

13

OPERATING SYSTEM DESIGN

In the past 12 chapters, we have covered a lot of ground and taken a look at many concepts and examples relating to operating systems. But studying existing operating systems is different from designing a new one. In this chapter we are going to take a quick look at some of the issues and trade-offs that operating systems designers have to consider when designing and implementing a new system.

There is a certain amount of folklore about what is good and what is bad floating around in the operating systems community, but surprisingly little has been written down. Probably the most important book is Fred Brooks' classic (1975) book *The Mythical Man Month* in which he relates his experiences in designing and implementing IBM's OS/360. The 20th anniversary edition revises some of that material and adds four new chapters (Brooks, 1995).

Three classic papers on operating system design are "Hints for Computer System Design" (Lampson, 1984), "On Building Systems that Will Fail" (Corbató, 1991), and "End-to-End Arguments in System Design" (Saltzer et al., 1984). Like Brooks' book, all three papers have survived the years extremely well; most of their insights are still as valid now as when they were first published.

This chapter draws upon these sources, plus the author's personal experience as designer or co-designer of three systems: Amoeba (Tanenbaum et al., 1990), MINIX (Tanenbaum and Woodhull, 1997), and Globe (Van Steen et al., 1999a). Since no consensus exists among operating system designers about the best way to design an operating system, this chapter will thus be more personal, speculative, and undoubtedly more controversial than the previous ones.

13.1 THE NATURE OF THE DESIGN PROBLEM

Operating system design is more of an engineering project than an exact science. It is much harder to set clear goals and to meet them. Let us look at start with these points.

13.1.1 Goals

In order to design a successful operating system, the designers have to have a clear idea of what they want. Lack of a goal makes it very hard to make subsequent decisions. To make this point clearer, it is instructive to take a look at two programming languages PL/I and C. PL/I was designed by IBM in the 1960s because it was a nuisance to have to support both FORTRAN and COBOL, and embarrassing to have academics yapping in the background that Algol was better than both of them. So a committee was set up to produce a language that would be all things to all people: PL/I. It had a little bit of FORTRAN, a little bit of COBOL, and a little bit of Algol. It failed because it lacked any unifying vision. It was simply a collection of features at war with one another, and too cumbersome to be compiled efficiently, to boot.

Now consider C. It was designed by one person (Dennis Ritchie) for one purpose (system programming). It was a huge success, in no small part because Ritchie knew what he wanted and did not want. As a result, it is still in widespread use more than three decades after its appearance. Having a clear vision of what you want is crucial.

What do operating system designers want? It obviously varies from system to system, being different for embedded systems than for server systems. However, for general-purpose operating systems four main items come to mind:

1. Define abstractions.
2. Provide primitive operations.
3. Ensure isolation.
4. Manage the hardware.

Each of these items will be discussed below.

The most important, but probably hardest task of an operating system is to define the right abstractions. Some of them, such as processes, address spaces, and files, have been around so long that they may seem obvious. Other ones, such as threads, are newer, and are less mature. For example, if a multithreaded process that has one thread blocked waiting for keyboard input forks, is there a thread in the new process also waiting for keyboard input? Other abstractions relate to synchronization, signals, the memory model, modeling of I/O and many other areas.

Each of the abstractions can be instantiated in the form of concrete data structures. Users can create processes, files, semaphores, etc. The primitive operations manipulate these data structures. For example, users can read and write files. The primitive operations are implemented in the form of system calls. From the user's point of view, the heart of the operating system is formed by the abstractions and the operations on them available via the system calls.

Since multiple users can be logged into a computer at the same time, the operating system needs to provide mechanisms to keep them separated. One user may not interfere with another. The process concept is widely used to group resources together for protection purposes. Files and other data structures generally are protected as well. Making sure each user can perform only authorized operations on authorized data is a key goal of system design. However, users also want to share data and resources, so the isolation has to be selective and under user control. This makes it much harder. Even when there is only a single user, different processes need to be isolated. The e-mail

Closely related to this point is the need to isolate failures. If some part of the system goes down, most commonly a user process, it should not be able to take the rest of the system down with it. The system design should make sure that the various parts are well isolated from one another. Ideally, parts of the operating system should also be isolated from one another to allow independent failures.

Finally, the operating system has to manage the hardware. In particular, it has to take care of all the low-level chips, such as interrupt controllers and bus controllers. It also has to provide a framework for allowing device drivers to manage the larger I/O devices, such as disks, printers, and the display.

13.1.2 Why is it Hard to Design an Operating System?

Moore's law says that computer hardware improves by a factor of 100 every decade. Nobody has a law saying that operating systems improve by a factor of 100 every decade. Or even get better at all. In fact, a case can be made that some of them are worse in key respects (such as reliability) than UNIX Version 7 was back in the 1970s.

Why? Inertia and the desire for backward compatibility often get much of the blame, and the failure to adhere to good design principles is also a culprit. But there is more to it. Operating systems are fundamentally different in certain ways from small application programs sold in stores for \$49. Let us look at eight of the issues that make designing an operating system much harder than designing an application program.

First, operating systems have become extremely large programs. No one person can sit down at a PC and dash off a serious operating system in a few months. All current versions of UNIX exceed 3 million lines of code; Windows Vista has over 5 million lines of kernel code (and over 50 million lines of total code). No one person can understand 3–5 million lines of code, let alone 50 million lines of

code. When you have a product that none of the designers can hope to fully understand, it should be no surprise that the results are often far from optimal.

Operating systems are not the most complex systems around. Aircraft carriers are far more complicated, for example, but they partition into isolated subsystems better. The people designing the toilets on a aircraft carrier do not have to worry about the radar system. The two subsystems do not interact much. In an operating system, the file system often interacts with the memory system in unexpected and unforeseen ways.

Second, operating systems have to deal with concurrency. There are multiple users and multiple I/O devices all active at once. Managing concurrency is inherently much harder than managing a single sequential activity. Race conditions and deadlocks are just two of the problems that come up.

Third, operating systems have to deal with potentially hostile users—users who want to interfere with system operation or do things that are forbidden from doing, such as stealing another user’s files. The operating system needs to take measures to prevent these users from behaving improperly. Word processing programs and photo editors do not have this problem.

Fourth, despite the fact that not all users trust each other, many users do want to share some of their information and resources with selected other users. The operating system has to make this possible, but in such a way that malicious users cannot interfere. Again, application programs do not face anything like this challenge.

Fifth, operating systems live for a very long time. UNIX has been around for a quarter of a century; Windows has been around for over two decades and shows no signs of vanishing. Consequently, the designers have to think about how hardware and applications may change in the distant future and how they should prepare for it. Systems that are locked too closely into one particular vision of the world usually die off.

Sixth, operating system designers really do not have a good idea of how their systems will be used, so they need to provide for considerable generality. Neither UNIX nor Windows was designed with e-mail or Web browsers in mind, yet many computers running these systems do little else. Nobody tells a ship designer to build a ship without specifying whether they want a fishing vessel, a cruise ship, or a battleship. And even fewer change their minds after the product has arrived.

Seventh, modern operating systems are generally designed to be portable, meaning they have to run on multiple hardware platforms. They also have to support thousands of I/O devices, all of which are independently designed with no regard to one another. An example of where this diversity causes problems is the need for an operating system to run on both little-endian and big-endian machines. A second example was seen constantly under MS-DOS when users attempted to install, say, a sound card and a modem that used the same I/O ports or interrupt request lines. Few programs other than operating systems have to deal with sorting out problems caused by conflicting pieces of hardware.

Eighth, and last in our list, is the frequent need to be backward compatible with some previous operating system. That system may have restrictions on word lengths, file names, or other aspects that the designers now regard as obsolete, but are stuck with. It is like converting a factory to produce next year's cars instead of this year's cars, but while continuing to produce this year's cars at full capacity.

13.2 INTERFACE DESIGN

It should be clear by now that writing a modern operating system is not easy. But where does one begin? Probably the best place to begin is to think about the interfaces it provides. An operating system provides a set of abstractions, mostly implemented by data types (e.g., files) and operations on them (e.g., read). Together, these form the interface to its users. Note that in this context the users of the operating system are programmers who write code that use system calls, not people running application programs.

In addition to the main system call interface, most operating systems have additional interfaces. For example, some programmers need to write device drivers to insert into the operating system. These drivers see certain features and can make certain procedure calls. These features and calls also define an interface, but a very different one from one application programmers see. All of these interfaces must be carefully designed if the system is to succeed.

13.2.1 Guiding Principles

Are there any principles that can guide interface design? We believe there are. Briefly summarized, they are simplicity, completeness, and the ability to be implemented efficiently.

Principle 1: Simplicity

A simple interface is easier to understand and implement in a bug-free way. All system designers should memorize this famous quote from the pioneer French aviator and writer, Antoine de St. Exupéry:

Perfection is reached not when there is no longer anything to add, but when there is no longer anything to take away.

This principle says that less is better than more, at least in the operating system itself. Another way to say this is the KISS principle: Keep It Simple, Stupid.

Principle 2: Completeness

Of course, the interface must make it possible to do everything that the users need to do, that is, it must be complete. This brings us to another famous quote, this one from Albert Einstein:

Everything should be as simple as possible, but no simpler.

In other words, the operating system should do exactly what is needed of it and no more. If users need to store data, it must provide some mechanism for storing data. If users need to communicate with each other, the operating system has to provide a communication mechanism, and so on. In his 1991 Turing Award lecture, Fernando Corbató, one of the designers of CTSS and MULTICS, combined the concepts of simplicity and completeness and said:

First, it is important to emphasize the value of simplicity and elegance, for complexity has a way of compounding difficulties and as we have seen, creating mistakes. My definition of elegance is the achievement of a given functionality with a minimum of mechanism and a maximum of clarity.

The key idea here is *minimum of mechanism*. In other words, every feature, function, and system call should carry its own weight. It should do one thing and do it well. When a member of the design team proposes extending a system call or adding some new feature, the others should ask the question: “Would something awful happen if we left it out?” If the answer is: “No, but somebody might find this feature useful some day” put it in a user-level library, not in the operating system, even if it is slower that way. Not every feature has to be faster than a speeding bullet. The goal is to preserve what Corbató called minimum of mechanism.

Let us briefly consider two examples from my own experience: MINIX (Tanenbaum and Woodhull, 2006) and Amoeba (Tanenbaum et al., 1990). For all intents and purposes, MINIX has three system calls: `send`, `receive`, and `sendrec`. The system is structured as a collection of processes, with the memory manager, the file system, and each device driver being a separate schedulable process. To a first approximation, all the kernel does is schedule processes and handle message passing between them. Consequently, only two system calls are needed: `send`, to send a message, and `receive` to receive one. The third call, `sendrec` is simply an optimization for efficiency reasons to allow a message to be sent and the reply to be requested with only one kernel trap. Everything else is done by requesting some other process (for example, the file system process or the disk driver) to do the work.

Amoeba is even simpler. It has only one system call: perform remote procedure call. This call sends a message and waits for a reply. It is essentially the same as MINIX’ `sendrec`. Everything else is built on this one call.

Principle 3: Efficiency

The third guideline is efficiency of implementation. If a feature or system call cannot be implemented efficiently, it is probably not worth having. It should also be intuitively obvious to the programmer about how much a system call costs. For example, UNIX programmers expect the `lseek` system call to be cheaper than the `read` system call because the former just changes a pointer in memory while the latter performs disk I/O. If the intuitive costs are wrong, programmers will write inefficient programs.

13.2.2 Paradigms

Once the goals have been established, the design can begin. A good starting place is thinking about how the customers will view the system. One of the most important issues is how to make all the features of the system hang together well and present what is often called **architectural coherence**. In this regard, it is important to distinguish two kinds of operating system “customers.” On the one hand, there are the *users*, who interact with application programs; on the other are the *programmers*, who write them. The former mostly deal with the GUI; the latter mostly deal with the system call interface. If the intention is to have a single GUI that pervades the complete system, such as in the Macintosh, the design should start there. If, on the other hand, the intention is to support many possible GUIs, such as in UNIX, the system call interface should be designed first. Doing the GUI first is essentially a top-down design. The issues are what features will it have, how will the user interact with it, and how should the system be designed to support it? For example, if most programs display icons on the screen and then wait for the user to click on one of them, this suggests an event-driven model for the GUI and probably also for the operating system. On the other hand, if the screen is mostly full of text windows, then a model in which processes read from the keyboard is probably better.

Doing the system call interface first is a bottom-up design. Here the issues are what kinds of features programmers in general need. Actually, not many special features are needed to support a GUI. For example, the UNIX windowing system, X, is just a big C program that does reads and writes on the keyboard, mouse, and screen. X was developed long after UNIX and did not require many changes to the operating system to get it to work. This experience validated that fact that UNIX was sufficiently complete.

User Interface Paradigms

For both the GUI-level interface and the system-call interface, the most important aspect is having a good paradigm (sometimes called a metaphor) to provide a way of looking at the interface. Many GUIs for desktop machines use the

WIMP paradigm that we discussed in Chap. 5. This paradigm uses point-and-click, point-and-double-click, dragging, and other idioms throughout the interface to provide an architectural coherence to the whole. Often there are additional requirements for programs, such as having a menu bar with FILE, EDIT, and other entries, each of which has certain well-known menu items. In this way, users who know one program can quickly learn another one.

