UNIT - 1
OPERATING SYSTEM OVERVIEW

2.1 OPERATING SYSTEM OBJECTIVES AND FUNCTIONS

An OS is a program that controls the execution of application programs and acts as an interface between applications and the computer hardware. It can be thought of as having three objectives:

- **Convenience:** An OS makes a computer more convenient to use.
- **Efficiency:** An OS allows the computer system resources to be used in an efficient manner.
- **Ability to evolve:** An OS should be constructed in such a way as to permit the effective development, testing, and introduction of new system functions without interfering with service.

Let us examine these three aspects of an OS in turn.

The Operating System as a User/Computer Interface

The hardware and software used in providing applications to a user can be viewed in a layered or hierarchical fashion, as depicted in Figure 2.1. The user of those applications, the end user, generally is not concerned with the details of computer hardware. Thus, the end user views a computer system in terms of a set of applications. An application can be expressed in a programming language and is developed by an application programmer. If one were to develop an application program as a set of machine instructions that is completely responsible for controlling the computer hardware, one would be faced with an overwhelmingly complex undertaking. To ease this chore, a set of system programs is provided. Some of these programs are referred to as utilities, or library programs. These implement frequently used functions that assist in program creation, the management of files, and the control of

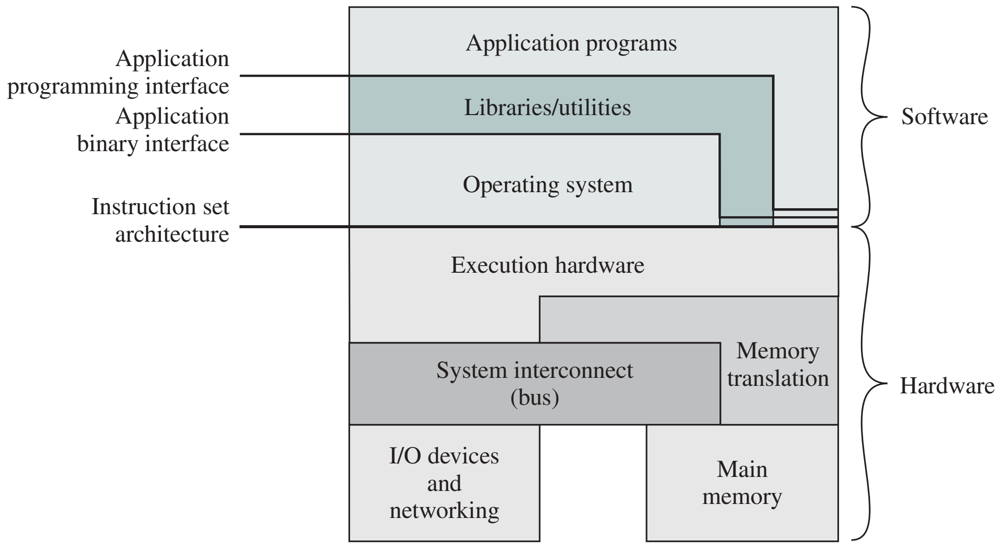
Application programming interface
Application binary interface
Instruction set architecture
Application programs
Libraries/utilities
Operating system
Execution hardware
Memory translation
System interconnect (bus)
I/O devices and networking
Main memory
Software
Hardware

Figure 2.1 Computer Hardware and Software Structure

I/O devices. A programmer will make use of these facilities in developing an application, and the application, while it is running, will invoke the utilities to perform certain functions. The most important collection of system programs comprises the OS. The OS masks the details of the hardware from the programmer and provides the programmer with a convenient interface for using the system. It acts as mediator, making it easier for the programmer and for application programs to access and use those facilities and services.

Briefly, the OS typically provides services in the following areas:

- **Program development:** The OS provides a variety of facilities and services, such as editors and debuggers, to assist the programmer in creating programs. Typically, these services are in the form of utility programs that, while not strictly part of the core of the OS, are supplied with the OS and are referred to as application program development tools.
- **Program execution:** A number of steps need to be performed to execute a program. Instructions and data must be loaded into main memory, I/O devices and files must be initialized, and other resources must be prepared. The OS handles these scheduling duties for the user.
- **Access to I/O devices:** Each I/O device requires its own peculiar set of instructions or control signals for operation. The OS provides a uniform interface that hides these details so that programmers can access such devices using simple reads and writes.
- **Controlled access to files:** For file access, the OS must reflect a detailed understanding of not only the nature of the I/O device (disk drive, tape drive) but also the structure of the data contained in the files on the storage medium. In the case of a system with multiple users, the OS may provide protection mechanisms to control access to the files.
- **System access:** For shared or public systems, the OS controls access to the system as a whole and to specific system resources. The access function must provide protection of resources and data from unauthorized users and must resolve conflicts for resource contention.
- **Error detection and response:** A variety of errors can occur while a computer system is running. These include internal and external hardware errors, such as a memory error, or a device failure or malfunction; and various software errors, such as division by zero, attempt to access forbidden memory location, and inability of the OS to grant the request of an application. In each case, the OS must provide a response that clears the error condition with the least impact on running applications. The response may range from ending the program that caused the error, to retrying the operation, to simply reporting the error to the application.
- **Accounting:** A good OS will collect usage statistics for various resources and monitor performance parameters such as response time. On any system, this information is useful in anticipating the need for future enhancements and in tuning the system to improve performance. On a multiuser system, the information can be used for billing purposes.

Figure 2.1 also indicates three key interfaces in a typical computer system:

- **Instruction set architecture (ISA)**: The ISA defines the repertoire of machine language instructions that a computer can follow. This interface is the boundary between hardware and software. Note that both application programs and utilities may access the ISA directly. For these programs, a subset of the instruction repertoire is available (user ISA). The OS has access to additional machine language instructions that deal with managing system resources (system ISA).
- **Application binary interface (ABI)**: The ABI defines a standard for binary portability across programs. The ABI defines the system call interface to the operating system and the hardware resources and services available in a system through the user ISA.
- **Application programming interface (API)**: The API gives a program access to the hardware resources and services available in a system through the user ISA supplemented with high-level language (HLL) library calls. Any system calls are usually performed through libraries. Using an API enables application software to be ported easily, through recompilation, to other systems that support the same API.

The Operating System as Resource Manager

A computer is a set of resources for the movement, storage, and processing of data and for the control of these functions. The OS is responsible for managing these resources.

Can we say that it is the OS that controls the movement, storage, and processing of data? From one point of view, the answer is yes: By managing the computer's resources, the OS is in control of the computer's basic functions. But this control is exercised in a curious way. Normally, we think of a control mechanism as something external to that which is controlled, or at least as something that is a distinct and separate part of that which is controlled. (For example, a residential heating system is controlled by a thermostat, which is separate from the heat-generation and heat-distribution apparatus.) This is not the case with the OS, which as a control mechanism is unusual in two respects:

- The OS functions in the same way as ordinary computer software; that is, it is a program or suite of programs executed by the processor.
- The OS frequently relinquishes control and must depend on the processor to allow it to regain control.

Like other computer programs, the OS provides instructions for the processor. The key difference is in the intent of the program. The OS directs the processor in the use of the other system resources and in the timing of its execution of other programs. But in order for the processor to do any of these things, it must cease executing the OS program and execute other programs. Thus, the OS relinquishes control for the processor to do some "useful" work and then resumes control long enough to prepare the processor to do the next piece of work. The mechanisms involved in all this should become clear as the chapter proceeds.

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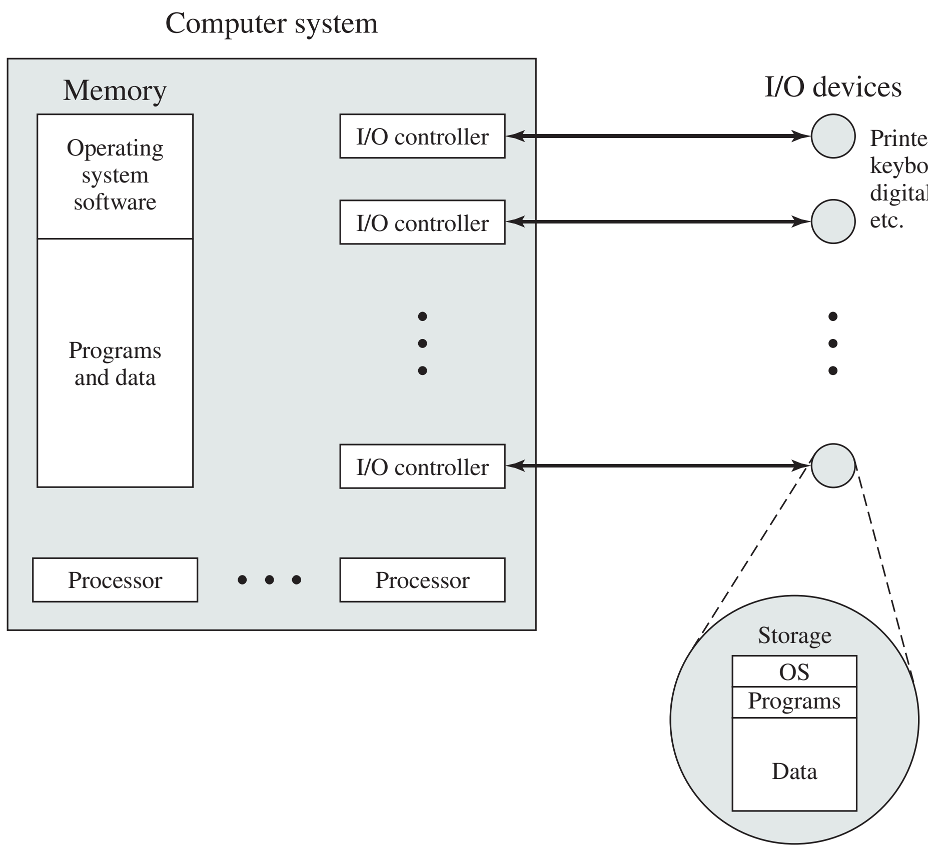

Figure 2.2 **The Operating System as Resource Manager**

Figure 2.2 suggests the main resources that are managed by the OS. A portion of the OS is in main memory. This includes the **kernel**, or **nucleus**, which contains the most frequently used functions in the OS and, at a given time, other portions of the OS currently in use. The remainder of main memory contains user programs and data. The memory management hardware in the processor and the OS jointly control the allocation of main memory, as we shall see. The OS decides when an I/O device can be used by a program in execution and controls access to and use of files. The processor itself is a resource, and the OS must determine how much processor time is to be devoted to the execution of a particular user program. In the case of a multiple-processor system, this decision must span all of the processors.

Ease of Evolution of an Operating System

A major OS will evolve over time for a number of reasons:

- **Hardware upgrades plus new types of hardware:** For example, early versions of UNIX and the Macintosh OS did not employ a paging mechanism because they were run on processors without paging hardware.[1] Subsequent versions of these operating systems were modified to exploit paging capabilities. Also,

[1]Paging is introduced briefly later in this chapter and is discussed in detail in Chapter 7.

the use of graphics terminals and page-mode terminals instead of line-at-a-time scroll mode terminals affects OS design. For example, a graphics terminal typically allows the user to view several applications at the same time through "windows" on the screen. This requires more sophisticated support in the OS.

- **New services:** In response to user demand or in response to the needs of system managers, the OS expands to offer new services. For example, if it is found to be difficult to maintain good performance for users with existing tools, new measurement and control tools may be added to the OS.
- **Fixes:** Any OS has faults. These are discovered over the course of time and fixes are made. Of course, the fix may introduce new faults.

The need to change an OS regularly places certain requirements on its design. An obvious statement is that the system should be modular in construction, with clearly defined interfaces between the modules, and that it should be well documented. For large programs, such as the typical contemporary OS, what might be referred to as straightforward modularization is inadequate [DENN80a]. That is, much more must be done than simply partitioning a program into modules. We return to this topic later in this chapter.

2.2 THE EVOLUTION OF OPERATING SYSTEMS

In attempting to understand the key requirements for an OS and the significance of the major features of a contemporary OS, it is useful to consider how operating systems have evolved over the years.

Serial Processing

With the earliest computers, from the late 1940s to the mid-1950s, the programmer interacted directly with the computer hardware; there was no OS. These computers were run from a console consisting of display lights, toggle switches, some form of input device, and a printer. Programs in machine code were loaded via the input device (e.g., a card reader). If an error halted the program, the error condition was indicated by the lights. If the program proceeded to a normal completion, the output appeared on the printer.

These early systems presented two main problems:

- **Scheduling:** Most installations used a hardcopy sign-up sheet to reserve computer time. Typically, a user could sign up for a block of time in multiples of a half hour or so. A user might sign up for an hour and finish in 45 minutes; this would result in wasted computer processing time. On the other hand, the user might run into problems, not finish in the allotted time, and be forced to stop before resolving the problem.
- **Setup time:** A single program, called a **job**, could involve loading the compiler plus the high-level language program (source program) into memory, saving the compiled program (object program) and then loading and linking together the object program and common functions. Each of these steps could

involve mounting or dismounting tapes or setting up card decks. If an error occurred, the hapless user typically had to go back to the beginning of the setup sequence. Thus, a considerable amount of time was spent just in setting up the program to run.

This mode of operation could be termed *serial processing*, reflecting the fact that users have access to the computer in series. Over time, various system software tools were developed to attempt to make serial processing more efficient. These include libraries of common functions, linkers, loaders, debuggers, and I/O driver routines that were available as common software for all users.

Simple Batch Systems

Early computers were very expensive, and therefore it was important to maximize processor utilization. The wasted time due to scheduling and setup time was unacceptable.

To improve utilization, the concept of a batch OS was developed. It appears that the first batch OS (and the first OS of any kind) was developed in the mid-1950s by General Motors for use on an IBM 701 [WEIZ81]. The concept was subsequently refined and implemented on the IBM 704 by a number of IBM customers. By the early 1960s, a number of vendors had developed batch operating systems for their computer systems. IBSYS, the IBM OS for the 7090/7094 computers, is particularly notable because of its widespread influence on other systems.

The central idea behind the simple batch-processing scheme is the use of a piece of software known as the **monitor**. With this type of OS, the user no longer has direct access to the processor. Instead, the user submits the job on cards or tape to a computer operator, who batches the jobs together sequentially and places the entire batch on an input device, for use by the monitor. Each program is constructed to branch back to the monitor when it completes processing, at which point the monitor automatically begins loading the next program.

To understand how this scheme works, let us look at it from two points of view: that of the monitor and that of the processor.

- **Monitor point of view:** The monitor controls the sequence of events. For this to be so, much of the monitor must always be in main memory and available for execution (Figure 2.3). That portion is referred to as the **resident monitor**. The rest of the monitor consists of utilities and common functions that are loaded as subroutines to the user program at the beginning of any job that requires them. The monitor reads in jobs one at a time from the input device (typically a card reader or magnetic tape drive). As it is read in, the current job is placed in the user program area, and control is passed to this job. When the job is completed, it returns control to the monitor, which immediately reads in the next job. The results of each job are sent to an output device, such as a printer, for delivery to the user.
- **Processor point of view:** At a certain point, the processor is executing instructions from the portion of main memory containing the monitor. These instructions cause the next job to be read into another portion of main

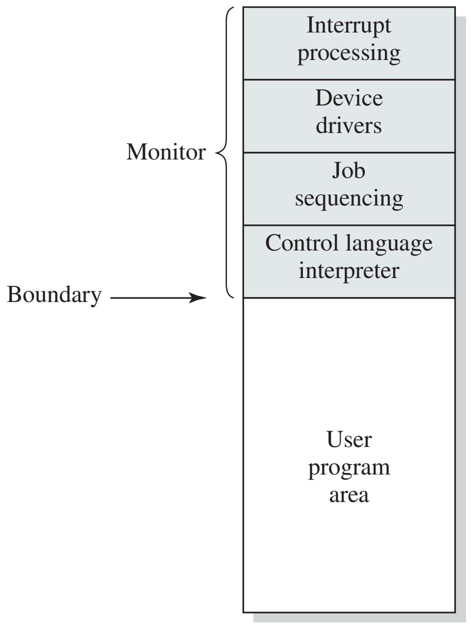

Figure 2.3 Memory Layout for a Resident Monitor

memory. Once a job has been read in, the processor will encounter a branch instruction in the monitor that instructs the processor to continue execution at the start of the user program. The processor will then execute the instructions in the user program until it encounters an ending or error condition. Either event causes the processor to fetch its next instruction from the monitor program. Thus the phrase "control is passed to a job" simply means that the processor is now fetching and executing instructions in a user program, and "control is returned to the monitor" means that the processor is now fetching and executing instructions from the monitor program.

The monitor performs a scheduling function: A batch of jobs is queued up, and jobs are executed as rapidly as possible, with no intervening idle time. The monitor improves job setup time as well. With each job, instructions are included in a primitive form of **job control language (JCL)**. This is a special type of programming language used to provide instructions to the monitor. A simple example is that of a user submitting a program written in the programming language FORTRAN plus some data to be used by the program. All FORTRAN instructions and data are on a separate punched card or a separate record on tape. In addition to FORTRAN and data lines, the job includes job control instructions, which are denoted by the beginning $. The overall format of the job looks like this:

```
$JOB
$FTN
•  ⎫
•  ⎬   FORTRAN instructions
•  ⎭
```

```
$LOAD
$RUN
•   )
•   }    Data
•   )
$END
```

To execute this job, the monitor reads the `$FTN` line and loads the appropriate language compiler from its mass storage (usually tape). The compiler translates the user's program into object code, which is stored in memory or mass storage. If it is stored in memory, the operation is referred to as "compile, load, and go." If it is stored on tape, then the `$LOAD` instruction is required. This instruction is read by the monitor, which regains control after the compile operation. The monitor invokes the loader, which loads the object program into memory (in place of the compiler) and transfers control to it. In this manner, a large segment of main memory can be shared among different subsystems, although only one such subsystem could be executing at a time.

During the execution of the user program, any input instruction causes one line of data to be read. The input instruction in the user program causes an input routine that is part of the OS to be invoked. The input routine checks to make sure that the program does not accidentally read in a JCL line. If this happens, an error occurs and control transfers to the monitor. At the completion of the user job, the monitor will scan the input lines until it encounters the next JCL instruction. Thus, the system is protected against a program with too many or too few data lines.

The monitor, or batch OS, is simply a computer program. It relies on the ability of the processor to fetch instructions from various portions of main memory to alternately seize and relinquish control. Certain other hardware features are also desirable:

- **Memory protection:** While the user program is executing, it must not alter the memory area containing the monitor. If such an attempt is made, the processor hardware should detect an error and transfer control to the monitor. The monitor would then abort the job, print out an error message, and load in the next job.
- **Timer:** A timer is used to prevent a single job from monopolizing the system. The timer is set at the beginning of each job. If the timer expires, the user program is stopped, and control returns to the monitor.
- **Privileged instructions:** Certain machine level instructions are designated privileged and can be executed only by the monitor. If the processor encounters such an instruction while executing a user program, an error occurs causing control to be transferred to the monitor. Among the privileged instructions are I/O instructions, so that the monitor retains control of all I/O devices. This prevents, for example, a user program from accidentally reading job control instructions from the next job. If a user program wishes to perform I/O, it must request that the monitor perform the operation for it.

- **Interrupts:** Early computer models did not have this capability. This feature gives the OS more flexibility in relinquishing control to and regaining control from user programs.

