawSpans ();

// We've drawn the frame; copy it to the screen
hdcScreen = GetDC(hwndOutput);
holdpal = SelectPalette(hdcScreen, hpalDIB, FALSE);
RealizePalette(hdcScreen);
hdcDIBSection = CreateCompatibleDC(hdcScreen);
holdbitmap = SelectObject(hdcDIBSection, hDIBSection);
BitBlt(hdcScreen, 0, 0, DIBWidth, DIBHeight, hdcDIBSection,
            0, 0, SRCCOPY);
    SelectPalette(hdcScreen, holdpal, FALSE);
    ReleaseDC(hwndOutput, hdcScreen);
    SelectObject(hdcDIBSection, holdbitmap);
    DeleteDC(hdcDIBSection);
}
```

By the same token, Listing 51.1 is quite a bit more complicated than the earlier code. The earlier code's HSR consisted of a z-sort of objects, followed by the drawing of the objects in back-to-front order, one polygon at a time. Apart from the simple object sorter, all that was needed was backface culling and a polygon rasterizer.

Listing 51.1 replaces this simple pipeline with a three-stage HSR process. After backface culling, the edges of each of the polygons in the scene are added to the global edge list, by way of **AddPolygonEdges()**. After all edges have been added, the edges are turned into spans by **ScanEdges()**, with each pixel on the screen being covered by one and only one span (that is, there's no overdraw). Once all the spans have been generated, they're drawn by **DrawSpans()**, and rasterization is complete.

There's nothing tricky about **AddPolygonEdges()**, and **DrawSpans()**, as implemented in Listing 51.1, is very straightforward as well. In an implementation that supported texture mapping, however, all the spans wouldn't be put on one global span list and drawn at once, as is done in Listing 51.1, because that would result in drawing spans from all the surfaces in no particular order. (A surface is a drawing object that's originally described by a polygon, but in **ScanEdges()** there is no polygon in the classic sense of a set of vertices bounding an area, but rather just a set of edges and a surface that describes how to draw the spans outlined by those edges.) That would mean constantly skipping from one texture to another, which in turn would hurt processor cache coherency a great deal, and would also incur considerable overhead in setting up gradient and perspective calculations each time a surface was drawn. In Quake, we have a linked list of spans hanging off each surface, and draw all the spans for one surface before moving on to the next surface.

The core of Listing 51.1, and the most complex aspect of 1/z-sorted spans, is **ScanEdges()**, where the global edge list is converted into a set of spans describing the nearest surface at each pixel. This process is actually pretty simple, though, if you think of it as follows:

For each scan line, there is a set of active edges, which are those edges that intersect the scan line. A good part of **ScanEdges()** is dedicated to adding any edges that first appear on the current scan line (scan lines are processed from the top scan line on the screen to the bottom), removing edges that reach their bottom on the current scan line, and x-sorting the active edges so that the active edges for the next scan can be processed from left to right. All this is per-scan-line maintenance, and is basically just linked list insertion, deletion, and sorting.

The heart of the action is the loop in **ScanEdges()** that processes the edges on the current scan line from left to right, generating spans as needed. The best way to think of this loop is as a surface event processor, where each edge is an event with an associated surface. Each leading edge is an event marking the start of its surface on that scan line; if the surface is nearer than the current nearest surface, then a span ends for the nearest surface, and a span starts for the new surface. Each trailing edge is an event marking the end of its surface; if its surface is currently nearest, then a span ends for that surface, and a span starts for the next-nearest surface (the surface with the next-largest 1/z at the coordinate where the edge intersects the scan line). One handy aspect of this event-oriented processing is that leading and trailing edges do not need to be explicitly paired, because they are implicitly paired by pointing to the same surface. This saves the memory and time that would otherwise be needed to track edge pairs.

One more element is required in order for **ScanEdges()** to work efficiently. Each time a leading or trailing edge occurs, it must be determined whether its surface is nearest (at a larger 1/z value than any currently active surface). In addition, for leading edges, the currently topmost surface must be known, and for trailing edges, it may be necessary to know the currently next-to-topmost surface. The easiest way to accomplish this is with a *surface stack*; that is, a linked list of all currently active surfaces, starting with the nearest surface and progressing toward the farthest surface, which, as described below, is always the background surface. (The operation of this sort of edge event-based stack was described and illustrated in Chapter 50.) Each leading edge causes its surface to be 1/z-sorted into the surface stack, with a span emitted if necessary. Each trailing edge causes its surface to be removed from the surface stack, again with a span emitted if necessary. As you can see from Listing 51.1, it takes a fair bit of code to implement this, but all that's really going on is a surface stack driven by edge events.