However, the WIMP user interface is not the only possible one. Some palm-top computers use a stylized handwriting interface. Dedicated multimedia devices may use a VCR-like interface. And of course, voice input has a completely different paradigm. What is important is not so much the paradigm chosen, but the fact that there is a single overriding paradigm that unifies the entire user interface.

Whatever paradigm is chosen, it is important that all application programs use it. Consequently, the system designers need to provide libraries and tool kits to application developers that give them access to procedures that produce the uniform look-and-feel. User interface design is very important, but it is not the subject of this book, so we will now drop back down to the subject of the operating system interface.

Execution Paradigms

Architectural coherence is important at the user level, but equally important at the system call interface level. Here it is frequently useful to distinguish between the execution paradigm and the data paradigm, so we will do both, starting with the former.

Two execution paradigms are widespread: algorithmic and event driven. The **algorithmic paradigm** is based on the idea that a program is started to perform some function that it knows in advance or gets from its parameters. That function might be to compile a program, do the payroll, or fly an airplane to San Francisco. The basic logic is hardwired into the code with the program making system calls from time to time to get user input, obtain operating system services, etc. This approach is outlined in Fig. 13-1(a).

The other execution paradigm is the **event-driven paradigm** of Fig. 13-1(b). Here the program performs some kind of initialization, for example by displaying a certain screen, and then waiting for the operating system to tell it about the first event. The event is often a key being struck or a mouse movement. This design is useful for highly interactive programs.

Each of these ways of doing business engenders its own programming style. In the algorithmic paradigm, algorithms are central and the operating system is regarded as a service provider. In the event-driven paradigm, the operating system also provides services, but this role is overshadowed by its role as a coordinator of user activities and a generator of events that are consumed by processes.

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```

main()                               main()
{                                     {
    int ... ;                          mess_t msg;

    init();                             init();
    do_something();                     while (get_message(&msg)) {
    read(...);                           switch (msg.type) {
    do_something_else();                 case 1: ... ;
    write(...);                          case 2: ... ;
    keep_going();                         case 3: ... ;
    exit(0);                               }
}                                         }
(a)                                     (b)

```

Figure 13-1. (a) Algorithmic code. (b) Event-driven code.

Data Paradigms

The execution paradigm is not the only one exported by the operating system. An equally important one is the data paradigm. The key question here is how are system structures and devices presented to the programmer. In early FORTRAN batch systems, everything was modeled as a sequential magnetic tape. Card decks read in were treated as input tapes, card decks to be punched were treated as output tapes, and output for the printer was treated as an output tape. Disk files were also treated as tapes. Random access to a file was possible only by rewinding the tape corresponding to the file and reading it again.

The mapping was done using job control cards like these:

```

MOUNT(TAPE08, REEL781)
RUN(INPUT, MYDATA, OUTPUT, PUNCH, TAPE08)

```

The first card instructed the operator to go get tape reel 781 from the tape rack and mount it on tape drive 8. The second card instructed the operating system to run the just compiled FORTRAN program, mapping *INPUT* (meaning the card reader) to logical tape 1, disk file *MYDATA* to logical tape 2, the printer (called *OUTPUT*) to logical tape 3, the card punch (called *PUNCH*) to logical tape 4, and physical tape drive 8 to logical tape 5.

FORTRAN had a syntax for reading and writing logical tapes. By reading from logical tape 1, the program got card input. By writing to logical tape 3, output would later appear on the printer. By reading from logical tape 5, tape reel 781 could be read in, and so on. Note that the tape idea was just a paradigm to integrate the card reader, printer, punch, disk files, and tapes. In this example, only logical tape 5 was a physical tape; the rest were ordinary (spooled) disk files. It was a primitive paradigm, but it was a start in the right direction.

Later came UNIX, which goes much further using the model of “everything is a file.” Using this paradigm, all I/O devices are treated as files and can be opened and manipulated as ordinary files. The C statements

```
fd1 = open("file1", O_RDWR);
fd2 = open("/dev/tty", O_RDWR);
```

open a true disk file and the user’s terminal (keyboard + display). Subsequent statements can use *fd1* and *fd2* to read and write them, respectively. From that point on, there is no difference between accessing the file and accessing the terminal, except that seeks on the terminal are not allowed.

Not only does UNIX unify files and I/O devices, but it also allows other processes to be accessed over pipes as files. Furthermore, when mapped files are supported, a process can get at its own virtual memory as though it were a file. Finally, in versions of UNIX that support the */proc* file system, the C statement

```
fd3 = open("/proc/501", O_RDWR);
```

allows the process to (try to) access process 501’s memory for reading and writing using file descriptor *fd3*, something useful for, say, a debugger.

Windows Vista goes further still and tries to make everything look like an object. Once a process has acquired a valid handle to a file, process, semaphore, mailbox, or other kernel object, it can perform operations on it. This paradigm is even more general than that of UNIX and much more general than that of FORTRAN.

Unifying paradigms occur in other contexts as well. One of them is worth mentioning here: the Web. The paradigm behind the Web is that cyberspace is full of documents, each of which has a URL. By typing in a URL or clicking on an entry backed by a URL, you get the document. In reality, many “documents” are not documents at all, but are generated by a program or shell script when a request comes in. For example, when a user asks an online store for a list of CDs by a particular artist, the document is generated on-the-fly by a program; it certainly did not exist before the query was made.

We have now seen four cases: namely, everything is a tape, file, object, or document. In all four cases, the intention is to unify data, devices, and other resources to make them easier to deal with. Every operating system should have such a unifying data paradigm.

13.2.3 The System Call Interface

If one believes in Corbató’s dictum of minimal mechanism, then the operating system should provide as few system calls as it can get away with, and each one should be as simple as possible (but no simpler). A unifying data paradigm can play a major role in helping here. For example, if files, processes, I/O devices, and much more all look like files or objects, then they can all be read with a single

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read system call. Otherwise it may be necessary to have separate calls for `read_file`, `read_proc`, and `read_tty`, among others.

In some cases, system calls may appear to need several variants, but it is often better practice to have one system call that handles the general case, with different library procedures to hide this fact from the programmers. For example, UNIX has a system call for overlaying a process virtual address space, `exec`. The most general call is

```
exec(name, argp, envp);
```

which loads the executable file *name* and gives it arguments pointed to by *argp* and environment variables pointed to by *envp*. Sometimes it is convenient to list the arguments explicitly, so the library contains procedures that are called as follows:

```
execl(name, arg0, arg1, ..., argn, 0);
execle(name, arg0, arg1, ..., argn, envp);
```

All these procedures do is stick the arguments in an array and then call `exec` to do the work. This arrangement is the best of both worlds: a single straightforward system call keeps the operating system simple, yet the programmer gets the convenience of various ways to call `exec`.

Of course, trying to have one call to handle every possible case can easily get out of hand. In UNIX creating a process requires two calls: `fork` followed by `exec`. The former has no parameters; the latter has three parameters. In contrast, the Win32 API call for creating a process, `CreateProcess`, has 10 parameters, one of which is a pointer to a structure with an additional 18 parameters.

A long time ago, someone should have asked the question: “Would something awful happen if we left some of these out?” The truthful answer would have been: “In some cases programmers might have to do more work to achieve a particular effect, but the net result would have been a simpler, smaller, and more reliable operating system.” Of course, the person proposing the 10 + 18 parameter version might have added: “But users like all these features.” The rejoinder to that might have been: “They like systems that use little memory and never crash even more.” Trade-offs between more functionality at the cost of more memory are at least visible and can be given a price tag (since the price of memory is known). However, it is hard to estimate the additional crashes per year some feature will add and whether the users would make the same choice if they knew the hidden price. This effect can be summarized in Tanenbaum’s first law of software:

Adding more code adds more bugs.

Adding more features adds more code and thus adds more bugs. Programmers who believe adding new features does not add new bugs are either new to computers or believe the tooth fairy is out there watching over them.

Simplicity is not the only issue that comes out when designing system calls.

An important consideration is Lampson's (1984) slogan:

Don't hide power.

If the hardware has an extremely efficient way of doing something, it should be exposed to the programmers in a simple way and not buried inside some other abstraction. The purpose of abstractions is to hide undesirable properties, not hide desirable ones. For example, suppose that the hardware has a special way to move large bitmaps around the screen (i.e., the video RAM) at high speed. It would be justified to have a new system call to get at this mechanism, rather than just providing ways to read video RAM into main memory and write it back again. The new call should just move bits and nothing else. If a system call is fast, users can always build more convenient interfaces on top of it. If it is slow, nobody will use it.

Another design issue is connection-oriented versus connectionless calls. The standard UNIX and Win32 system calls for reading a file are connection-oriented. First you open a file, then you read it, finally you close it. Some remote file access protocols are also connection-oriented. For example, to use FTP, the user first logs in to the remote machine, reads the files, and then logs out.

On the other hand, some remote file access protocols are connectionless. The Web protocol (HTTP) is connectionless, for example. To read a Web page you just ask for it; there is no advance setup required (a TCP connection *is* required, but this is at a lower level of protocol; the HTTP protocol for accessing the Web itself is connectionless).

The trade-off between any connection-oriented mechanism and a connectionless one is the additional work required to set up the mechanism (e.g., open the file), and the gain from not having to do it on (possibly many) subsequent calls. For file I/O on a single machine, where the setup cost is low, probably the standard way (first open, then use) is the best way. For remote file systems, a case can be made both ways.

Another issue relating to the system call interface is its visibility. The list of POSIX-mandated system calls is easy to find. All UNIX systems support these, as well as a small number of other calls, but the complete list is always public. In contrast, Microsoft has never made the list of Windows Vista system calls public. Instead the Win32 API and other APIs have been made public, but these contain vast numbers of library calls (over 10,000 for Windows Vista), but only a small number are true system calls. The argument for making all the system calls public is that it lets programmers know what is cheap (functions performed in user space) and what is expensive (kernel calls). The argument for not making them public is that it gives the implementers the flexibility of changing the actual underlying system calls to make them better without breaking user programs.

13.3 IMPLEMENTATION

Turning away from the user and system call interfaces, let us now take a look at how to implement an operating system. In the next eight sections we will examine some general conceptual issues relating to implementation strategies. After that we will look at some low-level techniques that are often helpful.

13.3.1 System Structure

Probably the first decision the implementers have to make is what the system structure should be. We examined the main possibilities in Sec. 1.7, but will review them here. An unstructured monolithic design is really not a good idea, except maybe for a tiny operating system in, say, a refrigerator, but even there it is arguable.

Layered Systems

A reasonable approach that has been well established over the years is a layered system. Dijkstra's THE system (Fig. 1-25) was the first layered operating system. UNIX (Fig. 10-3???) and Windows Vista (Fig. 11-6) also have a layered structure, but the layering in both of them is more a way of trying to describe the system than a real guiding principle that was used in building the system.

For a new system, designers choosing to go this route should *first* very carefully choose the layers and define the functionality of each one. The bottom layer should always try to hide the worst idiosyncracies of the hardware, as the HAL does in Fig. 11-7. Probably the next layer should handle interrupts, context switching, and the MMU, so above this level, the code is mostly machine independent. Above this, different designers will have different tastes (and biases). One possibility is to have layer 3 manage threads, including scheduling and interthread synchronization, as shown in Fig. 13-2. The idea here is that starting at layer 4 we have proper threads that are scheduled normally and synchronize using a standard mechanism (e.g., mutexes).

In layer 4 we might find the device drivers, each one running as a separate thread, with its own state, program counter, registers, etc., possibly (but not necessarily) within the kernel address space. Such a design can greatly simplify the I/O structure because when an interrupt occurs, it can be converted into an unlock on a mutex and a call to the scheduler to (potentially) schedule the newly readied thread that was blocked on the mutex. MINIX uses this approach, but in UNIX, Linux, and Windows Vista, the interrupt handlers run in a kind of no-man's land, rather than as proper threads that can be scheduled, suspended, etc. Since a huge amount of the complexity of any operating system is in the I/O, any technique for making it more tractable and encapsulated is worth considering.

Above layer 4, we would expect to find virtual memory, one or more file

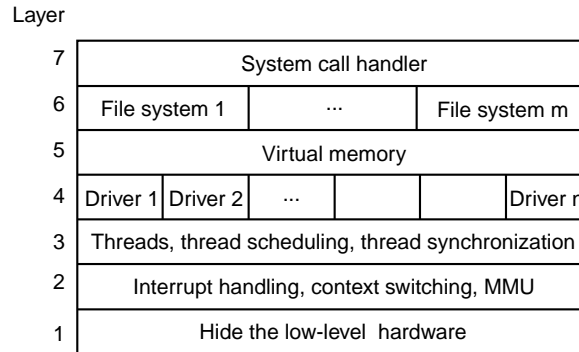


Figure 13-2. One possible design for a modern layered operating system.

systems, and the system call handlers. If the virtual memory is at a lower level than the file systems, then the block cache can be paged out, allowing the virtual memory manager to dynamically determine how the real memory should be divided among user pages and kernel pages, including the cache. Windows Vista works this way.

Exokernels

While layering has its supporters among system designers, there is also another camp that has precisely the opposite view (Engler et al., 1995). Their view is based on the **end-to-end argument** (Saltzer et al., 1984). This concept says that if something has to be done by the user program itself, it is wasteful to do it in a lower layer as well.

Consider an application of that principle to remote file access. If a system is worried about data being corrupted in transit, it should arrange for each file to be checksummed at the time it is written and the checksum stored along with the file. When a file is transferred over a network from the source disk to the destination process, the checksum is transferred, too, and also recomputed at the receiving end. If the two disagree, the file is discarded and transferred again.

This check is more accurate than using a reliable network protocol since it also catches disk errors, memory errors, software errors in the routers, and other errors besides bit transmission errors. The end-to-end argument says that using a reliable network protocol is then not necessary, since the end point (the receiving process) has enough information to verify the correctness of the file itself. The only reason for using a reliable network protocol in this view is for efficiency, that is, catching and repairing transmission errors earlier.

The end-to-end argument can be extended to almost all of the operating system. It argues for not having the operating system do anything that the user

program can do itself. For example, why have a file system? Just let the user read and write a portion of the raw disk in a protected way. Of course, most users like having files, but the end-to-end argument says that the file system should be a library procedure linked with any program that needs to use files. This approach allows different programs to have different file systems. This line of reasoning says that all the operating system should do is securely allocate resources (e.g., the CPU and the disks) among the competing users. The Exokernel is an operating system built according to the end-to-end argument (Engler et al., 1995).

Microkernel-Based Client-Server Systems

A compromise between having the operating system do everything and the operating system do nothing is to have the operating system do a little bit. This design leads to a microkernel with much of the operating system running as user-level server processes as illustrated in Fig. 13-3. This is the most modular and flexible of all the designs. The ultimate in flexibility is to have each device driver also run as a user process, fully protected against the kernel and other drivers, but even having the device drivers run in the kernel adds to the modularity. Note that this figure is similar to Fig. 1-27, only with all the clients and all the servers running on the same system now.

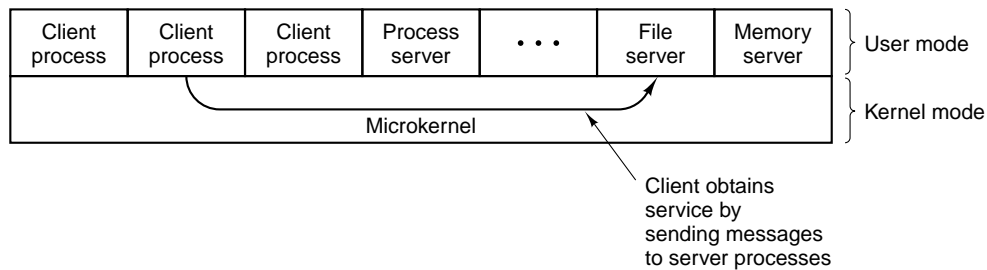


Figure 13-3. Client-server computing based on a microkernel.

When the device drivers are in the kernel, they can access the hardware device registers directly. When they are not, some mechanism is needed to provide this. If the hardware permits, each driver process could be given access to only those I/O devices it needs. For example, with memory-mapped I/O, each driver process could have the page for its device mapped in, but no other device pages. If the I/O port space can be partially protected, the correct portion of it could be made available to each driver.

Even if no hardware assistance is available, the idea can still be made to work. What is then needed is a new system call, available only to device driver processes, supplying a list of (port, value) pairs. What the kernel does is first check to see if the process owns all the ports in the list. If so, it then copies the

corresponding values to the ports to initiate device I/O. A similar call can be used to read I/O ports in a protected way.

This approach keeps device drivers from examining (and damaging) kernel data structures, which is (for the most part) a good thing. An analogous set of calls could be made available to allow driver processes to read and write kernel tables, but only in a controlled way and with the approval of the kernel.

The main problem with this approach, and microkernels in general, is the performance hit all the extra context switches cause. However, virtually all work on microkernels was done many years ago when CPUs were much slower. Nowadays, applications that use every drop of CPU power and cannot tolerate a small loss of performance, are few and far between. After all, when running a word processor or Web browser, the CPU is probably idle 95% of the time. If a microkernel-based operating system turned an unreliable 3-GHz system into a reliable 2.5 GHz system, probably few users would complain. After all, most of them were quite happy only a few years ago when they got their previous computer, at the then-stupendous speed of 1 GHz.

It is noteworthy that while microkernels are not popular on the desktop, they are very widely used in cell phones, PDAs, industrial systems, embedded systems, and military systems, where high reliability is absolutely essential.

essential.

Extensible Systems

With the client-server systems discussed above, the idea was to get as much out of the kernel as possible. The opposite approach is to put more modules into the kernel, but in a protected way. The key word here is *protected*, of course. We studied some protection mechanisms in Sec. 9.5.6 that were initially intended for importing applets over the Internet, but are equally applicable to inserting foreign code into kernel. The most important ones are sandboxing and code signing as interpretation is not really practical for kernel code.

Of course, an extensible system by itself is not a way to structure an operating system. However, by starting with a minimal system consisting of little more than a protection mechanism and then adding protected modules to the kernel one at a time until reaching the functionality desired, a minimal system can be built for the application at hand. In this view, a new operating system can be tailored to each application by including only the parts it requires. Paramecium is an example of such a system (Van Doorn, 2001).

Kernel Threads

Another issue relevant here is that of system threads, no matter which structuring model is chosen. It is sometimes convenient to allow kernel threads to exist, separate from any user process. These threads can run in the background, writing dirty pages to disk, swapping processes between main memory and disk, and so on. In fact, the kernel itself can be structured entirely of such threads, so that when a user does a system call, instead of the user's thread executing in kernel mode, the user's thread blocks and passes control to a kernel thread that takes over to do the work.

In addition to kernel threads running in the background, most operating systems start up many daemon processes in the background, too. While these are not part of the operating system, they often perform “system” type activities. These might include getting and sending e-mail and serving various kinds of requests for remote users, such as FTP and Web pages.

13.3.2 Mechanism versus Policy

Another principle that helps architectural coherence, along with keeping things small and well structured, is that of separating mechanism from policy. By putting the mechanism in the operating system and leaving the policy to user processes, the system itself can be left unmodified, even if there is a need to change policy. Even if the policy module has to be kept in the kernel, it should be isolated from the mechanism, if possible, so that changes in the policy module do not affect the mechanism module.

To make the split between policy and mechanism clearer, let us consider two real-world examples. As a first example, consider a large company that has a payroll department, which is in charge of paying the employees' salaries. It has computers, software, blank checks, agreements with banks, and more mechanism for actually paying out the salaries. However, the policy—determining who gets paid how much—is completely separate and is decided by management. The payroll department just does what it is told to do.

As the second example, consider a restaurant. It has the mechanism for serving diners, including tables, plates, waiters, a kitchen full of equipment, agreements with credit card companies, and so on. The policy is set by the chef, namely, what is on the menu. If the chef decides that tofu is out and big steaks are in, this new policy can be handled by the existing mechanism.

Now let us consider some operating system examples. First, consider thread scheduling. The kernel could have a priority scheduler, with k priority levels. The mechanism is an array, indexed by priority level, as shown in Fig. 10-11 or Fig. 11-28. Each entry is the head of a list of ready threads at that priority level. The scheduler just searches the array from highest priority to lowest priority, selecting the first threads it hits. The policy is setting the priorities. The

system may have different classes of users, each with a different priority, for example. It might also allow user processes to set the relative priority of its threads. Priorities might be increased after completing I/O or decreased after using up a quantum. There are numerous other policies that could be followed, but the idea here is the separation between setting policy and carrying it out.

A second example is paging. The mechanism involves MMU management, keeping lists of occupied pages and free pages, and code for shuttling pages to and from disk. The policy is deciding what to do when a page fault occurs. It could be local or global, LRU-based or FIFO-based, or something else, but this algorithm can (and should) be completely separate from the mechanics of actually managing the pages.

A third example is allowing modules to be loaded into the kernel. The mechanism concerns how they are inserted, how they are linked, what calls they can make, and what calls can be made on them. The policy is determining who is allowed to load a module into the kernel and which modules. Maybe only the superuser can load modules, but maybe any user can load a module that has been digitally signed by the appropriate authority.

13.3.3 Orthogonality

Good system design consists of separate concepts that can be combined independently. For example, in C, there are primitive data types including integers, characters, and floating-point numbers. There are also mechanisms for combining data types, including arrays, structures, and unions. These ideas combine independently, allowing arrays of integers, arrays of characters, structure and union members that are floating-point numbers, etc. In fact, once a new data type has been defined, such as an array of integers, it can be used as if it were a primitive data type, for example as a member of a structure or a union. The ability to combine separate concepts independently is called **orthogonality**. It is direct consequence of the simplicity and completeness principles.

The concept of orthogonality also occurs in operating systems in various disguises. One example is the Linux clone system call, which creates a new thread. The call has a bitmap as a parameter, which allows the address space, working directory, file descriptors, and signals to shared or copied individually. If everything is copied, we have a new process, the same as fork. If nothing is copied, a new thread is created in the current process. However, it is also possible to create intermediate forms of sharing not possible in traditional UNIX systems. By separating out the various features and making them orthogonal, a finer degree of control is possible.

Another use of orthogonality is the separation of the process concept from the thread concept in Windows Vista. A process is a container for resources, nothing more and nothing less. A thread is a schedulable entity. When one process is given a handle for another process, it does not matter how many threads it has.

When a thread is scheduled, it does not matter which process it belongs to. These concepts are orthogonal.

Our last example of orthogonality comes from UNIX. Process creation there is done in two steps: fork plus exec. Creating the new address space and loading it with a new memory image are separate, allowing things to be done in between (such as manipulating file descriptors). In Windows Vista, these two steps cannot be separated, that is, the concepts of making a new address space and filling it in are not orthogonal there. The Linux sequence of clone plus exec is yet more orthogonal, since there are even more fine-grained building blocks available. As a general rule, having a small number of orthogonal elements that can be combined in many ways leads to a small, simple, and elegant system.

13.3.4 Naming

Most long-lived data structures used by an operating system have some kind of name or identifier by which they can be referred. Obvious examples are login names, file names, device names, process IDs, and so on. How these names are constructed and managed is an important issue in system design and implementation.

Names designed for people to use are character-string names in ASCII or Unicode and are usually hierarchical. Directory paths, for example one such as */usr/ast/books/mos2/chap-12*, are clearly hierarchical, indicating a series of directories to search starting at the root. URLs are also hierarchical. For example, *www.cs.vu.nl/~ast/* indicates a specific machine (*www*) in a specific department (*cs*) at specific university (*vu*) in a specific country (*nl*). The part after the slash indicates a specific file on the designated machine, in this case, by convention, *www/index.html* in ast's home directory. Note that URLs (and DNS addresses in general, including e-mail addresses) are "backward," starting at the bottom of the tree and going up, unlike file names, which start at the top of the tree and go down. Another way of looking at this is whether the tree is written from the top starting at the left and going right or starting at the right and going left.

Often naming is done at two levels: external and internal. For example, files always have a character-string name for people to use. In addition, there is almost always an internal name that the system uses. In UNIX, the real name of a file is its i-node number; the ASCII name is not used at all internally. In fact, it is not even unique since a file may have multiple links to it. The analogous internal name in Windows Vista is the file's index in the MFT. The job of the directory is to provide the mapping between the external name and the internal name, as shown in Fig. 13-4.

In many cases (such as the file name example given above), the internal name is an unsigned integer that serves as an index into a kernel table. Other examples of table-index names are file descriptors in UNIX and object handles in Windows Vista. Note that neither of these has any external representation. They are strictly

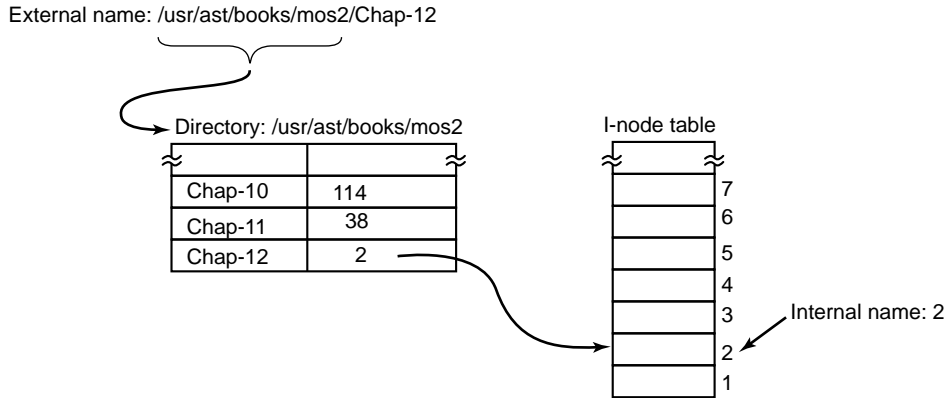


Figure 13-4. Directories are used to map external names onto internal names.

for use by the system and running processes. In general, using table indices for transient names that are lost when the system is rebooted is a good idea.

Operating systems often support multiple name spaces, both external and internal. For example, in Chap. 11 we looked at three external name spaces supported by Windows Vista: file names, object names, and registry names (and there is also the Active Directory name space, which we did not look at). In addition, there are innumerable internal name spaces using unsigned integers, for example, object handles, MFT entries, etc. Although the names in the external name spaces are all Unicode strings, looking up a file name in the registry will not work, just as using an MFT index in the object table will not work. In a good design, considerable thought is given to how many names spaces are needed, what the syntax of names is in each one, how they can be told apart, whether absolute and relative names exist, and so on.

13.3.5 Binding Time

As we have just seen, operating systems use various kinds of names to refer to objects. Sometimes the mapping between a name and an object is fixed, but sometimes it is not. In the latter case, it may matter when the name is bound to the object. In general, **early binding** is simple, but is not flexible, whereas **late binding** is more complicated but often more flexible.

To clarify the concept of binding time, let us look at some real-world examples. An example of early binding is the practice of some colleges to allow parents to enroll a baby at birth and prepay the current tuition. When the student shows up 18 years later, the tuition is fully paid up, no matter how high it may be at that moment.

In manufacturing, ordering parts in advance and maintaining an inventory of

them is early binding. In contrast, just-in-time manufacturing requires suppliers to be able to provide parts on the spot, with no advance notice required. This is late binding.

Programming languages often support multiple binding times for variables. Global variables are bound to a particular virtual address by the compiler. This exemplifies early binding. Variables local to a procedure are assigned a virtual address (on the stack) at the time the procedure is invoked. This is intermediate binding. Variables stored on the heap (those allocated by *malloc* in C or *new* in Java) are assigned virtual addresses only at the time they are actually used. Here we have late binding.

Operating systems often use early binding for most data structures, but occasionally use late binding for flexibility. Memory allocation is a case in point. Early multiprogramming systems on machines lacking address relocation hardware had to load a program at some memory address and relocate it to run there. If it was ever swapped out, it had to be brought back at the same memory address or it would fail. In contrast, paged virtual memory is a form of late binding. The actual physical address corresponding to a given virtual address is not known until the page is touched and actually brought into memory.

Another example of late binding is window placement in a GUI. In contrast to the early graphical systems, in which the programmer had to specify the absolute screen coordinates for all images on the screen, in modern GUIs, the software uses coordinates relative to the window's origin, but that is not determined until the window is put on the screen, and it may even be changed later.

13.3.6 Static versus Dynamic Structures

Operating system designers are constantly forced to choose between static and dynamic data structures. Static ones are always simpler to understand, easier to program, and faster in use; dynamic ones are more flexible. An obvious example is the process table. Early systems simply allocated a fixed array of per-process structures. If the process table consisted of 256 entries, then only 256 processes could exist at any one instant. An attempt to create a 257th one would fail for lack of table space. Similar considerations held for the table of open files (both per user and system wide), and many other kernel tables.

An alternative strategy is to build the process table as a linked list of minitables, initially just one. If this table fills up, another one is allocated from a global storage pool and linked to the first one. In this way, the process table cannot fill up until all of kernel memory is exhausted.

On the other hand, the code for searching the table becomes more complicated. For example, the code for searching a static process table to see if a given PID, *pid*, is given in Fig. 13-5. It is simple and efficient. Doing the same thing for a linked list of minitables is more work.

Static tables are best when there is plenty of memory or table utilizations can