Considerations of memory protection and privileged instructions lead to the concept of modes of operation. A user program executes in a **user mode**, in which certain areas of memory are protected from the user's use and in which certain instructions may not be executed. The monitor executes in a system mode, or what has come to be called **kernel mode**, in which privileged instructions may be executed and in which protected areas of memory may be accessed.

Of course, an OS can be built without these features. But computer vendors quickly learned that the results were chaos, and so even relatively primitive batch operating systems were provided with these hardware features.

With a batch OS, processor time alternates between execution of user programs and execution of the monitor. There have been two sacrifices: Some main memory is now given over to the monitor and some processor time is consumed by the monitor. Both of these are forms of overhead. Despite this overhead, the simple batch system improves utilization of the computer.

Multiprogrammed Batch Systems

Even with the automatic job sequencing provided by a simple batch OS, the processor is often idle. The problem is that I/O devices are slow compared to the processor. Figure 2.4 details a representative calculation. The calculation concerns a program that processes a file of records and performs, on average, 100 machine instructions per record. In this example, the computer spends over 96% of its time waiting for I/O devices to finish transferring data to and from the file. Figure 2.5a illustrates this situation, where we have a single program, referred to as uniprogramming. The processor spends a certain amount of time executing, until it reaches an I/O instruction. It must then wait until that I/O instruction concludes before proceeding.

This inefficiency is not necessary. We know that there must be enough memory to hold the OS (resident monitor) and one user program. Suppose that there is room for the OS and two user programs. When one job needs to wait for I/O, the processor can switch to the other job, which is likely not waiting for I/O (Figure 2.5b). Furthermore, we might expand memory to hold three, four, or more programs and switch among all of them (Figure 2.5c). The approach is known as **multiprogramming**, or **multitasking**. It is the central theme of modern operating systems.

Read one record from file	15 μs
Execute 100 instructions	1 μs
Write one record to file	15 μs
Total	31 μs

$$\text{Percent CPU Utilization} = \frac{1}{31} = 0.032 = 3.2\%$$

Figure 2.4 System Utilization Example

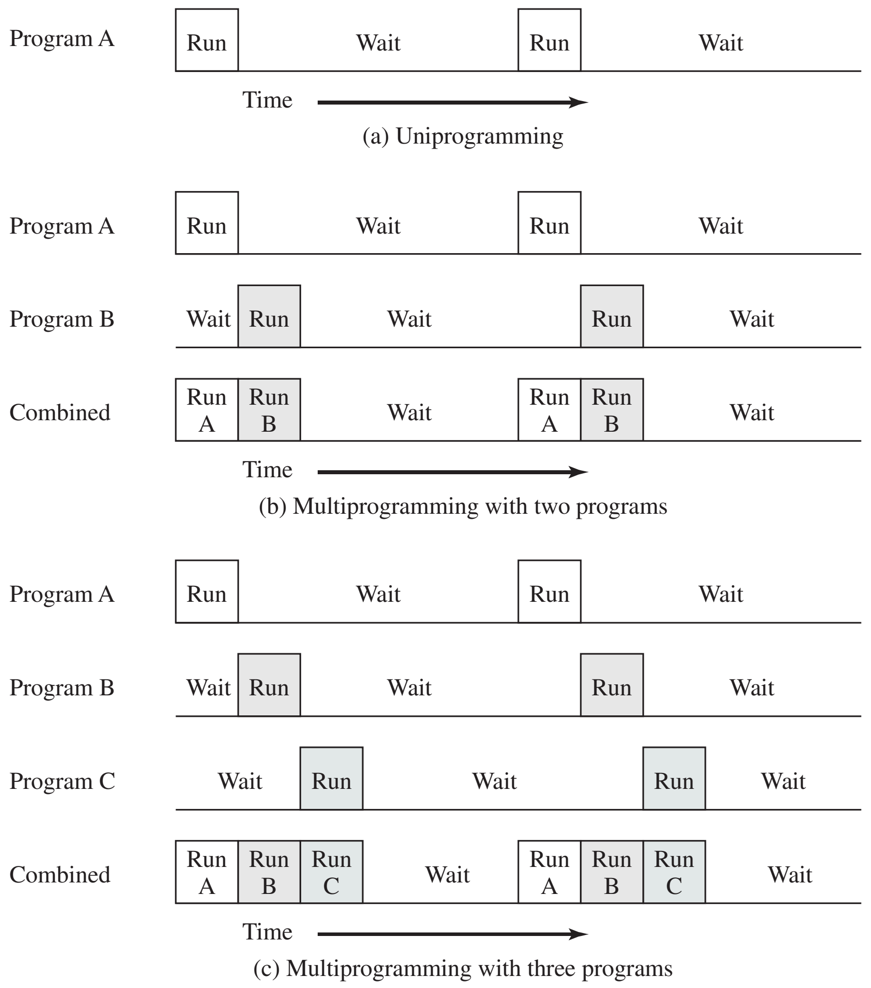

Figure 2.5 **Multiprogramming Example**

To illustrate the benefit of multiprogramming, we give a simple example. Consider a computer with 250 Mbytes of available memory (not used by the OS), a disk, a terminal, and a printer. Three programs, JOB1, JOB2, and JOB3, are submitted for execution at the same time, with the attributes listed in Table 2.1. We assume minimal processor requirements for JOB2 and JOB3 and continuous disk and printer use by JOB3. For a simple batch environment, these jobs will be executed in sequence. Thus, JOB1 completes in 5 minutes. JOB2 must wait until

Table 2.1 Sample Program Execution Attributes

	JOB1	**JOB2**	**JOB3**
Type of job	Heavy compute	Heavy I/O	Heavy I/O
Duration	5 min	15 min	10 min
Memory required	50 M	100 M	75 M
Need disk?	No	No	Yes
Need terminal?	No	Yes	No
Need printer?	No	No	Yes

Table 2.2 Effects of Multiprogramming on Resource Utilization

	Uniprogramming	Multiprogramming
Processor use	20%	40%
Memory use	33%	67%
Disk use	33%	67%
Printer use	33%	67%
Elapsed time	30 min	15 min
Throughput	6 jobs/hr	12 jobs/hr
Mean response time	18 min	10 min

the 5 minutes are over and then completes 15 minutes after that. JOB3 begins after 20 minutes and completes at 30 minutes from the time it was initially submitted. The average resource utilization, throughput, and response times are shown in the uniprogramming column of Table 2.2. Device-by-device utilization is illustrated in Figure 2.6a. It is evident that there is gross underutilization for all resources when averaged over the required 30-minute time period.

Now suppose that the jobs are run concurrently under a multiprogramming OS. Because there is little resource contention between the jobs, all three can run in nearly minimum time while coexisting with the others in the computer (assuming that JOB2 and JOB3 are allotted enough processor time to keep their input and output operations active). JOB1 will still require 5 minutes to complete, but at the end of that time, JOB2 will be one-third finished and JOB3 half finished. All three jobs will have finished within 15 minutes. The improvement is evident when examining the multiprogramming column of Table 2.2, obtained from the histogram shown in Figure 2.6b.

As with a simple batch system, a multiprogramming batch system must rely on certain computer hardware features. The most notable additional feature that is useful for multiprogramming is the hardware that supports I/O interrupts and DMA (direct memory access). With interrupt-driven I/O or DMA, the processor can issue an I/O command for one job and proceed with the execution of another job while the I/O is carried out by the device controller. When the I/O operation is complete, the processor is interrupted and control is passed to an interrupt-handling program in the OS. The OS will then pass control to another job.

Multiprogramming operating systems are fairly sophisticated compared to single-program, or **uniprogramming**, systems. To have several jobs ready to run, they must be kept in main memory, requiring some form of **memory management**. In addition, if several jobs are ready to run, the processor must decide which one to run, this decision requires an algorithm for scheduling. These concepts are discussed later in this chapter.

Time-Sharing Systems

With the use of multiprogramming, batch processing can be quite efficient. However, for many jobs, it is desirable to provide a mode in which the user interacts directly with the computer. Indeed, for some jobs, such as transaction processing, an interactive mode is essential.

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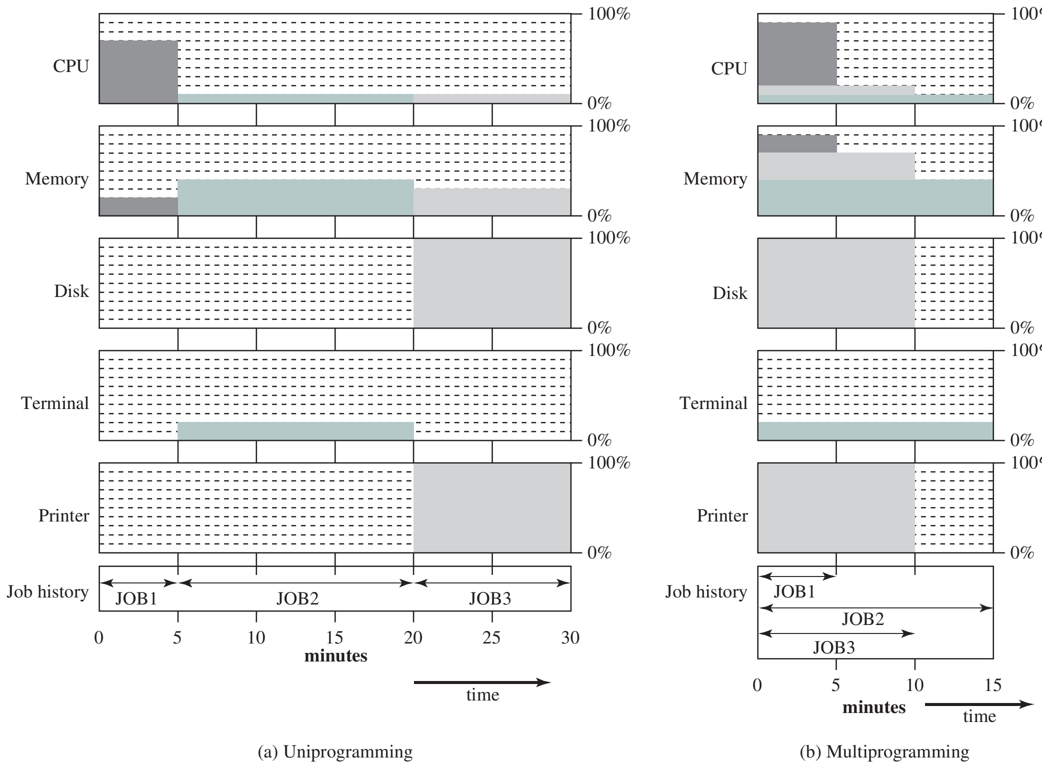

Figure 2.6 **Utilization Histograms**

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Today, the requirement for an interactive computing facility can be, and often is, met by the use of a dedicated personal computer or workstation. That option was not available in the 1960s, when most computers were big and costly. Instead, time sharing was developed.

Just as multiprogramming allows the processor to handle multiple batch jobs at a time, multiprogramming can also be used to handle multiple interactive jobs. In this latter case, the technique is referred to as **time sharing**, because processor time is shared among multiple users. In a time-sharing system, multiple users simultaneously access the system through terminals, with the OS interleaving the execution of each user program in a short burst or quantum of computation. Thus, if there are *n* users actively requesting service at one time, each user will only see on the average 1/*n* of the effective computer capacity, not counting OS overhead. However, given the relatively slow human reaction time, the response time on a properly designed system should be similar to that on a dedicated computer.

Both batch processing and time sharing use multiprogramming. The key differences are listed in Table 2.3.

One of the first time-sharing operating systems to be developed was the Compatible Time-Sharing System (CTSS) [CORB62], developed at MIT by a group known as Project MAC (Machine-Aided Cognition, or Multiple-Access Computers). The system was first developed for the IBM 709 in 1961 and later transferred to an IBM 7094.

Compared to later systems, CTSS is primitive. The system ran on a computer with 32,000 36-bit words of main memory, with the resident monitor consuming 5000 of that. When control was to be assigned to an interactive user, the user's program and data were loaded into the remaining 27,000 words of main memory. A program was always loaded to start at the location of the 5000th word; this simplified both the monitor and memory management. A system clock generated interrupts at a rate of approximately one every 0.2 seconds. At each clock interrupt, the OS regained control and could assign the processor to another user. This technique is known as **time slicing**. Thus, at regular time intervals, the current user would be preempted and another user loaded in. To preserve the old user program status for later resumption, the old user programs and data were written out to disk before the new user programs and data were read in. Subsequently, the old user program code and data were restored in main memory when that program was next given a turn.

To minimize disk traffic, user memory was only written out when the incoming program would overwrite it. This principle is illustrated in Figure 2.7. Assume that there are four interactive users with the following memory requirements, in words:

- JOB1: 15,000
- JOB2: 20,000

Table 2.3 Batch Multiprogramming versus Time Sharing

	Batch Multiprogramming	Time Sharing
Principal objective	Maximize processor use	Minimize response time
Source of directives to operating system	Job control language commands provided with the job	Commands entered at the terminal

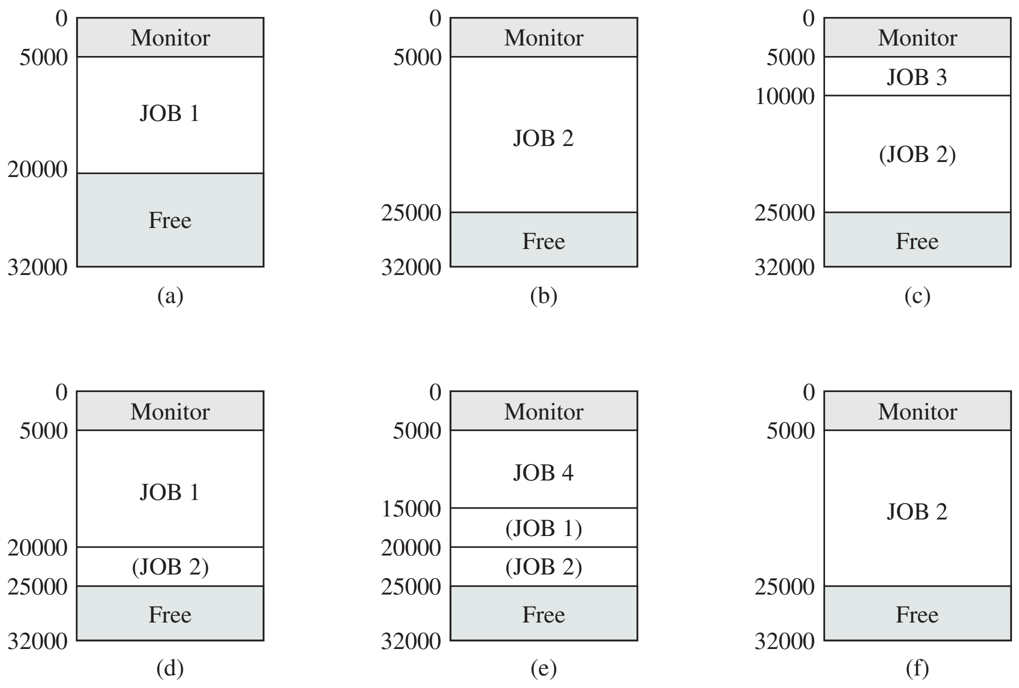

Figure 2.7 CTSS Operation

- JOB3: 5000
- JOB4: 10,000

Initially, the monitor loads JOB1 and transfers control to it (a). Later, the monitor decides to transfer control to JOB2. Because JOB2 requires more memory than JOB1, JOB1 must be written out first, and then JOB2 can be loaded (b). Next, JOB3 is loaded in to be run. However, because JOB3 is smaller than JOB2, a portion of JOB2 can remain in memory, reducing disk write time (c). Later, the monitor decides to transfer control back to JOB1. An additional portion of JOB2 must be written out when JOB1 is loaded back into memory (d). When JOB4 is loaded, part of JOB1 and the portion of JOB2 remaining in memory are retained (e). At this point, if either JOB1 or JOB2 is activated, only a partial load will be required. In this example, it is JOB2 that runs next. This requires that JOB4 and the remaining resident portion of JOB1 be written out and that the missing portion of JOB2 be read in (f).

The CTSS approach is primitive compared to present-day time sharing, but it was effective. It was extremely simple, which minimized the size of the monitor. Because a job was always loaded into the same locations in memory, there was no need for relocation techniques at load time (discussed subsequently). The technique of only writing out what was necessary minimized disk activity. Running on the 7094, CTSS supported a maximum of 32 users.

Time sharing and multiprogramming raise a host of new problems for the OS. If multiple jobs are in memory, then they must be protected from interfering with each other by, for example, modifying each other's data. With multiple interactive users, the file system must be protected so that only authorized users have access to a particular file. The contention for resources, such as printers and mass storage devices, must be handled. These and other problems, with possible solutions, will be encountered throughout this text.

2.3 MAJOR ACHIEVEMENTS

Operating systems are among the most complex pieces of software ever developed. This reflects the challenge of trying to meet the difficult and in some cases competing objectives of convenience, efficiency, and ability to evolve. [DENN80a] proposes that there have been four major theoretical advances in the development of operating systems:

- Processes
- Memory management
- Information protection and security
- Scheduling and resource management

Each advance is characterized by principles, or abstractions, developed to meet difficult practical problems. Taken together, these five areas span many of the key design and implementation issues of modern operating systems. The brief review of these five areas in this section serves as an overview of much of the rest of the text.

The Process

Central to the design of operating systems is the concept of *process*. This term was first used by the designers of Multics in the 1960s [DALE68]. It is a somewhat more general term than *job*. Many definitions have been given for the term *process*, including

- A program in execution
- An instance of a program running on a computer
- The entity that can be assigned to and executed on a processor
- A unit of activity characterized by a single sequential thread of execution, a current state, and an associated set of system resources

This concept should become clearer as we proceed.

Three major lines of computer system development created problems in timing and synchronization that contributed to the development of the concept of the process: multiprogramming batch operation, time sharing, and real-time transaction systems. As we have seen, multiprogramming was designed to keep the processor and I/O devices, including storage devices, simultaneously busy to achieve maximum efficiency. The key mechanism is this: In response to signals indicating the completion of I/O transactions, the processor is switched among the various programs residing in main memory.

UNIT - 2
PROCESS DESCRIPTION AND CONTROL

process and data structures that record other characteristics of processes that the OS needs to achieve its objectives. Next, we look at the ways in which the OS uses these data structures to control process execution. Finally, we discuss process management in UNIX SVR4. Chapter 4 provides more modern examples of process management.

This chapter occasionally refers to virtual memory. Much of the time, we can ignore this concept in dealing with processes, but at certain points in the discussion, virtual memory considerations are pertinent. Virtual memory is previewed in Chapter 2 and discussed in detail in Chapter 8. A set of animations that illustrate concepts in this chapter is available online. Click on the rotating globe at this book's Web site at WilliamStallings.com/OS/OS7e.html for access.