Implementation Notes

Finally, a few notes on Listing 51.1. First, you'll notice that although we clip all polygons to the view frustum in worldspace, we nonetheless later clamp them to valid screen coordinates before adding them to the edge list. This catches any cases where arithmetic imprecision results in clipped polygon vertices that are a bit outside the frustum. I've only found such imprecision to be significant at very small z distances, so clamping would probably be unnecessary if there were a near clip plane, and might not even be needed in Listing 51.1, because of the slight nudge inward that we give the frustum planes, as described in Chapter 49. However, my experience has consistently been that relying on worldspace or viewspace clipping to produce valid screen coordinates 100 percent of the time leads to sporadic and hard-to-debug errors.

There is no separate routine to clear the background in Listing 51.1. Instead, a special background surface at an effectively infinite distance is added, so whenever no polygons are active the background color is drawn. If desired, it's a simple matter to flag the background surface and draw the background specially. For example, the background could be drawn as a starfield or a cloudy sky.

The edge-processing code in Listing 51.1 is fully capable of handling concave polygons as easily as convex polygons, and can handle an arbitrary number of vertices per polygon, as well. One change is needed for the latter case: Storage for the maximum number of vertices per polygon must be allocated in the polygon structures. In a fully polished implementation, vertices would be linked together or pointed to, and would be dynamically allocated from a vertex pool, so each polygon wouldn't have to contain enough space for the maximum possible number of vertices.

Each surface has a field named **state**, which is incremented when a leading edge for that surface is encountered, and decremented when a trailing edge is reached. A surface is activated by a leading edge only if **state** increments to 1, and is deactivated by a trailing edge only if **state** decrements to 0. This is another guard against arithmetic problems, in this case quantization during the conversion of vertex coordinates from floating point to fixed point. Due to this conversion, it is possible, although rare, for a polygon that is viewed nearly edge-on to have a trailing edge that occurs slightly *before* the corresponding leading edge, and the span-generation code will behave badly if it tries to emit a span for a surface that hasn't yet started. It would help performance if this sort of fix-up could be eliminated by careful arithmetic, but I haven't yet found a way to do so for 1/z-sorted spans.

Lastly, as discussed in Chapter 50, Listing 51.1 uses the gradients for 1/z with respect to changes in screen x and y to calculate 1/z for active surfaces each time a leading edge needs to be sorted into the surface stack. The natural origin for gradient calculations is the center of the screen, which is (x,y) coordinate (0,0) in viewspace. However, when the gradients are calculated in **AddPolygonEdges()**, the origin value is calculated at the upper left corner of the screen. This is done so that screen x and y coordinates can be used directly to calculate 1/z, with no need to adjust the coordinates to be relative to the center of the screen. Also, the screen gradients grow more extreme as a polygon is viewed closer to edge-on. In order to keep the gradient calculations from becoming meaningless or generating errors, a small epsilon is applied to backface culling, so that polygons that are very nearly edge-on are culled. This calculation would be more accurate if it were based directly on the viewing angle, rather than on the dot product of a viewing ray to the polygon with the polygon normal, but that would require a square root, and in my experience the epsilon used in Listing 51.1 works fine.

Afterword

If you've followed me this far, you might agree that we've come through some rough country. Still, I'm of the opinion that hard-won knowledge is the best knowledge, not only because it sticks to you better, but also because winning a hard race makes it easier to win the next one.

This is an unusual book in that sense: In addition to being a compilation of much of what I know about fast computer graphics, it is a journal recording some of the process by which I discovered and refined that knowledge. I didn't just sit down one day to write this book—I wrote it over a period of years and published its component parts in many places. It is a journal of my successes and frustrations, with side glances of my life as it happened along the way.

And there is yet another remarkable thing about this book: You, the reader, helped me write it. Perhaps not you personally, but many people who have read my articles and columns over the years sent me notes asking me questions, suggesting improvements (occasionally by daring me to beat them at the code performance game!) or sometimes just dumping remarkable code into my lap. Where it seemed appropriate, I dropped in the code and sometimes even the words of my correspondents, and the book is much the richer for it.

Here and there, I learned things that had nothing at all to do with fast graphics.