```

found = 0;
for (p = &proc_table[0]; p < &proc_table[PROC_TABLE_SIZE]; p++) {
    if (p->proc_pid == pid) {
        found = 1;
        break;
    }
}

```

Figure 13-5. Code for searching the process table for a given PID.

be guessed fairly accurately. For example, in a single-user system, it is unlikely that the user will start up more than 64 processes at once and it is not a total disaster if an attempt to start a 65th one fails.

Yet another alternative is to use a fixed-size table, but if it fills up, allocate a new fixed-size table, say, twice as big. The current entries are then copied over to the new table and the old table is returned to the free storage pool. In this way, the table is always contiguous rather than linked. The disadvantage here is that some storage management is needed and the address of the table is now a variable instead of a constant.

A similar issue holds for kernel stacks. When a thread switches to kernel mode, or a kernel-mode thread is run, it needs a stack in kernel space. For user threads, the stack can be initialized to run down from the top of the virtual address space, so the size need not be specified in advance. For kernel threads, the size must be specified in advance because the stack takes up some kernel virtual address space and there may be many stacks. The question is: how much space should each one get? The trade-offs here are similar to those for the process table.

Another static-dynamic trade-off is process scheduling. In some systems, especially real-time ones, the scheduling can be done statically in advance. For example, an airline knows what time its flights will leave weeks before their departure. Similarly, multimedia systems know when to schedule audio, video, and other processes in advance. For general-purpose use, these considerations do not hold and scheduling must be dynamic.

Yet another static-dynamic issue is kernel structure. It is much simpler if the kernel is built as a single binary program and loaded into memory to run. The consequence of this design, however, is that adding a new I/O device requires a relinking of the kernel with the new device driver. Early versions of UNIX worked this way, and it was quite satisfactory in a minicomputer environment when adding new I/O devices was a rare occurrence. Nowadays, most operating systems allow code to be added to the kernel dynamically, with all the additional complexity that entails.

13.3.7 Top-Down versus Bottom-Up Implementation

While it is best to design the system top down, in theory it can be implemented top down or bottom up. In a top-down implementation, the implementers start with the system call handlers and see what mechanisms and data structures are needed to support them. These procedures are written and so on until the hardware is reached.

The problem with this approach is that it is hard to test anything with only the top-level procedures available. For this reason, many developers find it more practical to actually build the system bottom up. This approach entails first writing code that hides the low-level hardware, essentially the HAL in Fig. 11-6. Interrupt handling and the clock driver are also needed early on.

Then multiprogramming can be tackled, along with a simple scheduler (e.g., round-robin scheduling). At this point it should be possible to test the system to see if it can run multiple processes correctly. If that works, it is now time to begin the careful definition of the various tables and data structures needed throughout the system, especially those for process and thread management and later memory management. I/O and the file system can wait initially, except for a primitive way to read the keyboard and write to the screen for testing and debugging. In some cases, the key low-level data structures should be protected by allowing access only through specific access procedures—in effect, object-oriented programming, no matter what the programming language is. As lower layers are completed, they can be tested thoroughly. In this way, the system advances from the bottom up, much the way contractors build tall office buildings.

If a large team is available, an alternative approach is to first make a detailed design of the whole system, and then assign different groups to write different modules. Each one tests its own work in isolation. When all the pieces are ready, they are integrated and tested. The problem with this line of attack is that if nothing works initially, it may be hard to isolate whether one or more modules are malfunctioning, or one group misunderstood what some other module was supposed to do. Nevertheless, with large teams, this approach is often used to maximize the amount of parallelism in the programming effort.

13.3.8 Useful Techniques

We have just looked at some abstract ideas for system design and implementation. Now we will examine a number of useful concrete techniques for system implementation. There are numerous other ones, of course, but space limitations restrict us to just a few of them.

Hiding the Hardware

A lot of hardware is ugly. It has to be hidden early on (unless it exposes power, which most hardware does not). Some of the very low-level details can be hidden by a HAL-type layer of the type shown in Fig. 13-2. However, many hardware details cannot be hidden this way.

One thing that deserves early attention is how to deal with interrupts. They make programming unpleasant, but operating systems have to deal with them. One approach is to turn them into something else immediately. For example, every interrupt could be turned into a pop-up thread instantly. At that point we are dealing with threads, rather than interrupts.

A second approach is to convert each interrupt into an unlock operation on a mutex that the corresponding driver is waiting on. Then the only effect of an interrupt is to cause some thread to become ready.

A third approach is convert an interrupt into a message to some thread. The low-level code just builds a message telling where the interrupt came from, enqueues it, and calls the scheduler to (potentially) run the handler, which was probably blocked waiting for the message. All these techniques, and other ones like them, all try to convert interrupts into thread synchronization operations. Having each interrupt handled by a proper thread in a proper context is easier to manage than running a handler in the arbitrary context that it happened to occur in. Of course, this must be done efficiently, but deep within the operating system, everything must be done efficiently.

Most operating systems are designed to run on multiple hardware platforms. These platforms can differ in terms of the CPU chip, MMU, word length, RAM size, and other features that cannot easily be masked by the HAL or equivalent. Nevertheless, it is highly desirable to have a single set of source files that are used to generate all versions; otherwise each bug that later turns up must be fixed multiple times in multiple sources, with the danger that the sources drift apart.

Some hardware differences, such as RAM size, can be dealt with by having the operating system determine the value at boot time and keep it in a variable. Memory allocators, for example, can use the RAM size variable to determine how big to make the block cache, page tables, etc. Even static tables such as the process table can be sized based on the total memory available.

However, other differences, such as different CPU chips, cannot be solved by having a single binary that determines at run time which CPU it is running on. One way to tackle the problem of one source and multiple targets is to use conditional compilation. In the source files, certain compile-time flags are defined for the different configurations and these are used to bracket code that is dependent on the CPU, word length, MMU, etc. For example, imagine an operating system that is to run on the Pentium and UltraSPARC chips, which need different initialization code. The *init* procedure could be written as illustrated in Fig. 13-6(a). Depending on the value of *CPU*, which is defined in the header file *config.h*, one

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kind of initialization or other is done. Because the actual binary contains only the code needed for the target machine, there is no loss of efficiency this way.

```

#include "config.h"
init()
{
  #if (CPU == PENTIUM)
  /* Pentium initialization here. */
  #endif

  #if (CPU == ULTRASPARC)
  /* UltraSPARC initialization here. */
  #endif
}
  (a)

```

```

#include "config.h"
#if (WORD_LENGTH == 32)
typedef int Register;
#endif

#if (WORD_LENGTH == 64)
typedef long Register;
#endif

Register R0, R1, R2, R3;
  (b)

```

Figure 13-6. (a) CPU-dependent conditional compilation. (b) Word-length dependent conditional compilation.

As a second example, suppose there is a need for a data type *Register*, which should be 32 bits on the Pentium and 64 bits on the UltraSPARC. This could be handled by the conditional code of Fig. 13-6(b) (assuming that the compiler produces 32-bit ints and 64-bit longs). Once this definition has been made (probably in a header file included everywhere), the programmer can just declare variables to be of type *Register* and know they will be the right length.

The header file, *config.h*, has to be defined correctly, of course. For the Pentium it might be something like this:

```

#define CPU PENTIUM
#define WORD_LENGTH 32

```

To compile the system for the UltraSPARC, a different *config.h* would be used, with the correct values for the UltraSPARC, probably something like

```

#define CPU ULTRASPARC
#define WORD_LENGTH 64

```

Some readers may be wondering why *CPU* and *WORD_LENGTH* are handled by different macros. We could easily have bracketed the definition of *Register* with a test on *CPU*, setting it to 32 bits for the Pentium and 64 bits for the UltraSPARC. However, this is not a good idea. Consider what happens when we later port the system to the 64-bit Intel Itanium. We would have to add a third conditional to Fig. 13-6(b) for the Itanium. By doing it as we have, all we have to do is include the line

```

#define WORD_LENGTH 64

```

to the *config.h* file for the Itanium.

This example illustrates the orthogonality principle we discussed earlier. Those items that are CPU-dependent should be conditionally compiled based on the *CPU* macro and those things that are word-length dependent should use the *WORD_LENGTH* macro. Similar considerations hold for many other parameters.

Indirection

It is sometimes said that there is no problem in computer science that cannot be solved with another level of indirection. While something of an exaggeration, there is definitely a grain of truth here. Let us consider some examples. On Pentium-based systems, when a key is depressed, the hardware generates an interrupt and puts the key number, rather than an ASCII character code, in a device register. Furthermore, when the key is released later, a second interrupt is generated, also with the key number. This indirection allows the operating system the possibility of using the key number to index into a table to get the ASCII character, which makes it easy to handle the many keyboards used around the world in different countries. Getting both the depress and release information makes it possible to use any key as a shift key since the operating system knows the exact sequence the keys were depressed and released.

Indirection is also used on output. Programs can write ASCII characters to the screen, but these are interpreted as indices into a table for the current output font. The table entry contains the bitmap for the character. This indirection makes it possible to separate characters from fonts.

Another example of indirection is the use of major device numbers in UNIX. Within the kernel there is a table indexed by major device number for the block devices and another one for the character devices. When a process opens a special file such as */dev/hd0*, the system extracts the type (block or character) and major and minor device numbers from the i-node and indexes into the appropriate driver table to find the driver. This indirection makes it easy to reconfigure the system, because programs deal with symbolic device names, not actual driver names.

Yet another example of indirection occurs in message-passing systems that name a mailbox rather than a process as the message destination. By indirecting through mailboxes (as opposed to naming a process as the destination), considerable flexibility can be achieved (e.g., having a secretary handle her boss' messages).

In a sense, the use of macros, such as