3.1 WHAT IS A PROCESS?

Background

Before defining the term *process*, it is useful to summarize some of the concepts introduced in Chapters 1 and 2:

1. A computer platform consists of a collection of hardware resources, such as the processor, main memory, I/O modules, timers, disk drives, and so on.
2. Computer applications are developed to perform some task. Typically, they accept input from the outside world, perform some processing, and generate output.
3. It is inefficient for applications to be written directly for a given hardware platform. The principal reasons for this are as follows:
   a. Numerous applications can be developed for the same platform. Thus, it makes sense to develop common routines for accessing the computer's resources.
   b. The processor itself provides only limited support for multiprogramming. Software is needed to manage the sharing of the processor and other resources by multiple applications at the same time.
   c. When multiple applications are active at the same time, it is necessary to protect the data, I/O use, and other resource use of each application from the others.
4. The OS was developed to provide a convenient, feature-rich, secure, and consistent interface for applications to use. The OS is a layer of software between the applications and the computer hardware (Figure 2.1) that supports applications and utilities.
5. We can think of the OS as providing a uniform, abstract representation of resources that can be requested and accessed by applications. Resources include main memory, network interfaces, file systems, and so on. Once the OS has created these resource abstractions for applications to use, it must also manage their use. For example, an OS may permit resource sharing and resource protection.

Now that we have the concepts of applications, system software, and resources, we are in a position to discuss how the OS can, in an orderly fashion, manage the execution of applications so that

- Resources are made available to multiple applications.
- The physical processor is switched among multiple applications so all will appear to be progressing.
- The processor and I/O devices can be used efficiently.

The approach taken by all modern operating systems is to rely on a model in which the execution of an application corresponds to the existence of one or more processes.

Processes and Process Control Blocks

Recall from Chapter 2 that we suggested several definitions of the term *process*, including

- A program in execution
- An instance of a program running on a computer
- The entity that can be assigned to and executed on a processor
- A unit of activity characterized by the execution of a sequence of instructions, a current state, and an associated set of system resources

We can also think of a process as an entity that consists of a number of elements. Two essential elements of a process are **program code** (which may be shared with other processes that are executing the same program) and a **set of data** associated with that code. Let us suppose that the processor begins to execute this program code, and we refer to this executing entity as a process. At any given point in time, *while the program is executing*, this process can be uniquely characterized by a number of elements, including the following:

- **Identifier:** A unique identifier associated with this process, to distinguish it from all other processes.
- **State:** If the process is currently executing, it is in the running state.
- **Priority:** Priority level relative to other processes.
- **Program counter:** The address of the next instruction in the program to be executed.
- **Memory pointers:** Includes pointers to the program code and data associated with this process, plus any memory blocks shared with other processes.
- **Context data:** These are data that are present in registers in the processor while the process is executing.
- **I/O status information:** Includes outstanding I/O requests, I/O devices (e.g., disk drives) assigned to this process, a list of files in use by the process, and so on.
- **Accounting information:** May include the amount of processor time and clock time used, time limits, account numbers, and so on.

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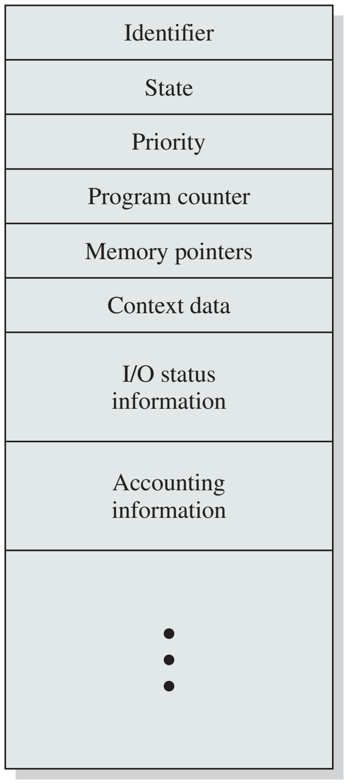


Figure 3.1 **Simplified Process Control Block**

The information in the preceding list is stored in a data structure, typically called a **process control block** (Figure 3.1), that is created and managed by the OS. The significant point about the process control block is that it contains sufficient information so that it is possible to interrupt a running process and later resume execution as if the interruption had not occurred. The process control block is the key tool that enables the OS to support multiple processes and to provide for multiprocessing. When a process is interrupted, the current values of the program counter and the processor registers (context data) are saved in the appropriate fields of the corresponding process control block, and the state of the process is changed to some other value, such as *blocked* or *ready* (described subsequently). The OS is now free to put some other process in the running state. The program counter and context data for this process are loaded into the processor registers and this process now begins to execute.

Thus, we can say that a process consists of program code and associated data plus a process control block. For a single-processor computer, at any given time, at most one process is executing and that process is in the *running* state.

3.2 PROCESS STATES

As just discussed, for a program to be executed, a process, or task, is created for that program. From the processor's point of view, it executes instructions from its repertoire in some sequence dictated by the changing values in the program counter

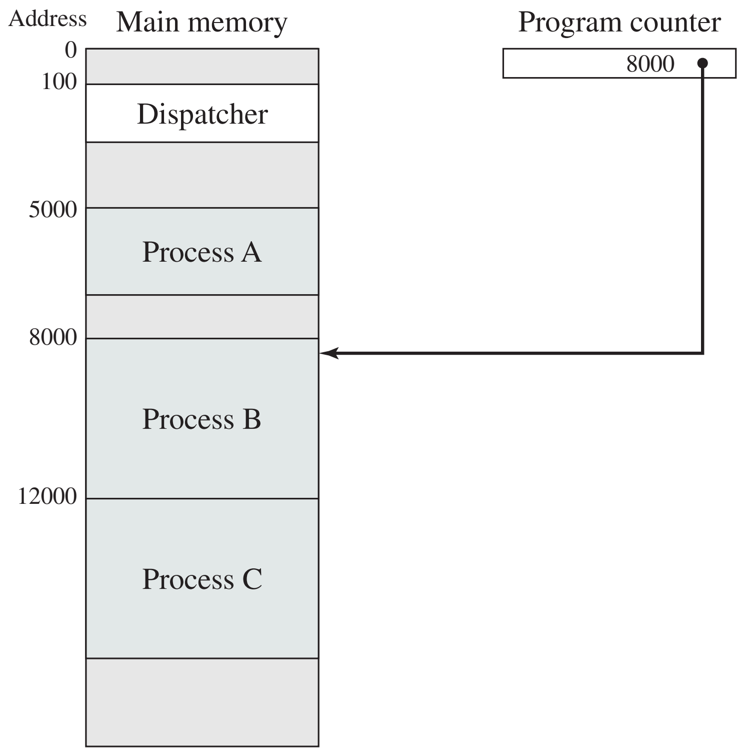


Figure 3.2 Snapshot of Example Execution (Figure 3.4) at Instruction Cycle 13

register. Over time, the program counter may refer to code in different programs that are part of different processes. From the point of view of an individual program, its execution involves a sequence of instructions within that program.

We can characterize the behavior of an individual process by listing the sequence of instructions that execute for that process. Such a listing is referred to as a **trace** of the process. We can characterize behavior of the processor by showing how the traces of the various processes are interleaved.

Let us consider a very simple example. Figure 3.2 shows a memory layout of three processes. To simplify the discussion, we assume no use of virtual memory; thus all three processes are represented by programs that are fully loaded in main memory. In addition, there is a small **dispatcher** program that switches the processor from one process to another. Figure 3.3 shows the traces of each of the processes during the early part of their execution. The first 12 instructions executed in processes A and C are shown. Process B executes four instructions, and we assume that the fourth instruction invokes an I/O operation for which the process must wait.

Now let us view these traces from the processor's point of view. Figure 3.4 shows the interleaved traces resulting from the first 52 instruction cycles (for convenience, the instruction cycles are numbered). In this figure, the shaded areas represent code executed by the dispatcher. The same sequence of instructions is executed by the dispatcher in each instance because the same functionality of the dispatcher is being executed. We assume that the OS only allows a process to continue execution for a maximum of six instruction cycles, after which it is interrupted;

5000	8000	12000
5001	8001	12001
5002	8002	12002
5003	8003	12003
5004		12004
5005		12005
5006		12006
5007		12007
5008		12008
5009		12009
5010		12010
5011		12011

(a) Trace of process A (b) Trace of process B (c) Trace of process C

5000 = Starting address of program of process A
8000 = Starting address of program of process B
12000 = Starting address of program of process C

Figure 3.3 Traces of Processes of Figure 3.2

this prevents any single process from monopolizing processor time. As Figure 3.4 shows, the first six instructions of process A are executed, followed by a time-out and the execution of some code in the dispatcher, which executes six instructions before turning control to process B.[2] After four instructions are executed, process B requests an I/O action for which it must wait. Therefore, the processor stops executing process B and moves on, via the dispatcher, to process C. After a time-out, the processor moves back to process A. When this process times out, process B is still waiting for the I/O operation to complete, so the dispatcher moves on to process C again.

A Two-State Process Model

The operating system's principal responsibility is controlling the execution of processes; this includes determining the interleaving pattern for execution and allocating resources to processes. The first step in designing an OS to control processes is to describe the behavior that we would like the processes to exhibit.

We can construct the simplest possible model by observing that, at any time, a process is either being executed by a processor or not. In this model, a process may be in one of two states: Running or Not Running, as shown in Figure 3.5a. When the OS creates a new process, it creates a process control block for the process and enters that process into the system in the Not Running state. The process exists, is known to the OS, and is waiting for an opportunity to execute. From time to time, the currently running process will be interrupted and the dispatcher portion of the OS will select some other process to run. The former process moves from the

[2]The small number of instructions executed for the processes and the dispatcher are unrealistically low; they are used in this simplified example to clarify the discussion.

1	5000	27	12004
2	5001	28	12005
3	5002	----------------------Time-out	
4	5003	29	100
5	5004	30	101
6	5005	31	102
----------------------Time-out		32	103
7	100	33	104
8	101	34	105
9	102	35	5006
10	103	36	5007
11	104	37	5008
12	105	38	5009
13	8000	39	5010
14	8001	40	5011
15	8002	----------------------Time-out	
16	8003	41	100
----------------------I/O request		42	101
17	100	43	102
18	101	44	103
19	102	45	104
20	103	46	105
21	104	47	12006
22	105	48	12007
23	12000	49	12008
24	12001	50	12009
25	12002	51	12010
26	12003	52	12011
		----------------------Time-out	

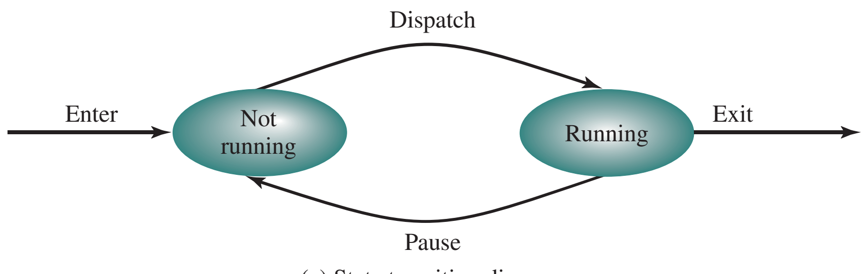
100 = Starting address of dispatcher program

Shaded areas indicate execution of dispatcher process;
first and third columns count instruction cycles;
second and fourth columns show address of instruction being executed

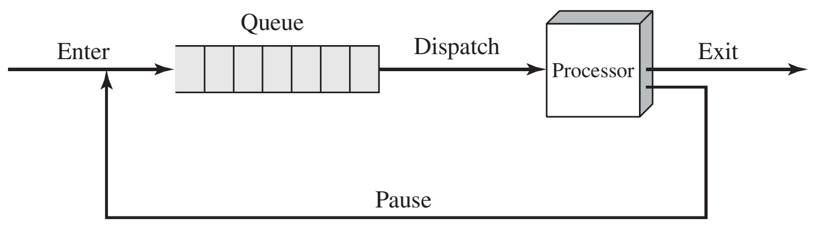
Figure 3.4 Combined Trace of Processes of Figure 3.2

Running state to the Not Running state, and one of the other processes moves to the Running state.

From this simple model, we can already begin to appreciate some of the design elements of the OS. Each process must be represented in some way so that the OS can keep track of it. That is, there must be some information relating to each process, including current state and location in memory; this is the process control block. Processes that are not running must be kept in some sort of queue, waiting their turn to execute. Figure 3.5b suggests a structure. There is a single queue in which each entry is a pointer to the process control block of a particular process. Alternatively,



(a) State transition diagram



(b) Queueing diagram

Figure 3.5 Two-State Process Model

the queue may consist of a linked list of data blocks, in which each block represents one process; we will explore this latter implementation subsequently.

We can describe the behavior of the dispatcher in terms of this queueing diagram. A process that is interrupted is transferred to the queue of waiting processes. Alternatively, if the process has completed or aborted, it is discarded (exits the system). In either case, the dispatcher takes another process from the queue to execute.

The Creation and Termination of Processes

Before refining our simple two-state model, it will be useful to discuss the creation and termination of processes; ultimately, and regardless of the model of process behavior that is used, the life of a process is bounded by its creation and termination.

Process Creation When a new process is to be added to those currently being managed, the OS builds the data structures that are used to manage the process and allocates address space in main memory to the process. We describe these data structures in Section 3.3. These actions constitute the creation of a new process.

Four common events lead to the creation of a process, as indicated in Table 3.1. In a batch environment, a process is created in response to the submission of a job. In an interactive environment, a process is created when a new user attempts to log on. In both cases, the OS is responsible for the creation of the new process. An OS may also create a process on behalf of an application. For example, if a user requests that a file be printed, the OS can create a process that will manage the printing. The requesting process can thus proceed independently of the time required to complete the printing task.

Table 3.1 Reasons for Process Creation

New batch job	The OS is provided with a batch job control stream, usually on tape or disk. When the OS is prepared to take on new work, it will read the next sequence of job control commands.
Interactive log-on	A user at a terminal logs on to the system.
Created by OS to provide a service	The OS can create a process to perform a function on behalf of a user program, without the user having to wait (e.g., a process to control printing).
Spawned by existing process	For purposes of modularity or to exploit parallelism, a user program can dictate the creation of a number of processes.

Traditionally, the OS created all processes in a way that was transparent to the user or application program, and this is still commonly found with many contemporary operating systems. However, it can be useful to allow one process to cause the creation of another. For example, an application process may generate another process to receive data that the application is generating and to organize those data into a form suitable for later analysis. The new process runs in parallel to the original process and is activated from time to time when new data are available. This arrangement can be very useful in structuring the application. As another example, a server process (e.g., print server, file server) may generate a new process for each request that it handles. When the OS creates a process at the explicit request of another process, the action is referred to as **process spawning**.

When one process spawns another, the former is referred to as the **parent process,** and the spawned process is referred to as the **child process.** Typically, the "related" processes need to communicate and cooperate with each other. Achieving this cooperation is a difficult task for the programmer; this topic is discussed in Chapter 5.

Process Termination Table 3.2 summarizes typical reasons for process termination. Any computer system must provide a means for a process to indicate its completion. A batch job should include a Halt instruction or an explicit OS service call for termination. In the former case, the Halt instruction will generate an interrupt to alert the OS that a process has completed. For an interactive application, the action of the user will indicate when the process is completed. For example, in a time-sharing system, the process for a particular user is to be terminated when the user logs off or turns off his or her terminal. On a personal computer or workstation, a user may quit an application (e.g., word processing or spreadsheet). All of these actions ultimately result in a service request to the OS to terminate the requesting process.

Additionally, a number of error and fault conditions can lead to the termination of a process. Table 3.2 lists some of the more commonly recognized conditions.[3]

Finally, in some operating systems, a process may be terminated by the process that created it or when the parent process is itself terminated.

[3]A forgiving operating system might, in some cases, allow the user to recover from a fault without terminating the process. For example, if a user requests access to a file and that access is denied, the operating system might simply inform the user that access is denied and allow the process to proceed.

Table 3.2 Reasons for Process Termination

Normal completion	The process executes an OS service call to indicate that it has completed running.
Time limit exceeded	The process has run longer than the specified total time limit. There are a number of possibilities for the type of time that is measured. These include total elapsed time ("wall clock time"), amount of time spent executing, and, in the case of an interactive process, the amount of time since the user last provided any input.
Memory unavailable	The process requires more memory than the system can provide.
Bounds violation	The process tries to access a memory location that it is not allowed to access.
Protection error	The process attempts to use a resource such as a file that it is not allowed to use, or it tries to use it in an improper fashion, such as writing to a read-only file.
Arithmetic error	The process tries a prohibited computation, such as division by zero, or tries to store numbers larger than the hardware can accommodate.
Time overrun	The process has waited longer than a specified maximum for a certain event to occur.
I/O failure	An error occurs during input or output, such as inability to find a file, failure to read or write after a specified maximum number of tries (when, for example, a defective area is encountered on a tape), or invalid operation (such as reading from the line printer).
Invalid instruction	The process attempts to execute a nonexistent instruction (often a result of branching into a data area and attempting to execute the data).
Privileged instruction	The process attempts to use an instruction reserved for the operating system.
Data misuse	A piece of data is of the wrong type or is not initialized.
Operator or OS intervention	For some reason, the operator or the operating system has terminated the process (e.g., if a deadlock exists).
Parent termination	When a parent terminates, the operating system may automatically terminate all of the offspring of that parent.
Parent request	A parent process typically has the authority to terminate any of its offspring.

A Five-State Model

If all processes were always ready to execute, then the queueing discipline suggested by Figure 3.5b would be effective. The queue is a first-in-first-out list and the processor operates in **round-robin** fashion on the available processes (each process in the queue is given a certain amount of time, in turn, to execute and then returned to the queue, unless blocked). However, even with the simple example that we have described, this implementation is inadequate: Some processes in the Not Running state are ready to execute, while others are blocked, waiting for an I/O operation to complete. Thus, using a single queue, the dispatcher could not just select the process at the oldest end of the queue. Rather, the dispatcher would have to scan the list looking for the process that is not blocked and that has been in the queue the longest.

A more natural way to handle this situation is to split the Not Running state into two states: Ready and Blocked. This is shown in Figure 3.6. For good measure,

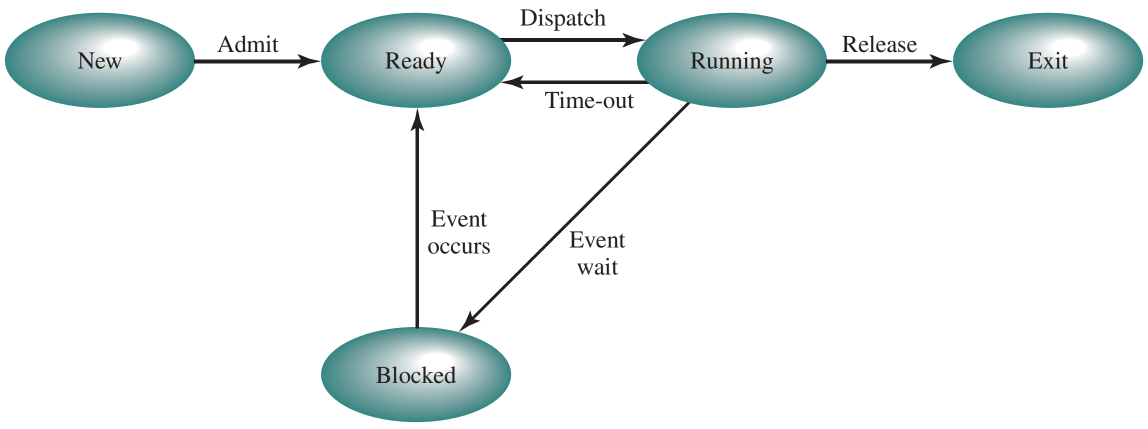


Figure 3.6 Five-State Process Model

we have added two additional states that will prove useful. The five states in this new diagram are:

- **Running:** The process that is currently being executed. For this chapter, we will assume a computer with a single processor, so at most one process at a time can be in this state.
- **Ready:** A process that is prepared to execute when given the opportunity.
- **Blocked/Waiting:**[4] A process that cannot execute until some event occurs, such as the completion of an I/O operation.
- **New:** A process that has just been created but has not yet been admitted to the pool of executable processes by the OS. Typically, a new process has not yet been loaded into main memory, although its process control block has been created.
- **Exit:** A process that has been released from the pool of executable processes by the OS, either because it halted or because it aborted for some reason.

