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Introduction

An **operating system** is a program that manages the computer hardware. It also provides a basis for application programs and acts as an intermediary between the computer user and the computer hardware. An amazing aspect of operating systems is how varied they are in accomplishing these tasks. Mainframe operating systems are designed primarily to optimize utilization of hardware. Personal computer (PC) operating systems support complex games, business applications, and everything in between. Operating systems for handheld computers are designed to provide an environment in which a user can easily interface with the computer to execute programs. Thus, some operating systems are designed to be *convenient,* others to be *efficient,* and others some combination of the two.

Before we can explore the details of computer system operation, we need to know something about system structure. We begin by discussing the basic functions of system startup, I/O, and storage. We also describe the basic computer architecture that makes it possible to write a functional operating system.

Because an operating system is large and complex, it must be created piece by piece. Each of these pieces should be a well-delineated portion of the system, with carefully defined inputs, outputs, and functions. In this chapter we provide a general overview of the major components of an operating system.

CHAPTER OBJECTIVES

- To provide a grand tour of the major operating systems components.
- To provide coverage of basic computer system organization.

1.1 What Operating Systems Do

We begin our discussion by looking at the operating system's role in the overall computer system. A computer system can be divided roughly into four components: the *hardware,* the *operating system,* the *application programs,* and the *users* (Figure 1.1).

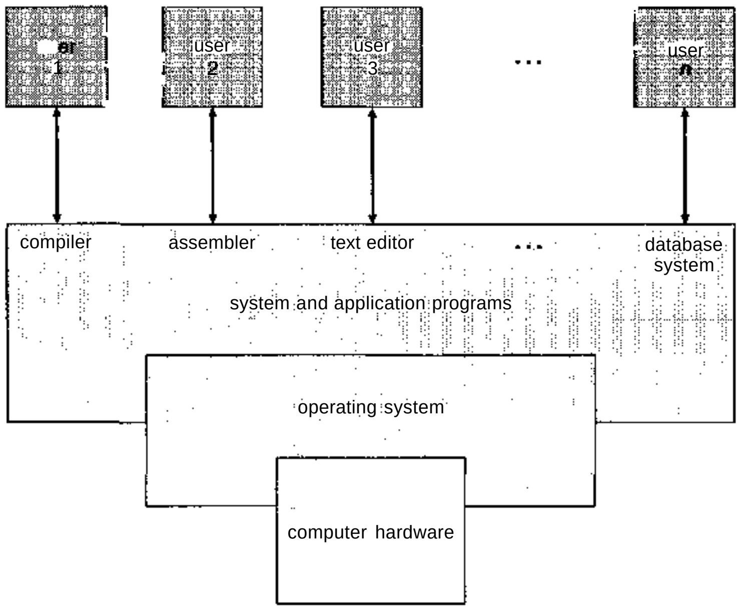

Figure 1.1 Abstract view of the components of a computer system.

The **hardware**—the **central processing unit (CPU),** the **memory,** and the **input/output (I/O) devices**—provides the basic computing resources for the system. The **application programs**—such as word processors, spreadsheets, compilers, and web browsers—define the ways in which these resources are used to solve users' computing problems. The operating system controls and coordinates the use of the hardware among the various application programs for the various users.

We can also view a computer system as consisting of hardware, software, and data. The operating system provides the means for proper use of these resources in the operation of the computer system. An operating system is similar to a *government*. Like a government, it performs no useful function by itself. It simply provides an *environment* within which other programs can do useful work.

To understand more fully the operating system's role, we next explore operating systems from two viewpoints: that of the user and that of the system.

1.1.1 User View

The user's view of the computer varies according to the interface being used. Most computer users sit in front of a PC, consisting of a monitor, keyboard, mouse, and system unit. Such a system is designed for one user to monopolize its resources. The goal is to maximize the work (or play) that the user is performing. In this case, the operating system is designed mostly for ease of **use,** with some attention paid to performance and none paid to **resource utilization**—how various hardware and software resources are shared. Performance is, of course, important to the user; but rather than resource utilization, such systems are optimized for the single-user experience.

In other cases, a user sits at a terminal connected to a **mainframe** or **minicomputer.** Other users are accessing the same computer through other terminals. These users share resources and may exchange information. The operating system in such cases is designed to maximize resource utilization—to assure that all available CPU time, memory, and I/O are used efficiently and that no individual user takes more than her fair share.

In still other cases, users sit at **workstations** connected to networks of other workstations and **servers.** These users have dedicated resources at their disposal, but they also share resources such as networking and servers—file, compute, and print servers. Therefore, their operating system is designed to compromise between individual usability and resource utilization.

Recently, many varieties of handheld computers have come into fashion. Most of these devices are standalone units for individual users. Some are connected to networks, either directly by wire or (more often) through wireless modems and networking. Because of power, speed, and interface limitations, they perform relatively few remote operations. Their operating systems are designed mostly for individual usability, but performance per amount of battery life is important as well.

Some computers have little or no user view. For example, embedded computers in home devices and automobiles may have numeric keypads and may turn indicator lights on or off to show status, but they and their operating systems are designed primarily to run without user intervention.

1.1.2 System View

From the computer's point of view, the operating system is the program most intimately involved with the hardware. In this context, we can view an operating system as a **resource allocator.** A computer system has many resources that may be required to solve a problem: CPU time, memory space, file-storage space, I/O devices, and so on. The operating system acts as the manager of these resources. Facing numerous and possibly conflicting requests for resources, the operating system must decide how to allocate them to specific programs and users so that it can operate the computer system efficiently and fairly. As we have seen, resource allocation is especially important where many users access the same mainframe or minicomputer.

A slightly different view of an operating system emphasizes the need to control the various I/O devices and user programs. An operating system is a control program. A **control program** manages the execution of user programs to prevent errors and improper use of the computer. It is especially concerned with the operation and control of I/O devices.

1.1.3 Defining Operating Systems

We have looked at the operating system's role from the views of the user and of the system. How, though, can we define what an operating system is? In general, we have no completely adequate definition of an operating system. Operating systems exist because they offer a reasonable way to solve the problem of creating a usable computing system. The fundamental goal of computer systems is to execute user programs and to make solving user problems easier. Toward this goal, computer hardware is constructed. Since bare hardware alone is not particularly easy to use, application programs are developed. These programs require certain common operations, such as those controlling the I/O devices. The common functions of controlling and allocating resources are then brought together into one piece of software: the operating system.

In addition, we have no universally accepted definition of what is part of the operating system. A simple viewpoint is that it includes everything a vendor ships when you order "the operating system." The features included, however, vary greatly across systems. Some systems take up less than 1 megabyte of space and lack even a full-screen editor, whereas others require gigabytes of space and are entirely based on graphical windowing systems. (A kilobyte, or KB, is 1,024 bytes; a megabyte, or MB, is $1{,}024^2$ bytes; and a gigabyte, or GB, is $1{,}024^3$ bytes. Computer manufacturers often round off these numbers and say that a megabyte is 1 million bytes and a gigabyte is 1 billion bytes.) A more common definition is that the operating system is the one program running at all times on the computer (usually called the **kernel),** with all else being systems programs and application programs. This last definition is the one that we generally follow.

The matter of what constitutes an operating system has become increasingly important. In 1998, the United States Department of Justice filed suit against Microsoft, in essence claiming that Microsoft included too much functionality in its operating systems and thus prevented application vendors from competing. For example, a web browser was an integral part of the operating system. As a result, Microsoft was found guilty of using its operating system monopoly to limit competition.

1.2 Computer-System Organization

Before we can explore the details of how computer systems operate, we need a general knowledge of the structure of a computer system. In this section, we look at several parts of this structure to round out our background knowledge. The section is mostly concerned with computer-system organization, so you can skim or skip it if you already understand the concepts.

1.2.1 Computer-System Operation

A modern general-purpose computer system consists of one or more CPUs and a number of device controllers connected through a common bus that provides access to shared memory (Figure 1.2). Each device controller is in charge of a specific type of device (for example, disk drives, audio devices, and video displays). The CPU and the device controllers can execute concurrently, competing for memory cycles. To ensure orderly access to the shared memory, a memory controller is provided whose function is to synchronize access to the memory.

For a computer to start running—for instance, when it is powered up or rebooted—it needs to have an initial program to run. This initial program, or **bootstrap program,** tends to be simple. Typically, it is stored in read-only memory (ROM) or electrically erasable programmable read-only memory (EEPROM), known by the general term **firmware,** within the computer hardware. It initializes all aspects of the system, from CPU registers to device

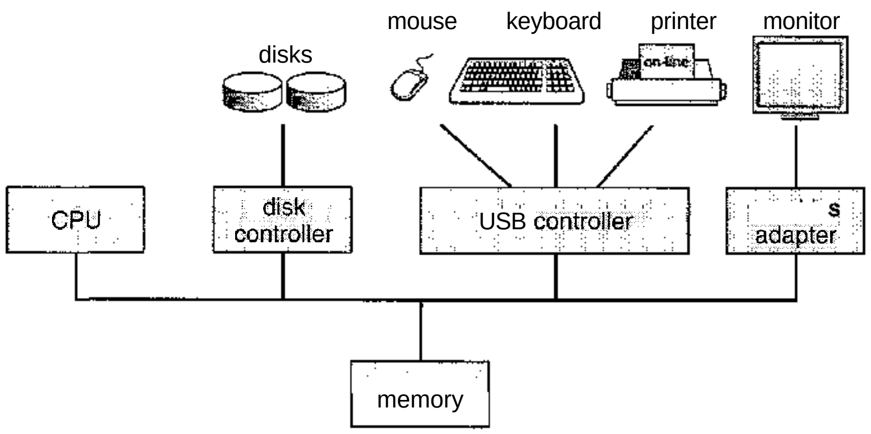

Figure 1.2 A modern computer system.

controllers to memory contents. The bootstrap program must know how to load the operating system and to start executing that system. To accomplish this goal, the bootstrap program must locate and load into memory the operating-system kernel. The operating system then starts executing the first process, such as "init," and waits for some event to occur.

The occurrence of an event is usually signaled by an **interrupt** from either the hardware or the software. Hardware may trigger an interrupt at any time by sending a signal to the CPU, usually by way of the system bus. Software may trigger an interrupt by executing a special operation called a **system call** (also called a **monitor call).**

When the CPU is interrupted, it stops what it is doing and immediately transfers execution to a fixed location. The fixed location usually contains the starting address where the service routine for the interrupt is located. The interrupt service routine executes; on completion, the CPU resumes the interrupted computation. A time line of this operation is shown in Figure 1.3.

Interrupts are an important part of a computer architecture. Each computer design has its own interrupt mechanism, but several functions are common. The interrupt must transfer control to the appropriate interrupt service routine.

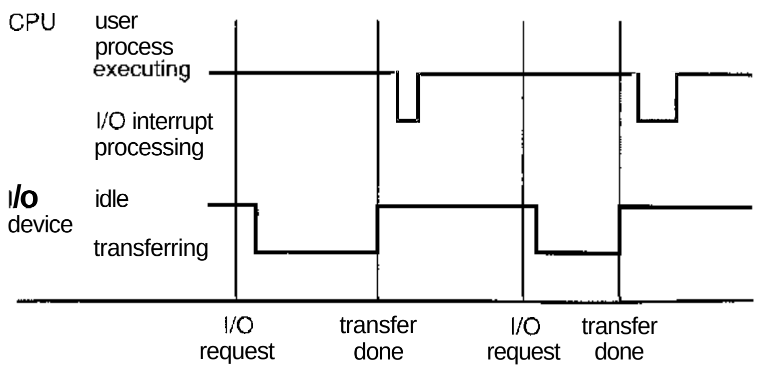

Figure 1.3 Interrupt time line for a single process doing output.

The straightforward method for handling this transfer would be to invoke a generic routine to examine the interrupt information; the routine, in turn, would call the interrupt-specific handler. However, interrupts must be handled quickly. Since only a predefined number of interrupts is possible, a table of pointers to interrupt routines can be used instead to provide the necessary speed. The interrupt routine is called indirectly through the table, with no intermediate routine needed. Generally, the table of pointers is stored in low memory (the first 100 or so locations). These locations hold the addresses of the interrupt service routines for the various devices. This array, or **interrupt vector,** of addresses is then indexed by a unique device number, given with the interrupt request, to provide the address of the interrupt service routine for the interrupting device. Operating systems as different as Windows and UNIX dispatch interrupts in this manner.

The interrupt architecture must also save the address of the interrupted instruction. Many old designs simply stored the interrupt address in a fixed location or in a location indexed by the device number. More recent architectures store the return address on the system stack. If the interrupt routine needs to modify the processor state—for instance, by modifying register values—it must explicitly save the current state and then restore that state before returning. After the interrupt is serviced, the saved return address is loaded into the program counter, and the interrupted computation resumes as though the interrupt had not occurred.

1.2.2 Storage Structure

Computer programs must be in main memory (also called **random-access memory** or **RAM)** to be executed. Main memory is the only large storage area (millions to billions of bytes) that the processor can access directly. It commonly is implemented in a semiconductor technology called **dynamic random-access memory (DRAM),** which forms an array of memory words. Each word has its own address. Interaction is achieved through a sequence of load or store instructions to specific memory addresses. The load instruction moves a word from main memory to an internal register within the CPU, whereas the store instruction moves the content of a register to main memory. Aside from explicit loads and stores, the CPU automatically loads instructions from main memory for execution.

A typical instruction-execution cycle, as executed on a system with a **von Neumann** architecture, first fetches an instruction from memory and stores that instruction in the **instruction register.** The instruction is then decoded and may cause operands to be fetched from memory and stored in some internal register. After the instruction on the operands has been executed, the result may be stored back in memory. Notice that the memory unit sees only a stream of memory addresses; it does not know how they are generated (by the instruction counter, indexing, indirection, literal addresses, or some other means) or what they are for (instructions or data). Accordingly, we can ignore *how* a memory address is generated by a program. We are interested only in the sequence of memory addresses generated by the running program.

Ideally, we want the programs and data to reside in main memory permanently. This arrangement usually is not possible for the following two reasons:

1. Main memory is usually too small to store all needed programs and data permanently.
2. Main memory is a *volatile* storage device that loses its contents when power is turned off or otherwise lost.

Thus, most computer systems provide **secondary storage** as an extension of main memory. The main requirement for secondary storage is that it be able to hold large quantities of data permanently.

The most common secondary-storage device is a **magnetic disk,** which provides storage for both programs and data. Most programs (web browsers, compilers, word processors, spreadsheets, and so on) are stored on a disk until they are loaded into memory. Many programs then use the disk as both a source and a destination of the information for their processing. Hence, the proper management of disk storage is of central importance to a computer system, as we discuss in Chapter 12.

In a larger sense, however, the storage structure that we have described—consisting of registers, main memory, and magnetic disks—is only one of many possible storage systems. Others include cache memory, CD-ROM, magnetic tapes, and so on. Each storage system provides the basic functions of storing a datum and of holding that datum until it is retrieved at a later time. The main differences among the various storage systems lie in speed, cost, size, and volatility.

The wide variety of storage systems in a computer system can be organized in a hierarchy (Figure 1.4) according to speed and cost. The higher levels are expensive, but they are fast. As we move down the hierarchy, the cost per bit

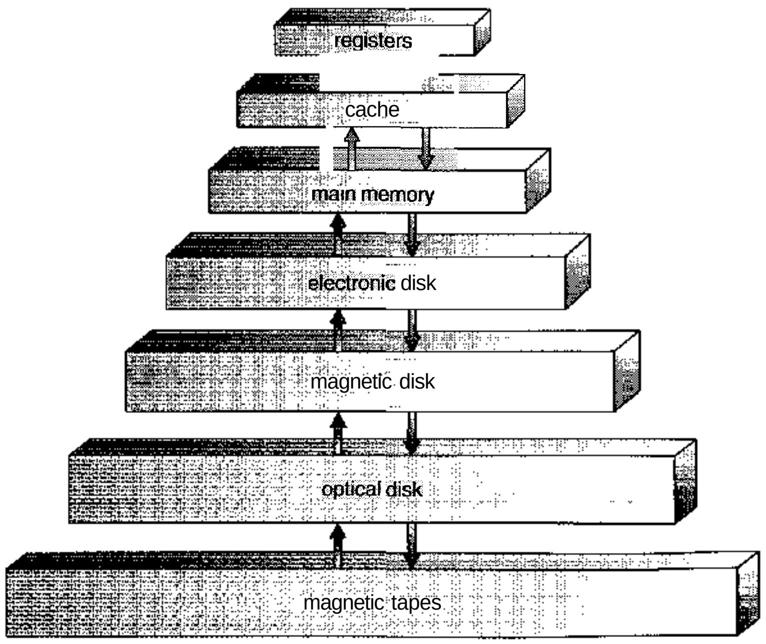

Figure 1.4 Storage-device hierarchy.

generally decreases, whereas the access time generally increases. This trade-off is reasonable; if a given storage system were both faster and less expensive than another—other properties being the same—then there would be no reason to use the slower, more expensive memory. In fact, many early storage devices, including paper tape and core memories, are relegated to museums now that magnetic tape and **semiconductor memory** have become faster and cheaper. The top four levels of memory in Figure 1.4 may be constructed using semiconductor memory.

In addition to differing in speed and cost, the various storage systems are either volatile or nonvolatile. As mentioned earlier, **volatile storage** loses its contents when the power to the device is removed. In the absence of expensive battery and generator backup systems, data must be written to **nonvolatile storage** for safekeeping. In the hierarchy shown in Figure 1.4, the storage systems above the electronic disk are volatile, whereas those below are nonvolatile. An **electronic disk** can be designed to be either volatile or nonvolatile. During normal operation, the electronic disk stores data in a large DRAM array, which is volatile. But many electronic-disk devices contain a hidden magnetic hard disk and a battery for backup power. If external power is interrupted, the electronic-disk controller copies the data from RAM to the magnetic disk. When external power is restored, the controller copies the data back into the RAM. Another form of electronic disk is flash memory, which is popular in cameras and **personal digital assistants (PDAs),** in robots, and increasingly as removable storage on general-purpose computers. Flash memory is slower than DRAM but needs no power to retain its contents. Another form of nonvolatile storage is NVRAM, which is DRAM with battery backup power. This memory can be as fast as DRAM but has a limited duration in which it is nonvolatile.

The design of a complete memory system must balance all the factors just discussed: It must use only as much expensive memory as necessary while providing as much inexpensive, nonvolatile memory as possible. Caches can be installed to improve performance where a large access-time or transfer-rate disparity exists between two components.

1.2.3 I/O Structure

Storage is only one of many types of I/O devices within a computer. A large portion of operating system code is dedicated to managing I/O, both because of its importance to the reliability and performance of a system and because of the varying nature of the devices. Therefore, we now provide an overview of I/O.

A general-purpose computer system consists of CPUs and multiple device controllers that are connected through a common bus. Each device controller is in charge of a specific type of device. Depending on the controller, there may be more than one attached device. For instance, seven or more devices can be attached to the **small computer-systems interface (SCSI)** controller. A device controller maintains some local buffer storage and a set of special-purpose registers. The device controller is responsible for moving the data between the peripheral devices that it controls and its local buffer storage. Typically, operating systems have a **device driver** for each device controller. This device

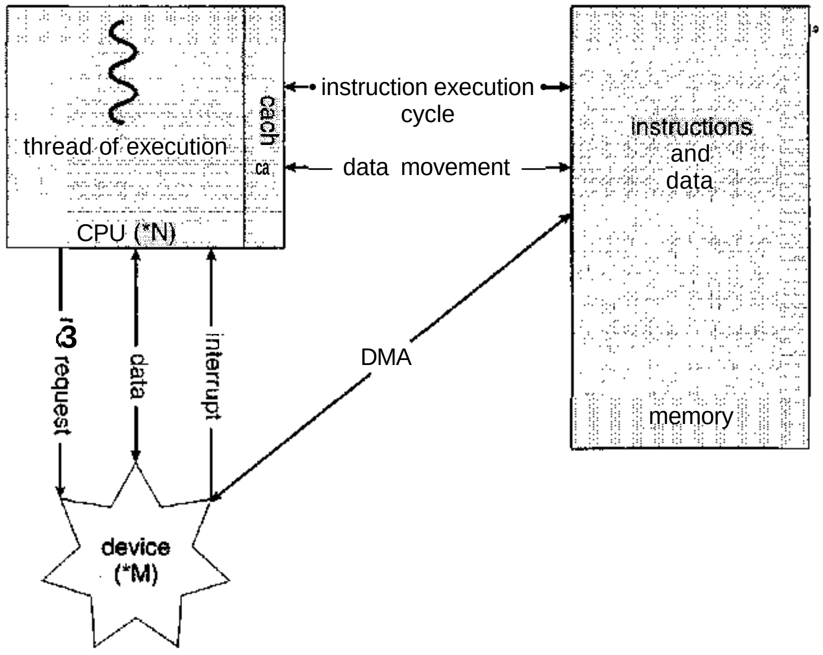

Figure 1.5 How a modern computer system works.

driver understands the device controller and presents a uniform interface to the device to the rest of the operating system.

To start an I/O operation, the device driver loads the appropriate registers within the device controller. The device controller, in turn, examines the contents of these registers to determine what action to take (such as "read a character from the keyboard"). The controller starts the transfer of data from the device to its local buffer. Once the transfer of data is complete, the device controller informs the device driver via an interrupt that it has finished its operation. The device driver then returns control to the operating system, possibly returning the data or a pointer to the data if the operation was a read. For other operations, the device driver returns status information.

This form of interrupt-driven I/O is fine for moving small amounts of data but can produce high overhead when used for bulk data movement such as disk I/O. To solve this problem, **direct memory access (DMA)** is used. After setting up buffers, pointers, and counters for the I/O device, the device controller transfers an entire block of data directly to or from its own buffer storage to memory, with no intervention by the CPU. Only one interrupt is generated per block, to tell the device driver that the operation has completed, rather than the one interrupt per byte generated for low-speed devices. While the device controller is performing these operations, the CPU is available to accomplish other work.

Some high-end systems use switch rather than bus architecture. On these systems, multiple components can talk to other components concurrently, rather than competing for cycles on a shared bus. In this case, DMA is even more effective. Figure 1.5 shows the interplay of all components of a computer system.

1.3 Computer-System Architecture

In Section 1.2 we introduced the general structure of a typical computer system. A computer system may be organized in a number of different ways, which we can categorize roughly according to the number of general-purpose processors used.

1.3.1 Single-Processor Systems

Most systems use a single processor. The variety of single-processor systems may be surprising, however, since these systems range from PDAs through mainframes. On a single-processor system, there is one main CPU capable of executing a general-purpose instruction set, including instructions from user processes. Almost all systems have other special-purpose processors as well. They may come in the form of device-specific processors, such as disk, keyboard, and graphics controllers; or, on mainframes, they may come in the form of more general-purpose processors, such as I/O processors that move data rapidly among the components of the system.

All of these special-purpose processors run a limited instruction set and do not run user processes. Sometimes they are managed by the operating system, in that the operating system sends them information about their next task and monitors their status. For example, a disk-controller microprocessor receives a sequence of requests from the main CPU and implements its own disk queue and scheduling algorithm. This arrangement relieves the main CPU of the overhead of disk scheduling. PCs contain a microprocessor in the keyboard to convert the keystrokes into codes to be sent to the CPU. In other systems or circumstances, special-purpose processors are low-level components built into the hardware. The operating system cannot communicate with these processors; they do their jobs autonomously. The use of special-purpose microprocessors is common and does not turn a single-processor system into a multiprocessor. If there is only one general-purpose CPU, then the system is a single-processor system.

1.3.2 Multiprocessor Systems

Although single-processor systems are most common, **multiprocessor systems** (also known as **parallel systems** or **tightly coupled systems)** are growing in importance. Such systems have two or more processors in close communication, sharing the computer bus and sometimes the clock, memory, and peripheral devices.

Multiprocessor systems have three main advantages:

1. **Increased throughput.** By increasing the number of processors, we expect to get more work done in less time. The speed-up ratio with *N* processors is not *N*, however; rather, it is less than N. When multiple processors cooperate on a task, a certain amount of overhead is incurred in keeping all the parts working correctly. This overhead, plus contention for shared resources, lowers the expected gain from additional processors. Similarly, *N* programmers working closely together do not produce *N* times the amount of work a single programmer would produce.

2. **Economy of scale.** Multiprocessor systems can cost less than equivalent multiple single-processor systems, because they can share peripherals, mass storage, and power supplies. If several programs operate on the same set of data, it is cheaper to store those data on one disk and to have all the processors share them than to have many computers with local disks and many copies of the data.

3. **Increased reliability.** If functions can be distributed properly among several processors, then the failure of one processor will not halt the system, only slow it down. If we have ten processors and one fails, then each of the remaining nine processors can pick up a share of the work of the failed processor. Thus, the entire system runs only 10 percent slower, rather than failing altogether.

Increased reliability of a computer system is crucial in many applications. The ability to continue providing service proportional to the level of surviving hardware is called **graceful degradation.** Some systems go beyond graceful degradation and are called **fault tolerant,** because they can suffer a failure of any single component and still continue operation. Note that fault tolerance requires a mechanism to allow the failure to be detected, diagnosed, and, if possible, corrected. The HP NonStop system (formerly Tandem) system uses both hardware and software duplication to ensure continued operation despite faults. The system consists of multiple pairs of CPUs, working in lockstep. Both processors in the pair execute each instruction and compare the results. If the results differ, then one CPU of the pair is at fault, and both are halted. The process that was being executed is then moved to another pair of CPUs, and the instruction that failed is restarted. This solution is expensive, since it involves special hardware and considerable hardware duplication.

The multiple-processor systems in use today are of two types. Some systems use **asymmetric multiprocessing,** in which each processor is assigned a specific task. A master processor controls the system; the other processors either look to the master for instruction or have predefined tasks. This scheme defines a master–slave relationship. The master processor schedules and allocates work to the slave processors.

The most common systems use **symmetric multiprocessing (SMP),** in which each processor performs all tasks within the operating system. SMP means that all processors are peers; no master-slave relationship exists between processors. Figure 1.6 illustrates a typical SMP architecture. An example of the SMP system is Solaris, a commercial version of UNIX designed by Sun Microsystems. A Solaris system can be configured to employ dozens of processors, all running Solaris. The benefit of this model is that many processes

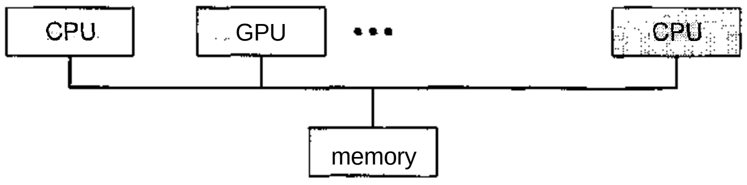

Figure 1.6 Symmetric multiprocessing architecture.

can run simultaneously—*N* processes can run if there are *N* CPUs—without causing a significant deterioration of performance. However, we must carefully control I/O to ensure that the data reach the appropriate processor. Also, since the CPUs are separate, one may be sitting idle while another is overloaded, resulting in inefficiencies. These inefficiencies can be avoided if the processors share certain data structures. A multiprocessor system of this form will allow processes and resources—such as memory—to be shared dynamically among the various processors and can lower the variance among the processors. Such a system must be written carefully, as we shall see in Chapter 6. Virtually all modern operating systems—including Windows, Windows XP, Mac OS X, and Linux—now provide support for SMP.

The difference between symmetric and asymmetric multiprocessing may result from either hardware or software. Special hardware can differentiate the multiple processors, or the software can be written to allow only one master and multiple slaves. For instance, Sun's operating system SunOS Version 4 provided asymmetric multiprocessing, whereas Version 5 (Solaris) is symmetric on the same hardware.

A recent trend in CPU design is to include multiple compute **cores** on a single chip. In essence, these are multiprocessor chips. Two-way chips are becoming mainstream, while *N*-way chips are going to be common in high-end systems. Aside from architectural considerations such as cache, memory, and bus contention, these multi-core CPUs look to the operating system just as *N* standard processors.

Lastly, **blade** servers are a recent development in which multiple processor boards, I/O boards, and networking boards are placed in the same chassis. The difference between these and traditional multiprocessor systems is that each blade-processor board boots independently and runs its own operating system. Some blade-server boards are multiprocessor as well, which blurs the lines between types of computers. In essence, those servers consist of multiple independent multiprocessor systems.

1.3.3 Clustered Systems

Another type of multiple-CPU system is the **clustered system.** Like multiprocessor systems, clustered systems gather together multiple CPUs to accomplish computational work. Clustered systems differ from multiprocessor systems, however, in that they are composed of two or more individual systems coupled together. The definition of the term *clustered* is not concrete; many commercial packages wrestle with what a clustered system is and why one form is better than another. The generally accepted definition is that clustered computers share storage and are closely linked via a **local-area network (LAN)** (as described in Section 1.10) or a faster interconnect such as InfiniBand.

Clustering is usually used to provide **high-availability** service; that is, service will continue even if one or more systems in the cluster fail. High availability is generally obtained by adding a level of redundancy in the system. A layer of cluster software runs on the cluster nodes. Each node can monitor one or more of the others (over the LAN). If the monitored machine fails, the monitoring machine can take ownership of its storage and restart the applications that were running on the failed machine. The users and clients of the applications see only a brief interruption of service.

Clustering can be structured asymmetrically or symmetrically. In **asymmetric clustering,** one machine is in **hot-standby mode** while the other is running the applications. The hot-standby host machine does nothing but monitor the active server. If that server fails, the hot-standby host becomes the active server. In **symmetric mode,** two or more hosts are running applications, and are monitoring each other. This mode is obviously more efficient, as it uses all of the available hardware. It does require that more than one application be available to run.

Other forms of clusters include parallel clusters and clustering over a wide-area network (WAN) (as described in Section 1.10). Parallel clusters allow multiple hosts to access the same data on the shared storage. Because most operating systems lack support for simultaneous data access by multiple hosts, parallel clusters are usually accomplished by use of special versions of software and special releases of applications. For example, Oracle Parallel Server is a version of Oracle's database that has been designed to run on a parallel cluster. Each machine runs Oracle, and a layer of software tracks access to the shared disk. Each machine has full access to all data in the database. To provide this shared access to data, the system must also supply access control and locking to ensure that no conflicting operations occur. This function, commonly known as a **distributed lock manager (DLM),** is included in some cluster technology.

Cluster technology is changing rapidly. Some cluster products support dozens of systems in a cluster, as well as clustered nodes that are separated by miles. Many of these improvements are made possible by **storage-area networks (SANs),** as described in Section 12.3.3, which allow many systems to attach to a pool of storage. If the applications and their data are stored on the SAN, then the cluster software can assign the application to run on any host that is attached to the SAN. If the host fails, then any other host can take over. In a database cluster, dozens of hosts can share the same database, greatly increasing performance and reliability.

1.4 Operating-System Structure

Now that we have discussed basic information about computer-system organization and architecture, we are ready to talk about operating systems. An operating system provides the environment within which programs are executed. Internally, operating systems vary greatly in their makeup, since they are organized along many different lines. There are, however, many commonalities, which we consider in this section.

One of the most important aspects of operating systems is the ability to multiprogram. A single user cannot, in general, keep either the CPU or the I/O devices busy at all times. **Multiprogramming** increases CPU utilization by organizing jobs (code and data) so that the CPU always has one to execute.

The idea is as follows: The operating system keeps several jobs in memory simultaneously (Figure 1.7). This set of jobs can be a subset of the jobs kept in the job pool—which contains all jobs that enter the system—since the number of jobs that can be kept simultaneously in memory is usually smaller than the number of jobs that can be kept in the job pool. The operating system picks and begins to execute one of the jobs in memory. Eventually, the job may have to wait for some task, such as an I/O operation, to complete. In a

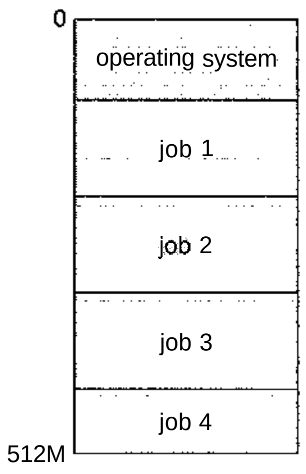

Figure 1.7 Memory layout for a multiprogramming system.

non-multiprogrammed system, the CPU would sit idle. In a multiprogrammed system, the operating system simply switches to, and executes, another job. When *that* job needs to wait, the CPU is switched to *another* job, and so on. Eventually, the first job finishes waiting and gets the CPU back. As long as at least one job needs to execute, the CPU is never idle.

This idea is common in other life situations. A lawyer does not work for only one client at a time, for example. While one case is waiting to go to trial or have papers typed, the lawyer can work on another case. If he has enough clients, the lawyer will never be idle for lack of work. (Idle lawyers tend to become politicians, so there is a certain social value in keeping lawyers busy.)

Multiprogrammed systems provide an environment in which the various system resources (for example, CPU, memory, and peripheral devices) are utilized effectively, but they do not provide for user interaction with the computer system. **Time sharing** (or **multitasking)** is a logical extension of multiprogramming. In time-sharing systems, the CPU executes multiple jobs by switching among them, but the switches occur so frequently that the users can interact with each program while it is running.

Time sharing requires an **interactive** (or **hands-on) computer system,** which provides direct communication between the user and the system. The user gives instructions to the operating system or to a program directly, using a input device such as a keyboard or a mouse, and waits for immediate results on an output device. Accordingly, the **response time** should be short—typically less than one second.