```
#define PROC_TABLE_SIZE 256
```

is also a form of indirection, since the programmer can write code without having to know how big the table really is. It is good practice to give symbolic names to all constants (except sometimes -1 , 0 , and 1), and put these in headers with

comments explaining what they are for.

Reusability

It is frequently possible to reuse the same code in slightly different contexts. Doing so is a good idea as it reduces the size of the binary and means that the code has to be debugged only once. For example, suppose that bitmaps are used to keep track of free blocks on the disk. Disk block management can be handled by having procedures *alloc* and *free* that manage the bitmaps.

As a bare minimum, these procedures should work for any disk. But we can go further than that. The same procedures can also work for managing memory blocks, blocks in the file system's block cache, and i-nodes. In fact, they can be used to allocate and deallocate any resources that can be numbered linearly.

Reentrancy

Reentrancy refers for the ability of code to be executed two or more times simultaneously. On a multiprocessor, there is always the danger that while one CPU is executing some procedure, another CPU will start executing it as well, before the first one has finished. In this case, two (or more) threads on different CPUs might be executing the same code at the same time. This situation must be protected against by using mutexes or some other means to protect critical regions.

However, the problem also exists on a uniprocessor. In particular, most of any operating system runs with interrupts enabled. To do otherwise, would lose many interrupts and make the system unreliable. While the operating system is busy executing some procedure, *P*, it is entirely possible that an interrupt occurs and that the interrupt handler also calls *P*. If the data structures of *P* were in an inconsistent state at the time of the interrupt, the handler will see them in an inconsistent state and fail.

An obvious example where this can happen is if *P* is the scheduler. Suppose that some process used up its quantum and the operating system was moving it to the end of its queue. Part way through the list manipulation, the interrupt occurs, makes some process ready, and runs the scheduler. With the queues in an inconsistent state, the system will probably crash. As a consequence even on a uniprocessor, it is best that most of the operating system is reentrant, critical data structures are protected by mutexes, and interrupts are disabled at moments when they cannot be tolerated.

Brute Force

Using brute force to solve a problem has acquired a bad name over the years, but it is often the way to go in the name of simplicity. Every operating system has many procedures that are rarely called or operate with so little data that optimizing them is not worthwhile. For example, it is frequently necessary to search various tables and arrays within the system. The brute force algorithm is just leave the table in the order the entries are made and search it linearly when something has to be looked up. If the number of entries is small (say, under 1000), the gain from sorting the table or hashing it is small, but the code is far more complicated and more likely to have bugs in it.

Of course, for functions that are on the critical path, say, context switching, everything should be done to make them very fast, possibly even writing them in (heaven forbid) assembly language. But large parts of the system are not on the critical path. For example, many system calls are rarely invoked. If there is one fork every second, and it takes 1 msec to carry out, then even optimizing it to 0 wins only 0.1%. If the optimized code is bigger and buggier, a case can be made not to bother with the optimization.

Check for Errors First

Many system calls can potentially fail for a variety of reasons: the file to be opened belongs to someone else; process creation fails because the process table is full; or a signal cannot be sent because the target process does not exist. The operating system must painstakingly check for every possible error before carrying out the call.

Many system calls also require acquiring resources such as process table slots, i-node table slots, or file descriptors. A general piece of advice that can save a lot of grief is to first check to see if the system call can actually be carried out before acquiring any resources. This means putting all the tests at the beginning of the procedure that executes the system call. Each test should be of the form

```
if (error_condition) return(ERROR_CODE);
```

If the call gets all the way through the gauntlet of tests, then it is certain that it will succeed. At that point resources can be acquired.

Interspersing the tests with resource acquisition means that if some test fails along the way, all the resources acquired up to that point must be returned. If an error is made here and some resource is not returned, no damage is done immediately. For example, one process table entry may just become permanently unavailable. However, over a period of time, this bug may be triggered multiple times. Eventually, most or all the process table entries may become unavailable, leading to a system crash in an extremely unpredictable and difficult to debug way.

Many systems suffer from this problem in the form of memory leaks. Typically, the program calls *malloc* to allocate space but forgets to call *free* later to release it. Ever so gradually, all of memory disappears until the system is rebooted.

Engler et al. (2000) have proposed an interesting way to check for some of these errors at compile time. They observed that the programmer knows many invariants that the compiler does not know, such as when you lock a mutex, all paths starting at the lock must contain an unlock and no more locks of the same mutex. They have devised a way for the programmer to tell the compiler this fact and instruct it to check all the paths at compile time for violations of the invariant. The programmer can also specify that allocated memory must be released on all paths and many other conditions as well.

13.4 PERFORMANCE

All things being equal, a fast operating system is better than a slow one. However, a fast unreliable operating system is not as good as a reliable slow one. Since complex optimizations often lead to bugs, it is important to use them sparingly. This notwithstanding, there are places where performance is critical and optimizations are well worth the effort. In the following sections, we will look at some general techniques that can be used to improve performance in places where that is called for.

13.4.1 Why Are Operating Systems Slow?

Before talking about optimization techniques, it is worth pointing out that the slowness of many operating systems is to a large extent self-inflicted. For example, older operating systems, such as MS-DOS and UNIX Version 7, booted within a few seconds. Modern UNIX systems and Windows Vista can take minutes to boot, despite running on hardware that is 1000 times faster. The reason is that they are doing much more, wanted or not. A case in point. Plug and play makes it somewhat easier to install a new hardware device, but the price paid is that on *every* boot, the operating system has to go out and inspect all the hardware to see if there is anything new out there. This bus scan takes time.

An alternative (and in the author's opinion, better) approach would be to scrap plug-and-play altogether and have an icon on the screen labeled "Install new hardware." Upon installing a new hardware device, the user would click on this icon to start the bus scan, instead of doing it on every boot. The designers of current systems were well aware of this option, of course. They rejected it, basically, because they assumed that the users were too stupid to be able to do this correctly (although they would word it more kindly). This is only one example, but there are many more where the desire to make the system "user-friendly" (or

“idiot-proof,” depending on your viewpoint) slows the system down all the time for everyone.

Probably the biggest single thing system designers can do to improve performance is to be much more selective about adding new features. The question to ask is not: “Will some of the users like this?” but “Is this feature worth the inevitable price in code size, speed, complexity, and reliability?” Only if the advantages clearly outweigh the drawbacks should it be included. Programmers have a tendency to assume that code size and bug count will be 0 and speed will be infinite. Experience shows this view to be a bit optimistic.

Another factor that plays a role is product marketing. By the time version 4 or 5 of some product has hit the market, probably all the features that are actually useful have been included and most of the people who need the product already have it. To keep sales going, many manufacturers nevertheless continue to produce new versions, with more features, just so they can sell their existing customers upgrades. Adding new features just for the sake of adding new features may help sales but rarely helps performance.

13.4.2 What Should Be Optimized?

As a general rule, the first version of the system should be as straightforward as possible. The only optimizations should be things that are so obviously going to be a problem that they are unavoidable. Having a block cache for the file system is such an example. Once the system is up and running, careful measurements should be made to see where the time is *really* going. Based on these numbers, optimizations should be made where they will help most.

Here is a true story of where an optimization did more harm than good. One of the author’s students (who shall here remain nameless) wrote the MINIX *mkfs* program. This program lays down a fresh file system on a newly formatted disk. The student spent about 6 months optimizing it, including putting in disk caching. When he turned it in, it did not work and it required several additional months of debugging. This program typically runs once on the hard disk during the life of the computer, when the system is installed. It also runs once for each floppy disk that is formatted. Each run takes about 2 sec. Even if the unoptimized version had taken 1 minute, it was a poor use of resources to spend so much time optimizing a program that is used so infrequently.

A slogan that has considerable applicability to performance optimization is

Good enough is good enough.

By this we mean that once performance has achieved a reasonable level, it is probably not worth the effort and complexity to squeeze out the last few percent. If the scheduling algorithm is reasonably fair and keeps the CPU busy 90% of the time, it is doing its job. Devising a far more complex one that is 5% better is probably a bad idea. Similarly, if the page rate is low enough that it is not a

bottleneck, jumping through hoops to get optimal performance is usually not worth it. Avoiding disaster is far more important than getting optimal performance, especially since what is optimal with one load may not be optimal with another.

13.4.3 Space-Time Trade-offs

One general approach to improving performance is to trade off time versus space. It frequently occurs in computer science that there is a choice between an algorithm that uses little memory but is slow and an algorithm that uses much more memory but is faster. When making an important optimization, it is worth looking for algorithms that gain speed by using more memory or conversely save precious memory by doing more computation.

One technique that is often helpful is to replace small procedures by macros. Using a macro eliminates the overhead normally associated with a procedure call. The gain is especially significant if the call occurs inside a loop. As an example, suppose we use bitmaps to keep track of resources and frequently need to know how many units are free in some portion of the bitmap. For this purpose we need a procedure, *bit_count*, that counts the number of 1 bits in a byte. The straightforward procedure is given in Fig. 13-7(a). It loops over the bits in a byte counting them one at a time.

This procedure has two sources of inefficiency. First, it must be called, stack space must be allocated for it, and it must return. Every procedure call has this overhead. Second, it contains a loop, and there is always some overhead associated with a loop.

A completely different approach is to use the macro of Fig. 13-7(b). It is an inline expression that computes the sum of the bits by successively shifting the argument, masking out everything but the low-order bit, and adding up the eight terms. The macro is hardly a work of art, but it appears in the code only once. When the macro is called, for example, by

```
sum = bit_count(table[i]);
```

the macro call looks identical to the call of the procedure. Thus other than one somewhat messy definition, the code does not look any worse in the macro case than in the procedure case, but it is much more efficient since it eliminates both the procedure call overhead and the loop overhead.

We can take this example one step further. Why compute the bit count at all? Why not look it up in a table? After all, there are only 256 different bytes, each with a unique value between 0 and 8. We can declare a 256-entry table, *bits*, with each entry initialized (at compile time) to the bit count corresponding to that byte value. With this approach no computation at all is needed at run time, just one indexing operation. A macro to do the job is given in Fig. 13-7(c).

This is a clear example of trading computation time against memory.

```

#define BYTE_SIZE 8 /* A byte contains 8 bits */

int bit_count(int byte)
{
    int i, count = 0; /* Count the bits in a byte. */
    for (i = 0; i < BYTE_SIZE; i++) /* loop over the bits in a byte */
        if ((byte >> i) & 1) count++; /* if this bit is a 1, add to count */
    return(count); /* return sum */
}

```

(a)

```

/*Macro to add up the bits in a byte and return the sum. */
#define bit_count(b) ((b&1) + ((b>>1)&1) + ((b>>2)&1) + ((b>>3)&1) + \
    ((b>>4)&1) + ((b>>5)&1) + ((b>>6)&1) + ((b>>7)&1))

```

(b)