The New and Exit states are useful constructs for process management. The New state corresponds to a process that has just been defined. For example, if a new user attempts to log on to a time-sharing system or a new batch job is submitted for execution, the OS can define a new process in two stages. First, the OS performs the necessary housekeeping chores. An identifier is associated with the process. Any tables that will be needed to manage the process are allocated and built. At this point, the process is in the New state. This means that the OS has performed the necessary actions to create the process but has not committed itself to the execution of the process. For example, the OS may limit the number of processes that may be in the system for reasons of performance or main memory limitation. While a process is in the new state, information concerning the process that is needed by the OS is maintained in control tables in main memory. However, the process itself is

[4]*Waiting* is a frequently used alternative term for *Blocked* as a process state. Generally, we will use *Blocked*, but the terms are interchangeable.

not in main memory. That is, the code of the program to be executed is not in main memory, and no space has been allocated for the data associated with that program. While the process is in the New state, the program remains in secondary storage, typically disk storage.[5]

Similarly, a process exits a system in two stages. First, a process is terminated when it reaches a natural completion point, when it aborts due to an unrecoverable error, or when another process with the appropriate authority causes the process to abort. Termination moves the process to the exit state. At this point, the process is no longer eligible for execution. The tables and other information associated with the job are temporarily preserved by the OS, which provides time for auxiliary or support programs to extract any needed information. For example, an accounting program may need to record the processor time and other resources utilized by the process for billing purposes. A utility program may need to extract information about the history of the process for purposes related to performance or utilization analysis. Once these programs have extracted the needed information, the OS no longer needs to maintain any data relating to the process and the process is deleted from the system.

Figure 3.6 indicates the types of events that lead to each state transition for a process; the possible transitions are as follows:

- **Null → New:** A new process is created to execute a program. This event occurs for any of the reasons listed in Table 3.1.
- **New → Ready:** The OS will move a process from the New state to the Ready state when it is prepared to take on an additional process. Most systems set some limit based on the number of existing processes or the amount of virtual memory committed to existing processes. This limit assures that there are not so many active processes as to degrade performance.
- **Ready → Running:** When it is time to select a process to run, the OS chooses one of the processes in the Ready state. This is the job of the scheduler or dispatcher. Scheduling is explored in Part Four.
- **Running → Exit:** The currently running process is terminated by the OS if the process indicates that it has completed, or if it aborts. See Table 3.2.
- **Running → Ready:** The most common reason for this transition is that the running process has reached the maximum allowable time for uninterrupted execution; virtually all multiprogramming operating systems impose this type of time discipline. There are several other alternative causes for this transition, which are not implemented in all operating systems. Of particular importance is the case in which the OS assigns different levels of priority to different processes. Suppose, for example, that process A is running at a given priority level, and process B, at a higher priority level, is blocked. If the OS learns that the event upon which process B has been waiting has occurred, moving B to a ready state, then it can interrupt process A and dispatch process B. We

[5]In the discussion in this paragraph, we ignore the concept of virtual memory. In systems that support virtual memory, when a process moves from New to Ready, its program code and data are loaded into virtual memory. Virtual memory was briefly discussed in Chapter 2 and is examined in detail in Chapter 8.

say that the OS has **preempted** process A.[6] Finally, a process may voluntarily release control of the processor. An example is a background process that performs some accounting or maintenance function periodically.

- **Running → Blocked:** A process is put in the Blocked state if it requests something for which it must wait. A request to the OS is usually in the form of a system service call; that is, a call from the running program to a procedure that is part of the operating system code. For example, a process may request a service from the OS that the OS is not prepared to perform immediately. It can request a resource, such as a file or a shared section of virtual memory, that is not immediately available. Or the process may initiate an action, such as an I/O operation, that must be completed before the process can continue. When processes communicate with each other, a process may be blocked when it is waiting for another process to provide data or waiting for a message from another process.
- **Blocked → Ready:** A process in the Blocked state is moved to the Ready state when the event for which it has been waiting occurs.
- **Ready → Exit:** For clarity, this transition is not shown on the state diagram. In some systems, a parent may terminate a child' process at any time. Also, if a parent terminates, all child processes associated with that parent may be terminated.
- **Blocked → Exit:** The comments under the preceding item apply.

Returning to our simple example, Figure 3.7 shows the transition of each process among the states. Figure 3.8a suggests the way in which a queueing discipline might be implemented with two queues: a Ready queue and a Blocked queue. As each process is admitted to the system, it is placed in the Ready queue. When it is time for the OS to choose another process to run, it selects one from the Ready

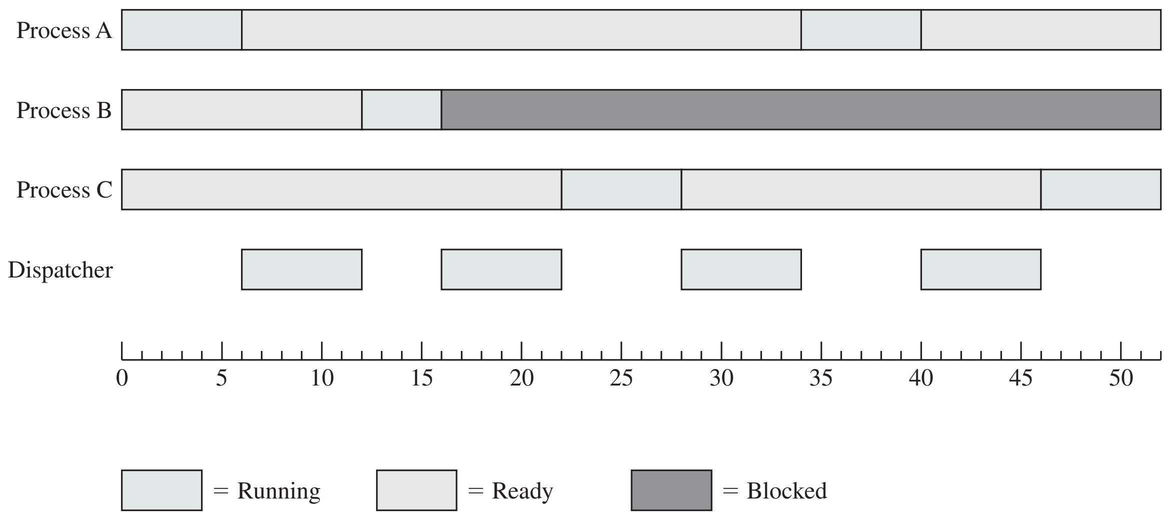
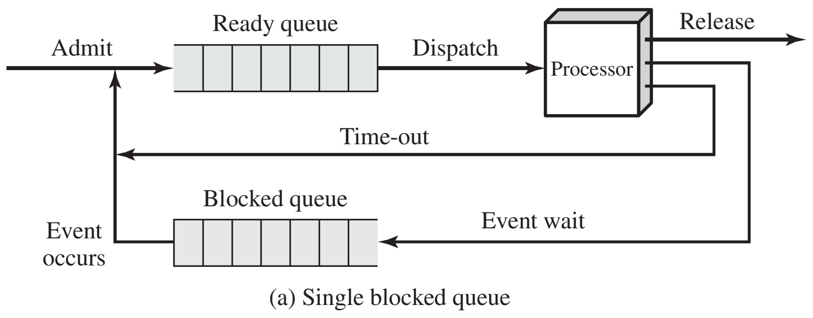
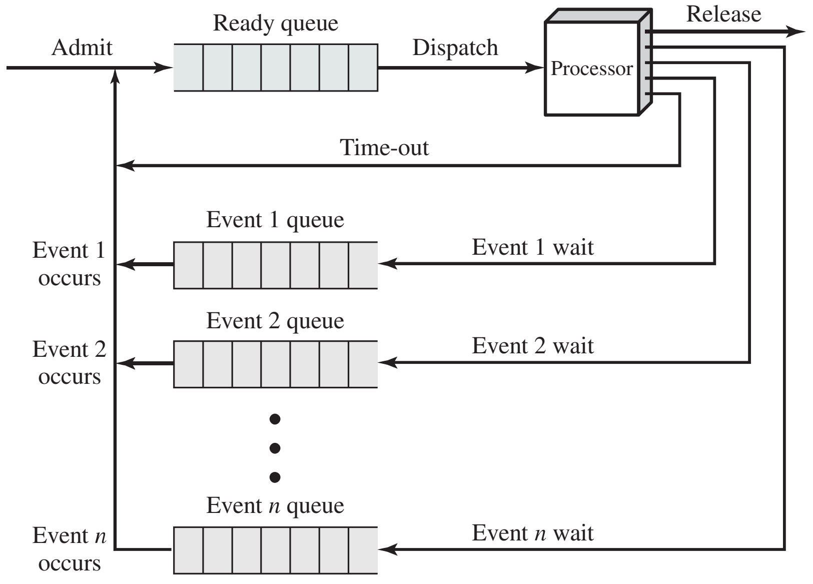


Figure 3.7 Process States for the Trace of Figure 3.4

[6]In general, the term *preemption* is defined to be the reclaiming of a resource from a process before the process has finished using it. In this case, the resource is the processor itself. The process is executing and could continue to execute, but is preempted so that another process can be executed.



(a) Single blocked queue



(b) Multiple blocked queues

Figure 3.8 Queueing Model for Figure 3.6

queue. In the absence of any priority scheme, this can be a simple first-in-first-out queue. When a running process is removed from execution, it is either terminated or placed in the Ready or Blocked queue, depending on the circumstances. Finally, when an event occurs, any process in the Blocked queue that has been waiting on that event only is moved to the Ready queue.

This latter arrangement means that, when an event occurs, the OS must scan the entire blocked queue, searching for those processes waiting on that event. In a large OS, there could be hundreds or even thousands of processes in that queue. Therefore, it would be more efficient to have a number of queues, one for each event. Then, when the event occurs, the entire list of processes in the appropriate queue can be moved to the Ready state (Figure 3.8b).

One final refinement: If the dispatching of processes is dictated by a priority scheme, then it would be convenient to have a number of Ready queues, one for each priority level. The OS could then readily determine which is the highest-priority ready process that has been waiting the longest.

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Suspended Processes

The Need for Swapping The three principal states just described (Ready, Running, Blocked) provide a systematic way of modeling the behavior of processes and guide the implementation of the OS. Some operating systems are constructed using just these three states.

However, there is good justification for adding other states to the model. To see the benefit of these new states, consider a system that does not employ virtual memory. Each process to be executed must be loaded fully into main memory. Thus, in Figure 3.8b, all of the processes in all of the queues must be resident in main memory.

Recall that the reason for all of this elaborate machinery is that I/O activities are much slower than computation and therefore the processor in a uniprogramming system is idle most of the time. But the arrangement of Figure 3.8b does not entirely solve the problem. It is true that, in this case, memory holds multiple processes and that the processor can move to another process when one process is blocked. But the processor is so much faster than I/O that it will be common for all of the processes in memory to be waiting for I/O. Thus, even with multiprogramming, a processor could be idle most of the time.

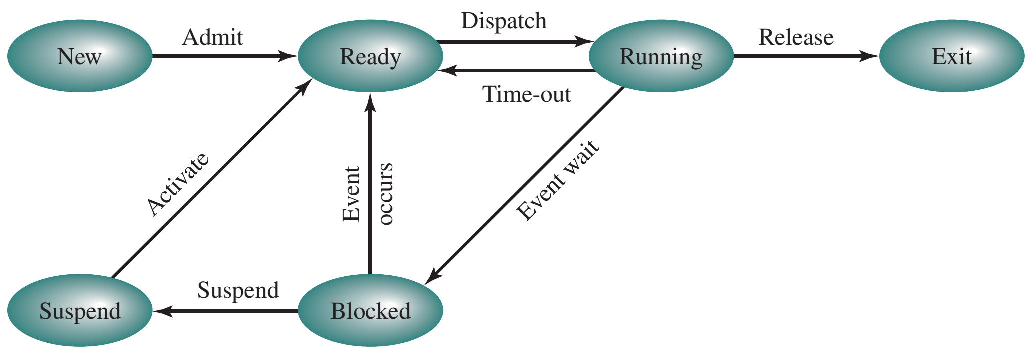
What to do? Main memory could be expanded to accommodate more processes. But there are two flaws in this approach. First, there is a cost associated with main memory, which, though small on a per-byte basis, begins to add up as we get into the gigabytes of storage. Second, the appetite of programs for memory has grown as fast as the cost of memory has dropped. So larger memory results in larger processes, not more processes.

Another solution is swapping, which involves moving part or all of a process from main memory to disk. When none of the processes in main memory is in the Ready state, the OS swaps one of the blocked processes out on to disk into a suspend queue. This is a queue of existing processes that have been temporarily kicked out of main memory, or suspended. The OS then brings in another process from the suspend queue, or it honors a new-process request. Execution then continues with the newly arrived process.

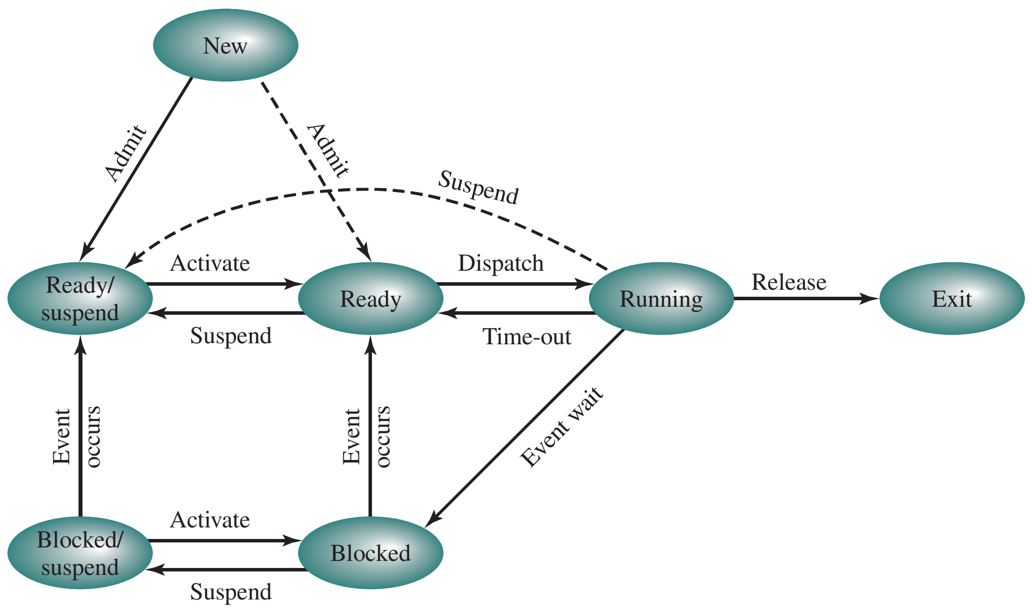
Swapping, however, is an I/O operation, and therefore there is the potential for making the problem worse, not better. But because disk I/O is generally the fastest I/O on a system (e.g., compared to tape or printer I/O), swapping will usually enhance performance.

With the use of swapping as just described, one other state must be added to our process behavior model (Figure 3.9a): the Suspend state. When all of the processes in main memory are in the Blocked state, the OS can suspend one process by putting it in the Suspend state and transferring it to disk. The space that is freed in main memory can then be used to bring in another process.

When the OS has performed a swapping-out operation, it has two choices for selecting a process to bring into main memory: It can admit a newly created process or it can bring in a previously suspended process. It would appear that the preference should be to bring in a previously suspended process, to provide it with service rather than increasing the total load on the system.



(a) With one suspend state



(b) With two suspend states

Figure 3.9 Process State Transition Diagram with Suspend States

But this line of reasoning presents a difficulty. All of the processes that have been suspended were in the Blocked state at the time of suspension. It clearly would not do any good to bring a blocked process back into main memory, because it is still not ready for execution. Recognize, however, that each process in the Suspend state was originally blocked on a particular event. When that event occurs, the process is not blocked and is potentially available for execution.

Therefore, we need to rethink this aspect of the design. There are two independent concepts here: whether a process is waiting on an event (blocked or not) and whether a process has been swapped out of main memory (suspended or not). To accommodate this 2×2 combination, we need four states:

- **Ready:** The process is in main memory and available for execution
- **Blocked:** The process is in main memory and awaiting an event.

- **Blocked/Suspend:** The process is in secondary memory and awaiting an event.
- **Ready/Suspend:** The process is in secondary memory but is available for execution as soon as it is loaded into main memory.

Before looking at a state transition diagram that encompasses the two new suspend states, one other point should be mentioned. The discussion so far has assumed that virtual memory is not in use and that a process is either all in main memory or all out of main memory. With a virtual memory scheme, it is possible to execute a process that is only partially in main memory. If reference is made to a process address that is not in main memory, then the appropriate portion of the process can be brought in. The use of virtual memory would appear to eliminate the need for explicit swapping, because any desired address in any desired process can be moved in or out of main memory by the memory management hardware of the processor. However, as we shall see in Chapter 8, the performance of a virtual memory system can collapse if there is a sufficiently large number of active processes, all of which are partially in main memory. Therefore, even in a virtual memory system, the OS will need to swap out processes explicitly and completely from time to time in the interests of performance.

Let us look now, in Figure 3.9b, at the state transition model that we have developed. (The dashed lines in the figure indicate possible but not necessary transitions.) Important new transitions are the following:

- **Blocked → Blocked/Suspend:** If there are no ready processes, then at least one blocked process is swapped out to make room for another process that is not blocked. This transition can be made even if there are ready processes available, if the OS determines that the currently running process or a ready process that it would like to dispatch requires more main memory to maintain adequate performance.
- **Blocked/Suspend → Ready/Suspend:** A process in the Blocked/Suspend state is moved to the Ready/Suspend state when the event for which it has been waiting occurs. Note that this requires that the state information concerning suspended processes must be accessible to the OS.
- **Ready/Suspend → Ready:** When there are no ready processes in main memory, the OS will need to bring one in to continue execution. In addition, it might be the case that a process in the Ready/Suspend state has higher priority than any of the processes in the Ready state. In that case, the OS designer may dictate that it is more important to get at the higher-priority process than to minimize swapping.
- **Ready → Ready/Suspend:** Normally, the OS would prefer to suspend a blocked process rather than a ready one, because the ready process can now be executed, whereas the blocked process is taking up main memory space and cannot be executed. However, it may be necessary to suspend a ready process if that is the only way to free up a sufficiently large block of main memory. Also, the OS may choose to suspend a lower–priority ready process rather than a higher–priority blocked process if it believes that the blocked process will be ready soon.