A time-shared operating system allows many users to share the computer simultaneously. Since each action or command in a time-shared system tends to be short, only a little CPU time is needed for each user. As the system switches rapidly from one user to the next, each user is given the impression that the entire computer system is dedicated to his use, even though it is being shared among many users.

A time-shared operating system uses CPU scheduling and multiprogramming to provide each user with a small portion of a time-shared computer. Each user has at least one separate program in memory. A program loaded into memory and executing is called a **process.** When a process executes, it typically executes for only a short time before it either finishes or needs to perform I/O. I/O may be interactive; that is, output goes to a display for the user, and input comes from a user keyboard, mouse, or other device. Since interactive I/O typically runs at "people speeds," it may take a long time to complete. Input, for example, may be bounded by the user's typing speed; seven characters per second is fast for people but incredibly slow for computers. Rather than let the CPU sit idle as this interactive input takes place, the operating system will rapidly switch the CPU to the program of some other user.

Time-sharing and multiprogramming require several jobs to be kept simultaneously in memory. Since in general main memory is too small to accommodate all jobs, the jobs are kept initially on the disk in the **job pool.** This pool consists of all processes residing on disk awaiting allocation of main memory. If several jobs are ready to be brought into memory, and if there is not enough room for all of them, then the system must choose among them. Making this decision is **job scheduling,** which is discussed in Chapter 5. When the operating system selects a job from the job pool, it loads that job into memory for execution. Having several programs in memory at the same time requires some form of memory management, which is covered in Chapters 8 and 9. In addition, if several jobs are ready to run at the same time, the system must choose among them. Making this decision is **CPU scheduling,** which is discussed in Chapter 5. Finally, running multiple jobs concurrently requires that their ability to affect one another be limited in all phases of the operating system, including process scheduling, disk storage, and memory management. These considerations are discussed throughout the text.

In a time-sharing system, the operating system must ensure reasonable response time, which is sometimes accomplished through **swapping,** where processes are swapped in and out of main memory to the disk. A more common method for achieving this goal is **virtual memory,** a technique that allows the execution of a process that is not completely in memory (Chapter 9). The main advantage of the virtual-memory scheme is that it enables users to run programs that are larger than actual **physical memory.** Further, it abstracts main memory into a large, uniform array of storage, separating **logical memory** as viewed by the user from physical memory. This arrangement frees programmers from concern over memory-storage limitations.

Time-sharing systems must also provide a file system (Chapters 10 and 11). The file system resides on a collection of disks; hence, disk management must be provided (Chapter 12). Also, time-sharing systems provide a mechanism for protecting resources from inappropriate use (Chapter 14). To ensure orderly execution, the system must provide mechanisms for job synchronization and communication (Chapter 6), and it may ensure that jobs do not get stuck in a deadlock, forever waiting for one another (Chapter 7).

1.5 Operating-System Operations

As mentioned earlier, modern operating systems are **interrupt driven.** If there are no processes to execute, no I/O devices to service, and no users to whom to respond, an operating system will sit quietly, waiting for something to happen. Events are almost always signaled by the occurrence of an interrupt or a trap. A **trap (or** an **exception)** is a software-generated interrupt caused either by an error (for example, division by zero or invalid memory access) or by a specific request from a user program that an operating-system service be performed. The interrupt-driven nature of an operating system defines that system's general structure. For each type of interrupt, separate segments of code in the operating system determine what action should be taken. An interrupt service routine is provided that is responsible for dealing with the interrupt.

Since the operating system and the users share the hardware and software resources of the computer system, we need to make sure that an error in a user program could cause problems only for the one program that was running. With sharing, many processes could be adversely affected by a bug in one program. For example, if a process gets stuck in an infinite loop, this loop could prevent the correct operation of many other processes. More subtle errors can occur in a multiprogramming system, where one erroneous program might modify another program, the data of another program, or even the operating system itself.

Without protection against these sorts of errors, either the computer must execute only one process at a time or all output must be suspect. A properly designed operating system must ensure that an incorrect (or malicious) program cannot cause other programs to execute incorrectly.

1.5.1 Dual-Mode Operation

In order to ensure the proper execution of the operating system, we must be able to distinguish between the execution of operating-system code and user-defined code. The approach taken by most computer systems is to provide hardware support that allows us to differentiate among various modes of execution.

At the very least, we need two separate **modes** of operation: **user mode** and **kernel mode** (also called **supervisor mode, system mode, or privileged mode).** A bit, called the **mode bit,** is added to the hardware of the computer to indicate the current mode: kernel (0) or user (1). With the mode bit, we are able to distinguish between a task that is executed on behalf of the operating system and one that is executed on behalf of the user. When the computer system is executing on behalf of a user application, the system is in user mode. However, when a user application requests a service from the operating system (via a system call), it must transition from user to kernel mode to fulfill the request. This is shown in Figure 1.8. As we shall see, this architectural enhancement is useful for many other aspects of system operation as well.

At system boot time, the hardware starts in kernel mode. The operating system is then loaded and starts user applications in user mode. Whenever a trap or interrupt occurs, the hardware switches from user mode to kernel mode (that is, changes the state of the mode bit to 0). Thus, whenever the operating system gains control of the computer, it is in kernel mode. The system always switches to user mode (by setting the mode bit to 1) before passing control to a user program.

The dual mode of operation provides us with the means for protecting the operating system from errant users—and errant users from one another. We accomplish this protection by designating some of the machine instructions that

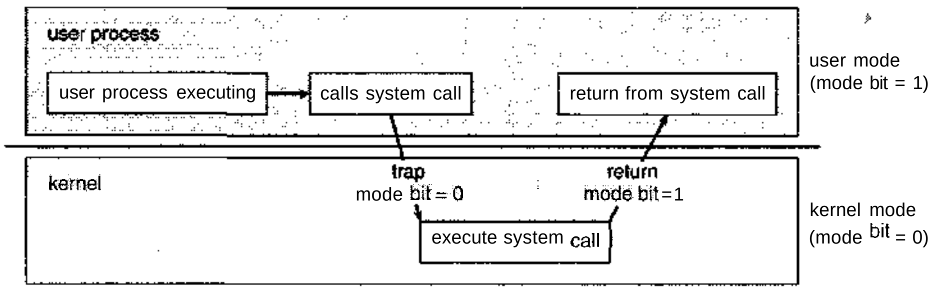

Figure 1.8 Transition from user to kernel mode.

may cause harm as **privileged instructions.** The hardware allows privileged instructions to be executed only in kernel mode. If an attempt is made to execute a privileged instruction in user mode, the hardware does not execute the instruction but rather treats it as illegal and traps it to the operating system.

The instruction to switch to user mode is an example of a privileged instruction. Some other examples include I/O control, timer management, and interrupt management. As we shall see throughout the text, there are many additional privileged instructions.

We can now see the life cycle of instruction execution in a computer system. Initial control is within the operating system, where instructions are executed in kernel mode. When control is given to a user application, the mode is set to user mode. Eventually, control is switched back to the operating system via an interrupt, a trap, or a system call.

System calls provide the means for a user program to ask the operating system to perform tasks reserved for the operating system on the user program's behalf. A system call is invoked in a variety of ways, depending on the functionality provided by the underlying processor. In all forms, it is the method used by a process to request action by the operating system. A system call usually takes the form of a trap to a specific location in the interrupt vector. This trap can be executed by a generic trap instruction, although some systems (such as the MIPS R2000 family) have a specific syscall instruction.

When a system call is executed, it is treated by the hardware as a software interrupt. Control passes through the interrupt vector to a service routine in the operating system, and the mode bit is set to kernel mode. The system-call service routine is a part of the operating system. The kernel examines the interrupting instruction to determine what system call has occurred; a parameter indicates what type of service the user program is requesting. Additional information needed for the request may be passed in registers, on the stack, or in memory (with pointers to the memory locations passed in registers). The kernel verifies that the parameters are correct and legal, executes the request, and returns control to the instruction following the system call. We describe system calls more fully in Section 2.3.

The lack of a hardware-supported dual mode can cause serious shortcomings in an operating system. For instance, MS-DOS was written for the Intel 8088 architecture, which has no mode bit and therefore no dual mode. A user program running awry can wipe out the operating system by writing over it with data; and multiple programs are able to write to a device at the same time, with possibly disastrous results. Recent versions of the Intel CPU, such is the Pentium, do provide dual-mode operation. Accordingly, most contemporary operating systems, such as Microsoft Windows 2000 and Windows XP, and Linux and Solaris for x86 systems, take advantage of this feature and provide greater protection for the operating system.

Once hardware protection is in place, errors violating modes are detected by the hardware. These errors are normally handled by the operating system. If a user program fails in some way—such as by making an attempt either to execute an illegal instruction or to access memory that is not in the user's address space—then the hardware will trap to the operating system. The trap transfers control through the interrupt vector to the operating system, just as an interrupt does. When a program error occurs, the operating system must terminate the program abnormally. This situation is handled by the same code as is a user-requested abnormal termination. An appropriate error message is given, and the memory of the program may be dumped. The memory dump is usually written to a file so that the user or programmer can examine it and perhaps correct it and restart the program.

1.5.2 Timer

We must ensure that the operating system maintains control over the CPU. We must prevent a user program from getting stuck in an infinite loop or not calling system services and never returning control to the operating system. To accomplish this goal, we can use a **timer.** A timer can be set to interrupt the computer after a specified period. The period may be fixed (for example, 1/60 second) or variable (for example, from 1 millisecond to 1 second). A **variable timer** is generally implemented by a fixed-rate clock and a counter. The operating system sets the counter. Every time the clock ticks, the counter is decremented. When the counter reaches 0, an interrupt occurs. For instance, a 10-bit counter with a 1-millisecond clock allows interrupts at intervals from 1 millisecond to 1,024 milliseconds, in steps of 1 millisecond.

Before turning over control to the user, the operating system ensures that the timer is set to interrupt. If the timer interrupts, control transfers automatically to the operating system, which may treat the interrupt as a fatal error or may give the program more time. Clearly, instructions that modify the content of the timer are privileged.

Thus, we can use the timer to prevent a user program from running too long. A simple technique is to initialize a counter with the amount of time that a program is allowed to run. A program with a 7-minute time limit, for example, would have its counter initialized to 420. Every second, the timer interrupts and the counter is decremented by 1. As long as the counter is positive, control is returned to the user program. When the counter becomes negative, the operating system terminates the program for exceeding the assigned time limit.

1.6 Process Management

A program does nothing unless its instructions are executed by a CPU. A program in execution, as mentioned, is a process. A time-shared user program such as a compiler is a process. A word-processing program being run by an individual user on a PC is a process. A system task, such as sending ©utput to a printer, can also be a process (or at least part of one). For now, you can consider a process to be a job or a time-shared program, but later you will learn that the concept is more general. As we shall see in Chapter 3, it is possible to provide system calls that allow processes to create subprocesses to execute concurrently.

A process needs certain resources—including CPU time, memory, files, and I/O devices—to accomplish its task. These resources are either given to the process when it is created or allocated to it while it is running. In addition to the various physical and logical resources that a process obtains when it is created, various initialization data (input) may be passed along. For example, consider a process whose function is to display the status of a file on the screen of a terminal. The process will be given as an input the name of the file and will execute the appropriate instructions and system calls to obtain and display on the terminal the desired information. When the process terminates, the operating system will reclaim any reusable resources.

We emphasize that a program by itself is not a process; a program is a *passive* entity, such as the contents of a file stored on disk, whereas a process is an *active* entity. A single-threaded process has one **program counter** specifying the next instruction to execute. (Threads will be covered in Chapter 4.) The execution of such a process must be sequential. The CPU executes one instruction of the process after another, until the process completes. Further, at any time, one instruction at most is executed on behalf of the process. Thus, although two processes may be associated with the same program, they are nevertheless considered two separate execution sequences. A multithreaded process has multiple program counters, each pointing to the next instruction to execute for a given thread.

A process is the unit of work in a system. Such a system consists of a collection of processes, some of which are operating-system processes (those that execute system code) and the rest of which are user processes (those that execute user code). All these processes can potentially execute concurrently—by multiplexing the CPU among them on a single CPU, for example.

The operating system is responsible for the following activities in connection with process management:

- Creating and deleting both user and system processes
- Suspending and resuming processes
- Providing mechanisms for process synchronization
- Providing mechanisms for process communication
- Providing mechanisms for deadlock handling

We discuss process-management techniques in Chapters 3 through 6.

1.7 Memory Management

As we discussed in Section 1.2.2, the main memory is central to the operation of a modern computer system. Main memory is a large array of words or bytes, ranging in size from hundreds of thousands to billions. Each word or byte has its own address. Main memory is a repository of quickly accessible data shared by the CPU and I/O devices. The central processor reads instructions from main memory during the instruction-fetch cycle and both reads and writes data from main memory during the data-fetch cycle (on a Von Neumann architecture). The main memory is generally the only large storage device that the CPU is able to address and access directly. For example, for the CPU to process data from disk, those data must first be transferred to main memory by CPU-generated I/O calls. In the same way, instructions must be in memory for the CPU to execute them.

For a program to be executed, it must be mapped to absolute addresses and loaded into memory. As the program executes, it accesses program instructions and data from memory by generating these absolute addresses. Eventually, the program terminates, its memory space is declared available, and the next program can be loaded and executed.

To improve both the utilization of the CPU and the speed of the computer's response to its users, general-purpose computers must keep several programs in memory, creating a need for memory management. Many different memory-management schemes are used. These schemes reflect various approaches, and the effectiveness of any given algorithm depends on the situation. In selecting a memory-management scheme for a specific system, we must take into account many factors—especially on the *hardware* design of the system. Each algorithm requires its own hardware support.

The operating system is responsible for the following activities in connection with memory management:

- Keeping track of which parts of memory are currently being used and by whom
- Deciding which processes (or parts thereof) and data to move into and out of memory
- Allocating and deallocating memory space as needed

Memory-management techniques will be discussed in Chapters 8 and 9.

1.8 Storage Management

To make the computer system convenient for users, the operating system provides a uniform, logical view of information storage. The operating system abstracts from the physical properties of its storage devices to define a logical storage unit, the file. The operating system maps files onto physical media and accesses these files via the storage devices.

1.8.1 File-System Management

File management is one of the most visible components of an operating system. Computers can store information on several different types of physical media. Magnetic disk, optical disk, and magnetic tape are the most common. Each of these media has its own characteristics and physical organization. Each medium is controlled by a device, such as a disk drive or tape drive, that also has its own unique characteristics. These properties include access speed, capacity, data-transfer rate, and access method (sequential or random).

A file is a collection of related information defined by its creator. Commonly, files represent programs (both source and object forms) and data. Data files may be numeric, alphabetic, alphanumeric, or binary. Files may be free-form (for example, text files), or they may be formatted rigidly (for example, fixed fields). Clearly, the concept of a file is an extremely general one.

The operating system implements the abstract concept of a file by managing mass storage media, such as tapes and disks, and the devices that control them. Also, files are normally organized into directories to make them easier to use-Finally, when multiple users have access to files, it may be desirable to control by whom and in what ways (for example, read, write, append) files may be accessed.

The operating system is responsible for the following activities in connection with file management:

- Creating and deleting files
- Creating and deleting directories to organize files
- Supporting primitives for manipulating files and directories
- Mapping files onto secondary storage
- Backing up files on stable (nonvolatile) storage media

File-management techniques will be discussed in Chapters 10 and 11.

1.8.2 Mass-Storage Management

As we have already seen, because main memory is too small to accommodate all data and programs, and because the data that it holds are lost when power is lost, the computer system must provide secondary storage to back up main memory. Most modern computer systems use disks as the principal on-line storage medium for both programs and data. Most programs—including compilers, assemblers, word processors, editors, and formatters—are stored on a disk until loaded into memory and then use the disk as both the source and destination of their processing. Hence, the proper management of disk storage is of central importance to a computer system. The operating system is responsible for the following activities in connection with disk management:

- Free-space management
- Storage allocation
- Disk scheduling

Because secondary storage is used frequently, it must be used efficiently. The entire speed of operation of a computer may hinge on the speeds of the disk subsystem and of the algorithms that manipulate that subsystem.

There are, however, many uses for storage that is slower and lower in cost (and sometimes of higher capacity) than secondary storage. Backups of disk data, seldom-used data, and long-term archival storage are some examples.

Magnetic tape drives and their tapes and CD and DVD drives and platters are typical **tertiary storage** devices. The media (tapes and optical platters) vary between WORM (write-once, read-many-times) and RW (read-write) formats.

Tertiary storage is not crucial to system performance, but it still must be managed. Some operating systems take on this task, while others leave tertiary-storage management to application programs. Some of the functions that operating systems can provide include mounting and unmounting media in devices, allocating and freeing the devices for exclusive use by processes, and migrating data from secondary to tertiary storage.

Techniques for secondary and tertiary storage management will be discussed in Chapter 12.

1.8.3 Caching

Caching is an important principle of computer systems. Information is normally kept in some storage system (such as main memory). As it is used, it is copied into a faster storage system—the cache—on a temporary basis. When we need a particular piece of information, we first check whether it is in the cache. If it is, we use the information directly from the cache; if it is not, we use the information from the source, putting a copy in the cache under the assumption that we will need it again soon.

In addition, internal programmable registers, such as index registers, provide a high-speed cache for main memory. The programmer (or compiler) implements the register-allocation and register-replacement algorithms to decide which information to keep in registers and which to keep in main memory. There are also caches that are implemented totally in hardware. For instance, most systems have an instruction cache to hold the next instructions expected to be executed. Without this cache, the CPU would have to wait several cycles while an instruction was fetched from main memory. For similar reasons, most systems have one or more high-speed data caches in the memory hierarchy. We are not concerned with these hardware-only caches in this text, since they are outside the control of the operating system.

Because caches have limited size, **cache management** is an important design problem. Careful selection of the cache size and of a replacement policy can result in greatly increased performance. See Figure 1.9 for a storage performance comparison in large workstations and small servers that shows the need for caching. Various replacement algorithms for software-controlled caches are discussed in Chapter 9.

Main memory can be viewed as a fast cache for secondary storage, since data in secondary storage must be copied into main memory for use, and data must be in main memory before being moved to secondary storage for safekeeping. The file-system data, which resides permanently on secondary storage, may appear on several levels in the storage hierarchy. At the highest level, the operating system may maintain a cache of file-system data in main memory Also, electronic RAM disks (also known as **solid-state disks)** may be used for high-speed storage that is accessed through the file-system interface. The bulk of secondary storage is on magnetic disks. The magnetic-disk storage, in turn, is often backed up onto magnetic tapes or removable disks to protect against data loss in case of a hard-disk failure. Some systems automatically

Level	1	2	3	4
Name	registers	cache	raaJft memory	disk storage
Typical size	< 1 KB	> 16 MB	> 16 GB	> 100 GB
Implementation technology	multiple ports, CMOS	on-chip or off-chip CMOS SRAM	CMOS DRAM	magnetic disk
Access time (ns)	0.25 – 0.5	0.5 – 25	80 – 250	5,000.000
Bandwidth (MB/sec)	20,000 – 100,000	5000 – 10,000	1000 – 5000	20 – 150
Managed by	compiler	hardware	i operating system	operating system
Backed by	cache	main memory	disk	CD or tape

Figure **1.9** Performance of various levels of storage.

archive old file data from secondary storage to tertiary storage, such as tape jukeboxes, to lower the storage cost (see Chapter 12).

The movement of information between levels of a storage hierarchy may be either explicit or implicit, depending on the hardware design and the controlling operating-system software. For instance, data transfer from cache to CPU and registers is usually a hardware function, with no operating-system intervention. In contrast, transfer of data from disk to memory is usually controlled by the operating system.

In a hierarchical storage structure, the same data may appear in different levels of the storage system. For example, suppose that an integer A that is to be incremented by 1 is located in file B, and file B resides on magnetic disk. The increment operation proceeds by first issuing an I/O operation to copy the disk block on which A resides to main memory. This operation is followed by copying A to the cache and to an internal register. Thus, the copy of A appears in several places: on the magnetic disk, in main memory, in the cache, and in an internal register (see Figure 1.10). Once the increment takes place in the internal register, the value of A differs in the various storage systems. The value of A becomes the same only after the new value of A is written from the internal register back to the magnetic disk.

In a computing environment where only one process executes at a time, this arrangement poses no difficulties, since an access to integer A will always be to the copy at the highest level of the hierarchy. However, in a multitasking environment, where the CPU is switched back and forth among various processes, extreme care must be taken to ensure that, if several processes wish to access A, then each of these processes will obtain the most recently updated value of A.

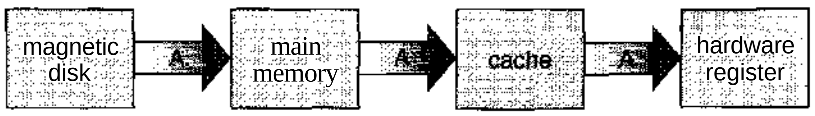

Figure **1.10** Migration of integer A from disk to register.

The situation becomes more complicated in a multiprocessor environment where, in addition to maintaining internal registers, each of the CPUs also contains a local cache. In such an environment, a copy of A may exist simultaneously in several caches. Since the various CPUs can all execute concurrently, we must make sure that an update to the value of A in one cache is immediately reflected in all other caches where A resides. This situation is called **cache coherency,** and it is usually a hardware problem (handled below the operating-system level).

In a distributed environment, the situation becomes even more complex. In this environment, several copies (or replicas) of the same file can be kept on different computers that are distributed in space. Since the various replicas may be accessed and updated concurrently, some distributed systems ensure that, when a replica is updated in one place, all other replicas are brought up to date as soon as possible. There are various ways to achieve this guarantee, as we discuss in Chapter 17.

1.8.4 I/O Systems

One of the purposes of an operating system is to hide the peculiarities of specific hardware devices from the user. For example, in UNIX, the peculiarities of I/O devices are hidden from the bulk of the operating system itself by the **I/O subsystem.** The I/O subsystem consists of several components:

- A memory-management component that includes buffering, caching, and spooling
- A general device-driver interface
- Drivers for specific hardware devices

Only the device driver knows the peculiarities of the specific device to which it is assigned.

We discussed in Section 1.2.3 how interrupt handlers and device drivers are used in the construction of efficient I/O subsystems. In Chapter 13, we discuss how the I/O subsystem interfaces to the other system components, manages devices, transfers data, and detects I/O completion.

1.9 Protection and Security

If a computer system has multiple users and allows the concurrent execution of multiple processes, then access to data must be regulated. For that purpose, mechanisms ensure that files, memory segments, CPU, and other resources can be operated on by only those processes that have gained proper authorization from the operating system. For example, memory-addressing hardware ensures that a process can execute only within its own address space. The timer ensures that no process can gain control of the CPU without eventually relinquishing control. Device-control registers are not accessible to users, so the integrity of the various peripheral devices is protected.

Protection, then, is any mechanism for controlling the access of processes or users to the resources defined by a computer system. This mechanism must provide means for specification of the controls to be imposed and means for enforcement.

Protection can improve reliability by detecting latent errors at the interfaces between component subsystems. Early detection of interface errors can often prevent contamination of a healthy subsystem by another subsystem that is malfunctioning. An unprotected resource cannot defend against use (or misuse) by an unauthorized or incompetent user. A protection-oriented system provides a means to distinguish between authorized and unauthorized usage, as we discuss in Chapter 14.

A system can have adequate protection but still be prone to failure and allow inappropriate access. Consider a user whose authentication information (her means of identifying herself to the system) is stolen. Her data could be copied or deleted, even though file and memory protection are working. It is the job of **security** to defend a system from external and internal attacks. Such attacks spread across a huge range and include viruses and worms, denial-of-service attacks (which use all of a system's resources and so keep legitimate users out of the system), identity theft, and theft of service (unauthorized use of a system). Prevention of some of these attacks is consider an operating-system function on some systems, while others leave the prevention to policy or additional software. Due to the alarming rise in security incidents, operating-system security features represent a fast-growing area of research and of implementation. Security is discussed in Chapter 15.

Protection and security require the system to be able to distinguish among all its users. Most operating systems maintain a list of user names and associated **user identifiers (user IDs).** In Windows NT parlance, this is a **security** ID (SID). These numerical IDs are unique, one per user. When a user logs in to the system, the authentication stage determines the appropriate user ID for the user. That user ID is associated with all of the user's processes and threads. When an ID needs to be user readable, it is translated back to the user name via the user name list.

In some circumstances, we wish to distinguish among sets of users rather than individual users. For example, the owner of a file on a UNIX system may be allowed to issue all operations on that file, whereas a selected set of users may only be allowed to read the file. To accomplish this, we need to define a group name and the set of users belonging to that group. Group functionality can be implemented as a system-wide list of group names and **group identifiers.** A user can be in one or more groups, depending on operating-system design decisions. The user's group IDs are also included in every associated process and thread.

In the course of normal use of a system, the user ID and group ID for a user are sufficient. However, a user sometimes needs to **escalate privileges** to gain extra permissions for an activity. The user may need access to a device that is restricted, for example. Operating systems provide various methods to allow privilege escalation. On UNIX, for example, the `setuid` attribute on a program causes that program to run with the user ID of the owner of the file, rather than the current user's ID. The process runs with this **effective** UID until it turns off the extra privileges or terminates. Consider an example of how this is done in Solaris 10. User pbg has user ID 101 and group ID 14, which are assigned via /etc/passwd:

```
pbg:x:101:14::/export/home/pbg:/usr/bin/bash
```

1.10 Distributed Systems

A distributed system is a collection of physically separate, possibly heterogeneous computer systems that are networked to provide the users with access to the various resources that the system maintains. Access to a shared resource increases computation speed, functionality, data availability, and reliability. Some operating systems generalize network access as a form of file access, with the details of networking contained in the network interface's device driver. Others make users specifically invoke network functions. Generally, systems contain a mix of the two modes—for example FTP and NFS. The protocols that create a distributed system can greatly affect that system's utility and popularity.

A **network,** in the simplest terms, is a communication path between two or more systems. Distributed systems depend on networking for their functionality. Networks vary by the protocols used, the distances between nodes, and the transport media. TCP/IP is the most common network protocol, although ATM and other protocols are in widespread use. Likewise, operating-system support of protocols varies. Most operating systems support TCP/IP, including the Windows and UNIX operating systems. Some systems support proprietary protocols to suit their needs. To an operating system, a network protocol simply needs an interface device—a network adapter, for example—with a device driver to manage it, as well as software to handle data. These concepts are discussed throughout this book.

Networks are characterized based on the distances between their nodes. A **local-area network (LAN)** connects computers within a room, a floor, or a building. A **wide-area network (WAN)** usually links buildings, cities, or countries. A global company may have a WAN to connect its offices worldwide. These networks may run one protocol or several protocols. The continuing advent of new technologies brings about new forms of networks. For example, a **metropolitan-area network** (MAN) could link buildings within a city. BlueTooth and 802.11 devices use wireless technology to communicate over a distance of several feet, in essence creating a **small-area network** such as might be found in a home.

The media to carry networks are equally varied. They include copper wires, fiber strands, and wireless transmissions between satellites, microwave dishes, and radios. When computing devices are connected to cellular phones, they create a network. Even very short-range infrared communication can be used for networking. At a rudimentary level, whenever computers communicate, they use or create a network. These networks also vary in their performance and reliability.

Some operating systems have taken the concept of networks and distributed systems further than the notion of providing network connectivity. A **network operating system** is an operating system that provides features such as file sharing across the network and that includes a communication scheme that allows different processes on different computers to exchange messages. A computer running a network operating system acts autonomously from all other computers on the network, although it is aware of the network and is able to communicate with other networked computers. A distributed operating system provides a less autonomous environment: The different operating systems communicate closely enough to provide the illusion that only a single operating system controls the network.

We cover computer networks and distributed systems in Chapters 16 through 18.

1.11 Special-Purpose Systems

The discussion thus far has focused on general-purpose computer systems that we are all familiar with. There are, however, different classes of computer systems whose functions are more limited and whose objective is to deal with limited computation domains.

1.11.1 Real-Time Embedded Systems

Embedded computers are the most prevalent form of computers in existence. These devices are found everywhere, from car engines and manufacturing robots to VCRs and microwave ovens. They tend to have very specific tasks. The systems they run on are usually primitive, and so the operating systems provide limited features. Usually, they have little or no user interface, preferring to spend their time monitoring and managing hardware devices, such as automobile engines and robotic arms.

These embedded systems vary considerably. Some are general-purpose computers, running standard operating systems—such as UNIX—with special-purpose applications to implement the functionality. Others are hardware devices with a special-purpose embedded operating system providing just the functionality desired. Yet others are hardware devices with application-specific integrated circuits (ASICs) that perform their tasks without an operating system.

The use of embedded systems continues to expand. The power of these devices, both as standalone units and as members of networks and the Web, is sure to increase as well. Even now, entire houses can be computerized, so that a central computer—either a general-purpose computer or an embedded system—can control heating and lighting, alarm systems, and even coffee makers. Web access can enable a home owner to tell the house to heat up before she arrives home. Someday, the refrigerator may call the grocery store when it notices the milk is gone.

Embedded systems almost always run **real-time operating systems.** A real-time system is used when rigid time requirements have been placed on the operation of a processor or the flow of data; thus, it is often used as a control device in a dedicated application. Sensors bring data to the computer. The computer must analyze the data and possibly adjust controls to modify the sensor inputs. Systems that control scientific experiments, medical imaging systems, industrial control systems, and certain display systems are real-time systems. Some automobile-engine fuel-injection systems, home-appliance controllers, and weapon systems are also real-time systems.

A real-time system has well-defined, fixed time constraints. Processing *must* be done within the defined constraints, or the system will fail. For instance, it would not do for a robot arm to be instructed to halt *after* it had smashed into the car it was building. A real-time system functions correctly only if it returns the correct result within its time constraints. Contrast this system with a time-sharing system, where it is desirable (but not mandatory) to respond quickly, or a batch system, which may have no time constraints at all.

In Chapter 19, we cover real-time embedded systems in great detail. In Chapter 5, we consider the scheduling facility needed to implement real-time functionality in an operating system. In Chapter 9, we describe the design of memory management for real-time computing. Finally, in Chapter 22, we describe the real-time components of the Windows XP operating system.

1.11.2 Multimedia Systems

Most operating systems are designed to handle conventional data such as text files, programs, word-processing documents, and spreadsheets. However, a recent trend in technology is the incorporation of **multimedia data** into computer systems. Multimedia data consist of audio and video files as well as conventional files. These data differ from conventional data in that multimedia data—such as frames of video—must be delivered (streamed) according to certain time restrictions (for example, 30 frames per second).

Multimedia describes a wide range of applications that are in popular use today. These include audio files such as MP3 DVD movies, video conferencing, and short video clips of movie previews or news stories downloaded over the Internet. Multimedia applications may also include live webcasts (broadcasting over the World Wide Web) of speeches or sporting events and even live webcams that allow a viewer in Manhattan to observe customers at a cafe in Paris. Multimedia applications need not be either audio or video; rather, a multimedia application often includes a combination of both. For example, a movie may consist of separate audio and video tracks. Nor must multimedia applications be delivered only to desktop personal computers. Increasingly, they are being directed toward smaller devices, including PDAs and cellular telephones. For example, a stock trader may have stock quotes delivered wirelessly and in real time to his PDA.

In Chapter 20, we explore the demands of multimedia applications, how multimedia data differ from conventional data, and how the nature of these data affects the desigii of operating systems that support the requirements of multimedia systems.

1.11.3 Handheld Systems

Handheld systems include personal digital assistants (PDAs), such as Palm and Pocket-PCs, and cellular telephones, many of which use special-purpose embedded operating systems. Developers of handheld systems and applications face many challenges, most of which are due to the limited size of such devices. For example, a PDA is typically about 5 inches in height and 3 inches in width, and it weighs less than one-half pound. Because of their size, most handheld devices have a small amount of memory, slow processors, and small display screens. We will take a look now at each of these limitations.

The amount of physical memory in a handheld depends upon the device, but typically is is somewhere between 512 KB and 128 MB. (Contrast this with a typical PC or workstation, which may have several gigabytes of memory!) As a result, the operating system and applications must manage memory efficiently. This includes returning all allocated memory back to the memory manager when the memory is not being used. In Chapter 9, we will explore virtual memory, which allows developers to write programs that behave as if the system has more memory than is physically available. Currently, not many handheld devices use virtual memory techniques, so program developers must work within the confines of limited physical memory.

A second issue of concern to developers of handheld devices is the speed of the processor used in the devices. Processors for most handheld devices run at a fraction of the speed of a processor in a PC. Faster processors require more power. To include a faster processor in a handheld device would require a larger battery, which would take up more space and would have to be replaced (or recharged) more frequently. Most handheld devices use smaller, slower processors that consume less power. Therefore, the operating system and applications must be designed not to tax the processor.

The last issue confronting program designers for handheld devices is I/O. A lack of physical space limits input methods to small keyboards, handwriting recognition, or small screen-based keyboards. The small display screens limit output options. Whereas a monitor for a home computer may measure up to 30 inches, the display for a handheld device is often no more than 3 inches square. Familiar tasks, such as reading e-mail and browsing web pages, must be condensed into smaller displays. One approach for displaying the content in web pages is **web clipping,** where only a small subset of a web page is delivered and displayed on the handheld device.