For example: I'm not a doomsayer who thinks American education lags hopelessly behind the rest of the Western world, but now and then something happens that makes me wonder. Some time back, I received a letter from one Melvyn J. Lafitte requesting that I spend some time in my columns describing fast 3-D animation techniques. Melvyn hoped that I would be so kind as to discuss, among other things, hidden surface removal and perspective projection, performed in real time, of course, and preferably in Mode X. Sound familiar?

Melvyn shared with me a hidden surface approach that he had developed. His technique involved defining polygon vertices in clockwise order, as viewed from the visible side. Then, he explained, one can use the cross-product equations found in any math book to determine which way the perpendicular to the polygon is pointing. Better yet, he pointed out, it's necessary to calculate only the Z component of the perpendicular, and only the sign of the Z component need actually be tested.

What Melvyn described is, of course, backface removal, a key hidden-surface technique that I used heavily in X-Sharp. In general, other hidden surface techniques must be used in conjunction with backface removal, but backface removal is nonetheless important and highly efficient. Simply put, Melvyn had devised for himself one of the fundamental techniques of 3-D drawing.

Melvyn lives in Moens, France. At the time he wrote me, Melvyn was 17 years old. Try to imagine any American 17-year-old of your acquaintance inventing backface removal. Try to imagine any teenager you know even using the phrase "the cross-product equations found in any math book." Not to mention that Melvyn was able to write a highly technical letter in English; and if Melvyn's English was something less than flawless, it was perfectly understandable, and, in my experience, vastly better than an average, or even well-educated, American's French. Please understand, I believe we Americans excel in a wide variety of ways, but I worry that when it comes to math and foreign languages, we are becoming a nation of *têtes de pomme de terre.*

Maybe I worry too much. If the glass is half empty, well, it's also half full. Plainly, something I wrote inspired Melvyn to do something that is wonderful, whether he realizes it or not. And it has been tremendously gratifying to sense in the letters I have received the same feeling of remarkably smart people going out there and doing amazing things just for the sheer unadulterated fun of it.

I don't think I'm exaggerating too much (well, maybe a little) when I say that this sort of fun is what I live for. I'm glad to see that so many of you share that same passion.

Good luck. Thank you for your input, your code, and all your kind words. Don't be afraid to attempt the impossible. Simply knowing what is impossible is useful knowledge—and you may well find, in the wake of some unexpected success, that not half of the things we call impossible have any right at all to wear the label.

—Michael Abrash

Further Reading

Perhaps the single most important book anyone interested in graphics should have is the second edition of Foley and van Dam's classic *Fundamentals of Interactive Computer Graphics*, the inspiration and primary reference for much of the nonmachine-specific material I've presented in this book. The almost entirely rewritten new version, retitled *Computer Graphics: Principles and Practice* (Addison-Wesley, 1990), nearly doubles the size of the first tome, to a total of 1,174 pages. You'll wish it were longer, too, because computer graphics has become such a broad field that even this massive book often merely touches on an area, providing the fundamental concepts, equations, and algorithms, and moves on. Still, just about everything you could want to know (or at least a reference to point you in the right direction) is in there somewhere. Truly a book to lose yourself in, and highly recommended.

Also, check out *The RenderMan Companion*, by Steve Upstill (Addison-Wesley, 1990). RenderMan is a comprehensive programming interface specification for 3-D graphics; implementations of the RenderMan interface have been the basis for stunning photorealistic imaging and special effects. (For background information on RenderMan, see Upstill's article "Photorealism in Computer Graphics," in *DDJ*, November 1988.) *Companion* takes you on a wide-ranging tour of the RenderMan interface, with plenty of sample code and output; even if you never program RenderMan directly, this book provides worthwhile insight into the nature of 3-D rendering. At the very least, read the foreword, a brief history of computer graphics and the development of RenderMan; it provides a sense of the dizzying pace of progress in computer graphics, and of the people behind the wonders.

Lord knows, I'm keenly interested in 3-D graphics, and *Programming in 3 Dimensions: 3-D Graphics, Ray Tracing, and Animation* by Christopher D. Watkins and Larry Sharp (M&T Books, 1992) is good stuff. There's a fair amount of theory, and lots of 3-D implementation, from modeling and scenes to ray tracing and finally, animation. The animation is the precomputed, playback kind, of the Autodesk Animator sort, and while it lacks the on-the-fly flexibility of the real-time animation we've discussed in this book, my oh my, it *does* look good. If you buy the book, I strongly suggest you get the disk as well; in which case, run ANIMATE.EXE, with BOUNCE as the input file, and marvel that you now have, in source form, all the software needed to implement that animation. Ten years ago, I'll bet you couldn't have produced this level of fully rendered, real-time playback animation for less than $50,000 in hardware and software; now, a couple of thousand will easily do the trick. What a great time this is to be a programmer! Recommended.