Several other transitions that are worth considering are the following:

- **New → Ready/Suspend and New → Ready:** When a new process is created, it can either be added to the Ready queue or the Ready/Suspend queue. In either case, the OS must create a process control block and allocate an address space to the process. It might be preferable for the OS to perform these housekeeping duties at an early time, so that it can maintain a large pool of processes that are not blocked. With this strategy, there would often be insufficient room in main memory for a new process; hence the use of the (New → Ready/Suspend) transition. On the other hand, we could argue that a just-in-time philosophy of creating processes as late as possible reduces OS overhead and allows that OS to perform the process-creation duties at a time when the system is clogged with blocked processes anyway.
- **Blocked/Suspend → Blocked:** Inclusion of this transition may seem to be poor design. After all, if a process is not ready to execute and is not already in main memory, what is the point of bringing it in? But consider the following scenario: A process terminates, freeing up some main memory. There is a process in the (Blocked/Suspend) queue with a higher priority than any of the processes in the (Ready/Suspend) queue and the OS has reason to believe that the blocking event for that process will occur soon. Under these circumstances, it would seem reasonable to bring a blocked process into main memory in preference to a ready process.
- **Running → Ready/Suspend:** Normally, a running process is moved to the Ready state when its time allocation expires. If, however, the OS is preempting the process because a higher-priority process on the Blocked/Suspend queue has just become unblocked, the OS could move the running process directly to the (Ready/Suspend) queue and free some main memory.
- **Any State → Exit:** Typically, a process terminates while it is running, either because it has completed or because of some fatal fault condition. However, in some operating systems, a process may be terminated by the process that created it or when the parent process is itself terminated. If this is allowed, then a process in any state can be moved to the Exit state.

Other Uses of Suspension So far, we have equated the concept of a suspended process with that of a process that is not in main memory. A process that is not in main memory is not immediately available for execution, whether or not it is awaiting an event.

We can generalize the concept of a suspended process. Let us define a suspended process as having the following characteristics:

1. The process is not immediately available for execution.
2. The process may or may not be waiting on an event. If it is, this blocked condition is independent of the suspend condition, and occurrence of the blocking event does not enable the process to be executed immediately.

Table 3.3 Reasons for Process Suspension

Swapping	The OS needs to release sufficient main memory to bring in a process that is ready to execute.
Other OS reason	The OS may suspend a background or utility process or a process that is suspected of causing a problem.
Interactive user request	A user may wish to suspend execution of a program for purposes of debugging or in connection with the use of a resource.
Timing	A process may be executed periodically (e.g., an accounting or system monitoring process) and may be suspended while waiting for the next time interval.
Parent process request	A parent process may wish to suspend execution of a descendent to examine or modify the suspended process, or to coordinate the activity of various descendants.

3. The process was placed in a suspended state by an agent: either itself, a parent process, or the OS, for the purpose of preventing its execution.
4. The process may not be removed from this state until the agent explicitly orders the removal.

Table 3.3 lists some reasons for the suspension of a process. One reason that we have discussed is to provide memory space either to bring in a Ready/Suspended process or to increase the memory allocated to other Ready processes. The OS may have other motivations for suspending a process. For example, an auditing or tracing process may be employed to monitor activity on the system; the process may be used to record the level of utilization of various resources (processor, memory, channels) and the rate of progress of the user processes in the system. The OS, under operator control, may turn this process on and off from time to time. If the OS detects or suspects a problem, it may suspend a process. One example of this is deadlock, which is discussed in Chapter 6. As another example, a problem is detected on a communications line, and the operator has the OS suspend the process that is using the line while some tests are run.

Another set of reasons concerns the actions of an interactive user. For example, if a user suspects a bug in the program, he or she may debug the program by suspending its execution, examining and modifying the program or data, and resuming execution. Or there may be a background process that is collecting trace or accounting statistics, which the user may wish to be able to turn on and off.

Timing considerations may also lead to a swapping decision. For example, if a process is to be activated periodically but is idle most of the time, then it should be swapped out between uses. A program that monitors utilization or user activity is an example.

Finally, a parent process may wish to suspend a descendent process. For example, process A may spawn process B to perform a file read. Subsequently, process B encounters an error in the file read procedure and reports this to process A. Process A suspends process B to investigate the cause.

In all of these cases, the activation of a suspended process is requested by the agent that initially requested the suspension.

3.3 PROCESS DESCRIPTION

The OS controls events within the computer system. It schedules and dispatches processes for execution by the processor, allocates resources to processes, and responds to requests by user processes for basic services. Fundamentally, we can think of the OS as that entity that manages the use of system resources by processes.

This concept is illustrated in Figure 3.10. In a multiprogramming environment, there are a number of processes ($P_1, \ldots, P_n$) that have been created and exist in virtual memory. Each process, during the course of its execution, needs access to certain system resources, including the processor, I/O devices, and main memory. In the figure, process P_1 is running; at least part of the process is in main memory, and it has control of two I/O devices. Process P_2 is also in main memory but is blocked waiting for an I/O device allocated to P_1. Process P_n has been swapped out and is therefore suspended.

We explore the details of the management of these resources by the OS on behalf of the processes in later chapters. Here we are concerned with a more fundamental question: What information does the OS need to control processes and manage resources for them?

Operating System Control Structures

If the OS is to manage processes and resources, it must have information about the current status of each process and resource. The universal approach to providing this information is straightforward: The OS constructs and maintains tables of information about each entity that it is managing. A general idea of the scope of this effort is indicated in Figure 3.11, which shows four different types of tables maintained by the OS: memory, I/O, file, and process. Although the details will differ from one OS to another, fundamentally, all operating systems maintain information in these four categories.

Memory tables are used to keep track of both main (real) and secondary (virtual) memory. Some of main memory is reserved for use by the OS; the remainder is available for use by processes. Processes are maintained on secondary memory using some sort of virtual memory or simple swapping mechanism. The memory tables must include the following information:

- The allocation of main memory to processes
- The allocation of secondary memory to processes

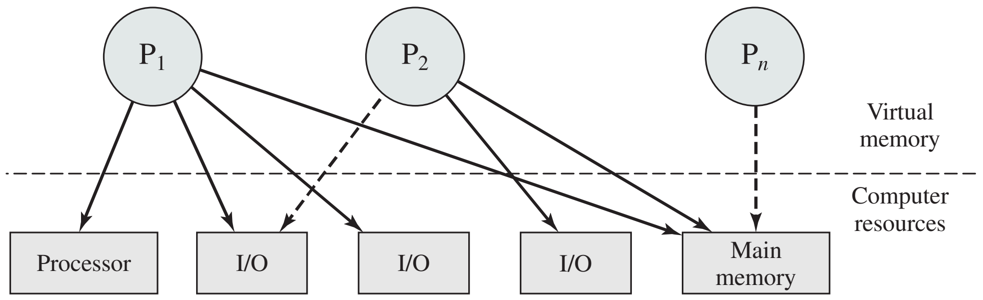


Figure 3.10 **Processes and Resources (resource allocation at one snapshot in time)**

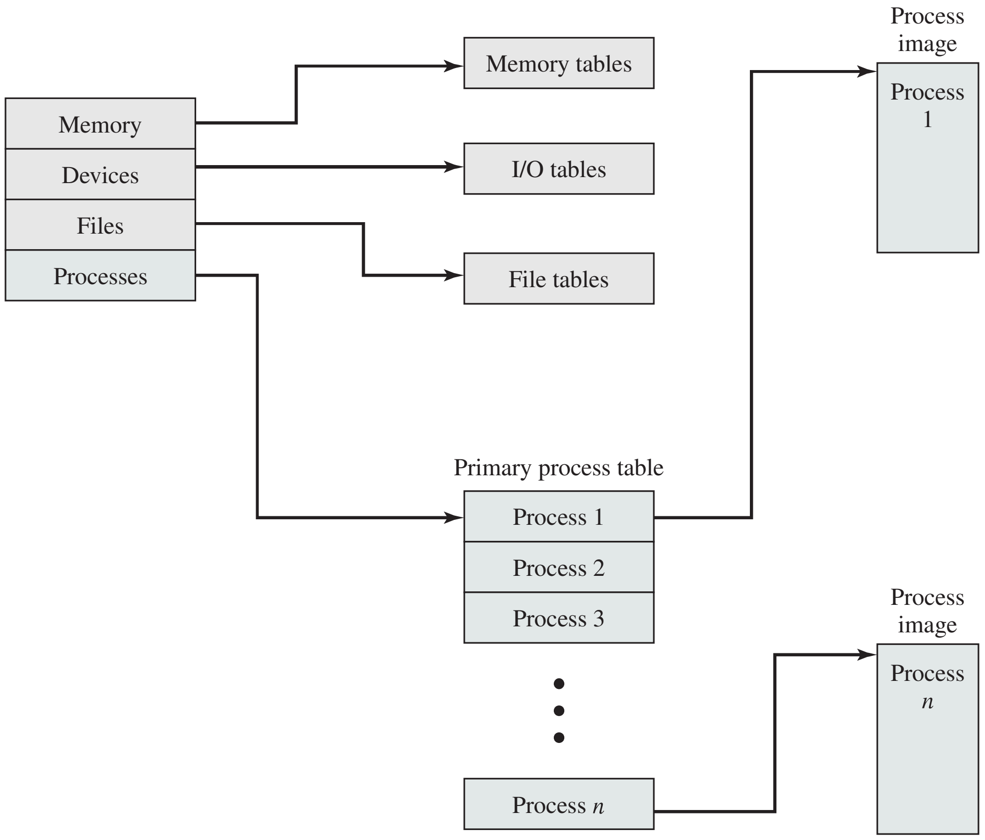


Figure 3.11 General Structure of Operating System Control Tables

- Any protection attributes of blocks of main or virtual memory, such as which processes may access certain shared memory regions
- Any information needed to manage virtual memory

We examine the information structures for memory management in detail in Part Three.

I/O tables are used by the OS to manage the I/O devices and channels of the computer system. At any given time, an I/O device may be available or assigned to a particular process. If an I/O operation is in progress, the OS needs to know the status of the I/O operation and the location in main memory being used as the source or destination of the I/O transfer. I/O management is examined in Chapter 11.

The OS may also maintain **file tables**. These tables provide information about the existence of files, their location on secondary memory, their current status, and other attributes. Much, if not all, of this information may be maintained and used by a file management system, in which case the OS has little or no knowledge of files. In other operating systems, much of the detail of file management is managed by the OS itself. This topic is explored in Chapter 12.

Finally, the OS must maintain **process tables** to manage processes. The remainder of this section is devoted to an examination of the required process tables. Before proceeding to this discussion, two additional points should be made. First, although Figure 3.11 shows four distinct sets of tables, it should be clear that these tables must be linked or cross-referenced in some fashion. Memory, I/O, and files are managed on behalf of processes, so there must be some reference to these resources, directly or indirectly, in the process tables. The files referred to in the file tables are accessible via an I/O device and will, at some times, be in main or virtual memory. The tables themselves must be accessible by the OS and therefore are subject to memory management.

Second, how does the OS know to create the tables in the first place? Clearly, the OS must have some knowledge of the basic environment, such as how much main memory exists, what are the I/O devices and what are their identifiers, and so on. This is an issue of configuration. That is, when the OS is initialized, it must have access to some configuration data that define the basic environment, and these data must be created outside the OS, with human assistance or by some autoconfiguration software.

Process Control Structures

Consider what the OS must know if it is to manage and control a process. First, it must know where the process is located; second, it must know the attributes of the process that are necessary for its management (e.g., process ID and process state).

Process Location Before we can deal with the questions of where a process is located or what its attributes are, we need to address an even more fundamental question: What is the physical manifestation of a process? At a minimum, a process must include a program or set of programs to be executed. Associated with these programs is a set of data locations for local and global variables and any defined constants. Thus, a process will consist of at least sufficient memory to hold the programs and data of that process. In addition, the execution of a program typically involves a stack (see Appendix P) that is used to keep track of procedure calls and parameter passing between procedures. Finally, each process has associated with it a number of attributes that are used by the OS for process control. Typically, the collection of attributes is referred to as a *process control block.*[7] We can refer to this collection of program, data, stack, and attributes as the **process image** (Table 3.4).

The location of a process image will depend on the memory management scheme being used. In the simplest case, the process image is maintained as a

Table 3.4 Typical Elements of a Process Image

User Data The modifiable part of the user space. May include program data, a user stack area, and programs that may be modified.
User Program The program to be executed.
Stack Each process has one or more last-in-first-out (LIFO) stacks associated with it. A stack is used to store parameters and calling addresses for procedure and system calls.
Process Control Block Data needed by the OS to control the process (see Table 3.5).

[7]Other commonly used names for this data structure are *task control block*, *process descriptor*, and *task descriptor.*

contiguous, or continuous, block of memory. This block is maintained in secondary memory, usually disk. So that the OS can manage the process, at least a small portion of its image must be maintained in main memory. To execute the process, the entire process image must be loaded into main memory or at least virtual memory. Thus, the OS needs to know the location of each process on disk and, for each such process that is in main memory, the location of that process in main memory. We saw a slightly more complex variation on this scheme with the CTSS OS, in Chapter 2. With CTSS, when a process is swapped out, part of the process image may remain in main memory. Thus, the OS must keep track of which portions of the image of each process are still in main memory.

Modern operating systems presume paging hardware that allows noncontiguous physical memory to support partially resident processes.[8] At any given time, a portion of a process image may be in main memory, with the remainder in secondary memory.[9] Therefore, process tables maintained by the OS must show the location of each page of each process image.

Figure 3.11 depicts the structure of the location information in the following way. There is a primary process table with one entry for each process. Each entry contains, at least, a pointer to a process image. If the process image contains multiple blocks, this information is contained directly in the primary process table or is available by cross-reference to entries in memory tables. Of course, this depiction is generic; a particular OS will have its own way of organizing the location information.

Process Attributes A sophisticated multiprogramming system requires a great deal of information about each process. As was explained, this information can be considered to reside in a process control block. Different systems will organize this information in different ways, and several examples of this appear at the end of this chapter and the next. For now, let us simply explore the type of information that might be of use to an OS without considering in any detail how that information is organized.

Table 3.5 lists the typical categories of information required by the OS for each process. You may be somewhat surprised at the quantity of information required. As you gain a greater appreciation of the responsibilities of the OS, this list should appear more reasonable.

We can group the process control block information into three general categories:

- Process identification
- Processor state information
- Process control information

[8]A brief overview of the concepts of pages, segments, and virtual memory is provided in the subsection on memory management in Section 2.3.

[9]This brief discussion slides over some details. In particular, in a system that uses virtual memory, all of the process image for an active process is always in secondary memory. When a portion of the image is loaded into main memory, it is copied rather than moved. Thus, the secondary memory retains a copy of all segments and/or pages. However, if the main memory portion of the image is modified, the secondary copy will be out of date until the main memory portion is copied back onto disk.

Table 3.5 Typical Elements of a Process Control Block

Process Identification

Identifiers
Numeric identifiers that may be stored with the process control block include

- Identifier of this process
- Identifier of the process that created this process (parent process)
- User identifier

Processor State Information

User-Visible Registers
A user-visible register is one that may be referenced by means of the machine language that the processor executes while in user mode. Typically, there are from 8 to 32 of these registers, although some RISC implementations have over 100.

Control and Status Registers
These are a variety of processor registers that are employed to control the operation of the processor. These include

- **Program counter:** Contains the address of the next instruction to be fetched
- **Condition codes:** Result of the most recent arithmetic or logical operation (e.g., sign, zero, carry, equal, overflow)
- **Status information:** Includes interrupt enabled/disabled flags, execution mode

Stack Pointers
Each process has one or more last-in-first-out (LIFO) system stacks associated with it. A stack is used to store parameters and calling addresses for procedure and system calls. The stack pointer points to the top of the stack.

Process Control Information

Scheduling and State Information
This is information that is needed by the operating system to perform its scheduling function. Typical items of information:

- **Process state:** Defines the readiness of the process to be scheduled for execution (e.g., running, ready, waiting, halted).
- **Priority:** One or more fields may be used to describe the scheduling priority of the process. In some systems, several values are required (e.g., default, current, highest-allowable).
- **Scheduling-related information:** This will depend on the scheduling algorithm used. Examples are the amount of time that the process has been waiting and the amount of time that the process executed the last time it was running.
- **Event:** Identity of event the process is awaiting before it can be resumed.

Data Structuring
A process may be linked to other process in a queue, ring, or some other structure. For example, all processes in a waiting state for a particular priority level may be linked in a queue. A process may exhibit a parent–child (creator–created) relationship with another process. The process control block may contain pointers to other processes to support these structures.

Interprocess Communication
Various flags, signals, and messages may be associated with communication between two independent processes. Some or all of this information may be maintained in the process control block.

Process Privileges
Processes are granted privileges in terms of the memory that may be accessed and the types of instructions that may be executed. In addition, privileges may apply to the use of system utilities and services.

Memory Management
This section may include pointers to segment and/or page tables that describe the virtual memory assigned to this process.

Resource Ownership and Utilization
Resources controlled by the process may be indicated, such as opened files. A history of utilization of the processor or other resources may also be included; this information may be needed by the scheduler.

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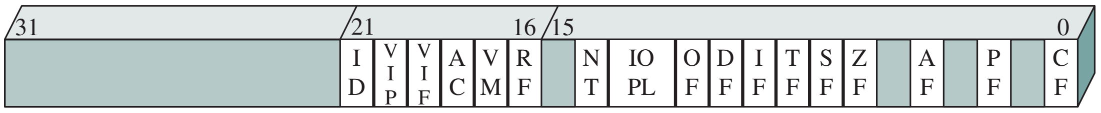
With respect to **process identification**, in virtually all operating systems, each process is assigned a unique numeric identifier, which may simply be an index into the primary process table (Figure 3.11); otherwise there must be a mapping that allows the OS to locate the appropriate tables based on the process identifier. This identifier is useful in several ways. Many of the other tables controlled by the OS may use process identifiers to cross-reference process tables. For example, the memory tables may be organized so as to provide a map of main memory with an indication of which process is assigned to each region. Similar references will appear in I/O and file tables. When processes communicate with one another, the process identifier informs the OS of the destination of a particular communication. When processes are allowed to create other processes, identifiers indicate the parent and descendents of each process.

In addition to these process identifiers, a process may be assigned a user identifier that indicates the user responsible for the job.

Processor state information consists of the contents of processor registers. While a process is running, of course, the information is in the registers. When a process is interrupted, all of this register information must be saved so that it can be restored when the process resumes execution. The nature and number of registers involved depend on the design of the processor. Typically, the register set will include user-visible registers, control and status registers, and stack pointers. These are described in Chapter 1.

Of particular note, all processor designs include a register or set of registers, often known as the program status word (PSW), that contains status information. The PSW typically contain condition codes plus other status information. A good example of a processor status word is that on Intel x86 processors, referred to as the EFLAGS register (shown in Figure 3.12 and Table 3.6). This structure is used by any OS (including UNIX and Windows) running on an x86 processor.

The third major category of information in the process control block can be called, for want of a better name, **process control information**. This is the additional information needed by the OS to control and coordinate the various active processes. The last part of Table 3.5 indicates the scope of this information. As



ID	= Identification flag	DF	= Direction flag
VIP	= Virtual interrupt pending	IF	= Interrupt enable flag
VIF	= Virtual interrupt flag	TF	= Trap flag
AC	= Alignment check	SF	= Sign flag
VM	= Virtual 8086 mode	ZF	= Zero flag
RF	= Resume flag	AF	= Auxiliary carry flag
NT	= Nested task flag	PF	= Parity flag
IOPL	= I/O privilege level	CF	= Carry flag
OF	= Overflow flag		

Figure 3.12 x86 EFLAGS Register

Table 3.6 Pentium EFLAGS Register Bits

Control Bits

AC (Alignment check)
Set if a word or doubleword is addressed on a nonword or non-doubleword boundary.

ID (Identification flag)
If this bit can be set and cleared, this processor supports the CPUID instruction. This instruction provides information about the vendor, family, and model.