Some handheld devices use wireless technology, such as BlueTooth or 802.11, allowing remote access to e-mail and web browsing. Cellular telephones with connectivity to the Internet fall into this category. However, for PDAs that do not provide wireless access, downloading data typically requires the user to first download the data to a PC or workstation and then download the data to the PDA. Some PDAs allow data to be directly copied from one device to another using an infrared link.

Generally, the limitations in the functionality of PDAs are balanced by their convenience and portability. Their use continues to expand as network connections become more available and other options, such as digital cameras and MP3 players, expand their utility.

1.12 Computing Environments

So far, we have provided an overview of computer-system organization and major operating-system components. We conclude with a brief overview of how these are used in a variety of computing environments.

1.12.1 Traditional Computing

As computing matures, the lines separating many of the traditional computing environments are blurring. Consider the "typical office environment." Just a few years ago, this environment consisted of PCs connected to a network, with servers providing file and print services. Remote access was awkward, and portability was achieved by use of laptop computers. Terminals attached to mainframes were prevalent at many companies as well, with even fewer remote access and portability options.

The current trend is toward providing more ways to access these computing environments. Web technologies are stretching the boundaries of traditional computing. Companies establish **portals,** which provide web accessibility to their internal servers. **Network computers** are essentially terminals that understand web-based computing. Handheld computers can synchronize with PCs to allow very portable use of company information. Handheld PDAs can also connect to **wireless networks** to use the company's web portal (as well as the myriad other web resources).

At home, most users had a single computer with a slow modem connection to the office, the Internet, or both. Today, network-connection speeds once available only at great cost are relatively inexpensive, giving home users more access to more data. These fast data connections are allowing home computers to serve up web pages and to run networks that include printers, client PCs, and servers. Some homes even have **firewalls** to protect their networks from security breaches. Those firewalls cost thousands of dollars a few years ago and did not even exist a decade ago.

In the latter half of the previous century, computing resources were scarce. (Before that, they were nonexistent!) For a period of time, systems were either batch or interactive. Batch system processed jobs in bulk, with predetermined input (from files or other sources of data). Interactive systems waited for input from users. To optimize the use of the computing resources, multiple users shared time on these systems. Time-sharing systems used a timer and scheduling algorithms to rapidly cycle processes through the CPU, giving each user a share of the resources.

Today, traditional time-sharing systems are uncommon. The same scheduling technique is still in use on workstations and servers, but frequently the processes are all owned by the same user (or a single user and the operating system). User processes, and system processes that provide services to the user, are managed so that each frequently gets a slice of computer time. Consider the windows created while a user is working on a PC, for example, and the fact that they may be performing different tasks at the same time.

1.12.2 Client-Server Computing

As PCs have become faster, more powerful, and cheaper, designers have shifted away from centralized system architecture. Terminals connected to centralized systems are now being supplanted by PCs. Correspondingly, user-interface functionality once handled directly by the centralized systems is increasingly being handled by the PCs. As a result, many of todays systems act as **server systems to** satisfy requests generated by **client systems.** This form of specialized distributed system, called **client-server** system, has the general structure depicted in Figure 1.11.

Server systems can be broadly categorized as compute servers and file servers:

- The **compute-server system** provides an interface to which a client can send a request to perform an action (for example, read data); in response, the server executes the action and sends back results to the client. A server running a database that responds to client requests for data is an example of such a system.

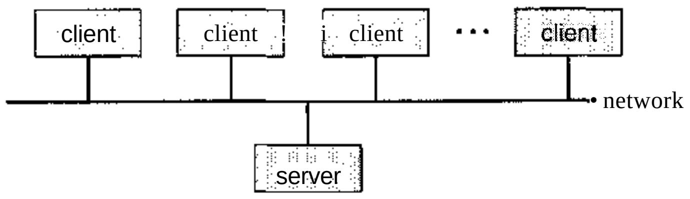

Figure 1.11 General structure of a client-server system.

- The **file-server system** provides a file-system interface where clients can create, update, read, and delete files. An example of such a system is a web server that delivers files to clients running web browsers.

1.12.3 Peer-to-Peer Computing

Another structure for a distributed system is the peer-to-peer (P2P) system model. In this model, clients and servers are not distinguished from one another; instead, all nodes within the system are considered peers, and each may act as either a client or a server, depending on whether it is requesting or providing a service. Peer-to-peer systems offer an advantage over traditional client-server systems. In a client-server system, the server is a bottleneck; but in a peer-to-peer system, services can be provided by several nodes distributed throughout the network.

To participate in a peer-to-peer system, a node must first join the network of peers. Once a node has joined the network, it can begin providing services to—and requesting services from—other nodes in the network. Determining what services are available is accomplished in one of two general ways:

- When a node joins a network, it registers its service with a centralized lookup service on the network. Any node desiring a specific service first contacts this centralized lookup service to determine which node provides the service. The remainder of the communication takes place between the client and the service provider.

- A peer acting as a client must first discover what node provides a desired service by broadcasting a request for the service to all other nodes in the network. The node (or nodes) providing that service responds to the peer making the request. To support this approach, a *discovery protocol* must be provided that allows peers to discover services provided by other peers in the network.

Peer-to-peer networks gained widespread popularity in the late 1990s with several file-sharing services, such as Napster and Gnutella, that enable peers to exchange files with one another. The Napster system uses an approach similar to the first type described above: a centralized server maintains an index of all files stored on peer nodes in the Napster network, and the actual exchanging of files takes place between the peer nodes. The Gnutella system uses a technique similar to the second type: a client broadcasts file requests to other nodes in the system, and nodes that can service the request respond directly to the client. The future of exchanging files remains uncertain because many of the files are copyrighted (music, for example), and there are laws governing the distribution of copyrighted material. In any case, though, peer-to-peer technology undoubtedly will play a role in the future of many services, such as searching, file exchange, and e-mail.

1.12.4 Web-Based Computing

The Web has become ubiquitous, leading to more access by a wider variety of devices than was dreamt of a few years ago. PCs are still the most prevalent access devices, with workstations, handheld PDAs, and even cell phones also providing access.

Web computing has increased the emphasis on networking. Devices that were not previously networked now include wired or wireless access. Devices that were networked now have faster network connectivity, provided by either improved networking technology, optimized network implementation code, or both.

The implementation of web-based computing has given rise to new categories of devices, such as **load balancers,** which distribute network connections among a pool of similar servers. Operating systems like Windows 95, which acted as web clients, have evolved into Linux and Windows XP, which can act as web servers as well as clients. Generally, the Web has increased the complexity of devices, because their users require them to be web-enabled.

1.13 Summary

An operating system is software that manages the computer hardware as well as providing an environment for application programs to run. Perhaps the most visible aspect of an operating system is the interface to the computer system it provides to the human user.

For a computer to do its job of executing programs, the programs must be in main memory. Main memory is the only large storage area that the processor can access directly. It is an array of words or bytes, ranging in size from millions to billions. Each word in memory has its own address. The main memory is usually a volatile storage device that loses its contents when power is turned off or lost. Most computer systems provide secondary storage as an extension of main memory. Secondary storage provides a form of non-volatile storage that is capable of holding large quantities of data permanently. The most common secondary-storage device is a magnetic disk, which provides storage of both programs and data.

The wide variety of storage systems in a computer system can be organized in a hierarchy according to speed and cost. The higher levels are expensive, but they are fast. As we move down the hierarchy, the cost per bit generally decreases, whereas the access time generally increases.

There are several different strategies for designing a computer system. Uniprocessor systems have only a single processor while multiprocessor systems contain two or more processors that share physical memory and peripheral devices. The most common multiprocessor design is symmetric multiprocessing (or SMP), where all processors are considered peers and run independently of one another. Clustered systems are a specialized form of multiprocessor systems and consist of multiple computer systems connected by a local area network.

To best utilize the CPU, modern operating systems employ multiprogramming, which allows several jobs to be in memory at the same time, thus ensuring the CPU always has a job to execute. Timesharing systems are an extension of multiprogramming whereby CPU scheduling algorithms rapidly switch between jobs, thus providing the illusion each job is running concurrently.

The operating system must ensure correct operation of the computer system. To prevent user programs from interfering with the proper operation of the system, the hardware has two modes: user mode and kernel mode. Various instructions (such as I/O instructions and halt instructions) are privileged and can be executed only in kernel mode. The memory in which the operating system resides must also be protected from modification by the user. A timer prevents infinite loops. These facilities (dual mode, privileged instructions, memory protection, and timer interrupt) are basic building blocks used by operating systems to achieve correct operation.

A process (or job) is the fundamental unit of work in an operating system. Process management includes creating and deleting processes and providing mechanisms for processes to communicate and synchronize with another. An operating system manages memory by keeping track of what parts of memory are being used and by whom. The operating system is also responsible for dynamically allocating and freeing memory space. Storage space is also managed by the operating system and this includes providing file systems for representing files and directories and managing space on mass storage devices.

Operating systems must also be concerned with protecting and securing the operating system and users. Protection are mechanisms that control the access of processes or users to the resources made available by the computer system. Security measures are responsible for defending a computer system from external or internal attacks.

Distributed systems allow users to share resources on geographically dispersed hosts connected via a computer network. Services may be provided through either the client-server model or the peer-to-peer model. In a clustered system, multiple machines can perform computations on data residing on shared storage, and computing can continue even when some subset of cluster members fails.

LANs and WANs are the two basic types of networks. LANs enable processors distributed over a small geographical area to communicate, whereas WANs allow processors distributed over a larger area to communicate. LANs typically are faster than WANs.

There are several computer systems that serve specific purposes. These include real-time operating systems designed for embedded environments such as consumer devices, automobiles, and robotics. Real-time operating systems have well defined, fixed time constraints. Processing *must* be done within the defined constraints, or the system will fail. Multimedia systems involve the delivery of multimedia data and often have special requirements of displaying or playing audio, video, or synchronized audio and video streams.

Recently, the influence of the Internet and the World Wide Web has encouraged the development of modern operating systems that include web browsers and networking and communication software as integral features.

Exercises

1.1 In a multiprogramming and time-sharing environment, several users share the system simultaneously. This situation can result in various security problems.

a. What are two such problems?

b. Can we ensure the same degree of security in a time-shared machine as in a dedicated machine? Explain your answer.

1.2 The issue of resource utilization shows up in different forms in different types of operating systems. List what resources must be managed carefully in the following settings:

a. Mainframe or minicomputer systems

b. Workstations connected to servers

c. Handheld computers

1.3 Under what circumstances would a user be better off using a time-sharing system rather than a PC or single-user workstation?

1.4 Which of the functionalities listed below need to be supported by the operating system for the following two settings: (a) handheld devices and (b) real-time systems.

a. Batch programming

b. Virtual memory

c. Time sharing

1.5 Describe the differences between symmetric and asymmetric multiprocessing. What are three advantages and one disadvantage of multiprocessor systems?

1.6 How do clustered systems differ from multiprocessor systems? What is required for two machines belonging to a cluster to cooperate to provide a highly available service?

1.7 Distinguish between the client-server and peer-to-peer models of distributed systems.

1.8 Consider a computing cluster consisting of two nodes running a database. Describe two ways in which the cluster software can manage access to the data on the disk. Discuss the benefits and disadvantages of each.

1.9 How are network computers different from traditional personal computers? Describe some usage scenarios in which it is advantageous to use network computers.

1.10 What is the purpose of interrupts? What are the differences between a trap and an interrupt? Can traps be generated intentionally by a user program? If so, for what purpose?

1.11 Direct memory access is used for high-speed I/O devices in order to avoid increasing the CPU's execution load.

a. How does the CPU interface with the device to coordinate the transfer?

b. How does the CPU know when the memory operations are complete?

c. The CPU is allowed to execute other programs while the DMA controller is transferring data. Does this process interfere with the execution of the user programs? If so, describe what forms of interference are caused.

1.12 Some computer systems do not provide a privileged mode of operation in hardware. Is it possible to construct a secure operating system for these computer systems? Give arguments both that it is and that it is not possible.

1.13 Give two reasons why caches are useful. What problems do they solve? What problems do they cause? If a cache can be made as large as the device for which it is caching (for instance, a cache as large as a disk), why not make it that large and eliminate the device?

1.14 Discuss, with examples, how the problem of maintaining coherence of cached data manifests itself in the following processing environments:

a. Single-processor systems

b. Multiprocessor systems

c. Distributed systems

1.15 Describe a mechanism for enforcing memory protection in order to prevent a program from modifying the memory associated with other programs.

1.16 What network configuration would best suit the following environments?

a. A dormitory floor

b. A university campus

c. A state

d. A nation

1.17 Define the essential properties of the following types of operating systems:

a. Batch

b. Interactive

c. Time sharing

d. Real time

e. Network

f. Parallel

g. Distributed

h. Clustered

i. Handheld

1.18 What are the tradeoffs inherent in handheld computers?

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Operating-System Structures

An operating system provides the environment within which programs are executed. Internally, operating systems vary greatly in their makeup, since they are organized along many different lines. The design of a new operating system is a major task. It is important that the goals of the system be well defined before the design begins. These goals form the basis for choices among various algorithms and strategies.

We can view an operating system from several vantage points. One view focuses on the services that the system provides; another, on the interface that it makes available to users and programmers; a third, on its components and their interconnections. In this chapter, we explore all three aspects of operating systems, showing the viewpoints of users, programmers, and operating-system designers. We consider what services an operating system provides, how they are provided, and what the various methodologies are for designing such systems. Finally, we describe how operating systems are created and how a computer starts its operating system.

CHAPTER OBJECTIVES

- To describe the services an operating system provides to users, processes, and other systems.
- To discuss the various ways of structuring an operating system.
- To explain how operating systems are installed and customized and how they boot.

2.1 Operating-System Services

An operating system provides an environment for the execution of programs. It provides certain services to programs and to the users of those programs. The specific services provided, of course, differ from one operating system to another, but we can identify common classes. These operating-system services are provided for the convenience of the programmer, to make the programming task easier.

One set of operating-system services provides functions that are helpful to the user.

- **User interface.** Almost all operating systems have a **user interface (UI)**. This interface can take several forms. One is a **command-line interface (CLI)**, which uses text commands and a method for entering them (say, a program to allow entering and editing of commands). Another is a **batch interface,** in which commands and directives to control those commands are entered into files, and those files are executed. Most commonly/ a **graphical user interface (GUI)** is used. Here, the interface is a window system with a pointing device to direct I/O, choose from menus, and make selections and a keyboard to enter text. Some systems provide two or all three of these variations.

- **Program execution.** The system must be able to load a program into memory and to run that program. The program must be able to end its execution, either normally or abnormally (indicating error).

- **I/O operations.** A running program may require I/O, which may involve a file or an I/O device. For specific devices, special functions may be desired (such as recording to a CD or DVD drive or blanking a CRT screen). For efficiency and protection, users usually cannot control I/O devices directly. Therefore, the operating system must provide a means to do I/O.

- **File-system manipulation.** The file system is of particular interest. Obviously, programs need to read and write files and directories. They also need to create and delete them by name, search for a given file, and list file information. Finally, some programs include permissions management to allow or deny access to files or directories based on file ownership.

- **Communications.** There are many circumstances in which one process needs to exchange information with another process. Such communication may occur between processes that are executing on the same computer or between processes that are executing on different computer systems tied together by a computer network. Communications may be implemented via *shared memory* or through *message passing*, in which packets of information are moved between processes by the operating system.

- **Error detection.** The operating system needs to be constantly aware of possible errors. Errors may occur in the CPU and memory hardware (such as a memory error or a power failure), in I/O devices (such as a parity error on tape, a connection failure on a network, or lack of paper in the printer), and in the user program (such as an arithmetic overflow, an attempt to access an illegal memory location, or a too-great use of CPU time). For each type of error, the operating system should take the appropriate action to ensure correct and consistent computing. Debugging facilities can greatly enhance the user's and programmer's abilities to use the system efficiently.

Another set of operating-system functions exists not for helping the user but rather for ensuring the efficient operation of the system itself. Systems with multiple users can gain efficiency by sharing the computer resources among the users.

- **Resource allocation.** When there are multiple users or multiple jobs running at the same time, resources must be allocated to each of them. Many different types of resources are managed by the operating system. Some (such as CPU cycles, main memory, and file storage) may have special allocation code, whereas others (such as I/O devices) may have much more general request and release code. For instance, in determining how best to use the CPU, operating systems have CPU-scheduling routines that take into account the speed of the CPU, the jobs that must be executed, the number of registers available, and other factors. There may also be routines to allocate printers, modems, USB storage drives, and other peripheral devices.
- **Accounting.** We want to keep track of which users use how much and what kinds of computer resources. This record keeping may be used for accounting (so that users can be billed) or simply for accumulating usage statistics. Usage statistics may be a valuable tool for researchers who wish to reconfigure the system to improve computing services.
- **Protection and security.** The owners of information stored in a multiuser or networked computer system may want to control use of that information. When several separate processes execute concurrently, it should not be possible for one process to interfere with the others or with the operating system itself. Protection involves ensuring that all access to system resources is controlled. Security of the system from outsiders is also important. Such security starts with requiring each user to authenticate himself or herself to the system, usually by means of a password, to gain access to system resources. It extends to defending external I/O devices, including modems and network adapters, from invalid access attempts and to recording all such connections for detection of break-ins. If a system is to be protected and secure, precautions must be instituted throughout it. A chain is only as strong as its weakest link.

2.2 User Operating-System Interface

There are two fundamental approaches for users to interface with the operating system. One technique is to provide a command-line interface or **command interpreter** that allows users to directly enter commands that are to be performed by the operating system. The second approach allows the user to interface with the operating system via a graphical user interface or GUI.

2.2.1 Command Interpreter

Some operating systems include the command interpreter in the kernel. Others, such as Windows XP and UNIX, treat the command interpreter as a special program that is running when a job is initiated or when a user first logs on (on interactive systems). On systems with multiple command interpreters to choose from, the interpreters are known as **shells.** For example, on UNIX and Linux systems, there are several different shells a user may choose from including the *Bourne shell, C shell, Bourne-Again shell,* the *Korn shell,* etc. Most shells provide similar functionality with only minor differences; most users choose a shell based upon personal preference.

The main function of the command interpreter is to get and execute the next user-specified command. Many of the commands given at this level manipulate files: create, delete, list, print, copy, execute, and so on. The MS-DOS and UNIX shells operate in this way. There are two general ways in which these commands can be implemented.

In one approach, the command interpreter itself contains the code to execute the command. For example, a command to delete a file may cause the command interpreter to jump to a section of its code that sets up the parameters and makes the appropriate system call. In this case, the number of commands that can be given determines the size of the command interpreter, since each command requires its own implementing code.

An alternative approach—used by UNIX, among other operating systems—implements most commands through system programs. In this case, the command interpreter does not understand the command in any way; it merely uses the command to identify a file to be loaded into memory and executed. Thus, the UNIX command to delete a file

```
rm file.txt
```

would search for a file called rm, load the file into memory, and execute it with the parameter file.txt. The function associated with the rm command would be defined completely by the code in the file rm. In this way, programmers can add new commands to the system easily by creating new files with the proper names. The command-interpreter program, which can be small, does not have to be changed for new commands to be added.

2.2.2 Graphical User Interfaces

A second strategy for interfacing with the operating system is through a user-friendly graphical user interface or GUI. Rather than having users directly enter commands via a command-line interface, a GUI allows provides a mouse-based window-and-menu system as an interface. A GUI provides a **desktop** metaphor where the mouse is moved to position its pointer on images, or **icons,** on the screen (the desktop) that represent programs, files, directories, and system functions. Depending on the mouse pointer's location, clicking a button on the mouse can invoke a program, select a file or directory—known as a **folder—** or pull down a menu that contains commands.

Graphical user interfaces first appeared due in part to research taking place in the early 1970s at Xerox PARC research facility. The first GUI appeared on the Xerox Alto computer in 1973. However, graphical interfaces became more widespread with the advent of Apple Macintosh computers in the 1980s. The user interface to the Macintosh operating system (Mac OS) has undergone various changes over the years, the most significant being the adoption of the *Aqua* interface that appeared with Mac OS X. Microsoft's first version of Windows—version 1.0—was based upon a GUI interface to the MS-DOS operating system. The various versions of Windows systems proceeding this initial version have made cosmetic changes to the appearance of the GUI and several enhancements to its functionality, including the Windows Explorer.

Traditionally, UNIX systems have been dominated by command-line interfaces, although there are various GUI interfaces available, including the Common Desktop Environment (CDE) and X-Windows systems that are common on commercial versions of UNIX such as Solaris and IBM's AIX system. However, there has been significant development in GUI designs from various **open-source** projects such as *K Desktop Environment* (or *KDE)* and the *GNOME* desktop by the GNU project. Both the KDE and GNOME desktops run on Linux and various UNIX systems and are available under open-source licenses, which means their source code is in the public domain.

The choice of whether to use a command-line or GUI interface is mostly one of personal preference. As a very general rule, many UNIX users prefer a command-line interface as they often provide powerful shell interfaces. Alternatively, most Windows users are pleased to use the Windows GUI environment and almost never use the MS-DOS shell interface. The various changes undergone by the Macintosh operating systems provides a nice study in contrast. Historically, Mac OS has not provided a command line interface, always requiring its users to interface with the operating system using its GUI. However, with the release of Mac OS X (which is in part implemented using a UNIX kernel), the operating system now provides both a new Aqua interface and command-line interface as well.

The user interface can vary from system to system and even from user to user within a system. It typically is substantially removed from the actual system structure. The design of a useful and friendly user interface is therefore not a direct function of the operating system. In this book, we concentrate on the fundamental problems of providing adequate service to user programs. From the point of view of the operating system, we do not distinguish between user programs and system programs.

2.3 System Calls

System calls provide an interface to the services made available by an operating system. These calls are generally available as routines written in C and C++, although certain low-level tasks (for example, tasks where hardware must be accessed directly), may need to be written using assembly-language instructions.

Before we discuss how an operating system makes system calls available, let's first use an example to illustrate how system calls are used: writing a simple program to read data from one file and copy them to another file. The first input that the program will need is the names of the two files: the input file and the output file. These names can be specified in many ways, depending on the operating-system design. One approach is for the program to ask the user for the names of the two files. In an interactive system, this approach will require a sequence of system calls, first to write a prompting message on the screen and then to read from the keyboard the characters that define the two files. On mouse-based and icon-based systems, a menu of file names is usually displayed in a window. The user can then use the mouse to select the source name, and a window can be opened for the destination name to be specified. This sequence requires many I/O system calls.

Once the two file names are obtained, the program must open the input file and create the output file. Each of these operations requires another system call. There are also possible error conditions for each operation. When the program tries to open the input file, it may find that there is no file of that name or that the file is protected against access. In these cases, the program should print a message on the console (another sequence of system calls) and then terminate abnormally (another system call). If the input file exists, then we must create a new output file. We may find that there is already an output file with the same name. This situation may cause the program to abort (a system call), or we may delete the existing file (another system call) and create a new one (another system call). Another option, in an interactive system, is to ask the user (via a sequence of system calls to output the prompting message and to read the response from the terminal) whether to replace the existing file or to abort the program.

Now that both files are set up, we enter a loop that reads from the input file (a system call) and writes to the output file (another system call). Each read and write must return status information regarding various possible error conditions. On input, the program may find that the end of the file has been reached or that there was a hardware failure in the read (such as a parity error). The write operation may encounter various errors, depending on the output device (no more disk space, printer out of paper, and so on).

Finally, after the entire file is copied, the program may close both files (another system call), write a message to the console or window (more system calls), and finally terminate normally (the final system call). As we can see, even simple programs may make heavy use of the operating system. Frequently, systems execute thousands of system calls per second. This system-call sequence is shown in Figure 2.1.

Most programmers never see this level of detail, however. Typically, application developers design programs according to an **application programming interface (API).** The API specifies a set of functions that are available to an application programmer, including the parameters that are passed to each

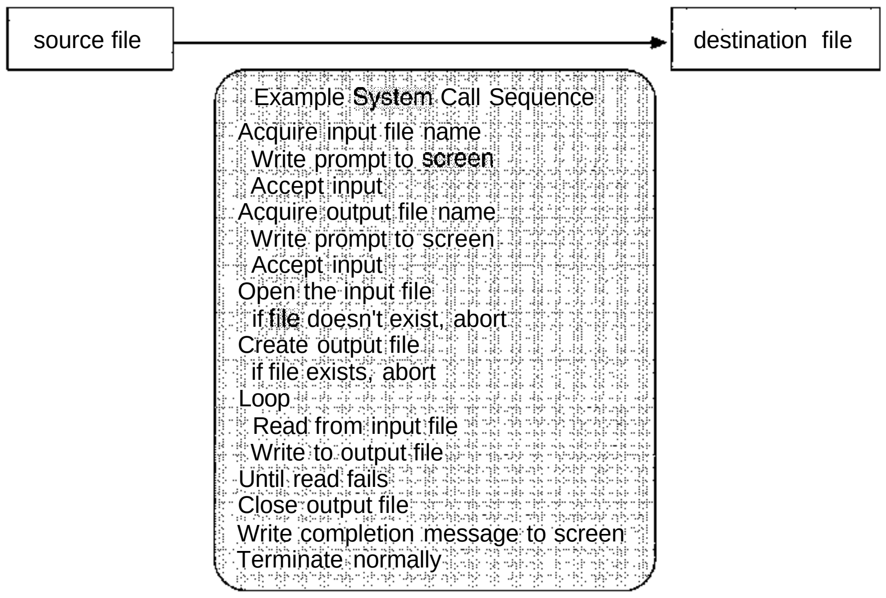
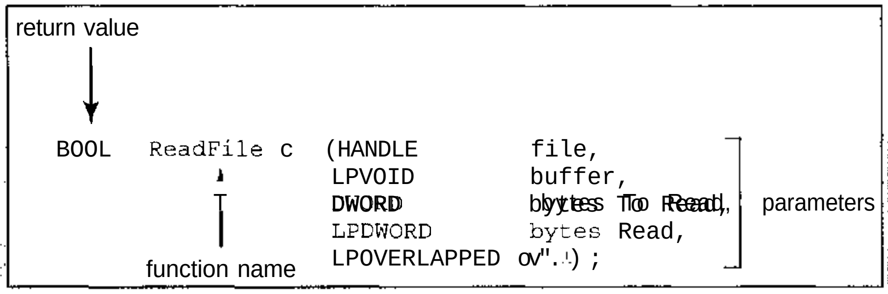


Figure 2.1 Example of how system calls are used.

EXAMPLE OF STANDARD API

As an example of a standard API, consider the ReadFile() function in the Win32 API—a function for reading from a file. The API for this function appears in Figure 2.2.



```
BOOL   ReadFile c  (HANDLE         file,
                    LPVOID         buffer,
                    DWORD          bytes To Read,
                    LPDWORD        bytes Read,
                    LPOVERLAPPED   ov".!) ;
```

Figure 2.2 The API for the ReadFile() function.

A description of the parameters passed to ReadFileO is as follows:

- HANDLE file—the file to be read.
- LPVOID buffer—a buffer where the data will be read into and written from.
- DWORD bytesToRead—the number of bytes to be read into the buffer.
- LPDWORD bytesRead—the number of bytes read during the last read.
- LPOVERLAPPED ovl—indicates i f overlapped I /O i s being used.

function and the return values the programmer can expect. Three of the most common APIs available to application programmers are the Win32 API for Windows systems, the POSIX API for POSIX-based systems (which includes virtually all versions of UNIX, Linux, and Mac OS X), and the Java API for designing programs that run on the Java virtual machine.

Note that the system-call names used throughout this text are generic examples. Each operating system has its own name for each system call.

Behind the scenes, the functions that make up an API typically invoke the actual system calls on behalf of the application programmer. For example, the Win32 function CreateProcess() (which unsurprisingly is used to create a new process) actually calls the NTCreateProcess() system call in the Windows kernel. Why would an application programmer prefer programming according to an API rather than invoking actual system calls? There are several reasons for doing so. One benefit of programming according to an API concerns program portability: An application programmer designing a program using an API can expect her program to compile and run on any system that supports the same API (although in reality, architectural differences often make this more difficult than it may appear). Furthermore, actual system calls can often be more detailed and difficult to work with than the API available to an application programmer. Regardless, there often exists a strong correlation between invoking a function in the API and its associated system call within the kernel. In fact, many of the POSIX and Win32 APIs are similar to the native system calls provided by the UNIX, Linux, and Windows operating systems.

The run-time support system (a set of functions built into libraries included with a compiler) for most programming languages provides a **system-call interface** that serves as the link to system calls made available by the operating system. The system-call interface intercepts function calls in the API and invokes the necessary system call within the operating system. Typically, a number is associated with each system call, and the system-call interface maintains a table indexed according to these numbers. The system call interface then invokes the intended system call in the operating system kernel and returns the status of the system call and any return values.

The caller needs to know nothing about how the system call is implemented or what it does during execution. Rather, it just needs to obey the API and understand what the operating system will do as a result of the execution of that system call. Thus, most of the details of the operating-system interface are hidden from the programmer by the API and are managed by the run-time support library. The relationship between an API, the system-call interface, and the operating system is shown in Figure 2.3, which illustrates how the operating system handles a user application invoking the open() system call.

System calls occur in different ways, depending on the computer in use. Often, more information is required than simply the identity of the desired system call. The exact type and amount of information vary according to the particular operating system and call. For example, to get input, we may need to specify the file or device to use as the source, as well as the address and

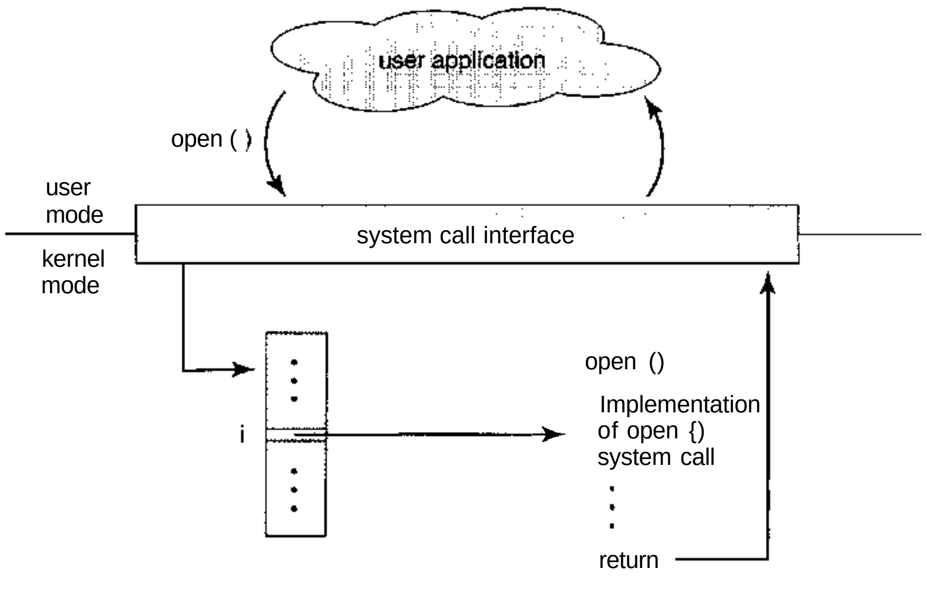


Figure 2.3 The handling of a user application invoking the open() system call.

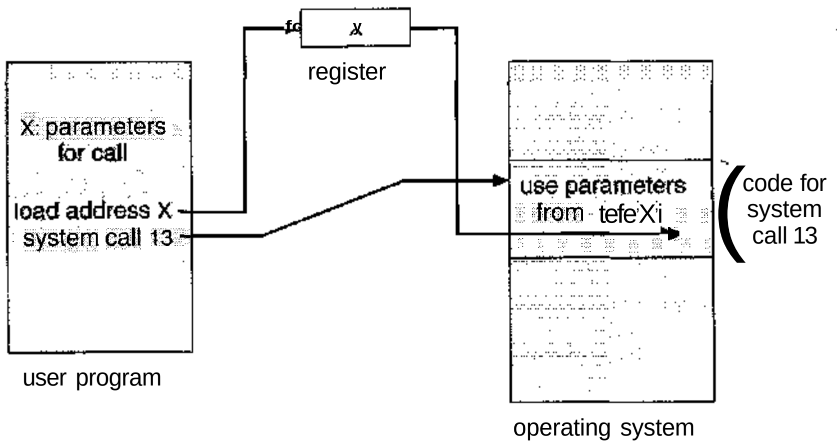


Figure 2.4 Passing of parameters as a table.

length of the memory buffer into which the input should be read. Of course, the device or file and length may be implicit in the call.

Three general methods are used to pass parameters to the operating system. The simplest approach is to pass the parameters in *registers.* In some cases, however, there may be more parameters than registers. In these cases, the parameters are generally stored in a *block,* or table, in memory, and the address of the block is passed as a parameter in a register (Figure 2.4). This is the approach taken by Linux and Solaris. Parameters also can be placed, or *pushed,* onto the *stack* by the program and *popped* off the stack by the operating system. Some operating systems prefer the block or stack method, because those approaches do not limit the number or length of parameters being passed.

2.4 Types of System Calls

System calls can be grouped roughly into five major categories: **process control, file manipulation, device manipulation, information maintenance,** and **communications.** In Sections 2.4.1 through 2.4.5, we discuss briefly the types of system calls that may be provided by an operating system. Most of these system calls support, or are supported by, concepts and functions that are discussed in later chapters. Figure 2.5 summarizes the types of system calls normally provided by an operating system.