My primary reason for beginning to write about EGA and VGA graphics so long ago was the near-total absence back then of useful reference material on graphics adapters. That situation was eased in 1987 by the appearance of Richard Wilton's excellent book, *Programmer's Guide to PC and PS/2 Video Systems*, from Microsoft Press. The PS/2 has faded into the shadows in the intervening years, and the second edition of Wilton's book is now available, as *Programmer's Guide to PC Video Systems*, again from Microsoft Press.

The chapters I have read are accurate, readable, and come with large quantities of sample code. The book covers all current graphics standards, including CGA, EGA, VGA, and Hercules, and does a good job of it. Simply put, *Programmer's Guide to PC Video Systems*, Second Edition, is the best general PC graphics hardware reference I've seen to date.

If you want a broad understanding of the math that underlies computer graphics, I highly recommend *Mathematical Elements for Computer Graphics*, Second Edition, by David F. Rogers and J. Alan Adams (McGraw-Hill, 1990). Unlike Foley and van Dam's *Computer Graphics: Priciples and Practice*, this is not an encyclopedic graphics reference, nor does it mean to be; rather, it pulls together the mathematical theory behind several fundamental areas of computer graphics. After the traditional and largely pointless first chapter on graphics hardware, the book covers two-dimensional transformations, three-dimensional transformations, plane curves, space curves, and surface description and generation, all in a straightforward and thorough fashion. This is not light reading, although I found it easier going than Foley and van Dam; the tone is that of a textbook (albeit without exercises for the reader), and an amazing volume of information is dispensed, in the form of clear, concise explanations and examples, over the course of about 500 pages. Particularly noteworthy are the 130 pages on space curves, including Béziers and B-splines, and the 100 pages on surfaces. In short, this book is an excellent and serious overview of the fundamental mathematics of computer graphics.

Andrew Glassner's *Graphics Gems* (Academic Press, 1990) is an oddly enjoyable book. Odd, because there's no overall coherency to the book; it's a collection of more than 100 largely unrelated contributions by various authors on a hodgepodge of graphics subjects. Enjoyable, because it's that rarest sort of graphics programming book: One that you can open at random and start reading for fun. A good example of the nature of Graphics Gems is a chapter on mapping RGB colors into a 4-bit color space; this chapter features somewhat arcane theory, an interesting perspective on color space, and a fast technique for RGB mapping in 16-color modes. On balance, the chapter is a little uneven, but useful, informative, and interesting—a description that would serve well for *Graphics Gems* as a whole, as well.

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Author Biography

Michael Abrash has developed performance software for microcomputers since 1980. In that time, he has written several video games, authored columns on performance and graphics in *Dr. Dobb's Journal*, *Programmer's Journal*, and *PC TECHNIQUES*, worked on the design of graphics hardware, written the performance programming cult classic *Zen of Assembly Language*, and written graphics drivers and GUIs for a variety of companies. *Zen of Code Optimization* is his sixth book about computer programming.

What's on This CD

The bound-in CD contains all the source code listings and demo programs discussed in this book, including Michael Abrash's texture-mapped 3-D animation library, X-Sharp, in its most recent version.

The listings have been tested immediately prior to publication. The compiler/assembler pair used for testing was Borland C++ 4.02, and Turbo Assembler 4.0. The C and ASM style used is very standard and non-fancy, so the code should also compile and assemble with Microsoft tools. We cannot guarantee that, however.

The X-Sharp library exists in several implementations of gradually increasing sophistication. Each of these libraries is also present as a self-extracting archive. There is an UNPAK.BAT in each directory containing an X-Sharp archive that will execute the archive with that very important -d switch.

The most recent version, X-Sharp 22, is stored in the subdirectory XSHARP22. Use X-Sharp 22 for all new work; the others are stored in the chapter subdirectories where they are discussed, and should be used for explanatory purposes in conjunction with the chapter text only.

We have also included the complete text to Michael's book, *Zen of Assembly Language.* The text is in RTF and Word Perfect format.