RF (Resume flag)
Allows the programmer to disable debug exceptions so that the instruction can be restarted after a debug exception without immediately causing another debug exception.

IOPL (I/O privilege level)
When set, causes the processor to generate an exception on all accesses to I/O devices during protected mode operation.

DF (Direction flag)
Determines whether string processing instructions increment or decrement the 16-bit half-registers SI and DI (for 16-bit operations) or the 32-bit registers ESI and EDI (for 32-bit operations).

IF (Interrupt enable flag)
When set, the processor will recognize external interrupts.

TF (Trap flag)
When set, causes an interrupt after the execution of each instruction. This is used for debugging.

Operating Mode Bits

NT (Nested task flag)
Indicates that the current task is nested within another task in protected mode operation.

VM (Virtual 8086 mode)
Allows the programmer to enable or disable virtual 8086 mode, which determines whether the processor runs as an 8086 machine.

VIP (Virtual interrupt pending)
Used in virtual 8086 mode to indicate that one or more interrupts are awaiting service.

VIF (Virtual interrupt flag)
Used in virtual 8086 mode instead of IF.

Condition Codes

AF (Auxiliary carry flag)
Represents carrying or borrowing between half-bytes of an 8-bit arithmetic or logic operation using the AL register.

CF (Carry flag)
Indicates carrying out or borrowing into the leftmost bit position following an arithmetic operation. Also modified by some of the shift and rotate operations.

OF (Overflow flag)
Indicates an arithmetic overflow after an addition or subtraction.

PF (Parity flag)
Parity of the result of an arithmetic or logic operation. 1 indicates even parity; 0 indicates odd parity.

SF (Sign flag)
Indicates the sign of the result of an arithmetic or logic operation.

ZF (Zero flag)
Indicates that the result of an arithmetic or logic operation is 0.

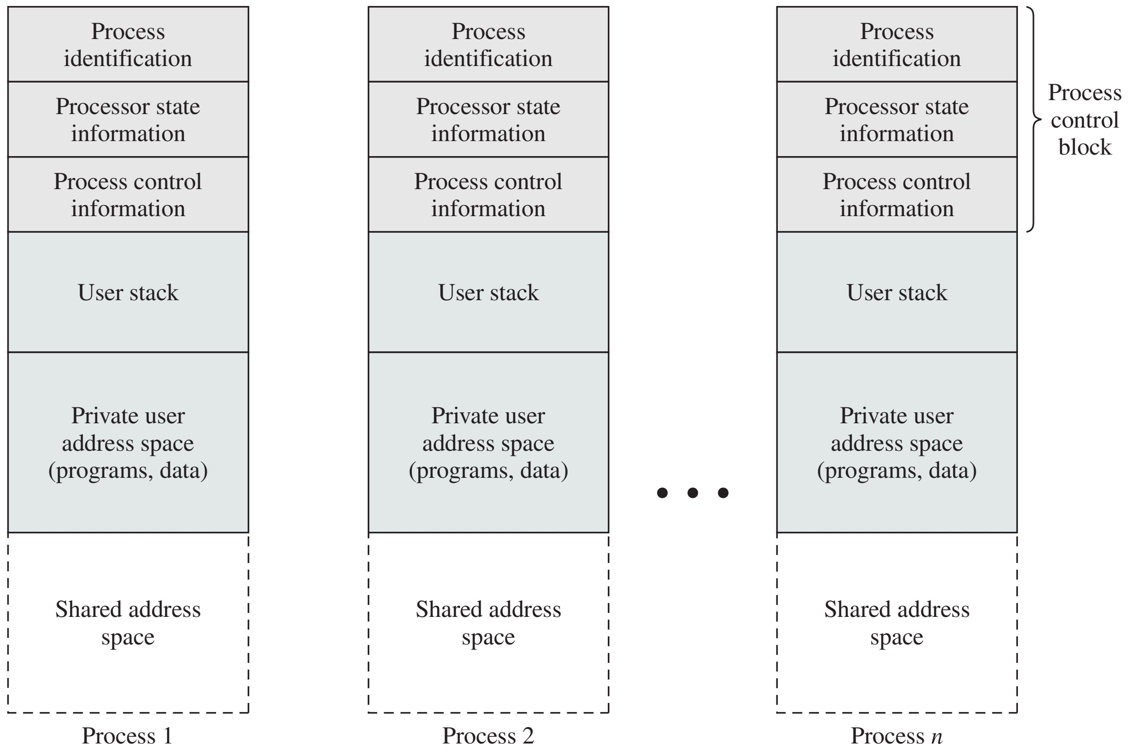


Figure 3.13 User Processes in Virtual Memory

we examine the details of operating system functionality in succeeding chapters, the need for the various items on this list should become clear.

Figure 3.13 suggests the structure of process images in virtual memory. Each process image consists of a process control block, a user stack, the private address space of the process, and any other address space that the process shares with other processes. In the figure, each process image appears as a contiguous range of addresses. In an actual implementation, this may not be the case; it will depend on the memory management scheme and the way in which control structures are organized by the OS.

As indicated in Table 3.5, the process control block may contain structuring information, including pointers that allow the linking of process control blocks. Thus, the queues that were described in the preceding section could be implemented as linked lists of process control blocks. For example, the queueing structure of Figure 3.8a could be implemented as suggested in Figure 3.14.

The Role of the Process Control Block The process control block is the most important data structure in an OS. Each process control block contains all of the information about a process that is needed by the OS. The blocks are read and/or modified by virtually every module in the OS, including those involved with scheduling, resource allocation, interrupt processing, and performance monitoring and analysis. One can say that the set of process control blocks defines the state of the OS.

This brings up an important design issue. A number of routines within the OS will need access to information in process control blocks. The provision of direct

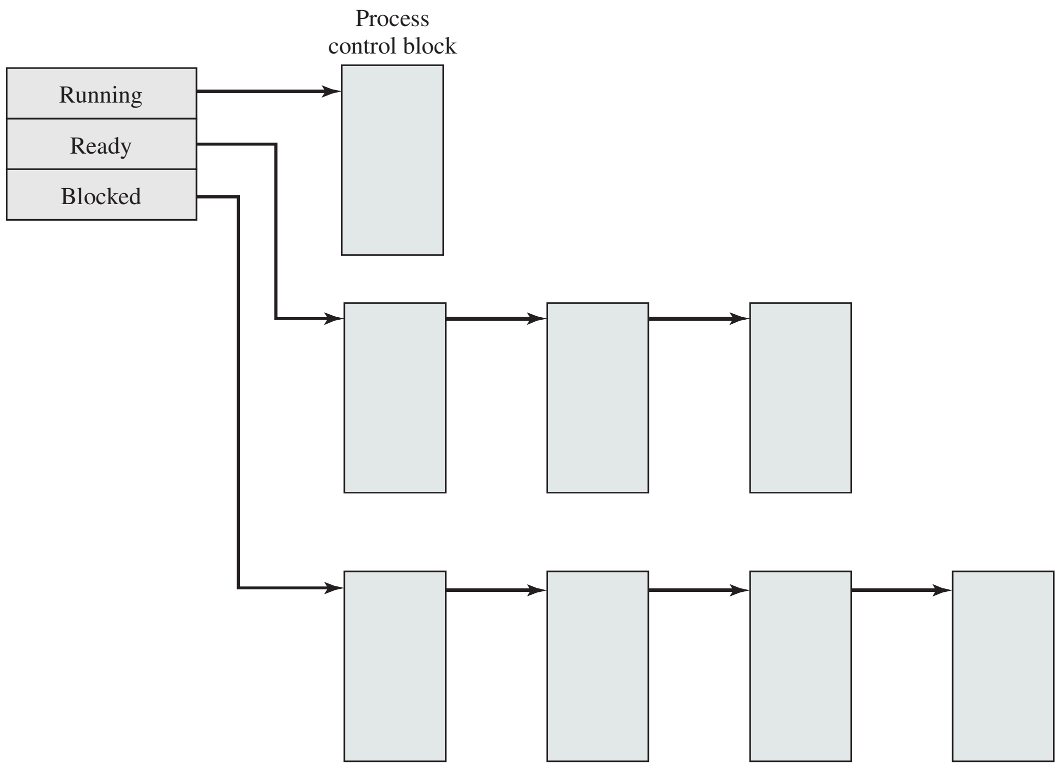


Figure 3.14 Process List Structures

access to these tables is not difficult. Each process is equipped with a unique ID, and this can be used as an index into a table of pointers to the process control blocks. The difficulty is not access but rather protection. Two problems present themselves:

- A bug in a single routine, such as an interrupt handler, could damage process control blocks, which could destroy the system's ability to manage the affected processes.
- A design change in the structure or semantics of the process control block could affect a number of modules in the OS.

These problems can be addressed by requiring all routines in the OS to go through a handler routine, the only job of which is to protect process control blocks, and which is the sole arbiter for reading and writing these blocks. The trade-off in the use of such a routine involves performance issues and the degree to which the remainder of the system software can be trusted to be correct.

3.4 PROCESS CONTROL

Modes of Execution

Before continuing with our discussion of the way in which the OS manages processes, we need to distinguish between the mode of processor execution normally associated with the OS and that normally associated with user programs. Most processors support at least two modes of execution. Certain instructions can only be executed in the more-privileged mode. These would include reading or altering a control register, such as the program status word; primitive I/O instructions; and instructions that relate to memory management. In addition, certain regions of memory can only be accessed in the more-privileged mode.

The less-privileged mode is often referred to as the **user mode,** because user programs typically would execute in this mode. The more-privileged mode is referred to as the **system mode, control mode,** or **kernel mode.** This last term refers to the kernel of the OS, which is that portion of the OS that encompasses the important system functions. Table 3.7 lists the functions typically found in the kernel of an OS.

The reason for using two modes should be clear. It is necessary to protect the OS and key operating system tables, such as process control blocks, from interference by user programs. In the kernel mode, the software has complete control of the processor and all its instructions, registers, and memory. This level of control is not necessary and for safety is not desirable for user programs.

Two questions arise: How does the processor know in which mode it is to be executing and how is the mode changed? Regarding the first question, typically there is a bit in the program status word (PSW) that indicates the mode of execution. This bit is changed in response to certain events. Typically, when a user makes a call to an operating system service or when an interrupt triggers execution of an operating system routine, the mode is set to the kernel mode and, upon return from the service to the user process, the mode is set to user mode. As an example, consider the Intel Itanium processor, which implements the 64-bit IA-64 architecture. The processor has a processor status register (psr) that includes a 2-bit cpl (current privilege level) field. Level 0 is the most privileged level, while level 3 is the least privileged level. Most operating systems, such as Linux, use level 0 for the kernel and one other level

Table 3.7 Typical Functions of an Operating System Kernel

Process Management
• Process creation and termination • Process scheduling and dispatching • Process switching • Process synchronization and support for interprocess communication • Management of process control blocks
Memory Management
• Allocation of address space to processes • Swapping • Page and segment management
I/O Management
• Buffer management • Allocation of I/O channels and devices to processes
Support Functions
• Interrupt handling • Accounting • Monitoring

for user mode. When an interrupt occurs, the processor clears most of the bits in the psr, including the cpl field. This automatically sets the cpl to level 0. At the end of the interrupt-handling routine, the final instruction that is executed is irt (interrupt return). This instruction causes the processor to restore the psr of the interrupted program, which restores the privilege level of that program. A similar sequence occurs when an application places a system call. For the Itanium, an application places a system call by placing the system call identifier and the system call arguments in a predefined area and then executing a special instruction that has the effect of interrupting execution at the user level and transferring control to the kernel.

Process Creation

In Section 3.2, we discussed the events that lead to the creation of a new process. Having discussed the data structures associated with a process, we are now in a position to describe briefly the steps involved in actually creating the process.

Once the OS decides, for whatever reason (Table 3.1), to create a new process, it can proceed as follows:

1. **Assign a unique process identifier to the new process.** At this time, a new entry is added to the primary process table, which contains one entry per process.
2. **Allocate space for the process.** This includes all elements of the process image. Thus, the OS must know how much space is needed for the private user address space (programs and data) and the user stack. These values can be assigned by default based on the type of process, or they can be set based on user request at job creation time. If a process is spawned by another process, the parent process can pass the needed values to the OS as part of the process-creation request. If any existing address space is to be shared by this new process, the appropriate linkages must be set up. Finally, space for a process control block must be allocated.
3. **Initialize the process control block.** The process identification portion contains the ID of this process plus other appropriate IDs, such as that of the parent process. The processor state information portion will typically be initialized with most entries zero, except for the program counter (set to the program entry point) and system stack pointers (set to define the process stack boundaries). The process control information portion is initialized based on standard default values plus attributes that have been requested for this process. For example, the process state would typically be initialized to Ready or Ready/Suspend. The priority may be set by default to the lowest priority unless an explicit request is made for a higher priority. Initially, the process may own no resources (I/O devices, files) unless there is an explicit request for these or unless they are inherited from the parent.
4. **Set the appropriate linkages.** For example, if the OS maintains each scheduling queue as a linked list, then the new process must be put in the Ready or Ready/Suspend list.
5. **Create or expand other data structures.** For example, the OS may maintain an accounting file on each process to be used subsequently for billing and/or performance assessment purposes.

Process Switching

On the face of it, the function of process switching would seem to be straightforward. At some time, a running process is interrupted and the OS assigns another process to the Running state and turns control over to that process. However, several design issues are raised. First, what events trigger a process switch? Another issue is that we must recognize the distinction between mode switching and process switching. Finally, what must the OS do to the various data structures under its control to achieve a process switch?

When to Switch Processes A process switch may occur any time that the OS has gained control from the currently running process. Table 3.8 suggests the possible events that may give control to the OS.

First, let us consider system interrupts. Actually, we can distinguish, as many systems do, two kinds of system interrupts, one of which is simply referred to as an interrupt, and the other as a trap. The former is due to some sort of event that is external to and independent of the currently running process, such as the completion of an I/O operation. The latter relates to an error or exception condition generated within the currently running process, such as an illegal file access attempt. With an ordinary **interrupt,** control is first transferred to an interrupt handler, which does some basic housekeeping and then branches to an OS routine that is concerned with the particular type of interrupt that has occurred. Examples include the following:

- **Clock interrupt:** The OS determines whether the currently running process has been executing for the maximum allowable unit of time, referred to as a **time slice**. That is, a time slice is the maximum amount of time that a process can execute before being interrupted. If so, this process must be switched to a Ready state and another process dispatched.
- **I/O interrupt:** The OS determines what I/O action has occurred. If the I/O action constitutes an event for which one or more processes are waiting, then the OS moves all of the corresponding blocked processes to the Ready state (and Blocked/Suspend processes to the Ready/Suspend state). The OS must then decide whether to resume execution of the process currently in the Running state or to preempt that process for a higher-priority Ready process.
- **Memory fault:** The processor encounters a virtual memory address reference for a word that is not in main memory. The OS must bring in the block

Table 3.8 Mechanisms for Interrupting the Execution of a Process

Mechanism	Cause	Use
Interrupt	External to the execution of the current instruction	Reaction to an asynchronous external event
Trap	Associated with the execution of the current instruction	Handling of an error or an exception condition
Supervisor call	Explicit request	Call to an operating system function

(page or segment) of memory containing the reference from secondary memory to main memory. After the I/O request is issued to bring in the block of memory, the process with the memory fault is placed in a blocked state; the OS then performs a process switch to resume execution of another process. After the desired block is brought into memory, that process is placed in the Ready state.

With a **trap,** the OS determines if the error or exception condition is fatal. If so, then the currently running process is moved to the Exit state and a process switch occurs. If not, then the action of the OS will depend on the nature of the error and the design of the OS. It may attempt some recovery procedure or simply notify the user. It may do a process switch or resume the currently running process.

Finally, the OS may be activated by a **supervisor call** from the program being executed. For example, a user process is running and an instruction is executed that requests an I/O operation, such as a file open. This call results in a transfer to a routine that is part of the operating system code. The use of a system call may place the user process in the Blocked state.

Mode Switching In Chapter 1, we discussed the inclusion of an interrupt stage as part of the instruction cycle. Recall that, in the interrupt stage, the processor checks to see if any interrupts are pending, indicated by the presence of an interrupt signal. If no interrupts are pending, the processor proceeds to the fetch stage and fetches the next instruction of the current program in the current process. If an interrupt is pending, the processor does the following:

1. It sets the program counter to the starting address of an interrupt handler program.
2. It switches from user mode to kernel mode so that the interrupt processing code may include privileged instructions.

The processor now proceeds to the fetch stage and fetches the first instruction of the interrupt handler program, which will service the interrupt. At this point, typically, the context of the process that has been interrupted is saved into that process control block of the interrupted program.

One question that may now occur to you is, What constitutes the context that is saved? The answer is that it must include any information that may be altered by the execution of the interrupt handler and that will be needed to resume the program that was interrupted. Thus, the portion of the process control block that was referred to as processor state information must be saved. This includes the program counter, other processor registers, and stack information.

Does anything else need to be done? That depends on what happens next. The interrupt handler is typically a short program that performs a few basic tasks related to an interrupt. For example, it resets the flag or indicator that signals the presence of an interrupt. It may send an acknowledgment to the entity that issued the interrupt, such as an I/O module. And it may do some basic housekeeping relating to the effects of the event that caused the interrupt. For example, if the interrupt relates to an I/O event, the interrupt handler will check for an error condition. If an error has occurred, the interrupt handler may send a signal to the process that originally requested the I/O operation. If the interrupt is by the clock, then the handler will hand control over to the dispatcher, which will want to pass control to another process because the time slice allotted to the currently running process has expired.

What about the other information in the process control block? If this interrupt is to be followed by a switch to another process, then some work will need to be done. However, in most operating systems, the occurrence of an interrupt does not necessarily mean a process switch. It is possible that, after the interrupt handler has executed, the currently running process will resume execution. In that case, all that is necessary is to save the processor state information when the interrupt occurs and restore that information when control is returned to the program that was running. Typically, the saving and restoring functions are performed in hardware.

Change of Process State It is clear, then, that the mode switch is a concept distinct from that of the process switch.[10] A mode switch may occur without changing the state of the process that is currently in the Running state. In that case, the context saving and subsequent restoral involve little overhead. However, if the currently running process is to be moved to another state (Ready, Blocked, etc.), then the OS must make substantial changes in its environment. The steps involved in a full process switch are as follows:

1. Save the context of the processor, including program counter and other registers.
2. Update the process control block of the process that is currently in the Running state. This includes changing the state of the process to one of the other states (Ready; Blocked; Ready/Suspend; or Exit). Other relevant fields must also be updated, including the reason for leaving the Running state and accounting information.
3. Move the process control block of this process to the appropriate queue (Ready; Blocked on Event *i*; Ready/Suspend).
4. Select another process for execution; this topic is explored in Part Four.
5. Update the process control block of the process selected. This includes changing the state of this process to Running.
6. Update memory management data structures. This may be required, depending on how address translation is managed; this topic is explored in Part Three.
7. Restore the context of the processor to that which existed at the time the selected process was last switched out of the Running state, by loading in the previous values of the program counter and other registers.

Thus, the process switch, which involves a state change, requires more effort than a mode switch.

[10]The term *context switch* is often found in OS literature and textbooks. Unfortunately, although most of the literature uses this term to mean what is here called a process switch, other sources use it to mean a mode switch or even a thread switch (defined in the next chapter). To avoid ambiguity, the term is not used in this book.