2.4.1 Process Control

A running program needs to be able to halt its execution either normally (end) or abnormally (abort). If a system call is made to terminate the currently running program abnormally, or if the program runs into a problem and causes an error trap, a dump of memory is sometimes taken and an error message generated. The dump is written to disk and may be examined by a **debugger**—a system program designed to aid the programmer in finding and correcting bugs—to determine the cause of the problem. Under either normal or abnormal circumstances, the operating system must transfer control to the

- Process control
  - end, abort
  - load, execute
  - create process, terminate process
  - get process attributes, set process attributes
  - wait for time
  - wait event, signal event
  - allocate and free memory
- File management
  - create file, delete file
  - open, close
  - read, write, reposition
  - get file attributes, set file attributes
- Device management
  - request device, release device
  - read, write, reposition
  - get device attributes, set device attributes
  - logically attach or detach devices
- Information maintenance
  - get time or date, set time or date
  - get system data, set system data
  - get process, file, or device attributes
  - set process, file, or device attributes
- Communications
  - create, delete communication connection
  - send, receive messages
  - transfer status information
  - attach or detach remote devices

Figure 2.5 Types of system calls.

invoking command interpreter. The command interpreter then reads the next command. In an interactive system, the command interpreter simply continues with the next command; it is assumed that the user will issue an appropriate command to respond to any error. In a GUI system, a pop-up window might alert the user to the error and ask for guidance. In a batch system, the command interpreter usually terminates the entire job and continues with the next job.

EXAMPLE OF STANDARD C LIBRARY

The standard C library provides a portion of the system-call interface for many versions of UNIX and Linux. As an example, lot's assume a C program invokes the `printf()` statement. The C library intercepts this call and invokes the necessary system call(s) in the operating system—in this instance, the `write()` system call. The C library takes the value returned by `write()` and passes it back to the user program. This is shown in Figure 2.6.

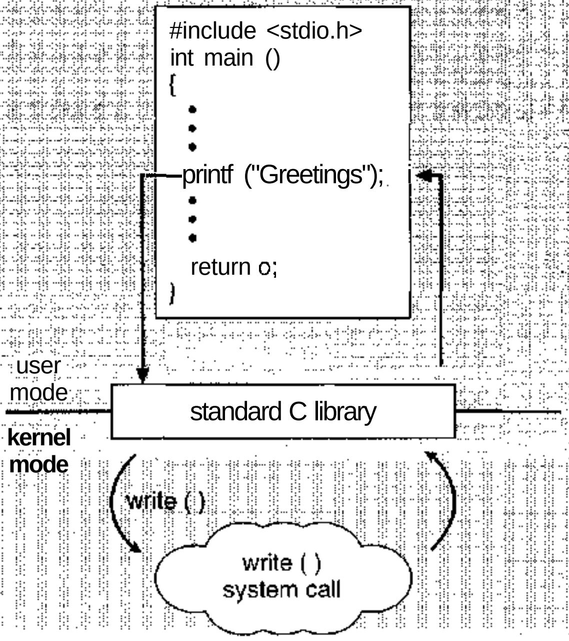


Figure 2.6 C library handling of `write()`.

Some systems allow control cards to indicate special recovery actions in case an error occurs. A control card is a batch system concept. It is a command to manage the execution of a process. If the program discovers an error in its input and wants to terminate abnormally, it may also want to define an error level. More severe errors can be indicated by a higher-level error parameter. It is then possible to combine normal and abnormal termination by defining a normal termination as an error at level 0. The command interpreter or a following program can use this error level to determine the next action automatically.

A process or job executing one program may want to load and execute another program. This feature allows the command interpreter to execute a program as directed by, for example, a user command, the click of a mouse, or a batch command. An interesting question is where to return control when the loaded program terminates. This question is related to the problem of whether the existing program is lost, saved, or allowed to continue execution concurrently with the new program.

If control returns to the existing program when the new program terminates, we must save the memory image of the existing program; thus, we have effectively created a mechanism for one program to call another program. If both programs continue concurrently, we have created a new job or process to be multiprogrammed. Often, there is a system call specifically for this purpose (`create process` or `submit job`).

If we create a new job or process, or perhaps even a set of jobs or processes, we should be able to control its execution. This control requires the ability to determine and reset the attributes of a job or process, including the job's priority, its maximum allowable execution time, and so on (`get process attributes` and `set process attributes`). We may also want to terminate a job or process that we created (`terminate process`) if we find that it is incorrect or is no longer needed.

Having created new jobs or processes, we may need to wait for them to finish their execution. We may want to wait for a certain amount of time to pass (`wait time`); more probably, we will want to wait for a specific event to occur (`wait event`). The jobs or processes should then signal when that event has occurred (`signal event`). System calls of this type, dealing with the coordination of concurrent processes, are discussed in great detail in Chapter 6.

Another set of system calls is helpful in debugging a program. Many systems provide system calls to dump memory. This provision is useful for debugging. A program `trace` lists each instruction as it is executed; it is provided by fewer systems. Even microprocessors provide a CPU mode known as *single step,* in which a trap is executed by the CPU after every instruction. The trap is usually caught by a debugger.

Many operating systems provide a time profile of a program to indicate the amount of time that the program executes at a particular location or set of locations. A time profile requires either a tracing facility or regular timer interrupts. At every occurrence of the timer interrupt, the value of the program

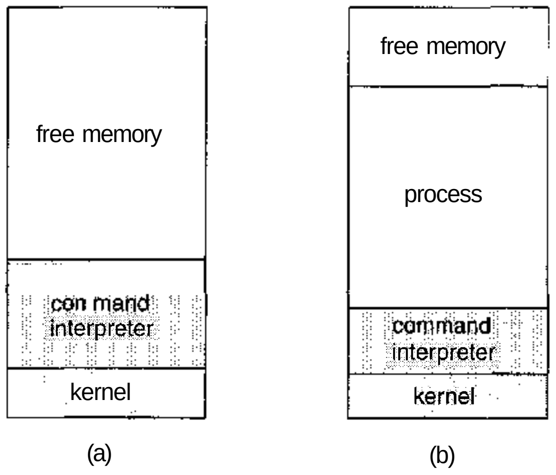


Figure 2.7 MS-DOS execution. (a) At system startup. (b) Running a program.

counter is recorded. With sufficiently frequent timer interrupts, a statistical picture of the time spent on various parts of the program can be obtained.

There are so many facets of and variations in process and job control that we next use two examples—one involving a single-tasking system and the other a multitasking system—to clarify these concepts. The MS-DOS operating system is an example of a single-tasking system. It has a command interpreter that is invoked when the computer is started (Figure 2.7(a)). Because MS-DOS is single-tasking, it uses a simple method to run a program and does not create a new process. It loads the program into memory, writing over most of itself to give the program as much memory as possible (Figure 2.7(b)). Next, it sets the instruction pointer to the first instruction of the program. The program then runs, and either an error causes a trap, or the program executes a system call to terminate. In either case, the error code is saved in the system memory for later use. Following this action, the small portion of the command interpreter that was not overwritten resumes execution. Its first task is to reload the rest of the command interpreter from disk. Then the command interpreter makes the previous error code available to the user or to the next program.

FreeBSD (derived from Berkeley UNIX) is an example of a multitasking system. When a user logs on to the system, the shell of the user's choice is run. This shell is similar to the MS-DOS shell in that it accepts commands and executes programs that the user requests. However, since FreeBSD is a multitasking system, the command interpreter may continue running while another program is executed (Figure 2.8). To start a new process, the shell executes a `fork()` system call. Then, the selected program is loaded into memory via an `exec()` system call, and the program is executed. Depending on the way the command was issued, the shell then either waits for the process to finish or runs the process "in the background." In the latter case, the shell immediately requests another command. When a process is running in the background, it cannot receive input directly from the keyboard, because the shell is using this resource. I/O is therefore done through files or through a GUI interface. Meanwhile, the user is free to ask the shell to run other programs, to monitor the progress of the running process, to change that program's priority,

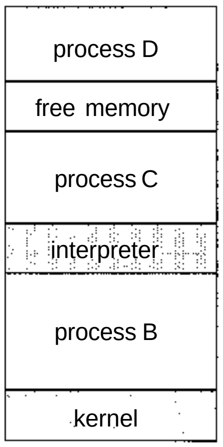


Figure 2.8 FreeBSD running multiple programs.

SOLARIS 10 DYNAMIC TRACING FACILITY

Making running operating systems easier to understand, debug, and tune is an active area of operating system research and implementation. For example, Solaris 10 includes the `dtrace` dynamic tracing facility. This facility dynamically adds probes to a running system. These probes can be queried via the D programming language to determine an astonishing amount about the kernel, the system state, and process activities. For example, Figure 2.9 follows an application as it executes a system call (`ioctl`) and further shows the functional calls within the kernel as they execute to perform the system call. Lines ending with "U" are executed in user mode, and lines ending in "K" in kernel mode.

```
# ./all.d 'pgrep xclock' XEventsQueued
dtrace: script './all.d' matched 52377 probes
CPU FUNCTION
  0  -> XEventsQueued                      U
  0    -> _XEventsQueued                   U
  0      -> _X11TransBytesReadable         U
  0      <- _X11TransBytesReadable         U
  0      -> _X11TransSocketBytesReadable   U
  0      <- _X11TransSocketBytesreadable   U
  0      -> ioctl                          U
  0        -> ioctl                        K
  0          -> getf                       K
  0            -> set_active_fd            K
  0            <- set_active_fd            K
  0          <- getf                       K
  0          -> get_udatamodel             K
  0          <- get_udatamodel             K
...
  0          -> releasef                   K
  0            -> clear_active_fd          K
  0            <- clear_active_fd          K
  0            -> cv_broadcast             K
  0            <- cv_broadcast             K
  0          <- releasef                   K
  0        <- ioctl                        K
  0      <- ioctl                          U
  0    <- _XEventsQueued                   U
  0  <- XEventsQueued                      U
```

Figure 2.9 Solaris 10 dtrace follows a system call within the kernel.

Other operating systems are starting to include various performance and tracing tools, fostered by research at various institutions, including the Paradyn project.

and so on. When the process is done, it executes an `exit()` system call to terminate, returning to the invoking process a status code of 0 or a nonzero error code. This status or error code is then available to the shell or other programs. Processes are discussed in Chapter 3 with an program example using the `fork()` and `exec()` system calls.

2.4.2 File Management

The file system will be discussed in more detail in Chapters 10 and 11. We can, however, identify several common system calls dealing with files,

We first need to be able to create and delete files. Either system call requires the name of the file and perhaps some of the file's attributes. Once the file is created, we need to open it and to use it. We may also read, write, or reposition (rewinding or skipping to the end of the file, for example). Finally, we need to close the file, indicating that we are no longer using it.

We may need these same sets of operations for directories if we have a directory structure for organizing files in the file system. In addition, for either files or directories, we need to be able to determine the values of various attributes and perhaps to reset them if necessary. File attributes include the file name, a file type, protection codes, accounting information, and so on. At least two system calls, get file attribute and set file attribute, are required for this function. Some operating systems provide many more calls, such as calls for file move and copy. Others might provide an API that performs those operations using code and other system calls, and others might just provide system programs to perform those tasks. If the system programs are callable by other programs, then each can be considered an API by other system programs.

2.4.3 Device Management

A process may need several resources to execute—main memory, disk drives, access to files, and so on. If the resources are available, they can be granted, and control can be returned to the user process. Otherwise, the process will have to wait until sufficient resources are available.

The various resources controlled by the operating sysstem can be thought of as devices. Some of these devices are physical devices (for example, tapes), while others can be thought of as abstract or virtual devices (for example, files). If there are multiple users of the system, the system may require us to first request the device, to ensure exclusive use of it. After we are finished with the device, we release it. These functions are similar to the open and close system calls for files. Other operating systems allow unmanaged access to devices. The hazard then is the potential for device contention and perhaps deadlock, which is described in Chapter 7.

Once the device has been requested (and allocated to us), we can read, write, and (possibly) reposition the device, just as we can with files. In fact, the similarity between I/O devices and files is so great that many operating systems, including UNIX, merge the two into a combined file-device structure. In this case, a set of system calls is used on files and devices. Sometimes, I/O devices are identified by special file names, directory placement, or file attributes.

The UI can also make files and devices appear to be similar, even though the underlying system calls are dissimilar. This is another example of the many design decisions that go into building an operating system and user interface.

2.4.4 Information Maintenance

Many system calls exist simply for the purpose of transferring information between the user program and the operating system. For example, most systems have a system call to return the current time and date. Other system calls may return information about the system, such as the number of current users, the version number of the operating system, the amount of free memory or disk space, and so on.

In addition, the operating system keeps information about all its processes, and system calls are used to access this information. Generally, calls are also used to reset the process information (get process attributes and set process attributes). In Section 3.1.3, we discuss what information is normally kept.

2.4.5 Communication

There are two common models of interprocess communication: the message-passing model and the shared-memory model. In the message-passing model, the communicating processes exchange messages with one another to transfer information. Messages can be exchanged between the processes either directly or indirectly through a common mailbox. Before communication can take place, a connection must be opened. The name of the other communicator must be known, be it another process on the same system or a process on another computer connected by a communications network. Each computer in a network has a *host name* by which it is commonly known. A host also has a network identifier, such as an IP address. Similarly, each process has a *process name,* and this name is translated into an identifier by which the operating system can refer to the process. The get hostid and get processid system calls do this translation. The identifiers are then passed to the general-purpose open and close calls provided by the file system or to specific open connection and close connection system calls, depending on the system's model of communication. The recipient process usually must give its permission for communication to take place with an accept connection call. Most processes that will be receiving connections are special-purpose *daemons,* which are systems programs provided for that purpose. They execute a wait for connection call and are awakened when a connection is made. The source of the communication, known as the *client,* and the receiving daemon, known as a *server,* then exchange messages by using read message and write message system calls. The close connection call terminates the communication.

In the shared-memory model, processes use shared memory create and shared memory attach system calls to create and gain access to regions of memory owned by other processes. Recall that, normally, the operating system tries to prevent one process from accessing another process's memory. Shared memory requires that two or more processes agree to remove this restriction. They can then exchange information by reading and writing data in the shared areas. The form of the data and the location are determined by the processes and are not under the operating system's control. The processes are also responsible for ensuring that they are not writing to the same location simultaneously. Such mechanisms are discussed in Chapter 6. In Chapter 4, we look at a variation of the process scheme—threads—in which memory is shared by default.

Both of the models just discussed are common in operating systems, and most systems implement both. Message passing is useful for exchanging smaller amounts of data, because no conflicts need be avoided. It is also easier to implement than is shared memory for intercomputer communication. Shared memory allows maximum speed and convenience of communication, since it can be done at memory speeds when it takes place within a computer. Problems exist, however, in the areas of protection and synchronization between the processes sharing memory.

2.5 System Programs

Another aspect of a modern system is the collection of system programs. Recall Figure 1.1, which depicted the logical computer hierarchy. At the lowest level is hardware. Next is the operating system, then the system programs, and finally the application programs. System programs provide a convenient environment for program development and execution. Some of them are simply user interfaces to system calls; others are considerably more complex. They can be divided into these categories:

- **File management.** These programs create, delete, copy, rename, print, dump, list, and generally manipulate files and directories.
- **Status information.** Some programs simply ask the system for the date, time, amount of available memory or disk space, number of users, or similar status information. Others are more complex, providing detailed performance, logging, and debugging information. Typically, these programs format and print the output to the terminal or other output devices or files or display it in a window of the GUI. Some systems also support a registry, which is used to store and retrieve configuration information.
- **File modification.** Several text editors may be available to create and modify the content of files stored on disk or other storage devices. There may also be special commands to search contents of files or perform transformations of the text.
- **Programming-language support.** Compilers, assemblers, debuggers and interpreters for common programming languages (such as C, C++, Java, Visual Basic, and PERL) are often provided to the user with the operating system.
- **Program loading and execution.** Once a program is assembled or compiled, it must be loaded into memory to be executed. The system may provide absolute loaders, relocatable loaders, linkage editors, and overlay loaders. Debugging systems for either higher-level languages or machine language are needed as well.
- **Communications.** These programs provide the mechanism for creating virtual connections among processes, users, and computer systems. They allow users to send messages to one another's screens, to browse web pages, to send electronic-mail messages, to log in remotely, or to transfer files from one machine to another.

In addition to systems programs, most operating systems are supplied with programs that are useful in solving common problems or performing common operations. Such programs include web browsers, word processors and text formatters, spreadsheets, database systems, compilers, plotting and statistical-analysis packages, and games. These programs are known as **system utilities** or **application programs.**

The view of the operating system seen by most users is defined by the application and system programs, rather than by the actual system calls. Consider PCs. When his computer is running the Mac OS X operating system, a user might see the GUI, featuring a mouse and windows interface. Alternatively, or even in one of the windows, he might have a command-line UNIX shell. Both use the same set of system calls, but the system calls look different and act in different ways.

2.6 Operating-System Design and Implementation

In this section, we discuss problems we face in designing and implementing an operating system. There are, of course, no complete solutions to such problems, but there are approaches that have proved successful.

2.6.1 Design Goals

The first problem in designing a system is to define goals and specifications. At the highest level, the design of the system will be affected by the choice of hardware and the type of system: batch, time shared, single user, multiuser, distributed, real time, or general purpose.

Beyond this highest design level, the requirements may be much harder to specify. The requirements can, however, be divided into two basic groups: *user* goals and *system* goals.

Users desire certain obvious properties in a system: The system should be convenient to use, easy to learn and to use, reliable, safe, and fast. Of course, these specifications are not particularly useful in the system design, since there is no general agreement on how to achieve them.

A similar set of requirements can be defined by those people who must design, create, maintain, and operate the system: The system should be easy to design, implement, and maintain; it should be flexible, reliable, error free, and efficient. Again, these requirements are vague and may be interpreted in various ways.

There is, in short, no unique solution to the problem of defining the requirements for an operating system. The wide range of systems in existence shows that different requirements can result in a large variety of solutions for different environments. For example, the requirements for VxWorks, a real-time operating system for embedded systems, must have been substantially different from those for MVS, a large multiuser, multiaccess operating system for IBM mainframes.

Specifying and designing an operating system is a highly creative task. Although no textbook can tell you how to do it, general principles have been developed in the field of **software engineering,** and we turn now to a discussion of some of these principles.

2.6.2 Mechanisms and Policies

One important principle is the separation of **policy** from **mechanism.** Mechanisms determine *how* to do something; policies determine *what* will be done.

For example, the timer construct (see Section 1.5.2) is a mechanism for ensuring CPU protection, but deciding how long the timer is to be set for a particular user is a policy decision.

The separation of policy and mechanism is important for flexibility. Policies are likely to change across places or over time. In the worst case, each change in policy would require a change in the underlying mechanism. A general mechanism insensitive to changes in policy would be more desirable. A change in policy would then require redefinition of only certain parameters of the system. For instance, consider a mechanism for giving priority to certain types of programs over others. If the mechanism is properly separated from policy, it can be used to support a policy decision that I/O-intensive programs should have priority over CPU-intensive ones or to support the opposite policy.

Microkernel-based operating systems (Section 2.7.3) take the separation of mechanism and policy to one extreme by implementing a basic set of primitive building blocks. These blocks are almost policy free, allowing more advanced mechanisms and policies to be added via user-created kernel modules or via user programs themselves. As an example, consider the history of UNIX. At first, it had a time-sharing scheduler. In the latest version of Solaris, scheduling is controlled by loadable tables. Depending on the table currently loaded, the system can be time shared, batch processing, real time, fair share, or any combination. Making the scheduling mechanism general purpose allows vast policy changes to be made with a single load-new-table command. At the other extreme is a system such as Windows, in which both mechanism and policy are encoded in the system to enforce a global look and feel. All applications have similar interfaces, because the interface itself is built into the kernel and system libraries. The Mac OS X operating system has similar functionality.

Policy decisions are important for all resource allocation. Whenever it is necessary to decide whether or not to allocate a resource, a policy decision must be made. Whenever the question is *how* rather than *what,* it is a mechanism that must be determined.

2.6.3 Implementation

Once an operating system is designed, it must be implemented. Traditionally, operating systems have been written in assembly language. Now, however, they are most commonly written in higher-level languages such as C or C++.

The first system that was not written in assembly language was probably the Master Control Program (MCP) for Burroughs computers. MCP was written in a variant of ALGOL. MULTICS, developed at MIT, was written mainly in PL/1. The Linux and Windows XP operating systems are written mostly in C, although there are some small sections of assembly code for device drivers and for saving and restoring the state of registers.

The advantages of using a higher-level language, or at least a systems-implementation language, for implementing operating systems are the same as those accrued when the language is used for application programs: The code can be written faster, is more compact, and is easier to understand and debug. In addition, improvements in compiler technology will improve the generated code for the entire operating system by simple recompilation. Finally, an operating system is far easier to *port*—to move to some other hardware—

if it is written in a higher-level language. For example, MS-DOS was wrftten in Intel 8088 assembly language. Consequently, it is available on only the Intel family of CPUs. The Linux operating system, in contrast, is written mostly in C and is available on a number of different CPUs, including Intel 80X86, Motorola 680X0, SPARC, and MIPS RX000.

The only possible disadvantages of implementing an operating system in a higher-level language are reduced speed and increased storage requirements. This, however, is no longer a major issue in today's systems. Although an expert assembly-language programmer can produce efficient small routines, for large programs a modern compiler can perform complex analysis and apply sophisticated optimizations that produce excellent code. Modern processors have deep pipelining and multiple functional units that can handle complex dependencies that can overwhelm the limited ability of the human mind to keep track of details.

As is true in other systems, major performance improvements in operating systems are more likely to be the result of better data structures and algorithms than of excellent assembly-language code. In addition, although operating systems are large, only a small amount of the code is critical to high performance; the memory manager and the CPU scheduler are probably the most critical routines. After the system is written and is working correctly, bottleneck routines can be identified and can be replaced with assembly-language equivalents.

To identify bottlenecks, we must be able to monitor system performance. Code must be added to compute and display measures of system behavior. In a number of systems, the operating system does this task by producing trace listings of system behavior. All interesting events are logged with their time and important parameters and are written to a file. Later, an analysis program can process the log file to determine system performance and to identify bottlenecks and inefficiencies. These same traces can be run as input for a simulation of a suggested improved system. Traces also can help people to find errors in operating-system behavior.

2.7 Operating-System Structure

A system as large and complex as a modern operating system must be engineered carefully if it is to function properly and be modified easily. A common approach is to partition the task into small components rather than have one monolithic system. Each of these modules should be a well-defined portion of the system, with carefully defined inputs, outputs, and functions. We have already discussed briefly in Chapter 1 the common components of operating systems. In this section, we discuss how these components are interconnected and melded into a kernel.

2.7.1 Simple Structure

Many commercial systems do not have well-defined structures. Frequently, such operating systems started as small, simple, and limited systems and then grew beyond their original scope. MS-DOS is an example of such a system. It was originally designed and implemented by a few people who had no idea that it would become so popular. It was written to provide the most functionality in

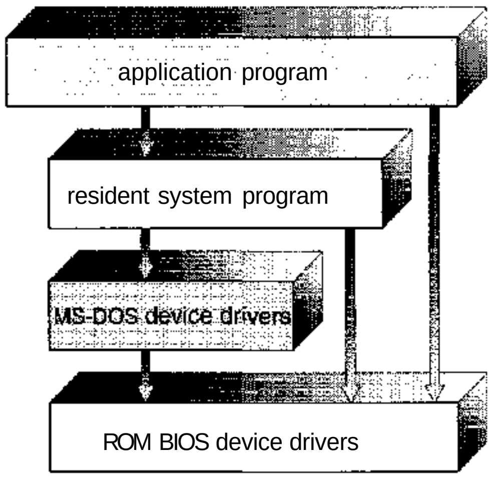


Figure 2.10 MS-DOS layer structure.

the least space, so it was not divided into modules carefully. Figure 2.10 shows its structure.

In MS-DOS, the interfaces and levels of functionality are not well separated. For instance, application programs are able to access the basic I/O routines to write directly to the display and disk drives. Such freedom leaves MS-DOS vulnerable to errant (or malicious) programs, causing entire system crashes when user programs fail. Of course, MS-DOS was also limited by the hardware of its era. Because the Intel 8088 for which it was written provides no dual mode and no hardware protection, the designers of MS-DOS had no choice but to leave the base hardware accessible.

Another example of limited structuring is the original UNIX operating system. UNIX is another system that initially was limited by hardware functionality. It consists of two separable parts: the kernel and the system programs. The kernel is further separated into a series of interfaces and device drivers, which have been added and expanded over the years as UNIX has evolved. We can view the traditional UNIX operating system as being layered, as shown in Figure 2.11. Everything below the system call interface and above the physical hardware is the kernel. The kernel provides the file system, CPU scheduling, memory management, and other operating-system functions through system calls. Taken in sum, that is an enormous amount of functionality to be combined into one level. This monolithic structure was difficult to implement and maintain.

2.7.2 Layered Approach

With proper hardware support, operating systems can be broken into pieces that are smaller and more appropriate than those allowed by the original MS-DOS or UNIX systems. The operating system can then retain much greater control over the computer and over the applications that make use of that computer. Implementers have more freedom in changing the inner workings of the system and in creating modular operating systems. Under the top-down approach, the overall functionality and features are determined and are

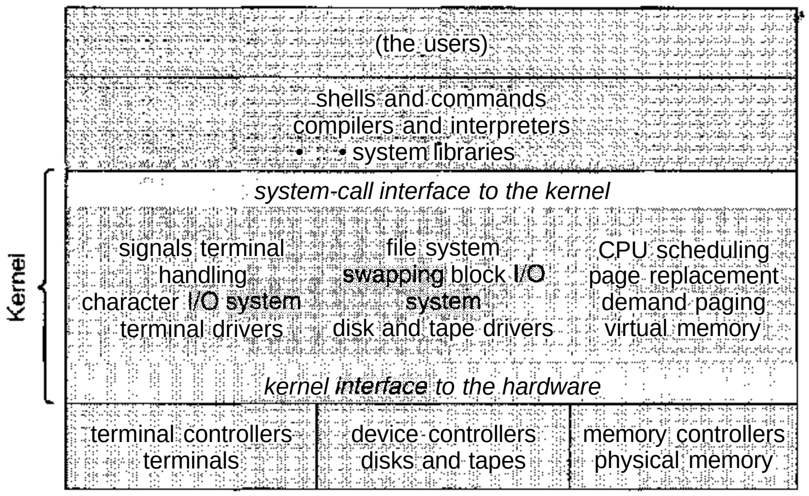


Figure 2.11 UNIX system structure.

separated into components. Information hiding is also important, because it leaves programmers free to implement the low-level routines as they see fit, provided that the external interface of the routine stays unchanged and that the routine itself performs the advertised task.

A system can be made modular in many ways. One method is the **layered approach,** in which the operating system is broken up into a number of layers (levels). The bottom layer (layer 0) is the hardware; the highest (layer N) is the user interface. This layering structure is depicted in Figure 2.12.

An operating-system layer is an implementation of an abstract object made up of data and the operations that can manipulate those data. A typical operating-system layer—say, layer *M*—consists of data structures and a set of routines that can be invoked by higher-level layers. Layer *M*, in turn, can invoke operations on lower-level layers.

The main advantage of the layered approach is simplicity of construction and debugging. The layers are selected so that each uses functions (operations) and services of only lower-level layers. This approach simplifies debugging and system verification. The first layer can be debugged without any concern for the rest of the system, because, by definition, it uses only the basic hardware (which is assumed correct) to implement its functions. Once the first layer is debugged, its correct functioning can be assumed while the second layer is debugged, and so on. If an error is found during the debugging of a particular layer, the error must be on that layer, because the layers below it are already debugged. Thus, the design and implementation of the system is simplified.

Each layer is implemented with only those operations provided by lower-level layers. A layer does not need to know how these operations are implemented; it needs to know only what these operations do. Hence, each layer hides the existence of certain data structures, operations, and hardware from higher-level layers.

The major difficulty with the layered approach involves appropriately defining the various layers. Because a layer can use only lower-level layers, careful planning is necessary. For example, the device driver for the backing

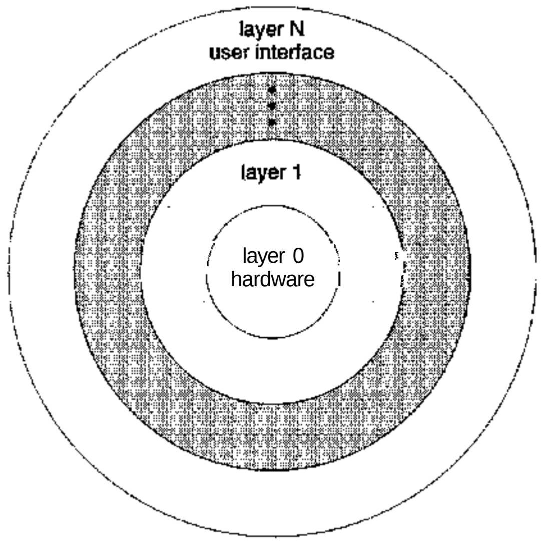


Figure 2.12 A layered operating system.

store (disk space used by virtual-memory algorithms) must be at a lower level than the memory-management routines, because memory management requires the ability to use the backing store.

Other requirements may not be so obvious. The backing-store driver would normally be above the CPU scheduler, because the driver may need to wait for I/O and the CPU can be rescheduled during this time. However, on a large system, the CPU scheduler may have more information about all the active processes than can fit in memory. Therefore, this information may need to be swapped in and out of memory, requiring the backing-store driver routine to be below the CPU scheduler.

A final problem with layered implementations is that they tend to be less efficient than other types. For instance, when a user program executes an I/O operation, it executes a system call that is trapped to the I/O layer, which calls the memory-management layer, which in turn calls the CPU-scheduling layer, which is then passed to the hardware. At each layer, the parameters may be modified, data may need to be passed, and so on. Each layer adds overhead to the system call; the net result is a system call that takes longer than does one on a nonlayered system.

These limitations have caused a small backlash against layering in recent years. Fewer layers with more functionality are being designed, providing most of the advantages of modularized code while avoiding the difficult problems of layer definition and interaction.

2.7.3 Microkernels

We have already seen that as UNIX expanded, the kernel became large and difficult to manage. In the mid-1980s, researchers at Carnegie Mellon University developed an operating system called **Mach** that modularized the kernel using the **microkernel** approach. This method structures the operating system by removing all nonessential components from the kernel and implementing them as system and user-level programs. The result is a smaller kernel. There is little consensus regarding which services should remain in the kernel and which should be implemented in user space. Typically, however, microkernels provide minimal process and memory management, in addition to a communication facility.

The main function of the microkernel is to provide a communication facility between the client program and the various services that are also running in user space. Communication is provided by *message passing,* which was described in Section 2.4.5. For example, if the client program wishes to access a file, it must interact with the file server. The client program and service never interact directly. Rather, they communicate indirectly by exchanging messages with the microkernel.

One benefit of the microkernel approach is ease of extending the operating system. All new services are added to user space and consequently do not require modification of the kernel. When the kernel does have to be modified, the changes tend to be fewer, because the microkernel is a smaller kernel. The resulting operating system is easier to port from one hardware design to another. The microkernel also provides more security and reliability, since most services are running as user—rather than kernel—processes. If a service fails, the rest of the operating system remains untouched.

Several contemporary operating systems have used the microkernel approach. Tru64 UNIX (formerly Digital UNIX) provides a UNIX interface to the user, but it is implemented with a Mach kernel. The Mach kernel maps UNIX system calls into messages to the appropriate user-level services.

Another example is QNX. QNX is a real-time operating system that is also based on the microkernel design. The QNX microkernel provides services for message passing and process scheduling. It also handles low-level network communication and hardware interrupts. All other services in QNX are provided by standard processes that run outside the kernel in user mode.

Unfortunately, microkernels can suffer from performance decreases due to increased system function overhead. Consider the history of Windows NT. The first release had a layered microkernel organization. However, this version delivered low performance compared with that of Windows 95. Windows NT 4.0 partially redressed the performance problem by moving layers from user space to kernel space and integrating them more closely. By the time Windows XP was designed, its architecture was more monolithic than microkernel.

2.7.4 Modules

Perhaps the best current methodology for operating-system design involves using object-oriented programming techniques to create a modular kernel. Here, the kernel has a set of core components and dynamically links in additional services either during boot time or during run time. Such a strategy uses dynamically loadable modules and is common in modern implementations of UNIX, such as Solaris, Linux, and Mac OS X. For example, the Solaris operating system structure, shown in Figure 2.13, is organized around a core kernel with seven types of loadable kernel modules:

1. Scheduling classes
2. File systems

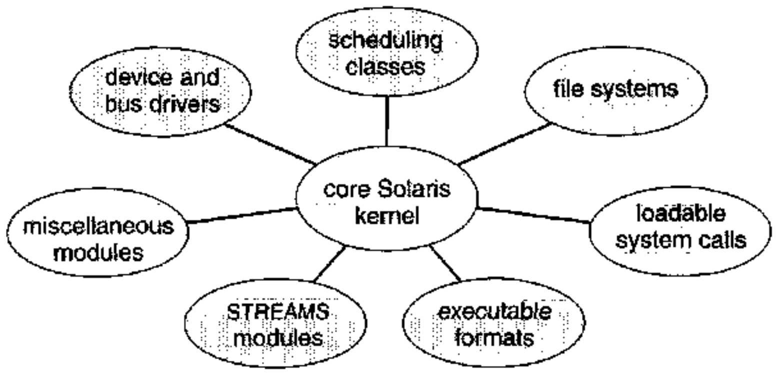


Figure 2.13 Solaris loadable modules.