```

/*Macro to look up the bit count in a table. */
char bits[256] = {0, 1, 1, 2, 1, 2, 2, 3, 1, 2, 2, 3, 2, 3, 3, 4, 1, 2, 2, 3, 2, 3, 3, ...};
#define bit_count(b) (int) bits[b]

```

(c)

Figure 13-7. (a) A procedure for counting bits in a byte. (b) A macro to count the bits. (c) A macro that counts bits by table lookup.

However, we could go still further. If the bit counts for whole 32-bit words are needed, using our *bit_count* macro, we need to perform four lookups per word. If we expand the table to 65,536 entries, we can suffice with two lookups per word, at the price of a much bigger table.

Looking answers up in tables can be used in other ways. For example, in Chap. 7 we saw how JPEG image compression works, with fairly complex discrete cosine transformations. An alternative compression technique, GIF, uses table lookup to encode 24-bit RGB pixels. However, GIF only works on images with 256 or fewer colors. For each image to be compressed, a palette of 256 entries is constructed, each entry containing one 24-bit RGB value. The compressed image then consists of an 8-bit index for each pixel instead of a 24-bit color value, a gain of a factor of three. This idea is illustrated for a 4×4 section of an image in Fig. 13-8. The original compressed image is shown in Fig. 13-8(a). Each value here is a 24-bit value, with 8 bits each giving the intensity for red, green, and blue. The GIF image is shown in Fig. 13-8(b). Here each value is an 8-bit index into the color palette. The color palette is stored as part of the image file, and is shown in Fig. 13-8(c). Actually, there is more to GIF, but the core of the idea is table lookup.

There is another way to reduce image size, and it illustrates a different trade-off. PostScript is a programming language that can be used to describe images.

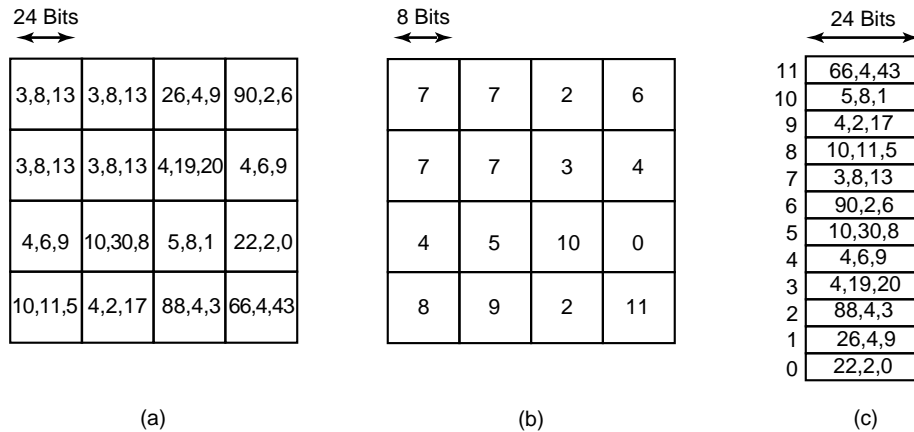


Figure 13-8. (a) Part of an uncompressed image with 24 bits per pixel. (b) The same part compressed with GIF, with 8 bits per pixel. (c) The color palette.

(Actually, any programming language can describe images, but PostScript is tuned for this purpose.) Many printers have a PostScript interpreter built into them to be able to run PostScript programs sent to them.

For example, if there is a rectangular block of pixels all the same color in an image, a PostScript program for the image would carry instructions to place a rectangle at a certain location and fill it with a certain color. Only a handful of bits are needed to issue this command. When the image is received at the printer, an interpreter there must run the program to construct the image. Thus PostScript achieves data compression at the expense of more computation, a different trade-off than table lookup, but a valuable one when memory or bandwidth is scarce.

Other trade-offs often involve data structures. Doubly-linked lists take up more memory than singly-linked lists, but often allow faster access to items. Hash tables are even more wasteful of space, but faster still. In short, one of the main things to consider when optimizing a piece of code is whether using different data structures would make the best time-space trade-off.

13.4.4 Caching

A well-known technique for improving performance is caching. It is applicable any time it is likely the same result will be needed multiple times. The general approach is to do the full work the first time, and then save the result in a cache. On subsequent attempts, the cache is first checked. If the result is there, it is used. Otherwise, the full work is done again.

We have already seen the use of caching within the file system to hold some number of recently used disk blocks, thus saving a disk read on each hit.

However, caching can be used for many other purposes as well. For example, parsing path names is surprising expensive. Consider the UNIX example of Fig. 4-35 again. To look up `/usr/ast/mbox` requires the following disk accesses:

1. Read the i-node for the root directory (i-node 1).
2. Read the root directory (block 1).
3. Read the i-node for `/usr` (i-node 6).
4. Read the `/usr` directory (block 132).
5. Read the i-node for `/usr/ast` (i-node 26).
6. Read the `/usr/ast` directory (block 406).

It takes six disk accesses just to discover the i-node number of the file. Then the i-node itself has to be read to discover the disk block numbers. If the file is smaller than the block size (e.g., 1024 bytes), it takes eight disk accesses to read the data.

Some systems optimize path name parsing by caching (path, i-node) combinations. For the example of Fig. 4-35, the cache will certainly hold the first three entries of Fig. 13-9 after parsing `/usr/ast/mbox`. The last three entries come from parsing other paths.

Path	i-node number
<code>/usr</code>	6
<code>/usr/ast</code>	26
<code>/usr/ast/mbox</code>	60
<code>/usr/ast/books</code>	92
<code>/usr/bal</code>	45
<code>/usr/bal/paper.ps</code>	85

Figure 13-9. Part of the i-node cache for Fig. 4-35.

When a path has to be looked up, the name parser first consults the cache and searches it for the longest substring present in the cache. For example, if the path `/usr/ast/grants/stw` is presented, the cache returns the fact that `/usr/ast` is i-node 26, so the search can start there, eliminating four disk accesses.

A problem with caching paths is that the mapping between file name and i-node number is not fixed for all time. Suppose that the file `/usr/ast/mbox` is removed from the system and its i-node reused for a different file owned by a different user. Later, the file `/usr/ast/mbox` is created again, and this time it gets i-node 106. If nothing is done to prevent it, the cache entry will now be wrong and subsequent lookups will return the wrong i-node number. For this reason, when a

file or directory is deleted, its cache entry and (if it is a directory) all the entries below it must be purged from the cache.

Disk blocks and path names are not the only items that are cacheable. I-nodes can be cached, too. If pop-up threads are used to handle interrupts, each one of them requires a stack and some additional machinery. These previously-used threads can also be cached, since refurbishing a used one is easier than creating a new one from scratch (to avoid having to allocate memory). Just about anything that is hard to produce can be cached.

13.4.5 Hints

Cache entries are always correct. A cache search may fail, but if it finds an entry, that entry is guaranteed to be correct and can be used without further ado. In some systems, it is convenient to have a table of **hints**. These are suggestions about the solution, but they are not guaranteed to be correct. The caller must verify the result itself.

A well-known example of hints are the URLs embedded on Web pages. Clicking on a link does not guarantee that the Web page pointed to is there. In fact, the page pointed to may have been removed 10 years ago. Thus the information on the pointing page is really only a hint.

Hints are also used in connection with remote files. The information is the hint tells something about the remote file, such as where it is located. However, the file may have moved or been deleted since the hint was recorded, so a check is always needed to see if it is correct.

13.4.6 Exploiting Locality

Processes and programs do not act at random. They exhibit a fair amount of locality in time and space, and this information can be exploited in various ways to improve performance. One well-known example of spatial locality is the fact that processes do not jump around at random within their address spaces. They tend to use a relatively small number of pages during a given time interval. The pages that a process is actively using can be noted as its working set and the operating system can make sure that when the process is allowed to run, its working set is in memory, thus reducing the number of page faults.

The locality principle also holds for files. When a process has selected a particular working directory, it is likely that many of its future file references will be to files in that directory. By putting all the i-nodes and files for each directory close together on the disk, performance improvements can be obtained. This principle is what underlies the Berkeley Fast File System (McKusick et al., 1984).

Another area in which locality plays a role is in thread scheduling in multiprocessors. As we saw in Chap. 8, one way to schedule threads on a multiprocessor is to try to run each thread on the CPU it last used, in hopes that some of its

memory blocks will still be in the memory cache.

13.4.7 Optimize the Common Case

It is frequently a good idea to distinguish between the most common case and the worst possible case and treat them differently. Often the code for the two is quite different. It is important to make the common case fast. For the worst case, if it occurs rarely, it is sufficient to make it correct.

As a first example, consider entering a critical region. Most of the time, the entry will succeed, especially if processes do not spend a lot of time inside critical regions. Windows Vista takes advantage of this expectation by providing a Win32 API call `EnterCriticalSection` that atomically tests a flag in user mode (using TSL or equivalent). If the test succeeds, the process just enters the critical region and no kernel call is needed. If the test fails, the library procedure does a down on a semaphore to block the process. Thus in the normal case, no kernel call is needed.

As a second example, consider setting an alarm (using signals in UNIX). If no alarm is currently pending, it is straightforward to make an entry and put it on the timer queue. However, if an alarm is already pending, it has to be found and removed from the timer queue. Since the alarm call does not specify whether there is already an alarm set, the system has to assume worst case, that there is. However, since most of the time there is no alarm pending, and since removing an existing alarm is expensive, it is a good idea to distinguish these two cases.

One way to do this is to keep a bit in the process table that tells whether an alarm is pending. If the bit is off, the easy path is followed (just add a new timer queue entry without checking). If the bit is on, the timer queue must be checked.

13.5 PROJECT MANAGEMENT

Programmers are perpetual optimists. Most of them think that the way to write a program is to run to the keyboard and start typing. Shortly thereafter the fully debugged program is finished. For very large programs, it does not quite work like that. In the following sections we have a bit to say about managing large software projects, especially large operating system projects.

13.5.1 The Mythical Man Month

In his classic book, Fred Brooks, one of the designers of OS/360, who later moved to academia, addresses the question of why it is so hard to build big operating systems (Brooks, 1975, 1995). When most programmers see his claim that programmers can produce only 1000 lines of debugged code per *year* on large projects, they wonder whether Prof. Brooks is living in outer space, perhaps on

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Planet Bug. After all, most of them can remember an all nighter when they produced a 1000-line program in one night. How could this be the annual output of anybody with an $IQ > 50$?

What Brooks pointed out is that large projects, with hundreds of programmers, are completely different than small projects and that the results obtained from small projects do not scale to large ones. In a large project, a huge amount of time is consumed planning how to divide the work into modules, carefully specifying the modules and their interfaces, and trying to imagine how the modules will interact, even before coding begins. Then the modules have to be coded and debugged in isolation. Finally, the modules have to be integrated and system as a whole has to be tested. The normal case is that each module works perfectly when tested by itself, but the system crashes instantly when all the pieces are put together. Brooks estimated the work as being

- 1/3 Planning
- 1/6 Coding
- 1/4 Module testing
- 1/4 System testing

In other words, writing the code is the easy part. The hard part is figuring out what the modules should be and making module *A* correctly talk to module *B*. In a small program written by a single programmer, all that is left over is the easy part.

The title of Brooks' book comes from his assertion that people and time are not interchangeable. There is no such unit as a man-month (or a person-month). If a project takes 15 people 2 years to build, it is inconceivable that 360 people could do it in one month and probably not possible to have 60 people do it in 6 months.

There are three reasons for this effect. First, the work cannot be fully parallelized. Until the planning is done and it has been determined what modules are needed and what their interfaces will be, no coding can be even started. On a two-year project, the planning alone may take 8 months.

Second, to fully utilize a large number of programmers, the work must be partitioned into large numbers of modules so everyone has something to do. Since every module may potentially interact with every other module, the number of module-module interactions that need to be considered grows as the square of the number of modules, that is, as the square of the number of programmers. This complexity quickly gets out of hand. Careful measurements of 63 software projects have confirmed that the trade-off between people and months is far from linear on large projects (Boehm, 1981).

Third, debugging is highly sequential. Setting ten debuggers on a problem does not find the bug ten times as fast. In fact, ten debuggers are probably slower than one because they will waste so much time talking to each other.

Brooks sums up his experience with trading-off people and time in Brooks'

law:

Adding manpower to a late software project makes it later.

The problem with adding people is that they have to be trained in the project, the modules have to be redivided to match the larger number of programmers now available, many meetings will be needed to coordinate all the efforts and so on. Abdel-Hamid and Madnick (1991) confirmed this law experimentally. A slightly irreverent way of restating Brooks law is

It takes 9 months to bear a child, no matter how many women you assign to the job.

13.5.2 Team Structure

Commercial operating systems are large software projects and invariably require large teams of people. The quality of the people matters immensely. It has been known for decades that top programmers are 10× more productive than bad programmers (Sackman et al., 1968). The trouble is, when you need 200 programmers, it is hard to find 200 top programmers; you have to settle for a wide spectrum of qualities.

What is also important in any large design project, software or otherwise, is the need for architectural coherence. There should be one mind controlling the design. Brooks cites the Reims cathedral as an example of a large project that took decades to build, and in which the architects who came later subordinated their desire to put their stamp on the project to carry out the initial architect's plans. The result is an architectural coherence unmatched in other European cathedrals.

In the 1970s, Harlan Mills combined the observation that some programmers are much better than others with the need for architectural coherence to propose the **chief programmer team** paradigm (Baker, 1972). His idea was to organize a programming team like a surgical team rather than like a hog-butchering team. Instead of everyone hacking away like mad, one person wields the scalpel. Everyone else is there to provide support. For a 10-person project, Mills suggested the team structure of Fig. 13-10.

Three decades have gone by since this was proposed and put into production. Some things have changed (such as the need for a language lawyer—C is simpler than PL/I), but the need to have only one mind controlling the design is still true. And that one mind should be able to work 100% on designing and programming, hence the need for the support staff, although with help from the computer, a smaller staff will suffice now. But in its essence, the idea is still valid.

Any large project needs to be organized as a hierarchy. At the bottom level are many small teams, each headed by a chief programmer. At the next level, groups of teams must be coordinated by a manager. Experience shows that each

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Title	Duties
Chief programmer	Performs the architectural design and writes the code
Copilot	Helps the chief programmer and serves as a sounding board
Administrator	Manages the people, budget, space, equipment, reporting, etc.
Editor	Edits the documentation, which must be written by the chief programmer
Secretaries	The administrator and editor each need a secretary
Program clerk	Maintains the code and documentation archives
Toolsmith	Provides any tools the chief programmer needs
Tester	Tests the chief programmer's code
Language lawyer	Part timer who can advise the chief programmer on the language

Figure 13-10. Mills' proposal for populating a 10-person chief programmer team.

person you manage costs you 10% of your time, so a full-time manager is needed for each group of 10 teams. These managers must be managed, and so on up the tree.

Brooks observed that bad news does not travel up the tree well. Jerry Saltzer of M.I.T. called this effect the **bad-news diode**. No chief programmer or manager wants to tell his boss that the project is 4 months late and has no chance whatsoever of meeting the deadline because there is a 1000-year old tradition of beheading the messenger who brings bad news. As a consequence, top management is generally in the dark about the state of the project. When it becomes obvious that the deadline cannot be met, top management responds by adding people, at which time Brooks' law kicks in.

In practice, large companies, which have had long experience producing software and know what happens if it is produced haphazardly, have a tendency to at least try to do it right. In contrast, smaller, newer companies, which are in a huge rush to get to market, do not always take the care to produce their software carefully. This haste often leads to far from optimal results.

Neither Brooks nor Mills foresaw the growth of the open source movement. Although it has had some successes, it remains to be seen if this is a viable model for producing large amounts of quality software once the novelty wears off. Recall that in its early days, radio was dominated by ham radio operators, but that soon gave way to commercial radio and later to commercial television. What is noticeable is that the open source software projects that have been most successful have clearly used the chief programmer model of having one mind control the architectural design (e.g., Linus Torvalds for the Linux kernel and Richard Stallman for the GNU C compiler).

13.5.3 The Role of Experience

Having experienced designers is critical to an operating systems project. Brooks points out that most of the errors are not in the code, but in the design. The programmers correctly did what they were told to do. What they were told to do was wrong. No amount of test software will catch bad specifications.

Brooks' solution is to abandon the classical development model of Fig. 13-11(a) and use the model of Fig. 13-11(b). Here the idea is to first write a main program that merely calls the top-level procedures, which are initially dummies. Starting on day 1 of the project, the system will compile and run, although it does nothing. As time goes on, modules are inserted into the full system. The result of this approach is that system integration testing is performed continuously, so errors in the design show up much earlier. In effect, the learning process caused by bad design decisions starts much earlier in the cycle.

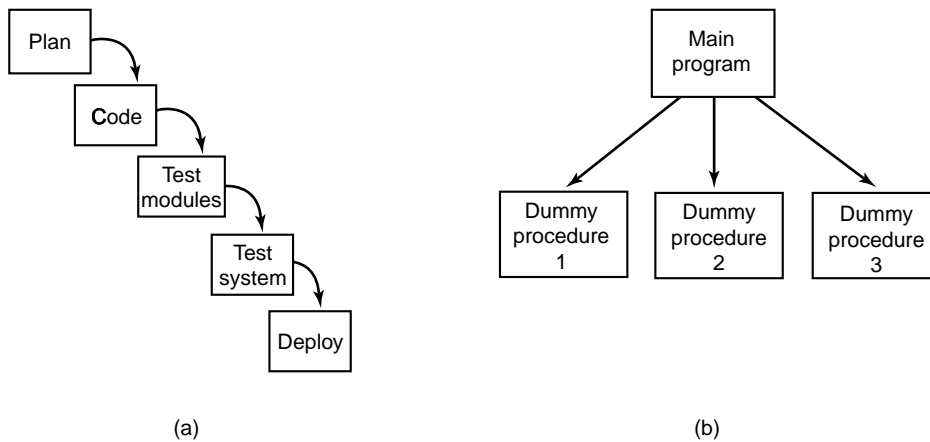


Figure 13-11. (a) Traditional software design progresses in stages. (b) Alternative design produces a working system (that does nothing) starting on day 1.

A little knowledge is a dangerous thing. Brooks observed what he called the **second system effect**. Often the first product produced by a design team is minimal because the designers are afraid it may not work at all. As a result, they are hesitant to put in many features. If the project succeeds, they build a follow-up system. Impressed by their own success, the second time the designers include all the bells and whistles that were intentionally left out the first time. As a result, the second system is bloated and performs poorly. The third time around they are sobered by the failure of the second system and are cautious again.

The CTSS-MULTICS pair is a clear case in point. CTSS was the first general-purpose timesharing system and was a huge success despite having minimal functionality. Its successor, MULTICS was too ambitious and suffered badly for it.

The ideas were good, but there were too many new things so the system performed poorly for years and was never a big commercial success. The third system in this line of development, UNIX, was much more cautious and much more successful.

13.5.4 No Silver Bullet

In addition to *The Mythical Man Month*, Brooks also wrote an influential paper called “No Silver Bullet” (Brooks, 1987). In it, he argued that none of the many nostrums being hawked by various people at the time was going to generate an order-of-magnitude improvement in software productivity within a decade. Experience shows that he was right.

Among the silver bullets that were proposed were better high-level languages, object-oriented programming, artificial intelligence, expert systems, automatic programming, graphical programming, program verification, and programming environments. Perhaps the next decade will see a silver bullet, but maybe we will have to settle for gradual, incremental improvements.

13.6 TRENDS IN OPERATING SYSTEM DESIGN

Making predictions is always difficult—especially about the future. For example, in 1899, the head of the U.S. Patent Office, Charles H. Duell, asked then-President McKinley to abolish the Patent Office (and his job!), because, as he put it: “Everything that can be invented, has been invented” (Cerf and Navasky, 1984). Nevertheless, Thomas Edison showed up on his doorstep within a few years with a couple of new items, including the electric light, the phonograph, and the movie projector. Let us put new batteries in our crystal ball and venture a guess on where operating systems are going in the near future.

13.6.1 Virtualization

Virtualization is an idea whose time has come—again—. It first surfaced in 1967 with the IBM CP/CMS system, but now it is back in full force on the Pentium platform. In the near future, many computers will be running hypervisors on the bare hardware, as illustrated in Fig. 13-12. The hypervisor will create a number of virtual machines, each with its own operating system. Some computers will have a virtual machine running Windows for legacy applications, several virtual machines running Linux for current applications, and perhaps one or more experimental operating systems in other virtual machines. This phenomenon was discussed in Chap. 8 and is definitely the wave of the future.

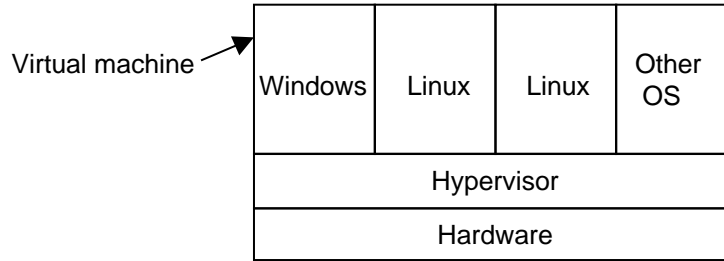


Figure 13-12. A hypervisor running four virtual machines.

13.6.2 Multicore Chips

Multicore chips are here already, but the operating systems for them do not use them well, not even with two cores, let alone 64 cores, which are expected before too long. What will all the cores do? What kind of software will be needed for them? It really is not known now. Initially, people will try to patch up current operating systems to work on them, but this is unlikely to be very successful with large numbers of cores do to the problem of locking tables and other software resources. There is definitely room here for radically new ideas.