3.5 EXECUTION OF THE OPERATING SYSTEM

In Chapter 2, we pointed out two intriguing facts about operating systems:

- The OS functions in the same way as ordinary computer software in the sense that the OS is a set of programs executed by the processor.
- The OS frequently relinquishes control and depends on the processor to restore control to the OS.

If the OS is just a collection of programs and if it is executed by the processor just like any other program, is the OS a process? If so, how is it controlled? These interesting questions have inspired a number of design approaches. Figure 3.15 illustrates a range of approaches that are found in various contemporary operating systems.

Nonprocess Kernel

One traditional approach, common on many older operating systems, is to execute the kernel of the OS outside of any process (Figure 3.15a). With this approach, when the currently running process is interrupted or issues a supervisor call, the mode context of this process is saved and control is passed to the kernel. The OS has its own region of memory to use and its own system stack for controlling procedure calls and returns. The OS can perform any desired functions and restore the context of the interrupted process, which causes execution to resume in the interrupted

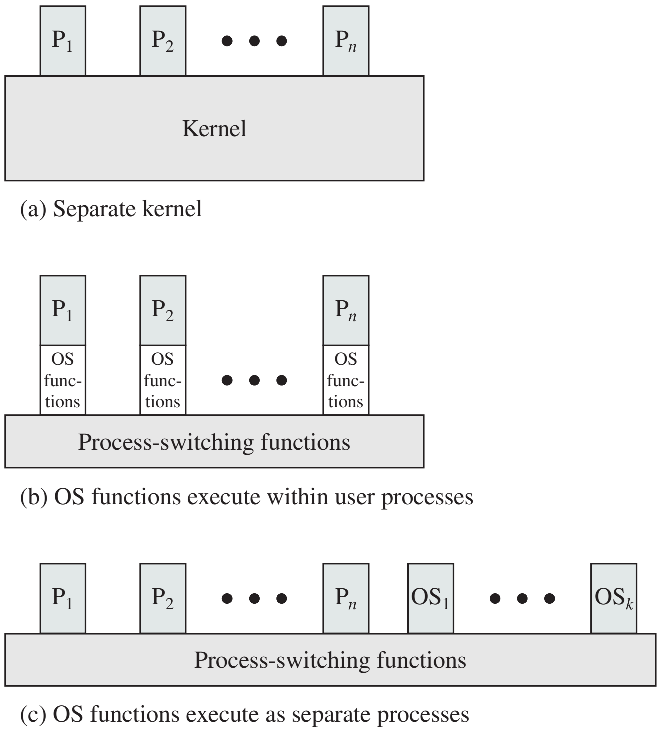

P1
P2
• • •
Pn
Kernel
(a) Separate kernel
P1
P2
Pn
OS func-tions
OS func-tions
• • •
OS func-tions
Process-switching functions
(b) OS functions execute within user processes
P1
P2
• • •
Pn
OS1
• • •
OSk
Process-switching functions
(c) OS functions execute as separate processes

Figure 3.15 Relationship between Operating System and User Processes

user process. Alternatively, the OS can complete the function of saving the environment of the process and proceed to schedule and dispatch another process. Whether this happens depends on the reason for the interruption and the circumstances at the time.

In any case, the key point here is that the concept of process is considered to apply only to user programs. The operating system code is executed as a separate entity that operates in privileged mode.

Execution within User Processes

An alternative that is common with operating systems on smaller computers (PCs, workstations) is to execute virtually all OS software in the context of a user process. The view is that the OS is primarily a collection of routines that the user calls to perform various functions, executed within the environment of the user's process. This is illustrated in Figure 3.15b. At any given point, the OS is managing *n* process images. Each image includes not only the regions illustrated in Figure 3.13, but also program, data, and stack areas for kernel programs.

Figure 3.16 suggests a typical process image structure for this strategy. A separate kernel stack is used to manage calls/returns while the process is in kernel mode.

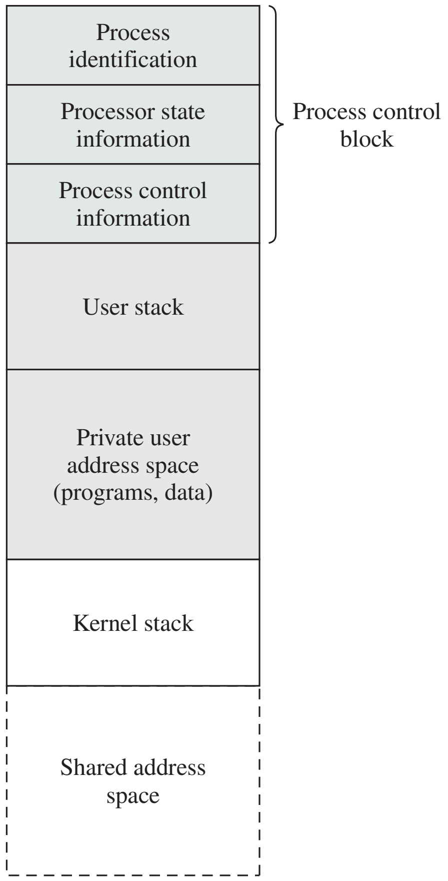

Process identification
Processor state information
Process control information
Process control block
User stack
Private user address space (programs, data)
Kernel stack
Shared address space

Figure 3.16 **Process Image: Operating System Executes within User Space**

Operating system code and data are in the shared address space and are shared by all user processes.

When an interrupt, trap, or supervisor call occurs, the processor is placed in kernel mode and control is passed to the OS. To pass control from a user program to the OS, the mode context is saved and a mode switch takes place to an operating system routine. However, execution continues within the current user process. Thus, a process switch is not performed, just a mode switch within the same process.

If the OS, upon completion of its work, determines that the current process should continue to run, then a mode switch resumes the interrupted program within the current process. This is one of the key advantages of this approach: A user program has been interrupted to employ some operating system routine, and then resumed, and all of this has occurred without incurring the penalty of two process switches. If, however, it is determined that a process switch is to occur rather than returning to the previously executing program, then control is passed to a process-switching routine. This routine may or may not execute in the current process, depending on system design. At some point, however, the current process has to be placed in a nonrunning state and another process designated as the running process. During this phase, it is logically most convenient to view execution as taking place outside of all processes.

In a way, this view of the OS is remarkable. Simply put, at certain points in time, a process will save its state information, choose another process to run from among those that are ready, and relinquish control to that process. The reason this is not an arbitrary and indeed chaotic situation is that during the critical time, the code that is executed in the user process is shared operating system code and not user code. Because of the concept of user mode and kernel mode, the user cannot tamper with or interfere with the operating system routines, even though they are executing in the user's process environment. This further reminds us that there is a distinction between the concepts of process and program and that the relationship between the two is not one to one. Within a process, both a user program and operating system programs may execute, and the operating system programs that execute in the various user processes are identical.

Process-Based Operating System

Another alternative, illustrated in Figure 3.15c, is to implement the OS as a collection of system processes. As in the other options, the software that is part of the kernel executes in a kernel mode. In this case, however, major kernel functions are organized as separate processes. Again, there may be a small amount of process-switching code that is executed outside of any process.

This approach has several advantages. It imposes a program design discipline that encourages the use of a modular OS with minimal, clean interfaces between the modules. In addition, some noncritical operating system functions are conveniently implemented as separate processes. For example, we mentioned earlier a monitor program that records the level of utilization of various resources (processor, memory, channels) and the rate of progress of the user processes in the system. Because this program does not provide a particular service to any active process, it can only be invoked by the OS. As a process, the function can run at an assigned priority level and be interleaved with other processes under dispatcher control. Finally, implementing the OS as a set of processes is useful in a multiprocessor or multicomputer environment, in which some of the operating system services can be shipped out to dedicated processors, improving performance.

3.6 SECURITY ISSUES

An OS associates a set of privileges with each process. These privileges dictate what resources the process may access, including regions of memory, files, privileged system instructions, and so on. Typically, a process that executes on behalf of a user has the privileges that the OS recognizes for that user. A system or utility process may have privileges assigned at configuration time.

On a typical system, the highest level of privilege is referred to as administrator, supervisor, or root access.[11] Root access provides access to all the functions and services of the operating system. With root access, a process has complete control of the system and can add or change programs and files, monitor other processes, send and receive network traffic, and alter privileges.

A key security issue in the design of any OS is to prevent, or at least detect, attempts by a user or a piece of malicious software (malware) from gaining unauthorized privileges on the system and, in particular, from gaining root access. In this section, we briefly summarize the threats and countermeasures related to this security issue. Part Seven provides more detail.

System Access Threats

System access threats fall into two general categories: intruders and malicious software.

Intruders One of the most common threats to security is the intruder (the other is viruses), often referred to as a hacker or cracker. In an important early study of intrusion, Anderson [ANDE80] identified three classes of intruders:

- **Masquerader:** An individual who is not authorized to use the computer and who penetrates a system's access controls to exploit a legitimate user's account
- **Misfeasor:** A legitimate user who accesses data, programs, or resources for which such access is not authorized, or who is authorized for such access but misuses his or her privileges
- **Clandestine user:** An individual who seizes supervisory control of the system and uses this control to evade auditing and access controls or to suppress audit collection

The masquerader is likely to be an outsider; the misfeasor generally is an insider; and the clandestine user can be either an outsider or an insider.

Intruder attacks range from the benign to the serious. At the benign end of the scale, there are many people who simply wish to explore internets and see what is

[11]On UNIX systems, the administrator, or *superuser*, account is called root; hence the term *root access*.

out there. At the serious end are individuals who are attempting to read privileged data, perform unauthorized modifications to data, or disrupt the system.

The objective of the intruder is to gain access to a system or to increase the range of privileges accessible on a system. Most initial attacks use system or software vulnerabilities that allow a user to execute code that opens a back door into the system. Intruders can get access to a system by exploiting attacks such as buffer overflows on a program that runs with certain privileges. We introduce buffer overflow attacks in Chapter 7.

Alternatively, the intruder attempts to acquire information that should have been protected. In some cases, this information is in the form of a user password. With knowledge of some other user's password, an intruder can log in to a system and exercise all the privileges accorded to the legitimate user.

Malicious Software Perhaps the most sophisticated types of threats to computer systems are presented by programs that exploit vulnerabilities in computing systems. Such threats are referred to as **malicious software**, or **malware**. In this context, we are concerned with threats to application programs as well as utility programs, such as editors and compilers, and kernel-level programs.

Malicious software can be divided into two categories: those that need a host program, and those that are independent. The former, referred to as **parasitic**, are essentially fragments of programs that cannot exist independently of some actual application program, utility, or system program. Viruses, logic bombs, and backdoors are examples. The latter are self-contained programs that can be scheduled and run by the operating system. Worms and bot programs are examples.

We can also differentiate between those software threats that do not replicate and those that do. The former are programs or fragments of programs that are activated by a trigger. Examples are logic bombs, backdoors, and bot programs. The latter consists of either a program fragment or an independent program that, when executed, may produce one or more copies of itself to be activated later on the same system or some other system. Viruses and worms are examples.

Malicious software can be relatively harmless or may perform one or more of a number of harmful actions, including destroying files and data in main memory, bypassing controls to gain privileged access, and providing a means for intruders to bypass access controls.

Countermeasures

Intrusion Detection RFC 2828 (*Internet Security Glossary*) defines intrusion detection as follows: A security service that monitors and analyzes system events for the purpose of finding, and providing real-time or near real-time warning of, attempts to access system resources in an unauthorized manner.

Intrusion detection systems (IDSs) can be classified as follows:

- **Host-based IDS:** Monitors the characteristics of a single host and the events occurring within that host for suspicious activity
- **Network-based IDS:** Monitors network traffic for particular network segments or devices and analyzes network, transport, and application protocols to identify suspicious activity

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An IDS comprises three logical components:

- **Sensors:** Sensors are responsible for collecting data. The input for a sensor may be any part of a system that could contain evidence of an intrusion. Types of input to a sensor include network packets, log files, and system call traces. Sensors collect and forward this information to the analyzer.
- **Analyzers:** Analyzers receive input from one or more sensors or from other analyzers. The analyzer is responsible for determining if an intrusion has occurred. The output of this component is an indication that an intrusion has occurred. The output may include evidence supporting the conclusion that an intrusion occurred. The analyzer may provide guidance about what actions to take as a result of the intrusion.
- **User interface:** The user interface to an IDS enables a user to view output from the system or control the behavior of the system. In some systems, the user interface may equate to a manager, director, or console component.

Intrusion detection systems are typically designed to detect human intruder behavior as well as malicious software behavior.

Authentication In most computer security contexts, user authentication is the fundamental building block and the primary line of defense. User authentication is the basis for most types of access control and for user accountability. RFC 2828 defines user authentication as follows:

> The process of verifying an identity claimed by or for a system entity. An authentication process consists of two steps:
>
> - **Identification step:** Presenting an identifier to the security system. (Identifiers should be assigned carefully, because authenticated identities are the basis for other security services, such as access control service.)
> - **Verification step:** Presenting or generating authentication information that corroborates the binding between the entity and the identifier.

For example, user Alice Toklas could have the user identifier ABTOKLAS. This information needs to be stored on any server or computer system that Alice wishes to use and could be known to system administrators and other users. A typical item of authentication information associated with this user ID is a password, which is kept secret (known only to Alice and to the system). If no one is able to obtain or guess Alice's password, then the combination of Alice's user ID and password enables administrators to set up Alice's access permissions and audit her activity. Because Alice's ID is not secret, system users can send her e-mail, but because her password is secret, no one can pretend to be Alice.

In essence, identification is the means by which a user provides a claimed identity to the system; user authentication is the means of establishing the validity of the claim.

There are four general means of authenticating a user's identity, which can be used alone or in combination:

- **Something the individual knows:** Examples include a password, a personal identification number (PIN), or answers to a prearranged set of questions.
- **Something the individual possesses:** Examples include electronic keycards, smart cards, and physical keys. This type of authenticator is referred to as a *token.*
- **Something the individual is (static biometrics):** Examples include recognition by fingerprint, retina, and face.
- **Something the individual does (dynamic biometrics):** Examples include recognition by voice pattern, handwriting characteristics, and typing rhythm.

All of these methods, properly implemented and used, can provide secure user authentication. However, each method has problems. An adversary may be able to guess or steal a password. Similarly, an adversary may be able to forge or steal a token. A user may forget a password or lose a token. Further, there is a significant administrative overhead for managing password and token information on systems and securing such information on systems. With respect to biometric authenticators, there are a variety of problems, including dealing with false positives and false negatives, user acceptance, cost, and convenience.

Access Control Access control implements a security policy that specifies who or what (e.g., in the case of a process) may have access to each specific system resource and the type of access that is permitted in each instance.

An access control mechanism mediates between a user (or a process executing on behalf of a user) and system resources, such as applications, operating systems, firewalls, routers, files, and databases. The system must first authenticate a user seeking access. Typically, the authentication function determines whether the user is permitted to access the system at all. Then the access control function determines if the specific requested access by this user is permitted. A security administrator maintains an authorization database that specifies what type of access to which resources is allowed for this user. The access control function consults this database to determine whether to grant access. An auditing function monitors and keeps a record of user accesses to system resources.

Firewalls Firewalls can be an effective means of protecting a local system or network of systems from network-based security threats while at the same time affording access to the outside world via wide area networks and the Internet. Traditionally, a firewall is a dedicated computer that interfaces with computers outside a network and has special security precautions built into it in order to protect sensitive files on computers within the network. It is used to service outside network, especially Internet, connections and dial-in lines. Personal firewalls that are implemented in hardware or software, and associated with a single workstation or PC, are also common.

[BELL94] lists the following design goals for a firewall:

1. All traffic from inside to outside, and vice versa, must pass through the firewall. This is achieved by physically blocking all access to the local network except via the firewall. Various configurations are possible, as explained later in this chapter.
2. Only authorized traffic, as defined by the local security policy, will be allowed to pass. Various types of firewalls are used, which implement various types of security policies.
3. The firewall itself is immune to penetration. This implies the use of a hardened system with a secured operating system. Trusted computer systems are suitable for hosting a firewall and often required in government applications.

3.7 UNIX SVR4 PROCESS MANAGEMENT

UNIX System V makes use of a simple but powerful process facility that is highly visible to the user. UNIX follows the model of Figure 3.15b, in which most of the OS executes within the environment of a user process. UNIX uses two categories of processes: system processes and user processes. System processes run in kernel mode and execute operating system code to perform administrative and housekeeping functions, such as allocation of memory and process swapping. User processes operate in user mode to execute user programs and utilities and in kernel mode to execute instructions that belong to the kernel. A user process enters kernel mode by issuing a system call, when an exception (fault) is generated, or when an interrupt occurs.

Process States

A total of nine process states are recognized by the UNIX SVR4 operating system; these are listed in Table 3.9 and a state transition diagram is shown in Figure 3.17

Table 3.9 UNIX Process States

User Running	Executing in user mode.
Kernel Running	Executing in kernel mode.
Ready to Run, in Memory	Ready to run as soon as the kernel schedules it.
Asleep in Memory	Unable to execute until an event occurs; process is in main memory (a blocked state).
Ready to Run, Swapped	Process is ready to run, but the swapper must swap the process into main memory before the kernel can schedule it to execute.
Sleeping, Swapped	The process is awaiting an event and has been swapped to secondary storage (a blocked state).
Preempted	Process is returning from kernel to user mode, but the kernel preempts it and does a process switch to schedule another process.
Created	Process is newly created and not yet ready to run.
Zombie	Process no longer exists, but it leaves a record for its parent process to collect.

The basic idea is that the several components in any complex system will perform particular subfunctions that contribute to the overall function.

—*The Sciences of the Artificial*, Herbert Simon

Learning Objectives

After studying this chapter, you should be able to:

- Understand the distinction between process and thread.
- Describe the basic design issues for threads.
- Explain the difference between user-level threads and kernel-level threads.
- Describe the thread management facility in Windows 7.
- Describe the thread management facility in Solaris.
- Describe the thread management facility in Linux.

This chapter examines some more advanced concepts related to process management, which are found in a number of contemporary operating systems. We show that the concept of process is more complex and subtle than presented so far and in fact embodies two separate and potentially independent concepts: one relating to resource ownership and another relating to execution. This distinction has led to the development, in many operating systems, of a construct known as the **thread**.

4.1 PROCESSES AND THREADS

The discussion so far has presented the concept of a process as embodying two characteristics:

- **Resource ownership:** A process includes a virtual address space to hold the process image; recall from Chapter 3 that the process image is the collection of program, data, stack, and attributes defined in the process control block. From time to time, a process may be allocated control or ownership of resources, such as main memory, I/O channels, I/O devices, and files. The OS performs a protection function to prevent unwanted interference between processes with respect to resources.
- **Scheduling/execution:** The execution of a process follows an execution path (trace) through one or more programs (e.g., Figure 1.5). This execution may be interleaved with that of other processes. Thus, a process has an execution state (Running, Ready, etc.) and a dispatching priority and is the entity that is scheduled and dispatched by the OS.