3. Loadable system calls
4. Executable formats
5. STREAMS modules
6. Miscellaneous
7. Device and bus drivers

Such a design allows the kernel to provide core services yet also allows certain features to be implemented dynamically. For example, device and bus drivers for specific hardware can be added to the kernel, and support for different file systems can be added as loadable modules. The overall result resembles a layered system in that each kernel section has defined, protected interfaces; but it is more flexible than a layered system in that any module can call any other module. Furthermore, the approach is like the microkernel approach in that the primary module has only core functions and knowledge of how to load and communicate with other modules; but it is more efficient, because modules do not need to invoke message passing in order to communicate.

The Apple Macintosh Mac OS X operating system uses a hybrid structure. Mac OS X (also known as *Darwin*) structures the operating system using a layered technique where one layer consists of the Mach microkernel. The structure of Mac OS X appears in Figure 2.14.

The top layers include application environments and a set of services providing a graphical interface to applications. Below these layers is the kernel environment, which consists primarily of the Mach microkernel and the BSD kernel. Mach provides memory management; support for remote procedure calls (RPCs) and interprocess communication (IPC) facilities, including message passing; and thread scheduling. The BSD component provides a BSD command line interface, support for networking and file systems, and an implementation of POSIX APIs, including Pthreads. In addition to Mach and BSD, the kernel environment provides an I/O kit for development of device drivers and dynamically loadable modules (which Mac OS X refers to as **kernel extensions).** As shown in the figure, applications and common services can make use of either the Mach or BSD facilities directly.

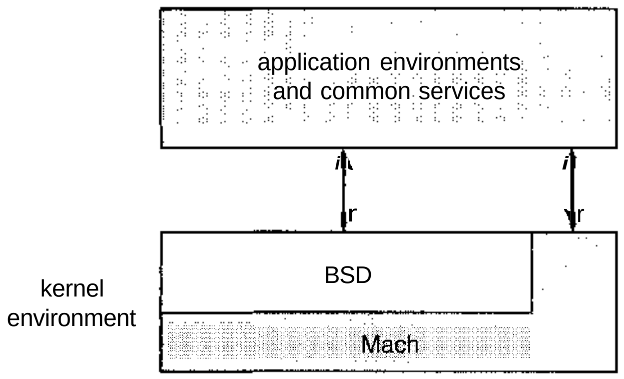


Figure 2.14 The Mac OS X structure.

2.8 Virtual Machines

The layered approach described in Section 2.7.2 is taken to its logical conclusion in the concept of a **virtual machine.** The fundamental idea behind a virtual machine is to abstract the hardware of a single computer (the CPU, memory, disk drives, network interface cards, and so forth) into several different execution environments, thereby creating the illusion that each separate execution environment is running its own private computer.

By using CPU scheduling (Chapter 5) and virtual-memory techniques (Chapter 9), an operating system can create the illusion that a process has its own processor with its own (virtual) memory. Normally, a process has additional features, such as system calls and a file system, that are not provided by the bare hardware. The virtual-machine approach does not provide any such additional functionality but rather provides an interface that is *identical* to the underlying bare hardware. Each process is provided with a (virtual) copy of the underlying computer (Figure 2.15).

There are several reasons for creating a virtual machine, all of which are fundamentally related to being able to share the same hardware yet run several different execution environments (that is, different operating systems) concurrently. We will explore the advantages of virtual machines in more detail in Section 2.8.2. Throughout much of this section, we discuss the VM operating system for IBM systems, as it provides a useful working example; furthermore IBM pioneered the work in this area.

A major difficulty with the virtual-machine approach involves disk systems. Suppose that the physical machine has three disk drives but wants to support seven virtual machines. Clearly, it cannot allocate a disk drive to each virtual machine, because the virtual-machine software itself will need substantial disk space to provide virtual memory and spooling. The solution is to provide virtual disks—termed *minidisks* in IBM's VM operating system—that are identical in all respects except size. The system implements each minidisk by allocating as many tracks on the physical disks as the minidisk needs. Obviously, the sum of the sizes of all minidisks must be smaller than the size of the physical disk space available.

Users thus are given their own virtual machines. They can then run any of the operating systems or software packages that are available on the underlying

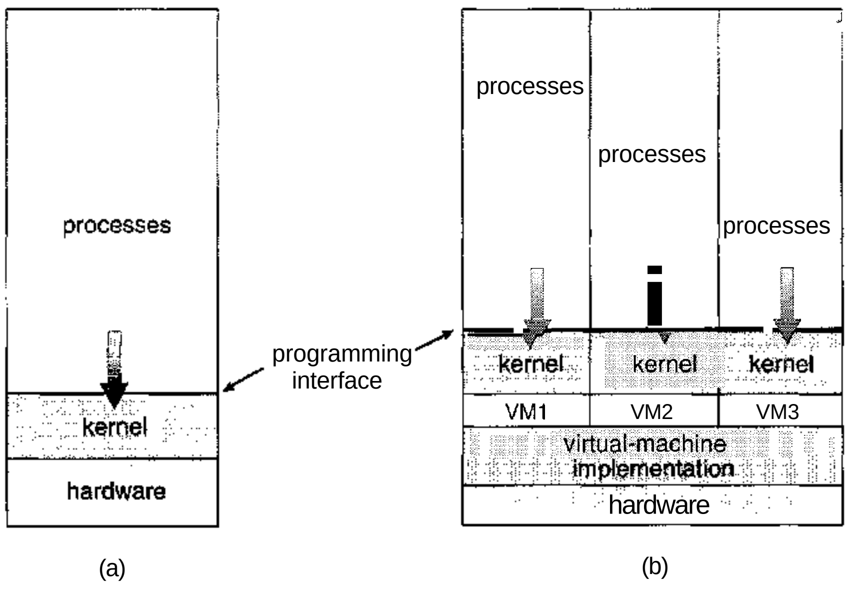


Figure 2.15 System models. (a) Nonvirtual machine. (b) Virtual machine.

machine. For the IBM VM system, a user normally runs CMS—a single-user interactive operating system. The virtual-machine software is concerned with multiprogramming multiple virtual machines onto a physical machine, but it does not need to consider any user-support software. This arrangement may provide a useful way to divide the problem of designing a multiuser interactive system into two smaller pieces.

2.8.1 Implementation

Although the virtual-machine concept is useful, it is difficult to implement. Much work is required to provide an *exact* duplicate of the underlying machine. Remember that the underlying machine has two modes: user mode and kernel mode. The virtual-machine software can run in kernel mode, since it is the operating system. The virtual machine itself can execute in only user mode. Just as the physical machine has two modes, however, so must the virtual machine. Consequently, we must have a virtual user mode and a virtual kernel mode, both of which run in a physical user mode. Those actions that cause a transfer from user mode to kernel mode on a real machine (such as a system call or an attempt to execute a privileged instruction) must also cause a transfer from virtual user mode to virtual kernel mode on a virtual machine.

Such a transfer can be accomplished as follows. When a system call, for example, is made by a program running on a virtual machine in virtual user mode, it will cause a transfer to the virtual-machine monitor in the real machine- When the virtual-machine monitor gains control, it can change the register contents and program counter for the virtual machine to simulate the effect of the system call. It can then restart the virtual machine, noting that it is now in virtual kernel mode.

The major difference, of course, is time. Whereas the real I/O might have taken 100 milliseconds, the virtual I/O might take less time (because it is spooled) or more time (because it is interpreted). In addition, the CPU is being multiprogrammed among many virtual machines, further slowing down the virtual machines in unpredictable ways. In the extreme case, it may be necessary to simulate all instructions to provide a true virtual machine. VM works for IBM machines because normal instructions for the virtual machines can execute directly on the hardware. Only the privileged instructions (needed mainly for I/O) must be simulated and hence execute more slowly.

2.8.2 Benefits

The virtual-machine concept has several advantages. Notice that, in this environment, there is complete protection of the various system resources. Each virtual machine is completely isolated from all other virtual machines, so there are no protection problems. At the same time, however, there is no direct sharing of resources. Two approaches to provide sharing have been implemented. First, it is possible to share a minidisk and thus to share files. This scheme is modeled after a physical shared disk but is implemented by software. Second, it is possible to define a network of virtual machines, each of which can send information over the virtual communications network. Again, the network is modeled after physical communication networks but is implemented in software.

Such a virtual-machine system is a perfect vehicle for operating-systems research and development. Normally, changing an operating system is a difficult task. Operating systems are large and complex programs, and it is difficult to be sure that a change in one part will not cause obscure bugs in some other part. The power of the operating system makes changing it particularly dangerous. Because the operating system executes in kernel mode, a wrong change in a pointer could cause an error that would destroy the entire file system. Thus, it is necessary to test all changes to the operating system carefully.

The operating system, however, runs on and controls the entire machine. Therefore, the current system must be stopped and taken out of use while changes are made and tested. This period is commonly called *system-development time.* Since it makes the system unavailable to users, system-development time is often scheduled late at night or on weekends, when system load is low.

A virtual-machine system can eliminate much of this problem. System programmers are given their own virtual machine, and system development is done on the virtual machine instead of on a physical machine. Normal system operation seldom needs to be disrupted for system development.

2.8.3 Examples

Despite the advantages of virtual machines, they received little attention for a number of years after they were first developed. Today, however, virtual machines are coming back into fashion as a means of solving system compatibility problems. In this section, we explore two popular contemporary virtual machines: VMware and the Java virtual machine. As we will see, these virtual machines typically run on top of an operating system of any of the design types discussed earlier. Thus, operating system design methods—

simple layers, microkernel, modules, and virtual machines—are not mutually exclusive.

2.8.3.1 VMware

VMware is a popular commercial application that abstracts Intel 80X86 hardware into isolated virtual machines. VMware runs as an application on a host operating system such as Windows or Linux and allows this host system to concurrently run several different **guest operating systems** as independent virtual machines.

Consider the following scenario: A developer has designed an application and would like to test it on Linux, FreeBSD, Windows NT, and Windows XP. One option is for her to obtain four different computers, each running a copy of one of these operating systems. Another alternative is for her first to install Linux on a computer system and test the application, then to install FreeBSD and test the application, and so forth. This option allows her to use the same physical computer but is time-consuming, since she must install a new operating system for each test. Such testing could be accomplished *concurrently* on the same physical computer using VMware. In this case, the programmer could test the application on a host operating system and on three guest operating systems with each system running as a separate virtual machine.

The architecture of such a system is shown in Figure 2.16. In this scenario, Linux is running as the host operating system; FreeBSD, Windows NT, and Windows XP are running as guest operating systems. The virtualization layer is the heart of VMware, as it abstracts the physical hardware into isolated virtual machines running as guest operating systems. Each virtual machine has its own virtual CPU, memory, disk drives, network interfaces, and so forth.

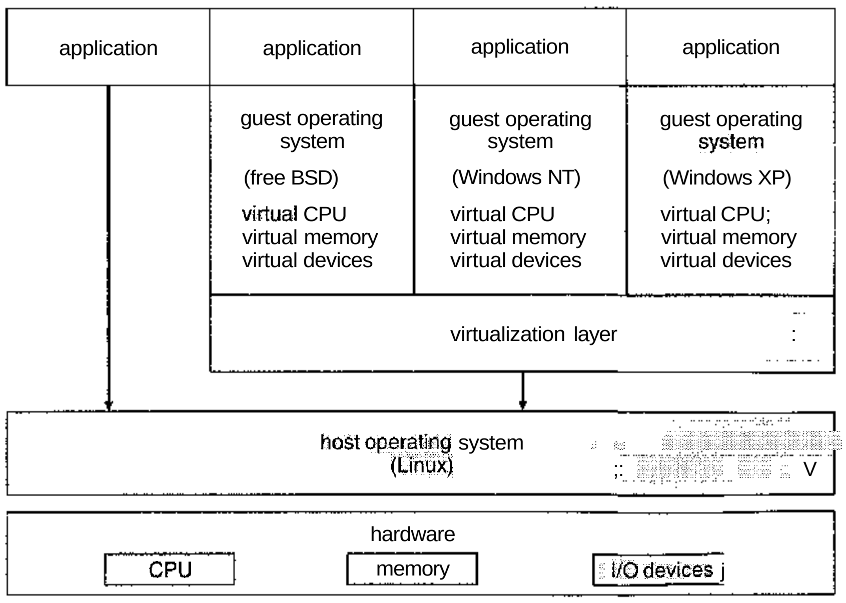


Figure 2.16 VMware architecture.

2.8.3.2 The Java Virtual Machine

Java is a popular object-oriented programming language introduced by Sun Microsystems in 1995. In addition to a language specification and a large API library, Java also provides a specification for a Java virtual machine—or JVM.

Java objects are specified with the `class` construct; a Java program consists of one or more classes. For each Java class, the compiler produces an architecture-neutral **bytecode** output (`.class`) file that will run on any implementation of the JVM.

The JVM is a specification for an abstract computer. It consists of a **class loader** and a Java interpreter that executes the architecture-neutral bytecodes, as diagrammed in Figure 2.17. The class loader loads the compiled `.class` files from both the Java program and the Java API for execution by the Java interpreter. After a class is loaded, the verifier checks that the `.class` file is valid Java bytecode and does not overflow or underflow the stack. It also ensures that the bytecode does not perform pointer arithmetic, which could provide illegal memory access. If the class passes verification, it is run by the Java interpreter. The JVM also automatically manages memory by performing **garbage collection**—the practice of reclaiming memory from objects no longer in use and returning it to the system. Much research focuses on garbage collection algorithms for increasing the performance of Java programs in the virtual machine.

The JVM may be implemented in software on top of a host operating system, such as Windows, Linux, or Mac OS X, or as part of a web browser. Alternatively, the JVM may be implemented in hardware on a chip specifically designed to run Java programs. If the JVM is implemented in software, the Java interpreter interprets the bytecode operations one at a time. A faster software technique is to use a **just-in-time (JIT)** compiler. Here, the first time a Java method is invoked, the bytecodes for the method are turned into native machine language for the host system. These operations are then cached so that subsequent invocations of a method are performed using the native machine instructions and the bytecode operations need not be interpreted all over again. A technique that is potentially even faster is to run the JVM in hardware on a special Java chip that executes the Java bytecode operations as native code, thus bypassing the need for either a software interpreter or a just-in-time compiler.

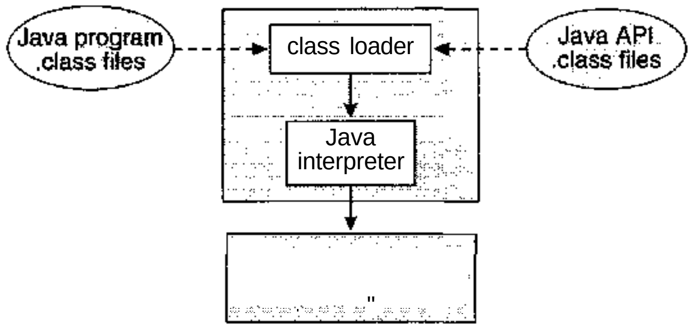


Figure 2.17 The Java virtual machine.

THE .NET FRAMEWORK

The .NET Framework is a collection of technologies, including a set of class libraries, and an execution environment that come together to provide a platform for developing software. This platform allows programs to be written to target the .NET Framework instead of a specific architecture. A program written for the .NET Framework need not worry about the specifics of the hardware or the operating system on which it will run. Thus, any architecture implementing .NET will be able to successfully execute the program, This is because the execution environment abstracts these details and provides a virtual machine as an intermediary between the executing program and the underlying architecture.

At the core of the .NET Framework is the Common Language Runtime (CLR). The CLR is the implementation of the .NET virtual machine. It provides an environment for execution of programs written in any of the languages targeted at the .NET Framework. Programs written in languages such as C# (pronounced *C-sharp*) and VB.NET are compiled into an intermediate, architecture-independent language called Microsoft Intermediate Language (MS-IL). These compiled files, called assemblies, include MS-IL instructions and metadata. They have a file extension of either .EXE or .DLL. Upon execution of a program, the CLR loads assemblies into what is known as the **Application Domain.** As instructions are requested by the executing program, the CLR converts the MS-IL instructions inside the assemblies into native code that is specific to the underlying arcliitecture using just-in-time compilation. Once instructions have been converted to native code, they are kept and will continue to run as native code for the CPU. The architecture of the CLR for the .NET framework is shown in Figure 2.18.

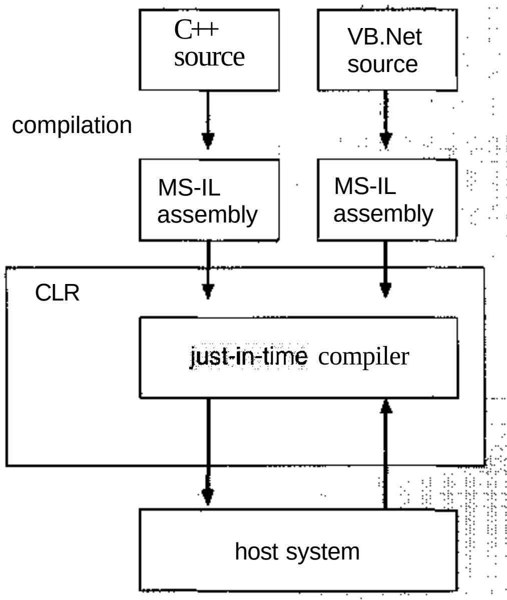


Figure 2.18 Architecture of the CLR for the .NET Framework.

2.9 Operating-System Generation

It is possible to design, code, and implement an operating system specifically for one machine at one site. More commonly, however, operating systems are designed to run on any of a class of machines at a variety of sites with a variety of peripheral configurations. The system must then be configured or generated for each specific computer site, a process sometimes known as **system generation** (SYSGEN).

The operating system is normally distributed on disk or CD-ROM. To generate a system, we use a special program. The SYSGEN program reads from a given file, or asks the operator of the system for information concerning the specific configuration of the hardware system, or probes the hardware directly to determine what components are there. The following kinds of information must be determined.

- What CPU is to be used? What options (extended instruction sets, floating-point arithmetic, and so on) are installed? For multiple CPU systems, each CPU must be described.
- How much memory is available? Some systems will determine this value themselves by referencing memory location after memory location until an "illegal address" fault is generated. This procedure defines the final legal address and hence the amount of available memory.
- What devices are available? The system will need to know how to address each device (the device number), the device interrupt number, the device's type and model, and any special device characteristics.
- What operating-system options are desired, or what parameter values are to be used? These options or values might include how many buffers of which sizes should be used, what type of CPU-scheduling algorithm is desired, what the maximum number of processes to be supported is, and soon.

Once this information is determined, it can be used in several ways. At one extreme, a system administrator can use it to modify a copy of the source code of the operating system. The operating system then is completely compiled. Data declarations, initializations, and constants, along with conditional compilation, produce an output object version of the operating system that is tailored to the system described.

At a slightly less tailored level, the system description can cause the creation of tables and the selection of modules from a precompiled library. These modules are linked together to form the generated operating system. Selection allows the library to contain the device drivers for all supported I/O devices, but only those needed are linked into the operating system. Because the system is not recompiled, system generation is faster, but the resulting system may be overly general.

At the other extreme, it is possible to construct a system that is completely table driven. All the code is always part of the system, and selection occurs at execution time, rather than at compile or link time. System generation involves simply creating the appropriate tables to describe the system.

The major differences among these approaches are the size and generality of the generated system and the ease of modification as the hardware configuration changes. Consider the cost of modifying the system to support a newly acquired graphics terminal or another disk drive. Balanced against that cost, of course, is the frequency (or infrequency) of such changes.

2.10 System Boot

After an operating system is generated, it must be made available for use by the hardware. But how does the hardware know where the kernel is or how to load that kernel? The procedure of starting a computer by loading the kernel is known as *booting* the system. On most computer systems, a small piece of code known as the **bootstrap program** or **bootstrap loader** locates the kernel, loads it into main memory, and starts its execution. Some computer systems, such as PCs, use a two-step process in which a simple bootstrap loader fetches a more complex boot program from disk, which in turn loads the kernel.

When a CPU receives a reset event—for instance, when it is powered up or rebooted—the instruction register is loaded with a predefined memory location, and execution starts there. At that location is the initial bootstrap program. This program is in the form of **read-only memory (ROM),** because the RAM is in an unknown state at system startup. ROM is convenient because it needs no initialization and cannot be infected by a computer virus.

The bootstrap program can perform a variety of tasks. Usually, one task is to run diagnostics to determine the state of the machine. If the diagnostics pass, the program can continue with the booting steps. It can also initialize all aspects of the system, from CPU registers to device controllers and the contents of main memory. Sooner or later, it starts the operating system.

Some systems—such as cellular phones, PDAs, and game consoles—store the entire operating system in ROM. Storing the operating system in ROM is suitable for small operating systems, simple supporting hardware, and rugged operation. A problem with this approach is that changing the bootstrap code requires changing the ROM hardware chips. Some systems resolve this problem by using **erasable programmable read-only memory** (EPROM), which is read-only except when explicitly given a command to become writable. All forms of ROM are also known as **firmware,** since their characteristics fall somewhere between those of hardware and those of software. A problem with firmware in general is that executing code there is slower than executing code in RAM. Some systems store the operating system in firmware and copy it to RAM for fast execution. A final issue with firmware is that it is relatively expensive, so usually only small amounts are available.

For large operating systems (including most general-purpose operating systems like Windows, Mac OS X, and UNIX) or for systems that change frequently, the bootstrap loader is stored in firmware, and the operating system is on disk. In this case, the bootstrap runs diagnostics and has a bit of code that can read a single block at a fixed location (say block zero) from disk into memory and execute the code from that **boot block.** The program stored in the boot block may be sophisticated enough to load the entire operating system into memory and begin its execution. More typically, it is simple code (as it fits in a single disk block) and only knows the address on disk and length of the remainder of the bootstrap program. All of the disk-bound bootstrap, and the operating system itself, can be easily changed by writing new versions to disk. A disk that has a boot partition (more on that in section 12.5.1) is called a **boot disk** or system disk.

Now that the full bootstrap program has been loaded, it can traverse the file system to find the operating system kernel, load it into memory, and start its execution. It is only at this point that the system is said to be **running.**

2.11 Summary

Operating systems provide a number of services. At the lowest level, system calls allow a running program to make requests from the operating system directly. At a higher level, the command interpreter or shell provides a mechanism for a user to issue a request without writing a program. Commands may come from files during batch-mode execution or directly from a terminal when in an interactive or time-shared mode. System programs are provided to satisfy many common user requests.

The types of requests vary according to level. The system-call level must provide the basic functions, such as process control and file and device manipulation. Higher-level requests, satisfied by the command interpreter or system programs, are translated into a sequence of system calls. System services can be classified into several categories: program control, status requests, and I/O requests. Program errors can be considered implicit requests for service.

Once the system services are defined, the structure of the operating system can be developed. Various tables are needed to record the information that defines the state of the computer system and the status of the system's jobs.

The design of a new operating system is a major task. It is important that the goals of the system be well defined before the design begins. The type of system desired is the foundation for choices among various algorithms and strategies that will be needed.

Since an operating system is large, modularity is important. Designing a system as a sequence of layers or using a microkernel is considered a good technique. The virtual-machine concept takes the layered approach and treats both the kernel of the operating system and the hardware as though they were hardware. Even other operating systems may be loaded on top of this virtual machine.

Throughout the entire operating-system design cycle, we must be careful to separate policy decisions from implementation details (mechanisms). This separation allows maximum flexibility if policy decisions are to be changed later.

Operating systems are now almost always written in a systems-implementation language or in a higher-level language. This feature improves their implementation, maintenance, and portability. To create an operating system for a particular machine configuration, we must perform system generation.

For a computer system to begin running, the CPU must initialize and start executing the bootstrap program in firmware. The bootstrap can execute the operating system directly if the operating system is also in the firmware, or it can complete a sequence in which it loads progressively smarter programs from firmware and disk until the operating system itself is loaded into memory and executed.

Exercises

2.1 The services and functions provided by an operating system can be divided into two main categories. Briefly describe the two categories and discuss how they differ.

2.2 List five services provided by an operating system that are designed to make it more convenient for users to use the computer system. In what cases it would be impossible for user-level programs to provide these services? Explain.

2.3 Describe three general methods for passing parameters to the operating system.

2.4 Describe how you could obtain a statistical profile of the amount of time spent by a program executing different sections of its code. Discuss the importance of obtaining such a statistical profile.

2.5 What are the five major activities of an operating system with regard to file management?

2.6 What are the advantages and disadvantages of using the same system-call interface for manipulating both files and devices?

2.7 What is the purpose of the command interpreter? Why is it usually separate from the kernel? Would it be possible for the user to develop a new command interpreter using the system-call interface provided by the operating system?

2.8 What are the two models of interprocess communication? What are the strengths and weaknesses of the two approaches?

2.9 Why is the separation of mechanism and policy desirable?

2.10 Why does Java provide the ability to call from a Java program native methods that are written in, say, C or C++? Provide an example of a situation in which a native method is useful,

2.11 It is sometimes difficult to achieve a layered approach if two components of the operating system are dependent on each other. Identify a scenario in which it is unclear how to layer two system components that require tight coupling of their functionalities.

2.12 What is the main advantage of the microkernel approach to system design? How do user programs and system services interact in a microkernel architecture? What are the disadvantages of using the microkernel approach?

2.13 In what ways is the modular kernel approach similar to the layered approach? In what ways does it differ from the layered approach?

2.14 What is the main advantage for an operating-system designer of using a virtual-machine architecture? What is the main advantage for a user?

2.15 Why is a just-in-time compiler useful for executing Java programs'?

2.16 What is the relationship between a guest operating system and a host operating system in a system like VMware? What factors need to be considered in choosing the host operating system?

2.17 The experimental Synthesis operating system has an assembler incorporated in the kernel. To optimize system-call performance, the kernel assembles routines within kernel space to minimize the path that the system call must take through the kernel. This approach is the antithesis of the layered approach, in which the path through the kernel is extended to make building the operating system easier. Discuss the pros and cons of the Synthesis approach to kernel design and system-performance optimization.

2.18 In Section 2.3, we described a program that copies the contents of one file to a destination file. This program works by first prompting the user for the name of the source and destination files. Write this program using either the Windows32 or POSIX API. Be sure to include all necessary error checking, including ensuring that the source file exists. Once you have correctly designed and tested the program, if you used a system that supports it, run the program using a utility that traces system calls. Linux systems provide the `ptrace` utility, and Solaris systems use the `truss` or `dtrace` command. On Mac OS X, the `ktrace` facility provides similar functionality.

Project—Adding a System Call to the Linux Kernel

In this project, you will study the system call interface provided by the Linux operating system and how user programs communicate with the operating system kernel via this interface. Your task is to incorporate a new system call into the kernel, thereby expanding the functionality of the operating system.

Getting Started

A user-mode procedure call is performed by passing arguments to the called procedure either on the stack or through registers, saving the current state and the value of the program counter, and jumping to the beginning of the code corresponding to the called procedure. The process continues to have the same privileges as before.

System calls appear as procedure calls to user programs, but result in a change in execution context and privileges. In Linux on the Intel 386 architecture, a system call is accomplished by storing the system call number into the EAX register, storing arguments to the system call in other hardware registers, and executing a trap instruction (which is the INT 0x80 assembly instruction). After the trap is executed, the system call number is used to index into a table of code pointers to obtain the starting address for the handler code implementing the system call. The process then jumps to this address and the privileges of the process are switched from user to kernel mode. With the expanded privileges, the process can now execute kernel code that might include privileged instructions that cannot be executed in user mode. The kernel code can then perform the requested services such as interacting with I/O devices, perform process management and other such activities that cannot be performed in user mode.

The system call numbers for recent versions of the Linux kernel are listed in `/usr/src/linux-2.x/include/asm-i386/unistd.h`. (For instance, `__NR_close`, which corresponds to the system call `close()` that is invoked for closing a file descriptor, is defined as value 6.) The list of pointers to system call handlers is typically stored in the file `/usr/src/linux-2.x/arch/i386/kernel/entry.S` under the heading `ENTRY(sys_call_table)`. Notice that `sys_close` is stored at entry numbered 6 in the table to be consistent with the system call number defined in `unistd.h` file. (The keyword `.long` denotes that the entry will occupy the same number of bytes as a data value of type long.)

Building a New Kernel

Before adding a system call to the kernel, you must familiarize yourself with the task of building the binary for a kernel from its source code and booting the machine with the newly built kernel. This activity comprises the following tasks, some of which are dependent on the particular installation of the Linux operating system.

- Obtain the kernel source code for the Linux distribution. If the source code package has been previously installed on your machine, the corresponding files might be available under `/usr/src/linux` or `/usr/src/linux-2.x` (where the suffix corresponds to the kernel version number). If the package has not been installed earlier, it can be downloaded from the provider of your Linux distribution or from `http://www.kernel.org`.

- Learn how to configure, compile, and install the kernel binary. This will vary between the different kernel distributions, but some typical commands for building the kernel (after entering the directory where the kernel source code is stored) include:

  - make `xconfig`
  - make `dep`
  - make `bzImage`

- Add a new entry to the set of bootable kernels supported by the system. The Linux operating system typically uses utilities such as `lilo` and grub to maintain a list of bootable kernels, from which the user can choose during machine boot-up. If your system supports `lilo`, add an entry to `lilo.conf`, such as:

```
image=/boot/bzImage.mykernel
label=mykernel
root=/dev/hda5
read-only
```

  where `/boot/bzImage.mykernel` is the kernel image and mykernel is the label associated with the new kernel allowing you to choose it during bootup process. By performing this step, you have the option of either booting a new kernel or booting the unmodified kernel if the newly built kernel does not function properly.

Extending Kernel Source

You can now experiment with adding a new file to the set of source files used for compiling the kernel. Typically, the source code is stored in the `/usr/src/linux-2.x/kernel` directory, although that location may differ in your Linux distribution. There are two options for adding the system call. The first is to add the system call to an existing source file in this directory. A second option is to create a new file in the source directory and modify `/usr/src/linux-2.x/kernel/Makefile` to include the newly created file in the compilation process. The advantage of the first approach is that by modifying an existing file that is already part of the compilation process, the Makefile does not require modification.

Adding a System Call to the Kernel

Now that you are familiar with the various background tasks corresponding to building and booting Linux kernels, you can begin the process of adding a new system call to the Linux kernel. In this project, the system call will have limited functionality; it will simply transition from user mode to kernel mode, print a message that is logged with the kernel messages, and transition back to user mode. We will call this the *helloworld* system call. While it has only limited functionality, it illustrates the system call mechanism and sheds light on the interaction between user programs and the kernel.

- Create a new file called `helloworld.c` to define your system call. Include the header files `linux/linkage.h` and `linux/kernel.h`. Add the following code to this file:

```
#include <linux/linkage.h>
#include <linux/kernel.h>
asmlinkage int sys_helloworld() {
  printk(KERN_EMERG "hello world!");

  return 1;
}
```

This creates a system call with the name `sys_helloworld()`. If you choose to add this system call to an existing file in the source directory, all that is necessary is to add the `sys_helloworld()` function to the file you choose. asmlinkage is a remnant from the days when Linux used both C++ and C code and is used to indicate that the code is written in C. The `printk()` function is used to print messages to a kernel log file and therefore may only be called from the kernel. The kernel messages specified in the parameter to printkO are logged in the file `/var/log/kernel/warnings`. The function prototype for the `printk()` call is defined in `/usr/include/linux/kernel.h`.

- Define a new system call number for `__NR_helloworld` in `/usr/src/linux-2.x/include/asm-i386/unistd.h`. A user program can use this number to identify the newly added system call. Also be sure to increment the value for `__NR_syscalls`, which is also stored in the same file. This constant tracks the number of system calls currently defined in the kernel.

- Add an entry `.long sys_helloworld` to the sys_call_table defined in `/usr/src/linux-2.x/arch/i386/kernel/entry.S` file. As discussed earlier, the system call number is used to index into this table to find the position of the handler code for the invoked system call.

- Add your file `helloworld.c` to the Makefile (if you created a new file for your system call.) Save a copy of your old kernel binary image (in case there are problems with your newly created kernel.) You can now build the new kernel, rename it to distinguish it from the unmodified kernel, and add an entry to the loader configuration files (such as lilo.conf). After completing these steps, you may now boot either the old kernel or the new kernel that contains your system call inside it.

Using the System Call From a User Program

When you boot with the new kernel it will support the newly defined system call; it is now simply a matter of invoking this system call from a user program. Ordinarily, the standard C library supports an interface for system calls defined for the Linux operating system. As your new system call is not linked into the standard C library, invoking your system call will require manual intervention.

As noted earlier, a system call is invoked by storing the appropriate value into a hardware register and performing a trap instruction. Unfortunately, these are low-level operations that cannot be performed using C language statements and instead require assembly instructions. Fortunately, Linux provides macros for instantiating wrapper functions that contain the appropriate assembly instructions. For instance, the following C program uses the `_syscall0()` macro to invoke the newly defined system call:

```
#include <linux/errno.h>
#include <sys/syscall.h>
#include <linux/unistd.h>

_syscall0(int, helloworld);

main()
{
  helloworld();
}
```

- The `_syscall0` macro takes two arguments. The first specifies the type of the value returned by the system call; the second argument is the name of the system call. The name is used to identify the system call number that is stored in the hardware register before the trap instruction is executed.

If your system call requires arguments, then a different macro (such as _syscall0, where the suffix indicates the number of arguments) could be used to instantiate the assembly code required for performing the system call.