The combination of virtualization and multicore chips creates a whole new environment. In this world, the number of CPUs available is programmable. With an eight-core chip, the software could do anything from just using one CPU and ignoring the other seven, to using all eight real CPUs, to two-way virtualization, leading to 16 virtual CPUs, or four-way virtualization and 32 virtual CPUs, or pretty much any other combination. A program could start out announcing how many CPUs it wants and it is up to the operating system to make them appear.

13.6.3 Large Address Space Operating Systems

As machines move from 32-bit address spaces to 64-bit address spaces, major shifts in operating system design become possible. A 32-bit address space is not really that big. If you tried to divide up 2^{32} bytes by giving everybody on earth his or her own byte, there would not be enough bytes to go around. In contrast, 2^{64} is about 2×10^{19} . Now everybody gets his or her personal 3 GB chunk.

What could we do with an address space of 2×10^{19} bytes? For starters, we could eliminate the file system concept. Instead, all files could be conceptually held in (virtual) memory all the time. After all, there is enough room in there for over 1 billion full-length movies, each compressed to 4 GB.

Another possible use is a persistent object store. Objects could be created in the address space and kept there until all references to them were gone, at which time they would be automatically deleted. Such objects would be persistent in the

address space, even over shutdowns and reboots of the computer. With a 64-bit address space, objects could be created at a rate of 100 MB/sec for 5000 years before we run out of address space. Of course, to actually store this amount of data, a lot of disk storage would be needed for the paging traffic, but for the first time in history, the limiting factor would be disk storage, not address space.

With large numbers of objects in the address space, it becomes interesting to allow multiple processes to run in the same address space at the same time, to share the objects in a general way. Such a design would clearly lead to very different operating systems than we now have. Some thoughts on this concept are contained in (Chase et al., 1994).

Another operating system issue that will have to be rethought with 64-bit addresses is virtual memory. With 2^{64} bytes of virtual address space and 8-KB pages we have 2^{51} pages. Conventional pages tables do not scale well to this size, so something else is needed. Inverted page tables are a possibility, but other ideas have been proposed as well (Talluri et al., 1995). In any event there is plenty of room for new research on 64-bit operating systems.

13.6.4 Networking

Current operating systems were designed for standalone computers. Networking was an afterthought and is generally accessed through special programs, such as Web browsers, FTP, or telnet. In the future, networking will probably be the basis for all operating systems. A standalone computer without a network connection will be as rare as a telephone without a connection to the network. And it is likely that multimegabit/sec connections will be the norm.

Operating systems will have to change to adapt to this paradigm shift. The difference between local data and remote data may blur to the point that virtually no one knows or cares where data are stored. Computers anywhere may be able to treat data anywhere as local data. To a limited extent, this is already true with NFS, but it is likely to become far more pervasive and better integrated.

Access to the Web, which now requires special programs (browsers) may also become completely integrated into the operating system in a seamless way. The standard way to store information may become Web pages, and these pages may contain a wide variety of nontext items, including audio, video, programs, and more, all managed as the operating system's fundamental data.

13.6.5 Parallel and Distributed Systems

Another area that is up and coming is parallel and distributed systems. Current operating systems for multiprocessors and multicomputers are just standard uniprocessor operating systems with minor adjustments to the scheduler to handle parallelism a bit better. In the future, we may see operating systems where parallelism is much more central than it now is. This effect will be enormously

stimulated if desktop machines soon have two, four, or more CPUs in a multiprocessor configuration. This may lead to many application programs being designed for multiprocessors, with the concurrent demand for better operating system support for them.

Multicomputers are likely to dominant large-scale scientific and engineering supercomputers in the coming years, but the operating systems for them are still fairly primitive. Process placement, load balancing, and communication need a lot of work.

Current distributed systems are often built as middleware because existing operating systems do not provide the right facilities for distributed applications. Future ones may be designed with distributed systems in mind, so all the necessary features are already present in the operating system from the start.

13.6.6 Multimedia

Multimedia systems are clearly a rising star in the computer world. It would surprise no one if computers, stereos, televisions, and telephones all merged into a single device capable of supporting high-quality still images, audio and video, and connected to high-speed networks so these files could easily be downloaded, exchanged, and accessed remotely. The operating systems for these devices, or even for standalone audio and video devices, will have to be substantially different from current ones. In particular, real-time guarantees will be needed, and these will drive the system design. Also, consumers will be very intolerant of weekly crashes of their digital television sets, so better software quality and fault tolerance will be required. Also, multimedia files tend to be very long, so file systems will have to change to be able to handle them efficiently.

13.6.7 Battery-Powered Computers

Powerful desktop PCs, probably with 64-bit address spaces, high-bandwidth networking, multiple processors, and high-quality audio and video will no doubt be commonplace soon. Their operating systems will have to be appreciably different from current ones to handle all these demands. However, an even faster growing segment of the market is battery-powered computers, including notebooks, palmtops, Webpads, and various telephone hybrids. Some of these will have wireless connections to the outside world; others will run in disconnected mode when not docked at home. They will need different operating systems that are smaller, faster, more flexible, and more reliable than current ones. Various kinds of microkernel and extensible systems may form the basis here.

These operating systems will have to handle fully connected (i.e., wired), weakly connected (i.e., wireless), and disconnected operation, including data hoarding before going offline and consistency resolution when going back online better than current systems. They will also have to handle the problems of

mobility better than current systems (e.g., find a laser printer, log onto it, and send it a file by radio). Power management, including extensive dialogs between the operating system and applications about how much battery power is left and how it can be best used, will be essential. Dynamic adaptation of applications to handle the limitations of tiny screens may become important. Finally, new input and output modes, including handwriting and speech, may require new techniques in the operating system to improve the quality. It is unlikely the operating system for a battery-powered, handheld wireless, voice-operated computer will have much in common with that of a desktop 64-bit four-CPU multiprocessor with a gigabit fiber-optic network connection. And of course, there will be innumerable hybrid machines with their own requirements.

13.6.8 Embedded Systems

One final area in which new operating systems will proliferate is embedded systems. The operating systems inside washing machines, microwave ovens, dolls, transistor (Internet?) radios, MP3 players, camcorders, elevators, and pacemakers will differ from all of the above and most likely from each other. Each one will probably be carefully tailored for its specific application, since it is unlikely anyone will ever stick a PCI card into a pacemaker to turn it into an elevator controller. Since all embedded systems run only a limited number of programs, known at design time, it may be possible to make optimizations not possible in general-purpose systems.

A promising idea for embedded systems are the extensible operating systems (e.g., Paramecium and Exokernel). These can be made as lightweight or heavyweight as the application in question demands, but in a consistent way across applications. Since embedded systems will be produced by the hundreds of millions, this will be a major market for new operating systems.

13.6.9 Sensor Nodes

While it is a niche market, sensor networks are being deployed in many contexts, from monitoring buildings and national borders, to detecting forest fires, and many others. The sensors used are low-cost and low-power and require extremely lean-and-mean operating systems, barely more than run-time libraries. Still, as more powerful nodes get cheaper, we will start to see real operating systems on them, but of course optimized for their tasks and consuming as little energy as possible. With battery lifetimes measured in months and wireless transmitters and receivers being big energy consumers, these systems will be organized for energy efficiency more than anything else.

13.7 SUMMARY

Designing an operating system starts with determining what it should do. The interface should be simple, complete, and efficient. It should have a clear user interface paradigm, execution paradigm, and data paradigm.

The system should be well structured, using one of several known techniques, such as layering or client-server. The internal components should be orthogonal to one another and clearly separate policy from mechanism. Considerable thought should be given to issues such as static versus dynamic data structure, naming, binding time, and order of implementing modules.

Performance is important, but optimizations should be chosen carefully so as not to ruin the system's structure. Space-time trade-offs, caching, hints, exploiting locality, and optimizing the common case are often worth doing.

Writing a system with a couple of people is different than producing a big system with 300 people. In the latter case, team structure and project management play a crucial role in the success or failure of the project.

Finally, operating systems will have to change in the coming years to follow new trends and meet new challenges. These may include hypervisor-based systems, multicore systems, 64-bit address spaces, massive connectivity, large-scale multiprocessors and multicomputers, multimedia, handheld wireless computers, embedded systems, and sensor nodes. The coming years will be exciting times for operating system designers.

PROBLEMS

1. Moore's law describes a phenomenon of exponential growth similar to the population growth of an animal species introduced into a new environment with abundant food and no natural enemies. In nature, an exponential growth curve is likely eventually to become a sigmoid curve with an asymptotic limit when food supplies become limiting or predators learn to take advantage of new prey. Discuss some factors that may eventually limit the rate of improvement of computer hardware.
2. In Fig. 13-1, two paradigms are shown, algorithmic and event driven. For each of the following kinds of programs, which paradigm is likely to be easiest to use:
 - (a) A compiler.
 - (b) A photo editing program.
 - (c) A payroll program.
3. On some of the early Apple Macintoshes, the GUI code was in ROM. Why?
4. Hierarchical file names always start at the top of the tree. Consider, for example, the file name `/usr/ast/books/mos2/chap-12` rather than `chap-12/mos2/books/ast/usr`. In contrast, DNS names start at the bottom of the tree and work up. Is there some fundamental reason for this difference?

5. Corbató's dictum is that the system should provide minimal mechanism. Here is a list of POSIX calls that were also present in UNIX Version 7. Which ones are redundant, that is, could be removed with no loss of functionality because simple combinations of other ones could do the same job with about the same performance? Access, alarm, chdir, chmod, chown, chroot, close, creat, dup, exec, exit, fcntl, fork, fstat, ioctl, kill, link, lseek, mkdir, mknod, open, pause, pipe, read, stat, time, times, umask, unlink, utime, wait, and write.
6. Suppose that layers 3 and 4 in Fig. 13-2 were exchanged. What implications would that have for the design of the system?
7. In a microkernel-based client-server system, the microkernel just does message passing and nothing else. Is it possible for user processes to nevertheless create and use semaphores? If so, how? If not, why not?
8. Careful optimization can improve system call performance. Consider the case in which one system call is made every 10 msec. The average time of a call is 2 msec. If the system calls can be speeded up by a factor of two, how long does a process that took 10 sec to run now take?
9. Give a short discussion of mechanism versus policy in the context of retail stores.
10. Operating systems often do naming at two different levels: external and internal. What are the differences between these names with respect to
 - (a) Length
 - (b) Uniqueness
 - (c) Hierarchies
11. One way to handle tables whose size is not known in advance is to make them fixed, but when one fills up, to replace it with a bigger one, copy the old entries over to the new one, then release the old one. What are the advantages and disadvantages of making the new one 2× the size of the original one, as compared to making it only 1.5× as big?
12. In Fig. 13-5, a flag, *found*, is used to tell whether the PID was located. Would it have been possible to forget about *found* and just test *p* at the end of the loop to see whether it got to the end or not?
13. In Fig. 13-6, the differences between the Pentium and the UltraSPARC are hidden by conditional compilation. Could this same approach be used to hide the difference between Pentiums with an IDE disk as the only disk and Pentiums with a SCSI disk as the only disk? Would it be a good idea?
14. Indirection is a way of making an algorithm more flexible. Does it have any disadvantages, and if so, which ones?
15. Can reentrant procedures have private static global variables? Discuss your answer.
16. The macro of Fig. 13-7(b) is clearly much more efficient than the procedure of Fig. 13-7(a). One disadvantage, however, is that it is hard to read. Are there any other disadvantages? If so, what are they?
17. Suppose that we need a way of computing whether the number of bits in a 32-bit word

- is odd or even. Devise an algorithm for performing this computation as fast as possible. You may use up to 256 KB of RAM for tables if need be. Write a macro to carry out your algorithm. *Extra Credit:* Write a procedure to do the computation by looping over the 32 bits. Measure how many times faster your macro is than the procedure.
18. In Fig. 13-8, we saw how GIF files use 8-bit values to index into a color palette. The same idea can be used with a 16-bit-wide color palette. Under what circumstances, if any, might a 24-bit color palette be a good idea?
 19. One disadvantage of GIF is that the image must include the color palette, which increases the file size. What is the minimum image size for which an 8-bit-wide color palette breaks even? Now repeat this question for a 16-bit-wide color palette.
 20. In the text we showed how caching path names can result in a significant speedup when looking up path names. Another technique that is sometimes used is having a daemon program that opens all the files in the root directory and keeps them open permanently, in order to force their i-nodes to be in memory all the time. Does pinning the i-nodes like this improve the path lookup even more?
 21. Even if a remote file has not been removed since a hint was recorded, it may have been changed since the last time it was referenced. What other information might it be useful to record?
 22. Consider a system that hoards references to remote files as hints, for example as (name, remote-host, remote-name). It is possible that a remote file will quietly be removed and then replaced. The hint may then retrieve the wrong file. How can this problem be made less likely to occur?
 23. In the text it is stated that locality can often be exploited to improve performance. But consider a case where a program reads input from one source and continuously outputs to two or more files. Can an attempt to take advantage of locality in the file system lead to a decrease in efficiency here? Is there a way around this?
 24. Fred Brooks claims that a programmer can write 1000 lines of debugged code per year, yet the first version of MINIX (13,000 lines of code) was produced by one person in under three years. How do you explain this discrepancy?
 25. Using Brooks' figure of 1000 lines of code per programmer per year, make an estimate of the amount of money it took to produce Windows Vista. Assume that a programmer costs \$100,000 per year (including overhead, such as computers, office space, secretarial support, and management overhead). Do you believe this answer? If not, what might be wrong with it?
 26. As memory gets cheaper and cheaper, one could imagine a computer with a big battery-backed up RAM instead of a hard disk. At current prices, how much would a low-end RAM-only PC cost? Assume that a 1-GB RAM-disk is sufficient for a low-end machine. Is this machine likely to be competitive?
 27. Name some features of a conventional operating system that are not needed in an embedded system used inside an appliance.
 28. Write a procedure in C to do a double precision addition on two given parameters. Write the procedure using conditional compilation in such a way that it works on 16-

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- bit machines and also on 32-bit machines.
29. Write programs that enter randomly generated short strings into an array and then can search the array for a given string using (a) a simple linear search (brute force), and (b) a more sophisticated method of your choice. Recompile your programs for array sizes ranging from small to as large as you can handle on your system. Evaluate the performance of both approaches). Where is the break-even point?
 30. Write a program to simulate an in-memory file system.

SOLUTIONS TO CHAPTER 12 PROBLEMS

1. Improvements in computer hardware have been largely due to smaller transistors. Some factors that can limit this are: (a) the wave properties of light may limit conventional photolithographic techniques for producing integrated circuits, (b) the mobility of individual atoms in solids can lead to degradation of the properties of very thin layers of semiconductors, insulators, and conductors, and (c) background radioactivity can disrupt molecular bonds or affect very small stored charges. There are certainly others.
2. For highly interactive programs, the event model may be better. Of these, only (b) is interactive. Thus (a) and (c) are algorithmic and (b) is event driven.
3. Putting it there saved some RAM and reduced loading time to 0, but most important, it made it easy for third-party software developers to use the GUI, thus ensuring a uniformity of look and feel across all software.
4. No. The difference relates more to the fact that DNS servers cache and are organized hierarchically. The paths could easily have been given in the top-down order, but the convention of doing it backward is now well established.
5. Possibly stat is redundant. It could be achieved by a combination of open, fstat, and close. It would be very difficult to simulate any of the others.
6. If drivers are put below the threads, then drivers cannot be independent threads in the style of MINIX. They have to run as part of some other thread, more in the UNIX style.
7. It is possible. What is needed is a user-level process, the semaphore server. To create a semaphore, a user sends it a message asking for a new semaphore. To use it, the user process passes the identity of the semaphore to other processes. They can then send messages to the semaphore server asking for an operation. If the operation blocks, no reply is sent back, thus blocking the caller.
8. The pattern is 8 msec of user code, then 2 msec of system code. With the optimization, each cycle is now 8 msec of user code and 1 msec of system code. Thus the cycle is reduced from 10 msec to 9 msec. Multiplying by 1000 such cycles, a 10-sec program now takes 9 sec.

9. The mechanism for selling to customers is a building with shelves, employees to stock the shelves, cashiers to handle payment, etc. The policy is what kind of products the store sells.
10. External names can be as long as needed and variable length. Internal names are generally 32 bits or 64 bits and always fixed length. External names need not be unique. Two names can point to the same object, for example, links in the UNIX file system. Internal names must be unique. External names may be hierarchical. Internal names are generally indices into tables and thus form a flat name space.
11. If the new table is $2\times$ as big as the old one, it will not fill up quickly, reducing the number of times an upgraded table will be needed. On the other hand, so much space may not be needed, so it may waste memory. This is a classic time versus space trade-off.
12. It would be risky to do that. Suppose that the PID was at the very last entry. In that case, exiting the loop would leave p pointing to the last entry. However, if the PID was not found, p might end up pointing to the last entry or to one beyond it, depending on the details of the compiled code, which optimizations are turned on, and so on. What might work with one compiler could fail with a different one. It is better to set a flag.
13. It could be done, but would not be a good idea. An IDE or SCSI driver is many pages long. Having conditional code so long makes the source code hard to follow. It would be better to put each one in a separate file and then use the *Makefile* to determine which one to include. Or at the very least, conditional compilation could be used to include one driver file or the other.
14. Yes. It makes the code slower. Also, more code means more bugs.
15. Not easily. Multiple invocations at the same time could interfere with one another. It might be possible if the static data were guarded by a mutex, but that would mean that a caller to a simple procedure might be unexpectedly blocked.
16. Yes. The code is replicated every time the macro is called. If it is called many times, the program will be much bigger. This is a typical time-space trade-off. A bigger, faster program instead of a smaller, slower program. However, in an extreme case, the larger program might not fit in the TLB, causing it to thrash and thus run slower.
17. Start by EXCLUSIVE ORing the lower and upper 16 bits of the word together to form a 16-bit integer, s . For each bit, there are four cases: 00 (results in a 0), 01 (results in a 1), 10 (results in a 1), and 11 (results in a 0). Thus if the number of 1s in s is odd, the parity is odd; otherwise it is even. Make a table with 65,536 entries, each containing one byte with the parity bit in it. The macro looks like this:


```
#define parity(w) bits[(w & 0xFFFF) ^ ((w>>16) & 0xFFFF)]
```
18. No circumstances. The “compressed” color value would be as big as the original, and in addition, a huge color palette could be needed. It makes no sense at all.

19. The 8-bit-wide color palette contains 256 entries of 3 bytes each for a total of 768 bytes. The saving per pixel is 2 bytes. Thus with more than 384 pixels, GIF wins. A 16-bit-wide color palette contains 65,536 entries of 3 bytes each, for 196,608 bytes. The saving here is 1 byte per pixel. Thus with more than 196,608 pixels, the 16-bit compression wins. Assuming a 4:3 ratio, the break-even point is an image of 512×384 pixels. For VGA (640×480), 16-bit color requires less data than true 24-bit color.
20. For a path that is in the path name cache, it has no effect because the i-node is bypassed anyway. If it is not read, it does not matter if it is already in memory. For a path that is not in the name cache but involves a pinned i-node, then pinning does help since it eliminates a disk read.
21. Recording the date of last modification, the size, and possibly a calculated signature such as a checksum or CRC can help determine if it has changed since last referenced. A caveat: a remote server could provide false information about a file, and local regeneration of a calculated signature might be necessary.
22. The file could be given a version number or a checksum and this information stored along with the hint. Before accessing a remote file, a check would be made to make sure the version number or checksum still agreed with the current file.
23. A file system will typically try to write new data to the nearest available disk block following the last one used. If two files are being written simultaneously this can result in interleaving the data blocks on the disk, resulting in both files being fragmented and thus more difficult to read. This effect can be ameliorated by buffering data in memory to maximize the size of writes, or writing to temporary files and then copying each output to a permanent file when the program terminates.
24. Brooks was talking about large projects in which communication between the programmers slows everything down. That problem does not occur with a 1-person project and so productivity can be higher.
25. If a programmer can produce 1000 lines of code for a cost of \$100,000, a line of code costs \$100. In Chap. 11, we stated that Windows Vista consisted of 70 million lines of code, which comes to \$7 billion. That seems like an awful lot. Probably Microsoft has managed to improve programmer productivity using better tools so a programmer can produce several thousand lines of code per year. On the other hand, Microsoft's annual revenue is around \$50 billion, so spending \$7 billion on Vista is possible.
26. Suppose that memory costs \$100 for 64 MB (check against current prices). Then a low-end machine needs \$1600 worth of disk. If the rest of the PC is \$500, the total cost comes to \$2100. This is too expensive for the low-end market.
27. An embedded system may run only one or a small number of programs. If all programs can be kept loaded into memory at all times there might be no need for either a memory manager or a file system. Additionally, drivers would be needed only for a few I/O devices, and it might make more sense to write the I/O drivers as library routines. Library routines might also be better compiled into individual programs, rather than into shared libraries, eliminating the need for shared libraries. Probably many other features could be eliminated in specific cases.