- Compile and execute the program with the newly built kernel. There should be a message "hello world!" in the kernel log file /var/log/kernel/warnings to indicate that the system call has executed.

As a next step, consider expanding the functionality of your system call. How would you pass an integer value or a character string to the system call and have it be printed into the kernel log file? What are the implications for passing pointers to data stored in the user program's address space as opposed to simply passing an integer value from the user program to the kernel using hardware registers?

Bibliographical Notes

Dijkstra [1968] advocated the layered approach to operating-system design. Brinch-Hansen [1970] was an early proponent of constructing an operating system as a kernel (or nucleus) on which more complete systems can be built.

System instrumentation and dynamic tracing are described in Tamches and Miller [1999]. DTrace is discussed in Cantrill et al. [2004]. Cheung and Loong [1995] explored issues of operating-system structure from microkernel to extensible systems.

MS-DOS, Version 3.1, is described in Microsoft [1986]. Windows NT and Windows 2000 are described by Solomon [1998] and Solomon and Russinovich [2000]. BSD UNIX is described in McKusick et al. [1996]. Bovet and Cesati [2002] cover the Linux kernel in detail. Several UNIX systems—including Mach—are treated in detail in Vahalia [1996]. Mac OS X is presented at http://www.apple.com/macosx. The experimental Synthesis operating system is discussed by Massalin and Pu [1989]. Solaris is fully described in Mauro and McDougall [2001].

The first operating system to provide a virtual machine was the CP/67 on an IBM 360/67. The commercially available IBM VM/370 operating system was derived from CP/67. Details regarding Mach, a microkernel-based operating system, can be found in Young et al. [1987]. Kaashoek et al. [1997] present details regarding exokernel operating systems, where the architecture separates management issues from protection, thereby giving untrusted software the ability to exercise control over hardware and software resources.

The specifications for the Java language and the Java virtual machine are presented by Gosling et al. [1996] and by Lindholm and Yellin [1999], respectively. The internal workings of the Java virtual machine are fully described by Verniers [1998]. Golm et al. [2002] highlight the JX operating system; Back et al. [2000] cover several issues in the design of Java operating systems. More information on Java is available on the Web at http://www.javasoft.com. Details about the implementation of VMware can be found in Sugerman et al. [2001].

Part Two

Process Management

A *process* can be thought of as a program in execution, A process will need certain resources—such as CPU time, memory, files, and I/O devices —to accomplish its task. These resources are allocated to the process either when it is created or while it is executing.

A process is the unit of work in most systems. Systems consist of a collection of processes: Operating-system processes execute system code, and user processes execute user code. All these processes may execute concurrently.

Although traditionally a process contained only a single *thread* of control as it ran, most modern operating systems now support processes that have multiple threads.

The operating system is responsible for the following activities in connection with process and thread management: the creation and deletion of both user and system processes; the scheduling of processes; and the provision of mechanisms for synchronization, communication, and deadlock handling for processes.

Processes

Early computer systems allowed only one program to be executed at a time. This program had complete control of the system and had access to all the system's resources. In contrast, current-day computer systems allow multiple programs to be loaded into memory and executed concurrently. This evolution required firmer control and more compartmentalization of the various programs; and these needs resulted in the notion of a process, which is a program in execution. A process is the unit of work in a modern time-sharing system.

The more complex the operating system is, the more it is expected to do on behalf of its users. Although its main concern is the execution of user programs, it also needs to take care of various system tasks that are better left outside the kernel itself. A system therefore consists of a collection of processes: operating-system processes executing system code and user processes executing user code. Potentially, all these processes can execute concurrently, with the CPU (or CPUs) multiplexed among them. By switching the CPU between processes, the operating system can make the computer more productive.

CHAPTER OBJECTIVES

- To introduce the notion of a process — a program in execution, which forms the basis of all computation.
- To describe the various features of processes, including scheduling, creation and termination, and communication.
- To describe communication in client-server systems.

3.1 Process Concept

A question that arises in discussing operating systems involves what to call all the CPU activities. A batch system executes *jobs*, whereas a time-shared system has *user programs*, or *tasks*. Even on a single-user system such as Microsoft Windows, a user may be able to run several programs at one time: a word processor, a web browser, and an e-mail package. Even if the user can execute only one program at a time, the operating system may need to suppoft its own internal programmed activities, such as memory management. In many respects, all these activities are similar, so we call all of them *processes.*

The terms *job* and *process* are used almost interchangeably in this text. Although we personally prefer the term *process,* much of operating-system theory and terminology was developed during a time when the major activity of operating systems was job processing. It would be misleading to avoid the use of commonly accepted terms that include the word *job* (such as *job scheduling)* simply because *process* has superseded *job.*

3.1.1 The Process

Informally, as mentioned earlier, a process is a program in execution. A process is more than the program code, which is sometimes known as the **text section.** It also includes the current activity, as represented by the value of the **program counter** and the contents of the processor's registers. A process generally also includes the process **stack,** which contains temporary data (such as function parameters, return addresses, and local variables), and a **data section,** which contains global variables. A process may also include a **heap,** which is memory that is dynamically allocated during process run time. The structure of a process in memory is shown in Figure 3.1.

We emphasize that a program by itself is not a process; a program is a *passive* entity, such as a file containing a list of instructions stored on disk (often called an **executable file),** whereas a process is an *active* entity, with a program counter specifying the next instruction to execute and a set of associated resources. A program becomes a process when an executable file is loaded into memory. Two common techniques for loading executable files are double-clicking an icon representing the executable file and entering the name of the executable file on the command line (as in `prog.` exe or `a.` out.)

Although two processes may be associated with the same program, they are nevertheless considered two separate execution sequences. For instance,

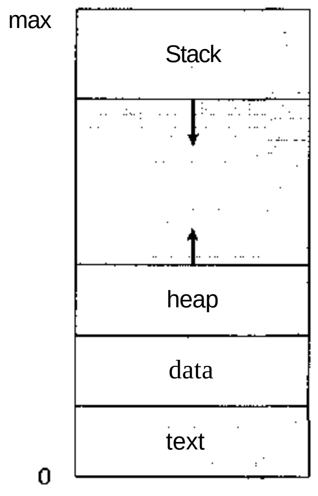


Figure 3.1 Process in memory.

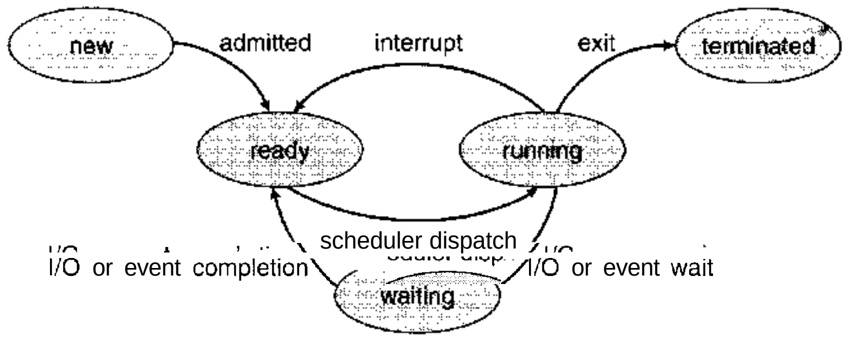


Figure 3.2 Diagram of process state.

several users may be running different copies of the mail program, or the same user may invoke many copies of the web browser program. Each of these is a separate process; and although the text sections are equivalent, the data, heap, and stack sections vary. It is also common to have a process that spawns many processes as it runs. We discuss such matters in Section 3.4.

3.1.2 Process State

As a process executes, it changes **state.** The state of a process is defined in part by the current activity of that process. Each process may be in one of the following states:

- **New.** The process is being created.
- **Running.** Instructions are being executed.
- **Waiting.** The process is waiting for some event to occur (such as an I/O completion or reception of a signal).
- **Ready.** The process is waiting to be assigned to a processor.
- **Terminated.** The process has finished execution.

These names are arbitrary, and they vary across operating systems. The states that they represent are found on all systems, however. Certain operating systems also more finely delineate process states. It is important to realize that only one process can be *running* on any processor at any instant. Many processes may be *ready* and *limiting,* however. The state diagram corresponding to these states is presented in Figure 3.2.

3.1.3 Process Control Block

Each process is represented in the operating system by a **process control block** (PCB)—also called a *task control block.* A PCB is shown in Figure 3.3. It contains many pieces of information associated with a specific process, including these:

- **Process state.** The state may be new, ready, running, waiting, halted, and so on.

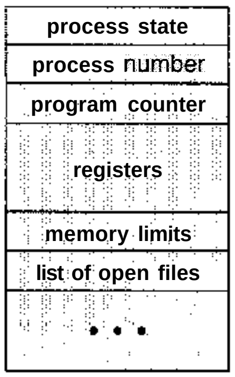


Figure 3.3 Process control block (PCB).

- **Program counter.** The counter indicates the address of the next instruction to be executed for this process.
- CPU **registers.** The registers vary in number and type, depending on the computer architecture. They include accumulators, index registers, stack pointers, and general-purpose registers, plus any condition-code information. Along with the program counter, this state information must be saved when an interrupt occurs, to allow the process to be continued correctly afterward (Figure 3.4).
- **CPU-scheduling information**. This information includes a process priority, pointers to scheduling queues, and any other scheduling parameters. (Chapter 5 describes process scheduling.)
- **Memory-management information.** This information may include such information as the value of the base and limit registers, the page tables, or the segment tables, depending on the memory system used by the operating system (Chapter 8).
- **Accounting information.** This information includes the amount of CPU and real time used, time limits, account numbers, job or process numbers, and so on.
- I/O **status information.** This information includes the list of I/O devices allocated to the process, a list of open files, and so on.

In brief, the PCB simply serves as the repository for any information that may vary from process to process.

3.1.4 Threads

The process model discussed so far has implied that a process is a program that performs a single **thread** of execution. For example, when a process is running a word-processor program, a single thread of instructions is being executed. This single thread of control allows the process to perform only one task at one time. The user cannot simultaneously type in characters and run the spell checker within the same process, for example. Many modern operating systems have extended the process concept to allow a process to have multiple

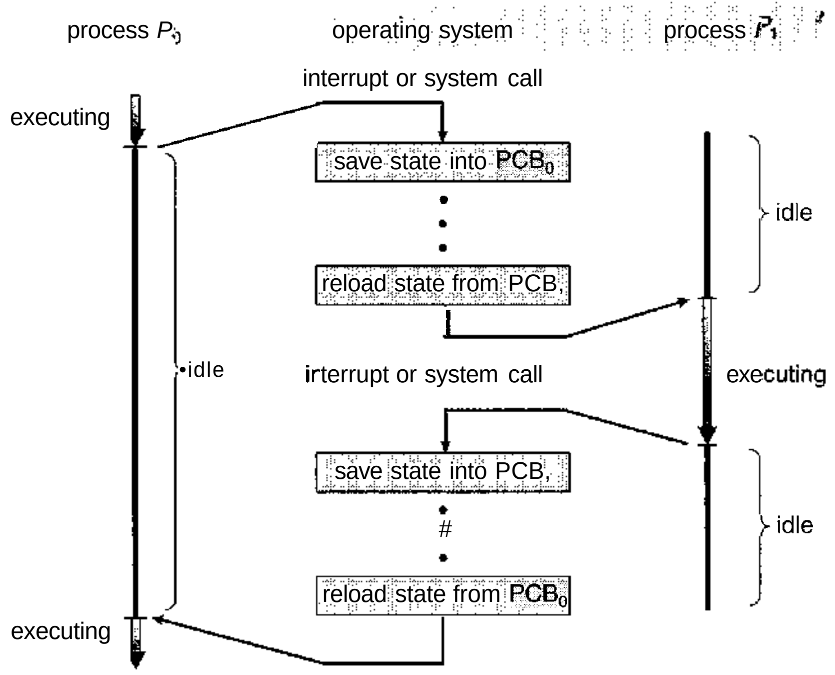


Figure 3.4 Diagram showing CPU switch from process to process.

threads of execution and thus to perform more than one task at a time. Chapter 4 explores multithreaded processes in detail.

3.2 Process Scheduling

The objective of multiprogramming is to have some process running at all times, to maximize CPU utilization. The objective of time sharing is to switch the CPU among processes so frequently that users can interact with each program while it is running. To meet these objectives, the **process scheduler** selects an available process (possibly from a set of several available processes) for program execution on the CPU. For a single-processor system, there will never be more than one running process. If there are more processes, the rest will have to wait until the CPU is free and can be rescheduled.

3.2.1 Scheduling Queues

As processes enter the system, they are put into a **job queue,** which consists of all processes in the system. The processes that are residing in main memory and are ready and waiting to execute are kept on a list called the **ready queue.** This queue is generally stored as a linked list. A ready-queue header contains pointers to the first and final PCBs in the list. Each PCB includes a pointer field that points to the next PCB in the ready queue.

The system also includes other queues. When a process is allocated the CPU, it executes for a while and eventually quits, is interrupted, or waits for the occurrence of a particular event, such as the completion of an I/O request.

PROCESS REPRESENTATION IN LINUX

The process control block in the Linux operating system is represented by the C structure `task_struct`. This structure contains all the necessary information for representing a process, including the state of the process, scheduling and memory management information, list of open files, and pointers to the process's parent and any of its children. (A process's *parent* is the process that created it; its *children* are any processes that it creates.) Some of these fields include:

```
pid_t pid; /* process identifier */
long state; /* state of the process */
unsigned int time_slice /* scheduling information */
struct files_struct *files; /* list of open files */
struct mm_struct *mm; /*• address space of this process */
```

For example, the state of a process is represented by the field `long state` in this structure. Within the Linux kernel, all active processes are represented using a doubly linked list of `task_struct`, and the kernel maintains a pointer — `current` — to the process currently executing on the system. This is shown in Figure 3.5.

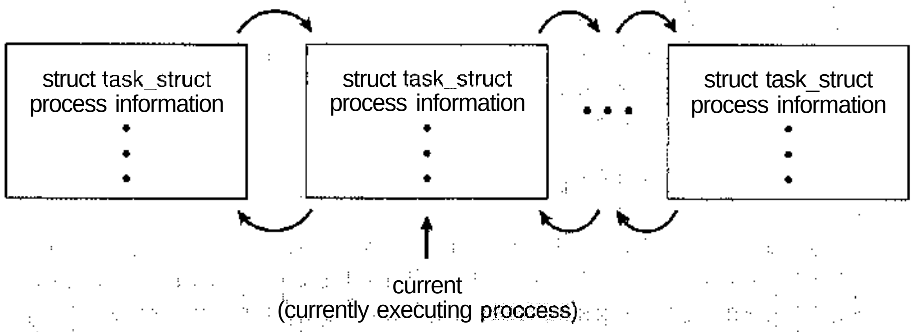


Figure 3.5 Active processes in Linux.

As an illustration of how the kernel might manipulate one of the fields in the `task_struct` for a specified process, let's assume the system would like to change the state of the process currently running to the value `new_state`. If `current` is a pointer to the process currently executing, its state is changed with the following:

```
current->state = new_state;
```

Suppose the process makes an I/O request to a shared device, such as a disk. Since there are many processes in the system, the disk may be busy with the I/O request of some other process. The process therefore may have to wait for the disk. The list of processes waiting for a particular I/O device is called a device **queue.** Each device has its own device queue (Figure 3.6).

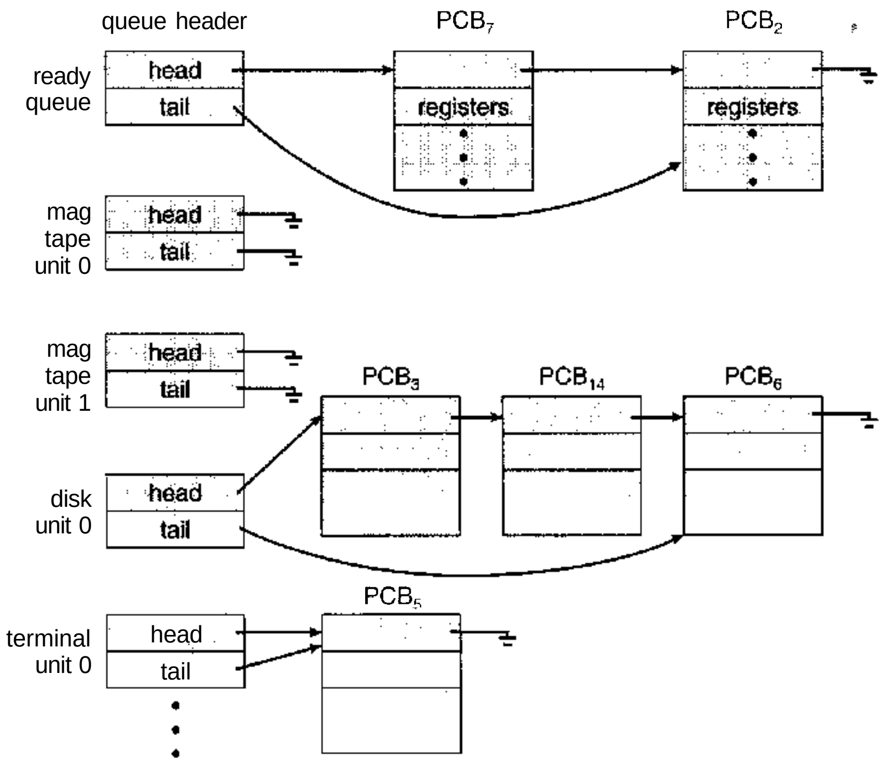


Figure 3.6 The ready queue and various I/O device queues.

A common representation for a discussion of process scheduling is a **queueing diagram,** such as that in Figure 3.7. Each rectangular box represents a queue. Two types of queues are present: the ready queue and a set of device queues. The circles represent the resources that serve the queues, and the arrows indicate the flow of processes in the system.

A new process is initially put in the ready queue. It waits there until it is selected for execution, or is **dispatched.** Once the process is allocated the CPU and is executing, one of several events could occur:

- The process could issue an I/O request and then be placed in an I/O queue.
- The process could create a new subprocess and wait for the subprocess's termination.
- The process could be removed forcibly from the CPU, as a result of an interrupt, and be put back in the ready queue.

In the first two cases, the process eventually switches from the waiting state to the ready state and is then put back in the ready queue. A process continues this cycle until it terminates, at which time it is removed from all queues and has its PCB and resources deallocated.

3.2.2 Schedulers

A process migrates among the various scheduling queues throughout its lifetime. The operating system must select, for scheduling purposes, processes

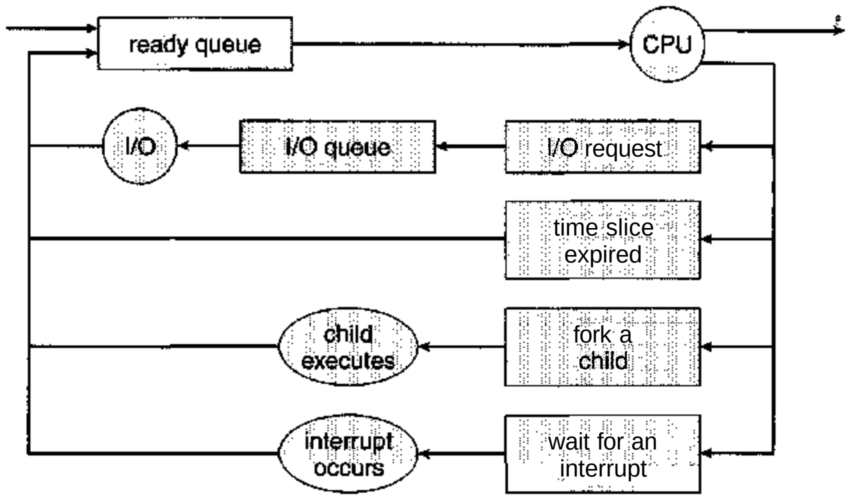


Figure 3.7 Queueing-diagram representation of process scheduling.

from these queues in some fashion. The selection process is carried out by the appropriate **scheduler.**

Often, in a batch system, more processes are submitted than can be executed immediately. These processes are spooled to a mass-storage device (typically a disk), where they are kept for later execution. The **long-term scheduler,** or **job scheduler,** selects processes from this pool and loads them into memory for execution. The **short-term scheduler, or** CPU **scheduler,** selects from among the processes that are ready to execute and allocates the CPU to one of them.

The primary distinction between these two schedulers lies in frequency of execution. The short-term scheduler must select a new process for the CPU frequently. A process may execute for only a few milliseconds before waiting for an I/O request. Often, the short-term scheduler executes at least once every 100 milliseconds. Because of the short time between executions, the short-term scheduler must be fast. If it takes 10 milliseconds to decide to execute a process for 100 milliseconds, then 10/(100 + 10) = 9 percent of the CPU is being used (wasted) simply for scheduling the work.

The long-term scheduler executes much less frequently; minutes may separate the creation of one new process and the next. The long-term scheduler controls the **degree of multiprogramming** (the number of processes in memory). If the degree of multiprogramming is stable, then the average rate of process creation must be equal to the average departure rate of processes leaving the system. Thus, the long-term scheduler may need to be invoked only when a process leaves the system. Because of the longer interval between executions, the long-term scheduler can afford to take more time to decide which process should be selected for execution.

It is important that the long-term scheduler make a careful selection. In general, most processes can be described as either I/O bound or CPU bound. An **I/O-bound process** is one that spends more of its time doing I/O than it spends doing computations. A **CPU-bound process,** in contrast, generates I/O requests infrequently, using more of its time doing computations. It is important that the long-term scheduler select a good **process mix** of I/O-bound and CPU-bound

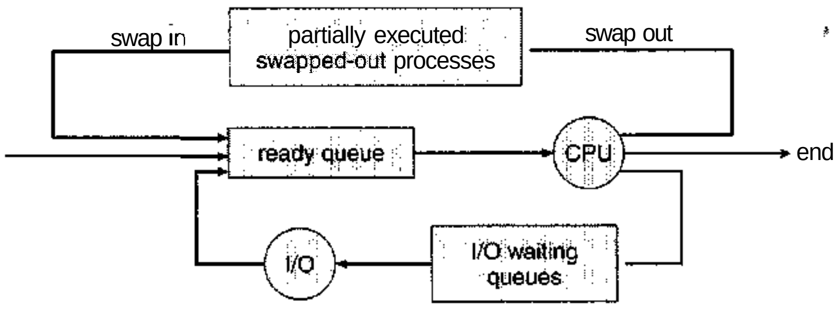


Figure 3.8 Addition of medium-term scheduling to the queueing diagram.

processes. If all processes are I/O bound, the ready queue will almost always be empty, and the short-term scheduler will have little to do. If all processes are CPU bound, the I/O waiting queue will almost always be empty, devices will go unused, and again the system will be unbalanced. The system with the best performance will thus have a combination of CPU-bound and I/O-bound processes.

On some systems, the long-term scheduler may be absent or minimal. For example, time-sharing systems such as UNIX and Microsoft Windows systems often have no long-term scheduler but simply put every new process in memory for the short-term scheduler. The stability of these systems depends either on a physical limitation (such as the number of available terminals) or on the self-adjusting nature of human users. If the performance declines to unacceptable levels on a multiuser system, some users will simply quit.

Some operating systems, such as time-sharing systems, may introduce an additional, intermediate level of scheduling. This **medium-term scheduler** is diagrammed in Figure 3.8. The key idea behind a medium-term scheduler is that sometimes it can be advantageous to remove processes from memory (and from active contention for the CPU) and thus reduce the degree of multiprogramming. Later, the process can be reintroduced into memory, and its execution can be continued where it left off. This scheme is called swapping. The process is swapped out, and is later swapped in, by the medium-term scheduler. Swapping may be necessary to improve the process mix or because a change in memory requirements has overcommitted available memory, requiring memory to be freed up. Swapping is discussed in Chapter 8.

3.2.3 Context Switch

As mentioned in 1.2.1, interrupts cause the operating system to change a CPU from its current task and to run a kernel routine. Such operations happen frequently on general-purpose systems. When an interrupt occurs, the system needs to save the current **context** of the process currently running on the CPU so that it can restore that context when its processing is done, essentially suspending the process and then resuming it. The context is represented in the PCB of the process; it includes the value of the CPU registers, the process state (see Figure 3.2), and memory-management information. Generically, we perform a **state save** of the current state of the CPU, be it in kernel or user mode, and then a **state restore** to resume operations.

Switching the CPU to another process requires performing a state save of the current process and a state restore of a different process. This task is known as a **context switch.** When a context switch occurs, the kernel saves the context of the old process in its PCB and loads the saved context of the new process scheduled to run. Context-switch time is pure overhead, because the system does no useful work while switching. Its speed varies from machine to machine, depending on the memory speed, the number of registers that must be copied, and the existence of special instructions (such as a single instruction to load or store all registers). Typical speeds are a few milliseconds.

Context-switch times are highly dependent on hardware support. For instance, some processors (such as the Sun UltraSPARC) provide multiple sets of registers. A context switch here simply requires changing the pointer to the current register set. Of course, if there are more active processes than there are register sets, the system resorts to copying register data to and from memory, as before. Also, the more complex the operating system, the more work must be done during a context switch. As we will see in Chapter 8, advanced memory-management techniques may require extra data to be switched with each context. For instance, the address space of the current process must be preserved as the space of the next task is prepared for use. How the address space is preserved, and what amount of work is needed to preserve it, depend on the memory-management method of the operating system.

3.3 Operations on Processes

The processes in most systems can execute concurrently, and they may be created and deleted dynamically. Thus, these systems must provide a mechanism for process creation and termination. In this section, we explore the mechanisms involved in creating processes and illustrate process creation on UNIX and Windows systems.

3.3.1 Process Creation

A process may create several new processes, via a create-process system call, during the course of execution. The creating process is called a **parent** process, and the new processes are called the **children** of that process. Each of these new processes may in turn create other processes, forming a **tree** of processes.

Most operating systems (including UNIX and the Windows family of operating systems) identify processes according to a unique **process identifier** (or **pid),** which is typically an integer number. Figure 3.9 illustrates a typical process tree for the Solaris operating system, showing the name of each process and its pid. In Solaris, the process at the top of the tree is the sched process, with pid of 0. The sched process creates several children processes—including pageout and fsflush. These processes are responsible for managing memory and file systems. The sched process also creates the init process, which serves as the root parent process for all user processes. In Figure 3.9, we see two children of init—inetd and dtlogin. inetd is responsible for networking services such as telnet and ftp; dtlogin is the process representing a user login screen. When a user logs in, dtlogin creates an X-windows session (Xsession), which in turns creates the sdt_shel process. Below sdt_shel, a user's command-line shell—the C-shell or `csh`—is created. It is this command-line interface where the user then invokes various child processes, such as the `ls` and `cat` commands. We also see a csh process with pid of 7778 representing a user who has logged onto the system using `telnet`. This user has started the Netscape browser (pid of 7785) and the emacs editor (pid of 8105).

On UNIX, a listing of processes can be obtained using the ps command. For example, entering the command `ps -el` will list complete information for all processes currently active in the system. It is easy to construct a process tree similar to what is shown in Figure 3.9 by recursively tracing parent processes all the way to the `init` process.

In general, a process will need certain resources (CPU time, memory, files, I/O devices) to accomplish its task. When a process creates a subprocess, that subprocess may be able to obtain its resources directly from the operatiiig system, or it may be constrained to a subset of the resources of the parent process. The parent may have to partition its resources among its children, or it may be able to share some resources (such as memory or files) among several of its children. Restricting a child process to a subset of the parent's resources prevents any process from overloading the system by creating too many subprocesses.

In addition to the various physical and logical resources that a process obtains when it is created, initialization data (input) may be passed along by the parent process to the child process. For example, consider a process whose function is to display the contents of a file—say, *img.jpg*—on the screen of a

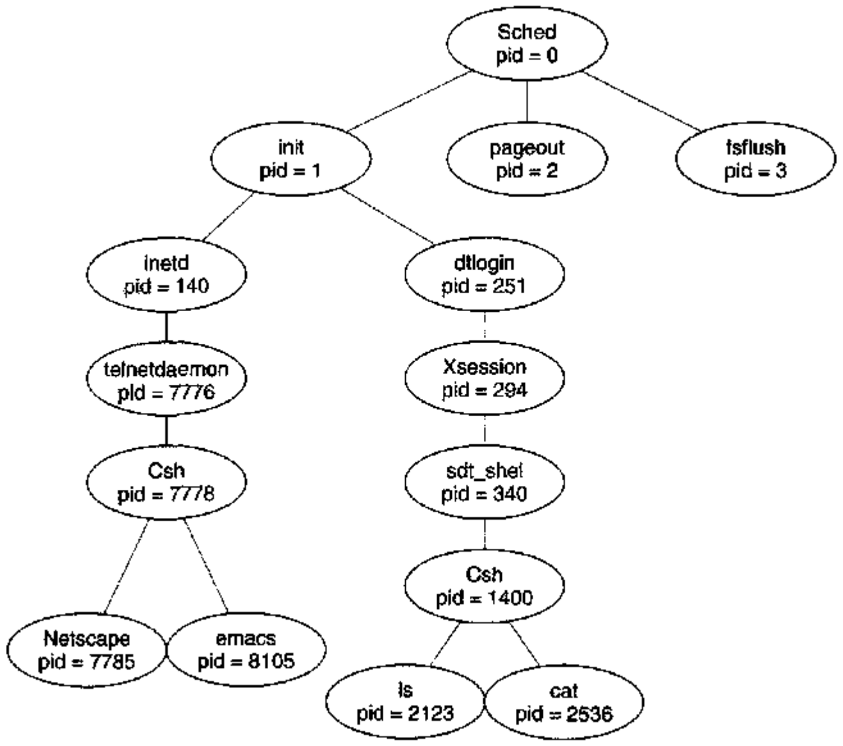


Figure 3.9 A tree of processes on a typical Solaris system.

terminal. When it is created, it will get, as an input from its parent process, the name of the file *img.jpg*, and it will use that file name, open the file, and write the contents out. It may also get the name of the output device. Some operating systems pass resources to child processes. On such a system, the new process may get two open files, *img.jpg* and the terminal device, and may simply transfer the datum between the two.

When a process creates a new process, two possibilities exist in terms of execution:

1. The parent continues to execute concurrently with its children.
2. The parent waits until some or all of its children have terminated.

There are also two possibilities in terms of the address space of the new process:

1. The child process is a duplicate of the parent process (it has the same program and data as the parent).
2. The child process has a new program loaded into it.

To illustrate these differences, let's first consider the UNIX operating system. In UNIX, as we've seen, each process is identified by its process identifier,

```
#include <sys/types.h>
#include <stdio.h>
#include <unistd.h>

int main()
{
pid_t pid;

    /* fork a child process */
    pid = fork();

    if (pid < 0) {/* error occurred */
      fprintf(stderr, "Fork Failed");
      exit(-1);
    }
    else if (pid == 0} {/* child process */
      execlp("/bin/ls","ls",NULL);
    }
    else {/* parent process */
      /* parent will wait for the child to complete */
      wait(NULL);
      printf("Child Complete");
      exit(0);
    }
}
```

Figure 3.10 C program forking a separate process.

which is a unique integer. A new process is created by the fork() system call. The new process consists of a copy of the address space of the original process. This mechanism allows the parent process to communicate easily with its child process. Both processes (the parent and the child) continue execution at the instruction after the fork(), with one difference: The return code for the fork() is zero for the new (child) process, whereas the (nonzero) process identifier of the child is returned to the parent.

Typically, the exec() system call is used after a forkO system call by one of the two processes to replace the process's memory space with a new program. The exec () system call loads a binary file into memory (destroying the memory image of the program containing the exec() system call) and starts its execution. In this manner, the two processes are able to communicate and then go their separate ways. The parent can then create more children; or, if it has nothing else to do while the child runs, it can issue a wait () system call to move itself off the ready queue until the termination of the child.

The C program shown in Figure 3.10 illustrates the UNIX system calls previously described. We now have two different processes running a copy of the same program. The value of pid for the child process is zero; that for the parent is an integer value greater than zero. The child process overlays its address space with the UNIX command /bin/ls (used to get a directory listing) using the execlpO system call (execlpO is a version of the execO system call). The parent waits for the child process to complete with the wait () system call. When the child process completes (by either implicitly or explicitly invoking exit ()) the parent process resumes from the call to wait (), where it completes using the exit () system call. This is also illustrated in Figure 3.11.

As an alternative example, we next consider process creation in Windows. Processes are created in the Win32 API using the CreateProcess() function, which is similar to f ork () in that a parent creates a new child process. However, whereas fork () has the child process inheriting the address space of its parent, CreateProcess () requires loading a specified program into the address space of the child process at process creation. Furthermore, whereas f ork () is passed no parameters, CreateProcess 0 expects no fewer than ten parameters.

The C program shown in Figure 3.12 illustrates the CreateProcess() function, which creates a child process that loads the application mspaint.exe. We opt for many of the default values of the ten parameters passed to CreateProcess(). Readers interested in pursuing the details on process creation and management in the Win32 API are encouraged to consult the bibliographical notes at the end of this chapter.

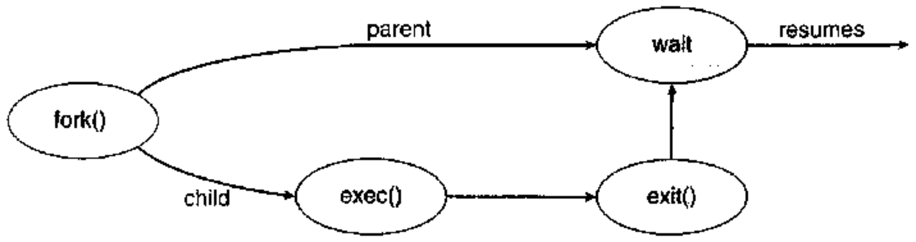


Figure 3.11 Process creation.

```
#include <stdio.h>
#include <windows.h>

int main(VOID)
{
STARTUPINFO si;
PROCESS_INFORMATION pi;

   // allocate memory
   ZeroMemory(&si, sizeof(si));
   si.cb = sizeof(si);
   ZeroMemory(&pi, sizeof(pi));

   // create child process
   if (!CreateProcess(NULL, // use command line
     "C:\\WINDOWS\\system32\\mspaint.exe", // command line
     NULL, // don't inherit process handle
     NULL, // don't inherit thread handle
     FALSE, // disable handle inheritance
     0, //no creation flags
     NULL, // use parent's environment block
     NULL, // use parent's existing directory
     &si,
     &pi))
   {
     fprintf(stderr, "Create Process Failed");
     return -1;
   }
   // parent will wait for the child to complete
   WaitForSingleObject(pi.hProcess, INFINITE);
   printf("Child Complete");

   // close handles
   CloseHandle(pi.hProcess);
   CloseHandle(pi.hThread);
}
```

Figure 3.12 Creating a separate process using the Win32 API.

Two parameters passed to CreateProcess () are instances of the STARTUPINFO and PROCESSJNFORMATION structures. STARTUPINFO specifies many properties of the new process, such as window size and appearance and handles to standard input and output files. The PROCESSJNFORMATION structure contains a handle and the identifiers to the newly created process and its thread. We invoke the ZeroMemoryO function to allocate memory for each of these structures before proceeding with CreateProcess ().

The first two parameters passed to CreateProcess () are the application name and command line parameters. If the application name is NULL (which in this case it is), the command line parameter specifies the application to load. In this instance we are loading the Microsoft Windows *mspaint.exe* application. Beyond these two initial parameters, we use the default parameters for inheriting process and thread handles as well as specifying no creation flags. We also use the parent's existing environment block and starting directory. Last, we provide two pointers to the STARTUPINFO and PROCESS-INFORMATION structures created at the beginning of the program. In Figure 3.10, the parent process waits for the child to complete by invoking the `wait()` system call. The equivalent of this in Win32 is `WaitForSingleObject()`, which is passed a handle of the child process—`pi.hProcess`—that it is waiting for to complete. Once the child process exits, control returns from the `WaitForSingleObject()` function in the parent process.

3.3.2 Process Termination

A process terminates when it finishes executing its final statement and asks the operating system to delete it by using the `exit()` system call. At that point, the process may return a status value (typically an integer) to its parent process (via the `wait()` system call). All the resources of the process—including physical and virtual memory, open files, and I/O buffers—are deallocated by the operating system.

Termination can occur in other circumstances as well. A process can cause the termination of another process via an appropriate system call (for example, `TerminateProcess()` in Win32). Usually, such a system call can be invoked only by the parent of the process that is to be terminated. Otherwise, users could arbitrarily kill each other's jobs. Note that a parent needs to know the identities of its children. Thus, when one process creates a new process, the identity of the newly created process is passed to the parent.

A parent may terminate the execution of one of its children for a variety of reasons, such as these:

- The child has exceeded its usage of some of the resources that it has been allocated. (To determine whether this has occurred, the parent must have a mechanism to inspect the state of its children.)
- The task assigned to the child is no longer required.
- The parent is exiting, and the operating system does not allow a child to continue if its parent terminates.

Some systems, including VMS, do not allow a child to exist if its parent has terminated. In such systems, if a process terminates (either normally or abnormally), then all its children must also be terminated. This phenomenon, referred to as cascading termination, is normally initiated by the operating system.

To illustrate process execution and termination, consider that, in UNIX, we can terminate a process by using the `exit()` system call; its parent process may wait for the termination of a child process by using the `wait()` system call. The `wait()` system call returns the process identifier of a terminated child so that the parent can tell which of its possibly many children has terminated. If the parent terminates, however, all its children have assigned as their new parent the `init` process. Thus, the children still have a parent to collect their status and execution statistics.

3.4 Interprocess Communication

Processes executing concurrently in the operating system may be either independent processes or cooperating processes. A process is **independent** if it cannot affect or be affected by the other processes executing in the system. Any process that does not share data with any other process is independent. A process is **cooperating** if **it** can affect or be affected by the other processes executing in the system. Clearly, any process that shares data with other processes is a cooperating process.

There are several reasons for providing an environment that allows process cooperation:

- **Information sharing.** Since several users may be interested in the same piece of information (for instance, a shared file), we must provide an environment to allow concurrent access to such information.
- **Computation speedup.** If we want a particular task to run faster, we must break it into subtasks, each of which will be executing in parallel with the others. Notice that such a speedup can be achieved only if the computer has multiple processing elements (such as CPUs or I/O channels).
- **Modularity.** We may want to construct the system in a modular fashion, dividing the system functions into separate processes or threads, as we discussed in Chapter 2.
- **Convenience.** Even an individual user may work on many tasks at the same time. For instance, a user may be editing, printing, and compiling in parallel.

Cooperating processes require an **interprocess communication** (IPC) mechanism that will allow them to exchange data and information. There are two fundamental models of interprocess communication: **(1) shared memory** and (2) **message passing.** In the shared-memory model, a region of memory that is shared by cooperating processes is established. Processes can then exchange information by reading and writing data to the shared region. In the message-passing model, communication takes place by means of messages exchanged between the cooperating processes. The two communications models are contrasted in Figure 3.13.

Both of the models just discussed are common in operating systems, and many systems implement both. Message passing is useful for exchanging smaller amounts of data, because no conflicts need be avoided. Message passing is also easier to implement than is shared memory for intercomputer communication. Shared memory allows maximum speed and convenience of communication, as it can be done at memory speeds when within a computer. Shared memory is faster than message passing, as message-passing systems are typically implemented using system calls and thus require the more time-consuming task of kernel intervention. In contrast, in shared-memory systems, system calls are required only to establish shared-memory regions. Once shared memory is established, all accesses are treated as routine memory accesses, and no assistance from the kernel is required. In the remainder of this section, we explore each of these IPC models in more detail.

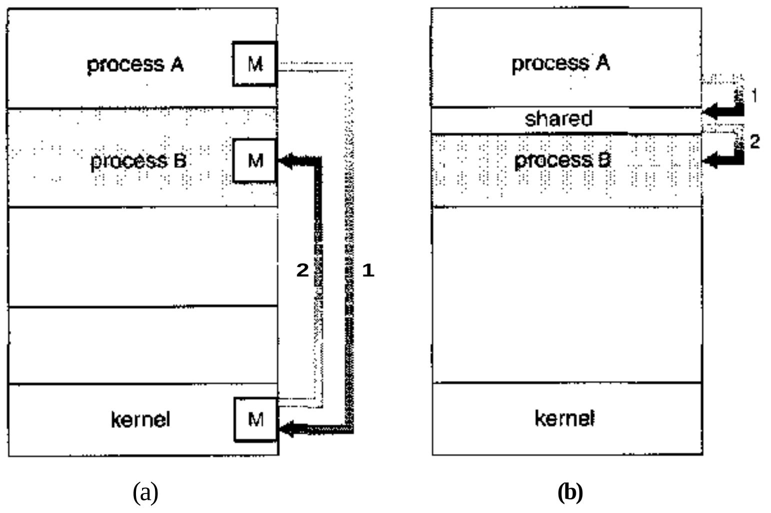


Figure 3.13 Communications models. (a) Message passing. (b) Shared memory.

3.4.1 Shared-Memory Systems

Interprocess communication using shared memory requires communicating processes to establish a region of shared memory. Typically, a shared-memory region resides in the address space of the process creating the shared-memory segment. Other processes that wish to communicate using this shared-memory segment must attach it to their address space. Recall that, normally, the operating system tries to prevent one process from accessing another process's memory. Shared memory requires that two or more processes agree to remove this restriction. They can then exchange information by reading and writing data in the shared areas. The form of the data and the location are determined by these processes and are not under the operating system's control. The processes are also responsible for ensuring that they are not writing to the same location simultaneously.

To illustrate the concept of cooperating processes, let's consider the producer-consumer problem, which is a common paradigm for cooperating processes. A **producer** process produces information that is consumed by a **consumer** process. For example, a compiler may produce assembly code, which is consumed by an assembler. The assembler, in turn, may produce object modules, which are consumed by the loader. The producer-consumer problem also provides a useful metaphor for the client-server paradigm. We generally think of a server as a producer and a client as a consumer. For example, a web server produces (that is, provides) HTML files and images, which are consumed (that is, read) by the client web browser requesting the resource.

One solution to the producer-consumer problem uses shared memory. To allow producer and consumer processes to run concurrently, we must have available a buffer of items that can be filled by the producer and emptied by the consumer. This buffer will reside in a region of memory that is shared by the producer and consumer processes. A producer can produce one item while the consumer is consuming another item. The producer and consumer must be synchronized, so that the consumer does not try to consume an item that has not yet been produced.

Two types of buffers can be used. The **unbounded buffer** places no practical limit on the size of the buffer. The consumer may have to wait for new items, but the producer can always produce new items. The **bounded buffer** assumes a fixed buffer size. In this case, the consumer must wait if the buffer is empty, and the producer must wait if the buffer is full.

Let's look more closely at how the bounded buffer can be used to enable processes to share memory. The following variables reside in a region of memory shared by the producer and consumer processes:

```
#define BUFFER_SIZE 10

typedef struct {
    . . .
}item;

item buffer[BUFFER_SIZE];
int in = 0;
int out = 0;
```

The shared buffer is implemented as a circular array with two logical pointers: in and out. The variable in points to the next free position in the buffer; out points to the first full position in the buffer. The buffer is empty when in == out; the buffer is full when ((in + 1) % BUFFER_SIZE) == out.

The code for the producer and consumer processes is shown in Figures 3.14 and 3.15, respectively. The producer process has a local variable nextProduced in which the new item to be produced is stored. The consumer process has a local variable nextConsumed in which the item to be consumed is stored.

This scheme allows at most BUFFER_SIZE − 1 items in the buffer at the same time. We leave it as an exercise for you to provide a solution where BUFFER_SIZE items can be in the buffer at the same time. In Section 3.5.1, we illustrate the POSIX API for shared memory.

One issue this illustration does not address concerns the situation in which both the producer process and the consumer process attempt to access the shared buffer concurrently. In Chapter 6, we discuss how synchronization among cooperating processes can be implemented effectively in a shared-memory environment.

```
item nextProduced;

while (true) {
     /* produce an item in nextProduced */
     while (((in + 1) % BUFFER-SIZE) == out)
        ; /* do nothing */
     buffer[in] = nextProduced;
     in = (in + 1) % BUFFER_SIZE;
}
```

Figure 3.14 The producer process.

```
item nextConsumed;

while (true) {
     while (in == out)
        ; //do nothing

     nextConsumed = buffer[out];
     out = (out + 1) % BUFFER_SIZE;
     /* consume the item in nextConsumed */
}
```

Figure 3.15 The consumer process.

3.4.2 Message-Passing Systems

In Section 3.4.1, we showed how cooperating processes can communicate in a shared-memory environment. The scheme requires that these processes share a region of memory and that the code for accessing and manipulating the shared memory be written explicitly by the application programmer. Another way to achieve the same effect is for the operating system to provide the means for cooperating processes to communicate with each other via a message-passing facility.

Message passing provides a mechanism to allow processes to communicate and to synchronize their actions without sharing the same address space and is particularly useful in a distributed environment, where the communicating processes may reside on different computers connected by a network. For example, a **chat** program used on the World Wide Web could be designed so that chat participants communicate with one another by exchanging messages.

A message-passing facility provides at least two operations: send(message) and receive(message). Messages sent by a process can be of either fixed or variable size. If only fixed-sized messages can be sent, the system-level implementation is straightforward. This restriction, however, makes the task of programming more difficult. Conversely, variable-sized messages require a more complex system-level implementation, but the programming task becomes simpler. This is a common kind of tradeoff seen throughout operating system design.

If processes *P* and *Q* want to communicate, they must send messages to and receive messages from each other; a **communication link** must exist between them. This link can be implemented in a variety of ways. We are concerned here not with the link's physical implementation (such as shared memory, hardware bus, or network, which are covered in Chapter 16) but rather with its logical implementation. Here are several methods for logically implementing a link and the send()/receive() operations:

- Direct or indirect communication
- Synchronous or asynchronous communication
- Automatic or explicit buffering

We look at issues related to each of these features next.

3.4.2.1 Naming

Processes that want to communicate must have a way to refer to each other. They can use either direct or indirect communication.

Under direct communication, each process that wants to communicate must explicitly name the recipient or sender of the communication. In this scheme, the send() and receive() primitives are defined as:

- send(P, message)—Send a message to process P.
- receive(Q, message)—Receive a message from process Q.

A communication link in this scheme has the following properties:

- A link is established automatically between every pair of processes that want to communicate. The processes need to know only each other's identity to communicate.
- A link is associated with exactly two processes.
- Between each pair of processes, there exists exactly one link.

This scheme exhibits *symmetry* in addressing; that is, both the sender process and the receiver process must name the other to communicate. A variant of this scheme employs *asymmetry* in addressing. Here, only the sender names the recipient; the recipient is not required to name the sender. In this scheme, the send() and receive () primitives are defined as follows:

- send(P, message)—Send a message to process P.
- receive(id, message)—Receive a message from any process; the variable *id* is set to the name of the process with which communication has taken place.

The disadvantage in both of these schemes (symmetric and asymmetric) is the limited modularity of the resulting process definitions. Changing the identifier of a process may necessitate examining all other process definitions. All references to the old identifier must be found, so that they can be modified to the new identifier. In general, any such hard-coding techniques, where identifiers must be explicitly stated, are less desirable than techniques involving indirection, as described next.

With indirect communication, the messages are sent to and received from mailboxes, or ports. A mailbox can be viewed abstractly as an object into which messages can be placed by processes and from which messages can be removed. Each mailbox has a unique identification. For example, POSIX message queues use an integer value to identify a mailbox. In this scheme, a process can communicate with some other process via a number of different mailboxes. Two processes can communicate only if the processes have a shared mailbox, however. The sendC) and receive() primitives are defined as follows:

- send(A, message)—Send a message to mailbox A.
- receive(A, message)—Receive a message from mailbox A.

In this scheme, a communication link has the following properties:

- A link is established between a pair of processes only if both members of the pair have a shared mailbox.
- A link may be associated with more than two processes.
- Between each pair of communicating processes, there may be a number of different links, with each link corresponding to one mailbox.

Now suppose that processes P_1, P_2, and P_3 all share mailbox A Process P_1 sends a message to A, while both P_2 and P_3 execute a `receive()` from A Which process will receive the message sent by P_1? The answer depends on which of the following methods we choose:

- Allow a link to be associated with two processes at most.
- Allow at most one process at a time to execute a `receive()` operation.
- Allow the system to select arbitrarily which process will receive the message (that is, either P_2 or P_3, but not both, will receive the message). The system also may define an algorithm for selecting which process will receive the message (that is, *round robin* where processes take turns receiving messages). The system may identify the receiver to the sender.

A mailbox may be owned either by a process or by the operating system. If the mailbox is owned by a process (that is, the mailbox is part of the address space of the process), then we distinguish between the owner (who can only receive messages through this mailbox) and the user (who can only send messages to the mailbox). Since each mailbox has a unique owner, there can be no confusion about who should receive a message sent to this mailbox. When a process that owns a mailbox terminates, the mailbox disappears. Any process that subsequently sends a message to this mailbox must be notified that the mailbox no longer exists.

In contrast, a mailbox that is owned by the operating system has an existence of its own. It is independent and is not attached to any particular process. The operating system then must provide a mechanism that allows a process to do the following:

- Create a new mailbox.
- Send and receive messages through the mailbox.
- Delete a mailbox.

The process that creates a new mailbox is that mailbox's owner by default. Initially, the owner is the only process that can receive messages through this mailbox. However, the ownership and receiving privilege may be passed to other processes through appropriate system calls. Of course, this provision could result in multiple receivers for each mailbox.

3.4.2.2 Synchronization

Communication between processes takes place through calls to `send()` and `receive()` primitives. There are different design options for implementing each primitive. Message passing may be either **blocking** or **nonblocking**— also known as **synchronous** and **asynchronous.**

- **Blocking send.** The sending process is blocked until the message is received by the receiving process or by the mailbox.
- **Nonblocking send.** The sending process sends the message and resumes operation.
- **Blocking receive.** The receiver blocks until a message is available.
- **Nonblocking receive.** The receiver retrieves either a valid message or a null.

Different combinations of send() and receive() are possible. When both send() and receive() are blocking, we have a **rendezvous** between the sender and the receiver. The solution to the producer-consumer problem becomes trivial when we use blocking send() and receive() statements. The producer merely invokes the blocking send() call and waits until the message is delivered to either the receiver or the mailbox. Likewise, when the consumer invokes receive(), it blocks until a message is available.

Note that the concepts of synchronous and asynchronous occur frequently in operating-system I/O algorithms, as you will see throughout this text.

3.4.2.3 Buffering

Whether communication is direct or indirect, messages exchanged by communicating processes reside in a temporary queue. Basically, such queues can be implemented in three ways:

- **Zero capacity.** The queue has a maximum length of zero; thus, the link cannot have any messages waiting in it. In this case, the sender must block until the recipient receives the message.
- **Bounded capacity.** The queue has finite length *n;* thus, at most *n* messages can reside in it. If the queue is not full when a new message is sent, the message is placed in the queue (either the message is copied or a pointer to the message is kept), and the sender can continue execution without waiting. The links capacity is finite, however. If the link is full, the sender must block until space is available in the queue.
- **Unbounded capacity.** The queues length is potentially infinite; thus, any number of messages can wait in it. The sender never blocks.

The zero-capacity case is sometimes referred to as a message system with no buffering; the other cases are referred to as systems with automatic buffering.

3.5 Examples of IPC Systems

In this section, we explore three different IPC systems. We first cover the POSIX API for shared memory and then discuss message passing in the Mach operating system. We conclude with Windows XP, which interestingly uses shared memory as a mechanism for providing certain types of message passing.

3.5.1 An Example: POSIX Shared Memory

Several IPC mechanisms are available for POSIX systems, including shared memory and message passing. Here, we explore the POSIX API for shared memory.

A process must first create a shared memory segment using the shmget() system call (shmget() is derived from SHared Memory GET). The following example illustrates the use of shmget ():

```
segment_id = shmget(IPC_PRIVATE, size, SJRUSR | SJVVUSR) ;
```

This first parameter specifies the key (or identifier) of the shared-memory segment. If this is set to IPC_PRIVATE, a new shared-memory segment is created. The second parameter specifies the size (in bytes) of the shared memory segment. Finally, the third parameter identifies the mode, which indicates how the shared-memory segment is to be used—that is, for reading, writing, or both. By setting the mode to SJRUSR | SJVVUSR, we are indicating that the owner may read or write to the shared memory segment. A successful call to shmget () returns an integer identifier for the shared-memory segment. Other processes that want to use this region of shared memory must specify this identifier.

Processes that wish to access a shared-memory segment must attach it to their address space using the shmat() (SHared Memory ATtach) system call. The call to shmat () expects three parameters as well. The first is the integer identifier of the shared-memory segment being attached, and the second is a pointer location in memory indicating where the shared memory will be attached. If we pass a value of NULL, the operating system selects the location on the user's behalf. The third parameter identifies a flag that allows the shared-memory region to be attached in read-only or read-write mode; by passing a parameter of 0, we allow both reads and writes to the shared region.

The third parameter identifies a mode flag. If set, the mode flag allows the shared-memory region to be attached in read-only mode; if set to 0, the flag allows both reads and writes to the shared region. We attach a region of shared memory using shmat () as follows:

```
shared_memory = (char *) shmat(id, NULL, 0);
```

If successful, shmat () returns a pointer to the beginning location in memory where the shared-memory region has been attached.

Once the region of shared memory is attached to a process's address space, the process can access the shared memory as a routine memory access using the pointer returned from shmat (). In this example, shmat () returns a pointer to a character string. Thus, we could write to the shared-memory region as follows:

```
sprintf(shared_memory, "Writing to shared memory");
```

Other processes sharing this segment would see the updates to the shared-memory segment.

Typically, a process using an existing shared-memory segment first attaches the shared-memory region to its address space and then accesses (and possibly updates) the region of shared memory. When a process no longer requires access to the shared-memory segment, it detaches the segment from its address

```
#include <stdio.h>
#include <sys/shm.h>
#include <sys/stat.h>

int main()
{
/* the identifier for the shared memory segment */
int segment_id;=
/* a pointer to the shared memory segment */
char* shared_memory;
/* the size (in bytes) of the shared memory segment */
const int size = 4096;

   /* allocate a shared memory segment */
   segment_id = shmget(IPC_PRIVATE, size, S_IRUSR | S_IWUSR);

   /* attach the shared memory segment */
   shared_memory = (char *) shmat(segment_id, NULL, 0);

   /* write a message to the shared memory segment */
   sprintf(shared-memory, "Hi there!");

   /* now print out the string from shared memory */
   printf("*%s\n", shared_memory),•

   /* now detach the shared memory segment */
   shmdt(sharedLmemory);

   /* now remove the shared memory segment */
   shmctl(segment_id, IPC_RMID, NULL);

   return 0;
}
```

Figure 3.16 C program illustrating POSIX shared-memory API.

space. To detach a region of shared memory, the process can pass the pointer of the shared-memory region to the shmdt () system call, as follows:

shmdt(shared_memory);

Finally, a shared-memory segment can be removed from the system with the shmctl() system call, which is passed the identifier of the shared segment along with the flag IPC_RMID.

The program shown in Figure 3.16 illustrates the POSIX shared-memory API discussed above. This program creates a 4,096-byte shared-memory segment. Once the region of shared memory is attached, the process writes the message Hi There! to shared memory. After outputting the contents of the updated memory, it detaches and removes the shared-memory region. We provide further exercises using the POSIX shared memory API in the programming exercises at the end of this chapter.

3.5.2 An Example: Mach

As an example of a message-based operating system, we next consider the Mach operating system, developed at Carnegie Mellon University. We introduced Mach in Chapter 2 as part of the Mac OS X operating system. The Mach kernel supports the creation and destruction of multiple tasks, which are similar to processes but have multiple threads of control. Most communication in Mach—including most of the system calls and all intertask information—is carried out by *messages*. Messages are sent to and received from mailboxes, called *ports* in Mach.

Even system calls are made by messages. When a task is created, two special mailboxes—the Kernel mailbox and the Notify mailbox—are also created. The Kernel mailbox is used by the kernel to communicate with the task. The kernel sends notification of event occurrences to the Notify port. Only three system calls are needed for message transfer. The `msg_send()` call sends a message to a mailbox. A message is received via `msg_receive()`. Remote procedure calls (RPCs) are executed via `msg_rpc()`, which sends a message and waits for exactly one return message from the sender. In this way, the RPC models a typical subroutine procedure call but can work between systems—hence the term *remote*.

The `port_allocate()` system call creates a new mailbox and allocates space for its queue of messages. The maximum size of the message queue defaults to eight messages. The task that creates the mailbox is that mailbox's owner. The owner is also allowed to receive from the mailbox. Only one task at a time can either own or receive from a mailbox, but these rights can be sent to other tasks if desired.

The mailbox has an initially empty queue of messages. As messages are sent to the mailbox, the messages are copied into the mailbox. All messages have the same priority. Mach guarantees that multiple messages from the same sender are queued in first-in, first-out (FIFO) order but does not guarantee an absolute ordering. For instance, messages from two senders may be queued in any order.

The messages themselves consist of a fixed-length header followed by a variable-length data portion. The header indicates the length of the message and includes two mailbox names. One mailbox name is the mailbox to which the message is being sent. Commonly, the sending thread expects a reply; so the mailbox name of the sender is passed on to the receiving task, which can use it as a "return address."

The variable part of a message is a list of typed data items. Each entry in the list has a type, size, and value. The type of the objects specified in the message is important, since objects defined by the operating system—such as ownership or receive access rights, task states, and memory segments—may be sent in messages.

The send and receive operations themselves are flexible. For instance, when a message is sent to a mailbox, the mailbox may be full. If the mailbox is not full, the message is copied to the mailbox, and the sending thread continues. If the mailbox is full, the sending thread has four options:

1. Wait indefinitely until there is room in the mailbox.
2. Wait at most *n* milliseconds.

3. Do not wait at all but rather return immediately.

4. Temporarily cache a message. One message can be given to the operating system to keep, even though the mailbox to which it is being sent is full. When the message can be put in the mailbox, a message is sent back to the sender; only one such message to a full mailbox can be pending at any time for a given sending thread.

The final option is meant for server tasks, such as a line-printer driver. After finishing a request, such tasks may need to send a one-time reply to the task that had requested service; but they must also continue with other service requests, even if the reply mailbox for a client is full.

The receive operation must specify the mailbox or mailbox set from which a message is to be received- A **mailbox set** is a collection of mailboxes, as declared by the task, which can be grouped together and treated as one mailbox for the purposes of the task. Threads in a task can receive only from a mailbox or mailbox set for which the task has receive access. A `port_status()` system call returns the number of messages in a given mailbox. The receive operation attempts to receive from (1) any mailbox in a mailbox set or (2) a specific (named) mailbox. If no message is waiting to be received, the receiving thread can either wait at most *n* milliseconds or not wait at all.

The Mach system was especially designed for distributed systems, which we discuss in Chapters 16 through 18, but Mach is also suitable for single-processor systems, as evidenced by its inclusion in the Mac OS X system. The major problem with message systems has generally been poor performance caused by double copying of messages; the message is copied first from the sender to the mailbox and then from the mailbox to the receiver. The Mach message system attempts to avoid double-copy operations by using virtual-memory-management techniques (Chapter 9). Essentially, Mach maps the address space containing the sender's message into the receiver's address space. The message itself is never actually copied. This message-management technique provides a large performance boost but works for only intrasystem messages. The Mach operating system is discussed in an extra chapter posted on our website.

3.5.3 An Example: Windows XP

The Windows XP operating system is an example of modern design that employs modularity to increase functionality and decrease the time needed to implement new features. Windows XP provides support for multiple operating environments, or *subsystems*, with which application programs communicate via a message-passing mechanism. The application programs can be considered clients of the Windows XP subsystem server.

The message-passing facility in Windows XP is called the **local procedure-call (LPC)** facility. The LPC in Windows XP communicates between two processes on the same machine. It is similar to the standard RPC mechanism that is widely used, but it is optimized for and specific to Windows XP. Like Mach, Windows XP uses a port object to establish and maintain a connection between two processes. Every client that calls a subsystem needs a communication channel, which is provided by a port object and is never inherited. Windows XP uses two types of ports: connection ports and communication ports. They are really the same but are given different names according to how they are used. Connection ports are named *objects* and are visible to all processes; they give applications a way to set up communication channels (Chapter 22). The communication works as follows:

- The client opens a handle to the subsystem's connection port object.
- The client sends a connection request.
- The server creates two private communication ports and returns the handle to one of them to the client.
- The client and server use the corresponding port handle to send messages or callbacks and to listen for replies.

Windows XP uses two types of message-passing techniques over a port that the client specifies when it establishes the channel. The simplest, which is used for small messages, uses the port's message queue as intermediate storage and copies the message from one process to the other. Under this method, messages of up to 256 bytes can be sent.

If a client needs to send a larger message, it passes the message through a section object, which sets up a region of shared memory. The client has to decide when it sets up the channel whether or not it will need to send a large message. If the client determines that it does want to send large messages, it asks for a section object to be created. Similarly, if the server decides that replies will be large, it creates a section object. So that the section object can be used, a small message is sent that contains a pointer and size information about the section object. This method is more complicated than the first method, but it avoids data copying. In both cases, a callback mechanism can be used when either the client or the server cannot respond immediately to a request. The callback mechanism allows them to perform asynchronous message handling. The structure of local procedure calls in Windows XP is shown in Figure 3.17.

It is important to note that the LPC facility in Windows XP is not part of the Win32 API and hence is not visible to the application programmer. Rather,

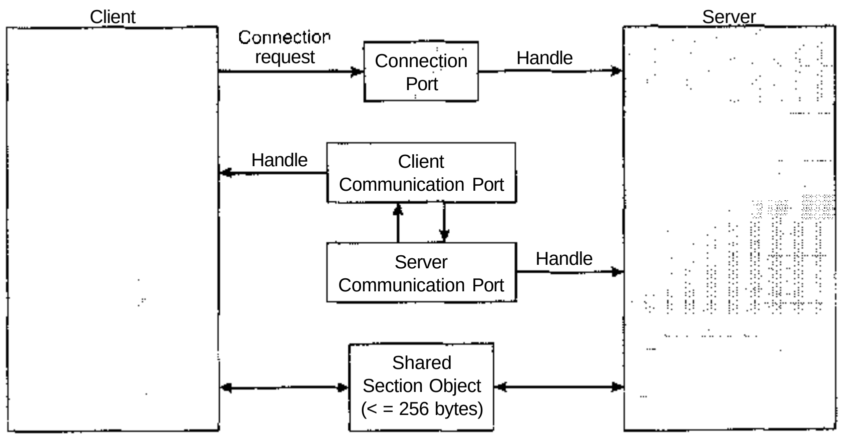

Client
Connection request
Connection Port
Handle
Server
Handle
Client Communication Port
Server Communication Port
Handle
Shared Section Object (< = 256 bytes)

Figure 3.17 Local procedure calls in Windows XP.

applications using the Win32 API invoke standard remote procedure calls. When the RPC is being invoked on a process on the same system, the RPC is indirectly handled through a local procedure call. LPCs are also used in a few other functions that are part of the Win32 API.

3.6 Communication in Client-Server Systems

In Section 3.4, we described how processes can communicate using shared memory and message passing. These techniques can be used for communication in client-server systems (1.12.2) as well. In this section, we explore three other strategies for communication in client-server systems: sockets, remote procedure calls (RPCs), and Java's remote method invocation (RMI).

3.6.1 Sockets

A socket is defined as an endpoint for communication. A pair of processes communicating over a network employ a pair of sockets—one for each process. A socket is identified by an IP address concatenated with a port number. In general, sockets use a client-server architecture. The server waits for incoming client requests by listening to a specified port. Once a request is received, the server accepts a connection from the client socket to complete the connection. Servers implementing specific services (such as telnet, ftp, and http) listen to well-known ports (a telnet server listens to port 23, an ftp server listens to port 21, and a web, or http, server listens to port 80). All ports below 1024 are considered *well known;* we can use them to implement standard services.

When a client process initiates a request for a connection, it is assigned a port by the host computer. This port is some arbitrary number greater than 1024. For example, if a client on host X with IP address 146.86.5.20 wishes to establish a connection with a web server (which is listening on port 80) at address 161.25.19.8, host X may be assigned port 1625. The connection will consist of a pair of sockets: (146.86.5.20:1625) on host X and (161.25.19.8:80) on the web server. This situation is illustrated in Figure 3.18. The packets

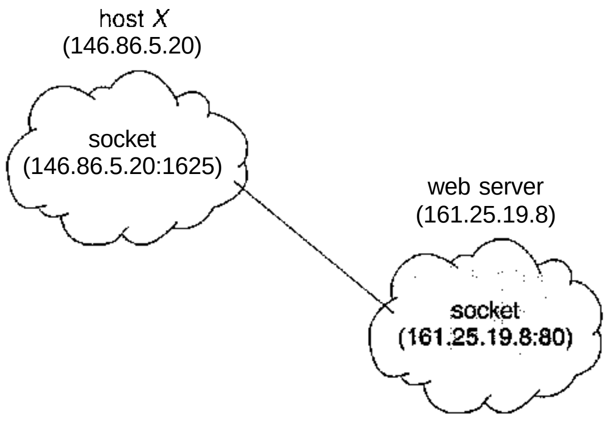


Figure 3.18 Communication using sockets.

traveling between the hosts are delivered to the appropriate process based on the destination port number.

All connections must be unique. Therefore, if another process also on host X wished to establish another connection with the same web server, it would be assigned a port number greater than 1024 and not equal to 1625. This ensures that all connections consist of a unique pair of sockets.

Although most program examples in this text use C, we will illustrate sockets using Java, as it provides a much easier interface to sockets and has a rich library for networking utilities. Those interested in socket programming in C or C++ should consult the bibliographical notes at the end of the chapter.

Java provides three different types of sockets. **Connection-oriented (TCP) sockets** are implemented with the Socket class. **Connectionless (UDP) sockets** use the DatagramSocket class. Finally, the MulticastSocket class is a subclass of the DatagramSocket class. A multicast socket allows data to be sent to multiple recipients.

Our example describes a date server that uses connection-oriented TCP sockets. The operation allows clients to request the current date and time from

```
import java.net.*;
import java.io.*;

public class DateServer
{
  public static void main(String[] args) {
    try {
      ServerSocket sock = new ServerSocket(6013);

      // now listen for connections
      while (true) {
        Socket client = sock.accept();

        PrintWriter pout = new
         PrintWriter(client.getOutputStream(), true);

        // write the Date to the socket
        pout.println(new java.util.Date().toString());

        // close the socket and resume
        // listening for connections
        client.close();
      }
    }
    catch (IOException ioe) {
      System.err.println(ioe);
    }
  }
}
```

Figure 3.19 Date server.

the server. The server listens to port 6013, although the port could have any arbitrary number greater than 1024. When a connection is received, the server returns the date and time to the client.

The date server is shown in Figure 3.19. The server creates a `ServerSocket` that specifies it will listen to port 6013. The server then begins listening to the port with the `accept()` method. The server blocks on the `accept()` method waiting for a client to request a connection. When a connection request is received, `accept()` returns a socket that the server can use to communicate with the client.

The details of how the server communicates with the socket are as follows. The server first establishes a `PrintWriter` object that it will use to communicate with the client. A `PrintWriter` object allows the server to write to the socket using the routine `print()` and `println()` methods for output. The server process sends the date to the client, calling the method `println()`. Once it has written the date to the socket, the server closes the socket to the client and resumes listening for more requests.

A client communicates with the server by creating a socket and connecting to the port on which the server is listening. We implement such a client in the Java program shown in Figure 3.20. The client creates a `Socket` and requests

```
import java.net.*;
import java.io.*;

public class DateClient
{
  public static void main(String[] args) {
    try {
      //make connection to server socket
      Socket sock = new Socket("127.0.0.1",6013);

      InputStream in = sock.getInputStream();
      BufferedReader bin = new
        BufferedReader(new InputStreamReader(in));

      // read the date from the socket
      String line;
      while ( (line = bin.readLine()) != null)
        System.out.println(line);

      // close the socket connection
      sock.close();
    }
    catch (IOException ioe) {
      System.err.println(ioe);
    }
  }
}
```

Figure 3.20 Date client.

a connection with the server at IP address 127.0.0.1 on port 6013. Once the connection is made, the client can read front the socket using normal stream I/O statements. After it has received the date from the server, the client closes the socket and exits. The IP address 127.0.0.1 is a special IP address known as the **loopback**. When a computer refers to IP address 127.0.0.1, it is referring to itself. This mechanism allows a client and server on the same host to communicate using the TCP/IP protocol. The IP address 127.0.0.1 could be replaced with the IP address of another host running the date server. In addition to an IP address, an actual host name, such as *www.westminstercollege.edu,* can be used as well.

Communication using sockets—although common and efficient—is considered a low-level form of communication between distributed processes. One reason is that sockets allow only an unstructured stream of bytes to be exchanged between the communicating threads. It is the responsibility of the client or server application to impose a structure on the data. In the next two subsections, we look at two higher-level methods of communication: remote procedure calls (RPCs) and remote method invocation (RMI).

3.6.2 Remote Procedure Calls

One of the most common forms of remote service is the RPC paradigm, which we discussed briefly in Section 3.5.2. The RPC was designed as a way to abstract the procedure-call mechanism for use between systems with network connections. It is similar in many respects to the IPC mechanism described in Section 3.4, and it is usually built on top of such a system. Here, however, because we are dealing with an environment in which the processes are executing on separate systems, we must use a message-based communication scheme to provide remote service. In contrast to the IPC facility, the messages exchanged in RPC communication are well structured and are thus no longer just packets of data. Each message is addressed to an RPC daemon listening to a port on the remote system, and each contains an identifier of the function to execute and the parameters to pass to that function. The function is then executed as requested, and any output is sent back to the requester in a separate message.

A *port* is simply a number included at the start of a message packet. Whereas a system normally has one network address, it can have many ports within that address to differentiate the many network services it supports. If a remote process needs a service, it addresses a message to the proper port. For instance, if a system wished to allow other systems to be able to list its current users, it would have a daemon supporting such an RPC attached to a port—say, port 3027. Any remote system could obtain the needed information (that is, the list of current users) by sending an RPC message to port 3027 on the server; the data would be received in a reply message.

The semantics of RPCs allow a client to invoke a procedure on a remote host as it would invoke a procedure locally. The RPC system hides the details that allow communication to take place by providing a **stub** on the client side. Typically, a separate stub exists for each separate remote procedure. When the client invokes a remote procedure, the RPC system calls the appropriate stub, passing it the parameters provided to the remote procedure. This stub locates the port on the server and *marshals* the parameters. Parameter marshalling involves packaging the parameters into a form that can be transmitted over a network. The stub then transmits a message to the server using message passing. A similar stub on the server side receives this message and invokes the procedure on the server. If necessary, return values are passed back to the client using the same technique.

One issue that must be dealt with concerns differences in data representation on the client and server machines. Consider the representation of 32-bit integers. Some systems (known as *big-endian)* use the high memory address to store the most significant byte, while other systems (known as *little-endian)* store the least significant byte at the high memory address. To resolve differences like this, many RPC systems define a machine-independent representation of data. One such representation is known as **external data representation (XDR).** On the client side, parameter marshalling involves converting the machine-dependent data into XDR before they are sent to the server. On the server side, the XDR data are unmarshalled and converted to the machine-dependent representation for the server.

Another important issue involves the semantics of a call. Whereas local procedure calls fail only under extreme circumstances, RPCs can fail, or be duplicated and executed more than once, as a result of common network errors. One way to address this problem is for the operating system to ensure that messages are acted on *exactly once,* rather than *at most once.* Most local procedure calls have the "exactly once" functionality, but it is more difficult to implement.

First, consider "at most once". This semantic can be assured by attaching a timestamp to each message. The server must keep a history of all the timestamps of messages it has already processed or a history large enough to ensure that repeated messages are detected. Incoming messages that have a timestamp already in the history are ignored. The client can then send a message one or more times and be assured that it only executes once. (Generation of these timestamps is discussed in Section 18.1.)

For "exactly once," we need to remove the risk that the server never receives the request. To accomplish this, the server must implement the "at most once" protocol described above but must also acknowledge to the client that the RPC call was received and executed. These ACK messages are common throughout networking. The client must resend each RPC call periodically until it receives the ACK for that call.

Another important issue concerns the communication between a server and a client. With standard procedure calls, some form of binding takes place during link, load, or execution time (Chapter 8) so that a procedure call's name is replaced by the memory address of the procedure call. The RPC scheme requires a similar binding of the client and the server port, but how does a client know the port numbers on the server? Neither system has full information about the other because they do not share memory.

Two approaches are common. First, the binding information may be predetermined, in the form of fixed port addresses. At compile time, an RPC call has a fixed port number associated with it. Once a program is compiled, the server cannot change the port number of the requested service. Second, binding can be done dynamically by a rendezvous mechanism. Typically, an operating system provides a rendezvous (also called a **matchmaker)** daemon on a fixed RPC port. A client then sends a message containing the name of the RPC to the rendezvous daemon requesting the port address of the RPC it

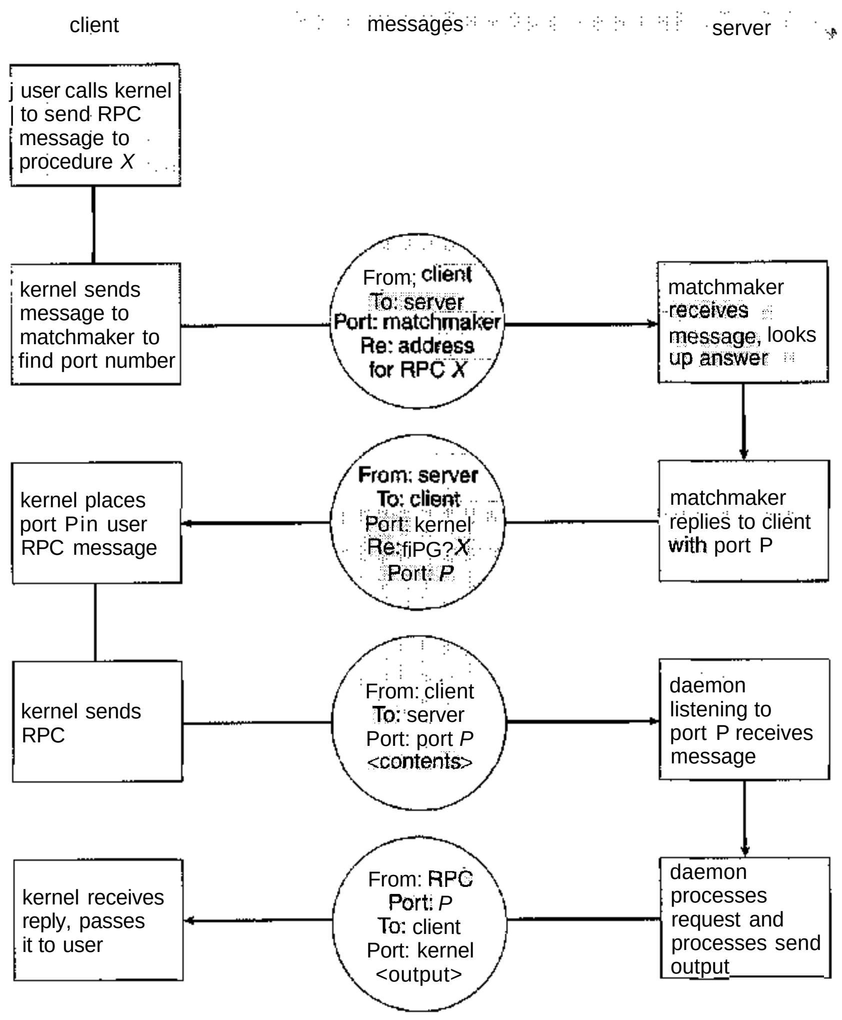

client
messages
server
user calls kernel to send RPC message to procedure X
kernel sends message to matchmaker to find port number
From: client To: server Port: matchmaker Re: address for RPC X
matchmaker receives message, looks up answer
kernel places port P in user RPC message
From: server To: client Port: kernel Re: RPC X Port: P
matchmaker replies to client with port P
kernel sends RPC
From: client To: server Port: port P <contents>
daemon listening to port P receives message
kernel receives reply, passes it to user
From: RPC Port: P To: client Port: kernel <output>
daemon processes request and processes send output

Figure 3.21 Execution of a remote procedure call (RPC).

needs to execute. The port number is returned, and the RPC calls can be sent to that port until the process terminates (or the server crashes). This method requires the extra overhead of the initial request but is more flexible than the first approach. Figure 3.21 shows a sample interaction.

The RPC scheme is useful in implementing a distributed file system (Chapter 17). Such a system can be implemented as a set of RPC daemons and clients. The messages are addressed to the distributed file system port on a server on which a file operation is to take place. The message contains the disk operation to be performed. The disk operation might be read, write, rename, delete, or status, corresponding to the usual file-related system calls. The return message contains any data resulting from that call, which is executed by the DFS daemon on behalf of the client. For instance, a message might contain a request to transfer a whole file to a client or be limited to a simple block request. In the latter case, several such requests may be needed if a whole file is to be transferred.

3.6.3 Remote Method Invocation

Remote method invocation (RMI) is a Java feature similar to RPCs. RMI allows a thread to invoke a method on a remote object. Objects are considered remote if they reside in a different Java virtual machine (JVM). Therefore, the remote object may be in a different JVM on the same computer or on a remote host connected by a network. This situation is illustrated in Figure 3.22.

RMI and RPCs differ in two fundamental ways. First, RPCs support procedural programming, whereby only remote *procedures* or *functions* can be called. In contrast, RMI is object-based: It supports invocation of *methods* on remote objects. Second, the parameters to remote procedures are ordinary data structures in RPC; with RMI, it is possible to pass objects as parameters to remote methods. By allowing a Java program to invoke methods on remote objects, RMI makes it possible for users to develop Java applications that are distributed across a network.

To make remote methods transparent to both the client and the server, RMI implements the remote object using stubs and skeletons. A **stub** is a proxy for the remote object; it resides with the client. When a client invokes a remote method, the stub for the remote object is called. This client-side stub is responsible for creating a parcel consisting of the name of the method to be invoked on the server and the marshalled parameters for the method. The stub then sends this parcel to the server, where the skeleton for the remote object receives it. The **skeleton** is responsible for unmarshalling the parameters and invoking the desired method on the server. The skeleton then marshals the return value (or exception, if any) into a parcel and returns this parcel to the client. The stub unmarshals the return value and passes it to the client.

Lets look more closely at how this process works. Assume that a client wishes to invoke a method on a remote object `server` with a signature `someMethod(Object, Object)` that returns a boolean value. The client executes the statement

```
boolean val = server.someMethod(A, B);
```

The call to `someMethod()` with the parameters A and B invokes the stub for the remote object. The stub marshals into a parcel the parameters A and B and the name of the method that is to be invoked on the server, then sends this parcel to the server. The skeleton on the server unmarshals the parameters and invokes the method `someMethod()`. The actual implementation of `someMethod()` resides on the server. Once the method is completed, the skeleton marshals

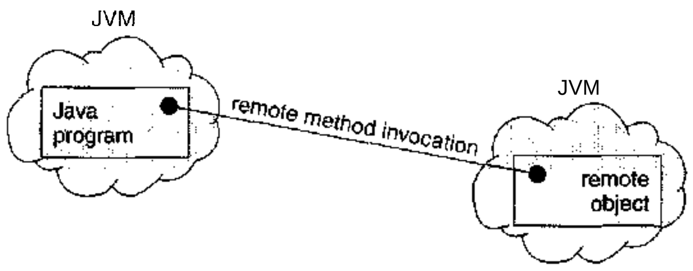


Figure 3.22 Remote method invocation.

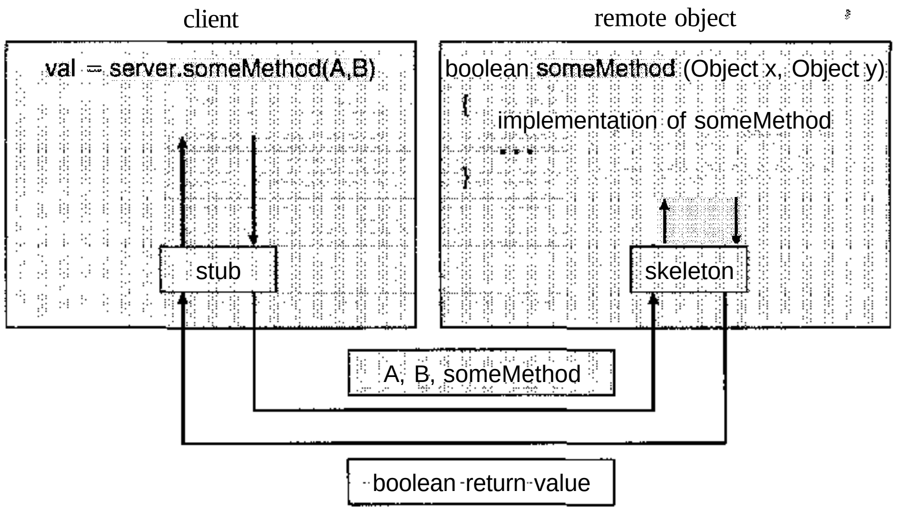

client
remote object
val = server.someMethod(A,B)
boolean someMethod (Object x, Object y)
{
implementation of someMethod
...
}
stub
skeleton
A, B, someMethod
boolean return value

Figure 3.23 Marshalling parameters.

the boolean value returned from someMethod() and sends this value back to the client. The stub unmarshals this return value and passes it to the client. The process is shown in Figure 3.23.

Fortunately, the level of abstraction that RMI provides makes the stubs and skeletons transparent, allowing Java developers to write programs that invoke distributed methods just as they would invoke local methods. It is crucial, however, to understand a few rules about the behavior of parameter passing.

- If the marshalled parameters are local (or nonremote) objects, they are passed by copy using a technique known as object serialization. However, if the parameters are also remote objects, they are passed by reference. In our example, if A is a local object and B a remote object, A is serialized and passed by copy, and B is passed by reference. This in turn allows the server to invoke methods on B remotely.
- If local objects are to be passed as parameters to remote objects, they must implement the interface java.io.Serializable. Many objects in the core Java API implement Serializable, allowing them to be used with RMI. Object serialization allows the state of an object to be written to a byte stream.

3.7 Summary

A process is a program in execution. As a process executes, it changes state. The state of a process is defined by that process's current activity. Each process may be in one of the following states: new, ready, running, waiting, or terminated. Each process is represented in the operating system by its own process-control block (PCB).

A process, when it is not executing, is placed in some waiting queue. There are two major classes of queues in an operating system: I/O request queues and the ready queue. The ready queue contains all the processes that are ready to execute and are waiting for the CPU. Each process is represented by a PCB, and the PCBs can be linked together to form a ready queue. Long-term (job) scheduling is the selection of processes that will be allowed to contend for the CPU. Normally, long-term scheduling is heavily influenced by resource-allocation considerations, especially memory management. Short-term (CPU) scheduling is the selection of one process from the ready queue.

Operating systems must provide a mechanism for parent processes to create new child processes. The parent may wait for its children to terminate before proceeding, or the parent and children may execute concurrently. There are several reasons for allowing concurrent execution: information sharing, computation speedup, modularity, and convenience.

The processes executing in the operating system may be either independent processes or cooperating processes. Cooperating processes require an interprocess communication mechanism to communicate with each other. Principally, communication is achieved through two schemes: shared memory and message passing. The shared-memory method requires communicating processes to share some variables. The processes are expected to exchange information through the use of these shared variables. In a shared-memory system, the responsibility for providing communication rests with the application programmers; the operating system needs to provide only the shared memory. The message-passing method allows the processes to exchange messages. The responsibility for providing communication may rest with the operating system itself. These two schemes are not mutually exclusive and can be used simultaneously within a single operating system.

Communication in client-server systems may use (1) sockets, (2) remote procedure calls (RPCs), or (3) Java's remote method invocation (RMI). A socket is defined as an endpoint for communication. A connection between a pair of applications consists of a pair of sockets, one at each end of the communication channel. RPCs are another form of distributed communication. An RPC occurs when a process (or thread) calls a procedure on a remote application. RMI is the Java version of RPCs. RMI allows a thread to invoke a method on a remote object just as it would invoke a method on a local object. The primary distinction between RPCs and RMI is that in RPCs data are passed to a remote procedure in the form of an ordinary data structure, whereas RMI allows objects to be passed in remote method calls.

Exercises

3.1 Describe the differences among short-term, medium-term, and long-term scheduling.

3.2 Describe the actions taken by a kernel to context-switch between processes.

3.3 Consider the RPC mechanism. Describe the undesirable consequences that could arise from not enforcing either the "at most once" or "exactly once" semantic. Describe possible uses for a mechanism that has neither of these guarantees.

```
#include <sys/types.h>
#include <stdio.h>
#include <unistd.h>

int value = 5;

int main()
{
pid_t pid;

   pid = fork();

   if (pid == 0) {/* child process */
     value += 15;
   }
   else if (pid > 0) {/* parent process */
     wait(NULL);
     printf("PARENT: value = %d",value); /* LINE A */
     exit(0);
   }
}
```

Figure 3.24 C program.

3.4 Using the program shown in Figure 3.24, explain what will be output at Line A.

3.5 What are the benefits and the disadvantages of each of the following? Consider both the system level and the programmer level.

a. Synchronous and asynchronous communication

b. Automatic and explicit buffering

c. Send by copy and send by reference

d. Fixed-sized and variable-sized messages

3.6 The Fibonacci sequence is the series of numbers 0,1,1,2,3,5,8.... Formally, it can be expressed as:

$$fib_0 = 0$$
$$fib_1 = 1$$
$$fib_n = fib_{n-1} + fib_{n-2}$$

Write a C program using the `fork()` system call that that generates the Fibonacci sequence in the child process. The number of the sequence will be provided in the command line. For example, if 5 is provided, the first five numbers in the Fibonacci sequence will be output by the child process. Because the parent and child processes have their own copies of the data, it will be necessary for the child to output the sequence. Have the parent invoke the `wait()` call to wait for the child process to complete before exiting the program. Perform necessary error checking to ensure that a non-negative number is passed on the command line.

3.7 Repeat the preceding exercise, this time using the CreateProcess() in the Win32 API. In this instance, you will need to specify a separate program to be invoked from CreateProcess(). It is this separate program that will run as a child process outputting the Fibonacci sequence. Perform necessary error checking to ensure that a non-negative number is passed on the command line.

3.8 Modify the date server shown in Figure 3.19 so that it delivers random fortunes rather than the current date. Allow the fortunes to contain multiple lines. The date client shown in Figure 3.20 can be used to read the multi-line fortunes returned by the fortune server.

3.9 An **echo** server is a server that echoes back whatever it receives from a client. For example, if a client sends the server the string *Hello there!* the server will respond with the exact data it received from the client—that is, *Hello there!*

Write an echo server using the Java networking API described in Section 3.6.1. This server will wait for a client connection using the accept() method. When a client connection is received, the server will loop, performing the following steps:

- Read data from the socket into a buffer.
- Write the contents of the buffer back to the client.

The server will break out of the loop only when it has determined that the client has closed the connection.

The date server shown in Figure 3.19 uses the java.io.BufferedReader class. BufferedReader extends the java.io.Reader class, which is used for reading character streams. However, the echo server cannot guarantee that it will read characters from clients; it may receive binary data as well. The class java.io.InputStream deals with data at the byte level rather than the character level. Thus, this echo server must use an object that extends java.io.InputStream. The read() method in the java.io.InputStream class returns —1 when the client has closed its end of the socket connection.

3.10 In Exercise 3.6, the child process must output the Fibonacci sequence, since the parent and child have their own copies of the data. Another approach to designing this program is to establish a shared-memory segment between the parent and child processes. This technique allows the child to write the contents of the Fibonacci sequence to the shared-memory segment and has the parent output the sequence when the child completes. Because the memory is shared, any changes the child makes to the shared memory will be reflected in the parent process as well.

This program will be structured using POSIX shared memory as described in Section 3.5.1. The program first requires creating the data structure for the shared-memory segment. This is most easily accomplished using a struct. This data structure will contain two items: (1) a fixed-sized array of size MAX_SEQUENCE that will hold the Fibonacci values; and (2) the size of the sequence the child process is to generate

—sequence_size where sequence_size ≤ MAX_SEQUENCE. These items can be represented in a struct as follows:

```
#define MAX_SEQUENCE 10

typedef struct {
   long fib_sequence[MAX_SEQUENCE];
   int sequence_size;
}shared_data;
```

The parent process will progress through the following steps:

a. Accept the parameter passed on the command line and perform error checking to ensure that the parameter is ≤ MAX_SEQUENCE.

b. Create a shared-memory segment of size shared_data.

c. Attach the shared-memory segment to its address space.

d. Set the value of sequence_size to the parameter on the command line.

e. Fork the child process and invoke the wait () system call to wait for the child to finish.

f. Output the value of the Fibonacci sequence in the shared-memory segment.

g. Detach and remove the shared-memory segment.

Because the child process is a copy of the parent, the shared-memory region will be attached to the child's address space as well. The child process will then write the Fibonacci sequence to shared memory and finally will detach the segment.

One issue of concern with cooperating processes involves synchronization issues. In this exercise, the parent and child processes must be synchronized so that the parent does not output the Fibonacci sequence until the child finishes generating the sequence. These two processes will be synchronized using the wait() system call; the parent process will invoke wait (), which will cause it to be suspended until the child process exits.

3.11 Most UNIX and Linux systems provide the ipcs command. This command lists the status of various POSIX interprocess communication mechanisms, including shared-memory segments. Much of the information for the command comes from the data structure struct shmid_ds, which is available in the /usr/include/sys/shm.h file. Some of the fields of this structure include:

- int shm_segsz—size of the shared-memory segment
- short shm_nattch—number of attaches to the shared-memory segment
- struct ipc_perm shm_perm—permission structure of the shared-memory segment

The struct ipc_perm data structure (which is available in the file /usr/include/sys/ipc.h) contains the fields:

- unsigned short uid—identifier of the user of the shared-memory segment
- unsigned short mode—permission modes
- key_t key (on Linux systems, __key)—user-specified key identifier

The permission modes are set according to how the shared-memory segment is established with the shmget() system call. Permissions are identified according to the following:

mode	meaning
0400	Read permission of owner.
0200	Write permission of owner.
0040	Read permission of group.
0020	Write permission of group.
0004	Read permission of world.
0002	Write permission of world.

Permissions can be accessed by using the bitwise *AND* operator &. For example, if the statement mode & 0400 evaluates to true, the permission mode allows read permission by the owner of the shared-memory segment.

Shared-memory segments can be identified according to a user-specified key or according to the integer value returned from the shmget() system call, which represents the integer identifier of the shared-memory segment created. The shm_ds structure for a given integer segment identifier can be obtained with the following shmctl () system call:

```
/* identifier of the shared memory segment*/
int segment_id;
shm_ds shmbuffer;

shmctl(segment_id, IPC_STAT, &shmbuffer);
```

If successful, shmctl () returns 0; otherwise, it returns -1.

Write a C program that is passed an identifier for a shared-memory segment. This program will invoke the shmctl () function to obtain its shm_ds structure. It will then output the following values of the given shared-memory segment:

- Segment ID
- Key
- Mode

- Owner UID
- Size
- Number of attaches

Project—UNIX Shell and History Feature

This project consists of modifying a C program which serves as a shell interface that accepts user commands and then executes each command in a separate process. A shell interface provides the user a prompt after which the next command is entered. The example below illustrates the prompt `sh>` and the user's next command: `cat prog.c`. This command displays the file `prog.c` on the terminal using the UNIX `cat` command.

```
sh> cat prog.c
```

One technique for implementing a shell interface is to have the parent process first read what the user enters on the command line (i.e. `cat prog.c`), and then create a separate child process that performs the command- Unless otherwise specified, the parent process waits for the child to exit before continuing. This is similar in functionality to what is illustrated in Figure 3.11. However, UNIX shells typically also allow the child process to run in the background—or concurrently—as well by specifying the ampersand (`&`) at the end of the command. By rewriting the above command as

```
sh> cat prog.c &
```

the parent and child processes now run concurrently.

The separate child process is created using the `fork()` system call and the user's command is executed by using one of the system calls in the `exec()` family (as described in Section 3.3.1).

Simple Shell

A C program that provides the basic operations of a command line shell is supplied in Figure 3.25. This program is composed of two functions: `main()` and `setup()`. The `setup()` function reads in the user's next command (which can be up to 80 characters), and then parses it into separate tokens that are used to fill the argument vector for the command to be executed. (If the command is to be run in the background, it will end with '&', and `setupO` will update the parameter background so the `main()` function can act accordingly. This program is terminated when the user enters <ControlxD> and `setup0` then invokes `exit ()`.

The `main()` function presents the prompt COMMAND-> and then invokes `setupO`, which waits for the user to enter a command. The contents of the command entered by the user is loaded into the `args` array. For example, if the user enters `ls -1` at the `COMMAND->` prompt, `args [0]` becomes equal to the string `ls` and `args[l]` is set to the string to `-1`. (By "string", we mean a null-terminated, C-style string variable.)

```
#include <stdio.h>
#include <unistd.h>

#define MAX_LINE 80

/** setup() reads in the next command line, separating it into
distinct tokens using whitespace as delimiters.
setup() modifies the args parameter so that it holds pointers
to the null-terminated strings that are the tokens in the most
recent user command line as well as a NULL pointer, indicating
the end of the argument list, which comes after the string
pointers that have been assigned to args. */

void setup(char inputBuffer[], char *args[],int *background)
{
   /** full source code available online */
}

int main(void)
{
char inputBuffer[MAX_LINE]; /* buffer to hold command entered */
int background; /* equals 1 if a command is followed by '&' */
char *args[MAX_LIN3/2 + 1]; /* command line arguments */

   while (1) {
      background = 0;
      printf(" COMMAND->");
      /* setup() calls exit() when Control-D is entered */
      setup(inputBuffer, args, fcbackground);

      /** the steps are:
      (1) fork a child process using fork()
      (2) the child process will invoke execvp()
      (3) if background == 1, the parent will wait,
      otherwise it will invoke the setup0 function again. */
   }
}
```

Figure 3.25 Outline of simple shell.

This project is organized into two parts: (1) creating the child process and executing the command in the child, and (2) modifying the shell to allow a history feature.

Creating a Child Process

The first part of this project is to modify the `main()` function in Figure 3.25 so that upon returning from `setup()`, a child process is forked and executes the command specified by the user.

As noted above, the `setup()` function loads the contents of the `args` array with the command specified by the user. This `args` array will be passed to the `execvp()` function, which has the following interface:

```
execvp(char *command, char *params[]);
```

where `command` represents the command to be performed and `params` stores the parameters to this command. For this project, the `execvp()` function should be invoked as `execvp(args[0],args);` be sure to check the value of background to determine if the parent process is to wait for the child to exit or not.

Creating a History Feature

The next task is to modify the program in Figure 3.25 so that it provides a *history* feature that allows the user access up to the 10 most recently entered commands. These commands will be numbered starting at 1 and will continue to grow larger even past 10, e.g. if the user has entered 35 commands, the 10 most recent commands should be numbered 26 to 35. This history feature will be implementing using a few different techniques.

First, the user will be able to list these commands when he/she presses <Control> <C>, which is the SIGINT signal. UNIX systems use signals to notify a process that a particular event has occurred. Signals may be either synchronous or asynchronous, depending upon the source and the reason for the event being signaled. Once a signal has been generated by the occurrence of a certain event (e.g., division by zero, illegal memory access, user entering <Control> <C>, etc.), the signal is delivered to a process where it must be handled. A process receiving a signal may handle it by one of the following techniques:

- Ignoring the signal
- using the default signal handler, or
- providing a separate signal-handling function.

Signals may be handled by first setting certain fields in the C structure `struct sigaction` and then passing this structure to the `sigaction()` function. Signals are defined in the include file `/usr/include/sys/signal.h`. For example, the signal SIGINT represents the signal for terminating a program with the control sequence <Control> <C>. The default signal handler for SIGINT is to terminate the program.

Alternatively, a program may choose to set up its own signal-handling function by setting the `sa_handler` field in `struct sigaction` to the name of the function which will handle the signal and then invoking the `sigaction()` function, passing it (1) the signal we are setting up a handler for, and (2) a pointer to `struct sigaction`.

In Figure 3.26 we show a C program that uses the function `handle_SIGINT()` for handling the SIGINT signal. This function prints out the message "`Caught Control C`" and then invokes the `exit()` function to terminate the program. (We must use the `write()` function for performing output rather than the more common `printf()` as the former is known as being

```
#include <signal.h>
#include <unistd.h>
#include <stdio.h>

#define BUFFER_SIZE 50
char buffer[BUFFER_SIZE] ;

/* the signal handling function */
void handle_SIGINT ()
{
   write(STDOUT_FILENO, buffer, strlen(buffer) ) ;

   exit (0);
}

int mainfint argc, char *argv[])
{
   /* set up the signal handler */
   struct sigaction handler;
   handler.sa_handler = handle_SIGINT;
   sigaction(SIGINT, &handler, NULL);

   /* generate the output message */
   strcpy(buffer,"Caught Control C\n");

   /* loop until we receive <ControlxC> */
   while (1)
      ;

   return 0;
}
```

Figure 3.26 Signal-handling program.

signal-safe, indicating it can be called from inside a signal-handling function; such guarantees cannot be made of printf ().) This program will run in the while(1) loop until the user enters the sequence <Control> <C>. When this occurs, the signal-handling function handle_SIGINT () is invoked.

The signal-handling function should be declared above main() and because control can be transferred to this function at any point, no parameters may be passed to it this function. Therefore, any data that it must access in your program must be declared globally, i.e. at the top of the source file before your function declarations. Before returning from the signal-handling function, it should reissue the command prompt.

If the user enters <Control><C>, the signal handler will output a list of the most recent 10 commands. With this list, the user can run any of the previous 10 commands by entering r x where 'x' is the first letter of that command. If more than one command starts with V, execute the most recent one. Also, the user should be able to run the most recent command again by just entering V. You can assume that only one space will separate the 'r' and the first letter and that the letter will be followed by '\n'. Again, 'r' alone will be immediately followed by the \n character if it is wished to execute the most recent command.

Any command that is executed in this fashion should be echoed on the user's screen and the command is also placed in the history buffer as the next command. (r x does not go into the history list; the actual command that it specifies, though, does.)

It the user attempts to use this history facility to run a command and the command is detected to be *erroneous*, an error message should be given to the user and the command not entered into the history list, and the `execvp()` function should not be called. (It would be nice to know about improperly formed commands that are handed off to `execvp()` that appear to look valid and are not, and not include them in the history as well, but that is beyond the capabilities of this simple shell program.) You should also modify `setup()` so it returns an `int` signifying if has successfully created a valid `args` list or not, and the `main()` should be updated accordingly.

Bibliographical Notes

Interprocess communication in the RC 4000 system was discussed by Brinch-Hansen [1970]. Schlichting and Schneider [1982] discussed asynchronous message-passing primitives. The IPC facility implemented at the user level was described by Bershad et al. [1990].

Details of interprocess communication in UNIX systems were presented by Gray [1997]. Barrera [1991] and Vahalia [1996] described interprocess communication in the Mach system. Solomon and Russinovich [2000] and Stevens [1999] outlined interprocess communication in Windows 2000 and UNIX respectively.

The implementation of RPCs was discussed by Birrell and Nelson [1984]. A design of a reliable RPC mechanism was described by Shrivastava and Panzieri [1982], and Tay and Ananda [1990] presented a survey of RPCs. Stankovic [1982] and Staunstrup [1982] discussed procedure calls versus message-passing communication. Grosso [2002] discussed RMI in significant detail. Calvert and Donahoo [2001] provided coverage of socket programming in Java.