Some thought should convince the reader that these two characteristics are independent and could be treated independently by the OS. This is done in a number of operating systems, particularly recently developed systems. To

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distinguish the two characteristics, the unit of dispatching is usually referred to as a thread or **lightweight process**, while the unit of resource ownership is usually referred to as a **process** or **task**.[1]

Multithreading

Multithreading refers to the ability of an OS to support multiple, concurrent paths of execution within a single process. The traditional approach of a single thread of execution per process, in which the concept of a thread is not recognized, is referred to as a single-threaded approach. The two arrangements shown in the left half of Figure 4.1 are single-threaded approaches. MS-DOS is an example of an OS that supports a single user process and a single thread. Other operating systems, such as some variants of UNIX, support multiple user processes but only support one thread per process. The right half of Figure 4.1 depicts multithreaded approaches. A Java run-time environment is an example of a system of one process with multiple threads. Of interest in this section is the use of multiple processes, each of which supports multiple threads. This approach is taken in Windows, Solaris, and many modern versions of UNIX, among others. In this section we give a general description

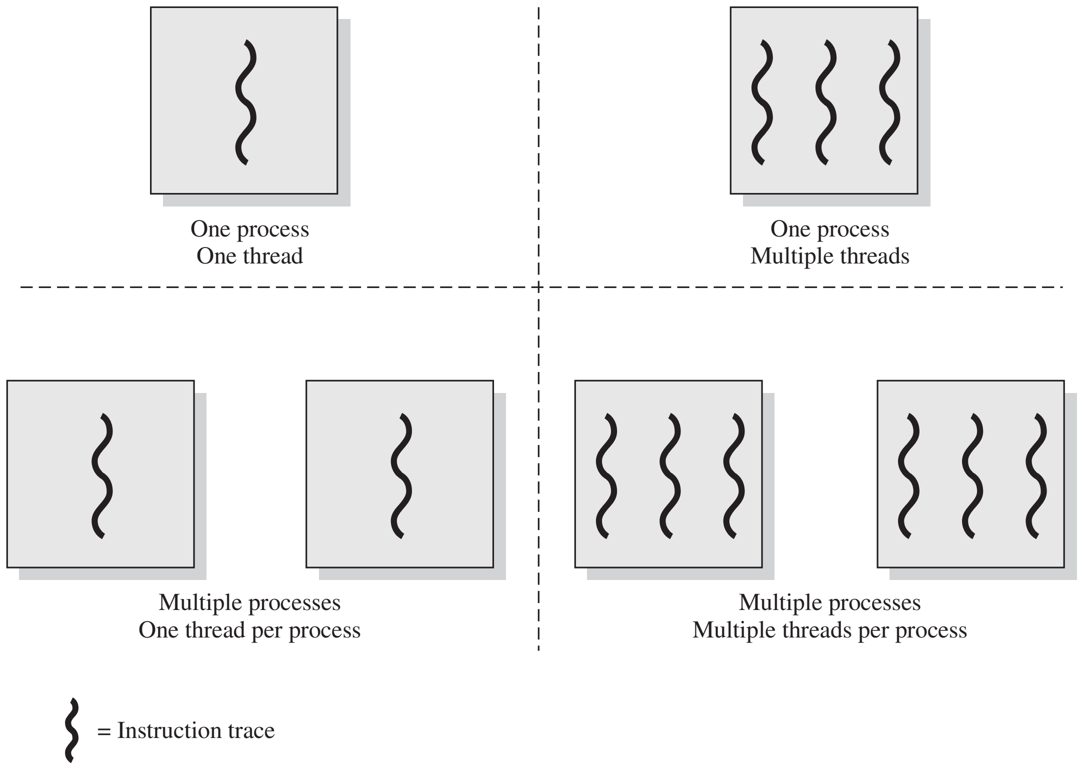


Figure 4.1 Threads and Processes [ANDE97]

[1]Alas, even this degree of consistency is not maintained. In IBM's mainframe operating systems, the concepts of address space and task, respectively, correspond roughly to the concepts of process and thread that we describe in this section. Also, in the literature, the term *lightweight process* is used as either (1) equivalent to the term *thread*, (2) a particular type of thread known as a kernel-level thread, or (3) in the case of Solaris, an entity that maps user-level threads to kernel-level threads.

of multithreading; the details of the Windows, Solaris, and Linux approaches are discussed later in this chapter.

In a multithreaded environment, a process is defined as the unit of resource allocation and a unit of protection. The following are associated with processes:

- A virtual address space that holds the process image
- Protected access to processors, other processes (for interprocess communication), files, and I/O resources (devices and channels)

Within a process, there may be one or more threads, each with the following:

- A thread execution state (Running, Ready, etc.)
- A saved thread context when not running; one way to view a thread is as an independent program counter operating within a process
- An execution stack
- Some per-thread static storage for local variables
- Access to the memory and resources of its process, shared with all other threads in that process

Figure 4.2 illustrates the distinction between threads and processes from the point of view of process management. In a single-threaded process model (i.e., there is no distinct concept of thread), the representation of a process includes its process control block and user address space, as well as user and kernel stacks to manage the call/return behavior of the execution of the process. While the process is running, it controls the processor registers. The contents of these registers are saved when the process is not running. In a multithreaded environment, there is still a single process control block and user address space associated with the process, but now there are separate stacks for each thread, as well as a separate control

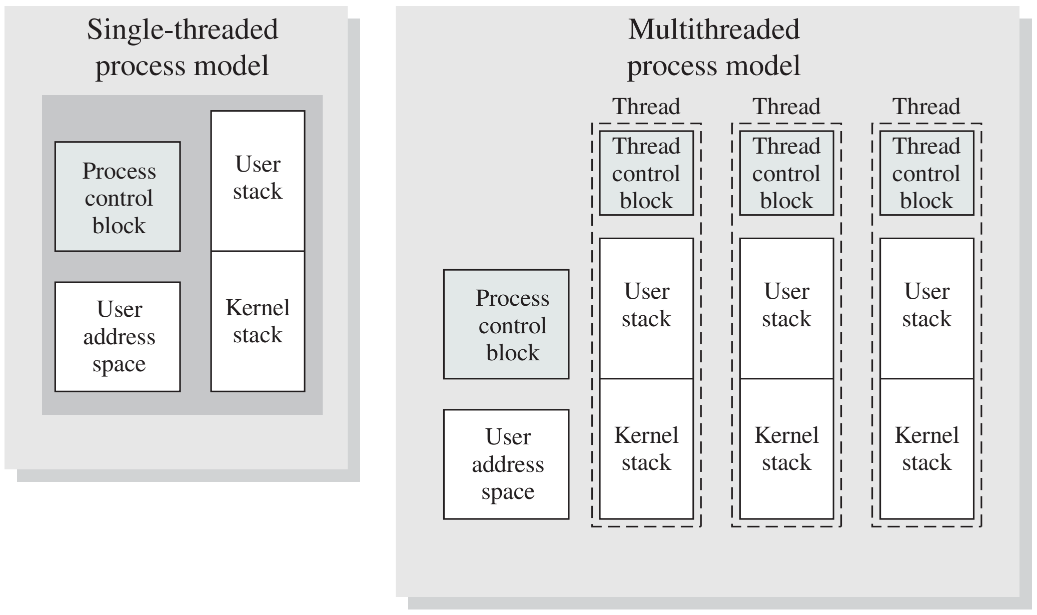


Figure 4.2 Single-Threaded and Multithreaded Process Models

block for each thread containing register values, priority, and other thread-related state information.

Thus, all of the threads of a process share the state and resources of that process. They reside in the same address space and have access to the same data. When one thread alters an item of data in memory, other threads see the results if and when they access that item. If one thread opens a file with read privileges, other threads in the same process can also read from that file.

The key benefits of threads derive from the performance implications:

1. It takes far less time to create a new thread in an existing process than to create a brand-new process. Studies done by the Mach developers show that thread creation is ten times faster than process creation in UNIX [TEVA87].
2. It takes less time to terminate a thread than a process.
3. It takes less time to switch between two threads within the same process than to switch between processes.
4. Threads enhance efficiency in communication between different executing programs. In most operating systems, communication between independent processes requires the intervention of the kernel to provide protection and the mechanisms needed for communication. However, because threads within the same process share memory and files, they can communicate with each other without invoking the kernel.

Thus, if there is an application or function that should be implemented as a set of related units of execution, it is far more efficient to do so as a collection of threads rather than a collection of separate processes.

An example of an application that could make use of threads is a file server. As each new file request comes in, a new thread can be spawned for the file management program. Because a server will handle many requests, many threads will be created and destroyed in a short period. If the server runs on a multiprocessor computer, then multiple threads within the same process can be executing simultaneously on different processors. Further, because processes or threads in a file server must share file data and therefore coordinate their actions, it is faster to use threads and shared memory than processes and message passing for this coordination.

The thread construct is also useful on a single processor to simplify the structure of a program that is logically doing several different functions.

[LETW88] gives four examples of the uses of threads in a single-user multiprocessing system:

- **Foreground and background work:** For example, in a spreadsheet program, one thread could display menus and read user input, while another thread executes user commands and updates the spreadsheet. This arrangement often increases the perceived speed of the application by allowing the program to prompt for the next command before the previous command is complete.
- **Asynchronous processing:** Asynchronous elements in the program can be implemented as threads. For example, as a protection against power failure, one can design a word processor to write its random access memory (RAM) buffer to disk once every minute. A thread can be created whose sole job is

periodic backup and that schedules itself directly with the OS; there is no need for fancy code in the main program to provide for time checks or to coordinate input and output.

- **Speed of execution:** A multithreaded process can compute one batch of data while reading the next batch from a device. On a multiprocessor system, multiple threads from the same process may be able to execute simultaneously. Thus, even though one thread may be blocked for an I/O operation to read in a batch of data, another thread may be executing.
- **Modular program structure:** Programs that involve a variety of activities or a variety of sources and destinations of input and output may be easier to design and implement using threads.

In an OS that supports threads, scheduling and dispatching is done on a thread basis; hence, most of the state information dealing with execution is maintained in thread-level data structures. There are, however, several actions that affect all of the threads in a process and that the OS must manage at the process level. For example, suspension involves swapping the address space of one process out of main memory to make room for the address space of another process. Because all threads in a process share the same address space, all threads are suspended at the same time. Similarly, termination of a process terminates all threads within that process.

Thread Functionality

Like processes, threads have execution states and may synchronize with one another. We look at these two aspects of thread functionality in turn.

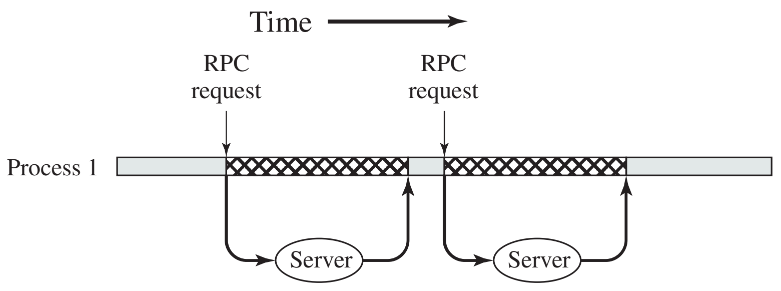
Thread States As with processes, the key states for a thread are Running, Ready, and Blocked. Generally, it does not make sense to associate suspend states with threads because such states are process-level concepts. In particular, if a process is swapped out, all of its threads are necessarily swapped out because they all share the address space of the process.

There are four basic thread operations associated with a change in thread state [ANDE04]:

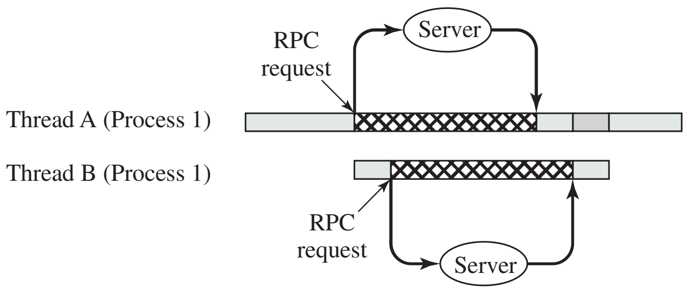
- **Spawn:** Typically, when a new process is spawned, a thread for that process is also spawned. Subsequently, a thread within a process may spawn another thread within the same process, providing an instruction pointer and arguments for the new thread. The new thread is provided with its own register context and stack space and placed on the ready queue.
- **Block:** When a thread needs to wait for an event, it will block (saving its user registers, program counter, and stack pointers). The processor may now turn to the execution of another ready thread in the same or a different process.
- **Unblock:** When the event for which a thread is blocked occurs, the thread is moved to the Ready queue.
- **Finish:** When a thread completes, its register context and stacks are deallocated.

A significant issue is whether the blocking of a thread results in the blocking of the entire process. In other words, if one thread in a process is blocked, does this prevent the running of any other thread in the same process even if that other thread is in a ready state? Clearly, some of the flexibility and power of threads is lost if the one blocked thread blocks an entire process.

We return to this issue subsequently in our discussion of user-level versus kernel-level threads, but for now let us consider the performance benefits of threads that do not block an entire process. Figure 4.3 (based on one in [KLEI96]) shows a program that performs two remote procedure calls (RPCs)[2] to two different hosts to obtain a combined result. In a single-threaded program, the results are obtained in sequence, so the program has to wait for a response from each server in turn. Rewriting the program to use a separate thread for each RPC results in a substantial speedup. Note that if this program operates on a uniprocessor, the requests must be generated sequentially and the results processed in sequence; however, the program waits concurrently for the two replies.



(a) RPC using single thread



(b) RPC using one thread per server (on a uniprocessor)

▨	Blocked, waiting for response to RPC
▩	Blocked, waiting for processor, which is in use by Thread B
▭	Running

Figure 4.3 Remote Procedure Call (RPC) Using Threads

[2]An RPC is a technique by which two programs, which may execute on different machines, interact using procedure call/return syntax and semantics. Both the called and calling program behave as if the partner program were running on the same machine. RPCs are often used for client/server applications and are discussed in Chapter 16.

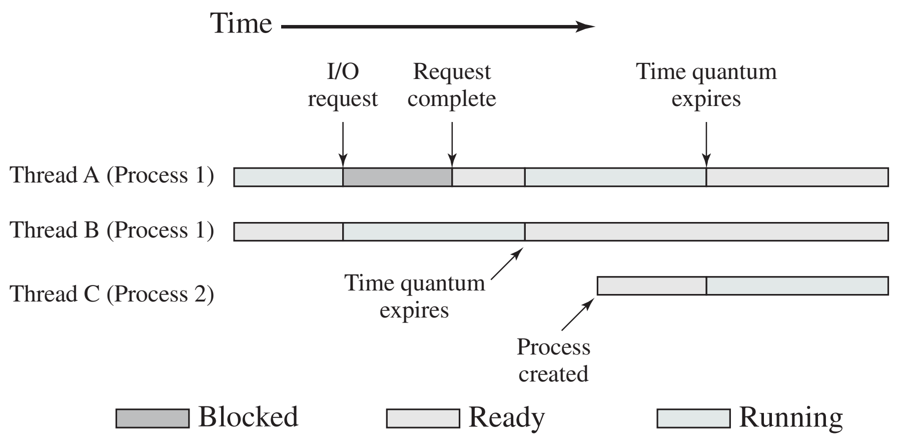


Figure 4.4 Multithreading Example on a Uniprocessor

On a uniprocessor, multiprogramming enables the interleaving of multiple threads within multiple processes. In the example of Figure 4.4, three threads in two processes are interleaved on the processor. Execution passes from one thread to another either when the currently running thread is blocked or when its time slice is exhausted.[3]

THREAD SYNCHRONIZATION All of the threads of a process share the same address space and other resources, such as open files. Any alteration of a resource by one thread affects the environment of the other threads in the same process. It is therefore necessary to synchronize the activities of the various threads so that they do not interfere with each other or corrupt data structures. For example, if two threads each try to add an element to a doubly linked list at the same time, one element may be lost or the list may end up malformed.

The issues raised and the techniques used in the synchronization of threads are, in general, the same as for the synchronization of processes. These issues and techniques are the subject of Chapters 5 and 6.

4.2 TYPES OF THREADS

User-Level and Kernel-Level Threads

There are two broad categories of thread implementation: user-level threads (ULTs) and kernel-level threads (KLTs).[4] The latter are also referred to in the literature as *kernel-supported threads* or *lightweight processes.*

USER-LEVEL THREADS In a pure ULT facility, all of the work of thread management is done by the application and the kernel is not aware of the existence of threads. Figure 4.5a illustrates the pure ULT approach. Any application can be

[3]In this example, thread C begins to run after thread A exhausts its time quantum, even though thread B is also ready to run. The choice between B and C is a scheduling decision, a topic covered in Part Four.
[4]The acronyms ULT and KLT are not widely used but are introduced for conciseness.

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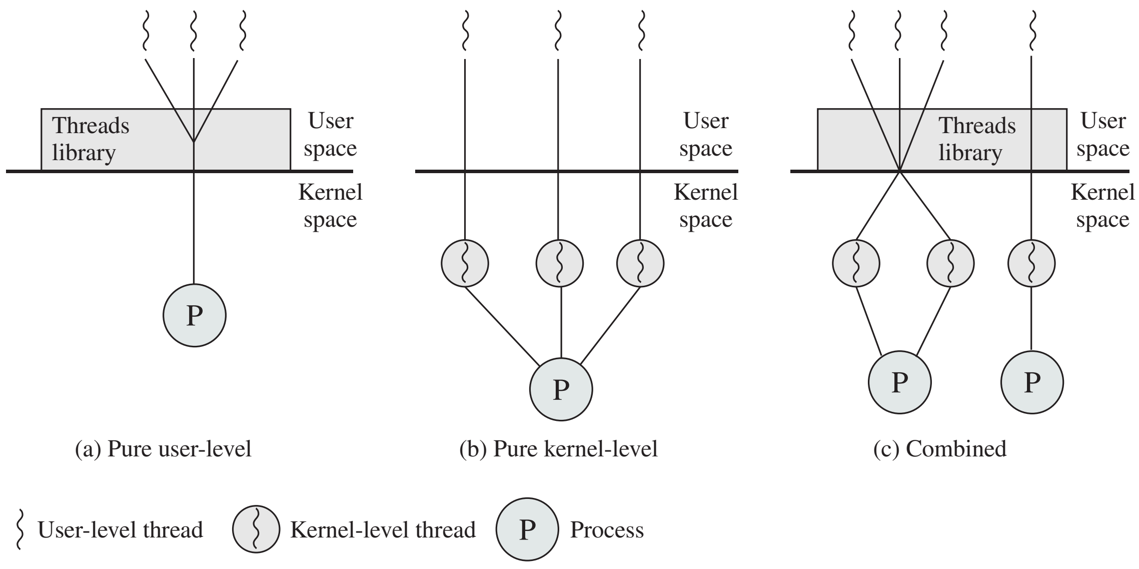

Figure 4.5 **User-Level and Kernel-Level Threads**

programmed to be multithreaded by using a threads library, which is a package of routines for ULT management. The threads library contains code for creating and destroying threads, for passing messages and data between threads, for scheduling thread execution, and for saving and restoring thread contexts.

By default, an application begins with a single thread and begins running in that thread. This application and its thread are allocated to a single process managed by the kernel. At any time that the application is running (the process is in the Running state), the application may spawn a new thread to run within the same process. Spawning is done by invoking the spawn utility in the threads library. Control is passed to that utility by a procedure call. The threads library creates a data structure for the new thread and then passes control to one of the threads within this process that is in the Ready state, using some scheduling algorithm. When control is passed to the library, the context of the current thread is saved, and when control is passed from the library to a thread, the context of that thread is restored. The context essentially consists of the contents of user registers, the program counter, and stack pointers.

All of the activity described in the preceding paragraph takes place in user space and within a single process. The kernel is unaware of this activity. The kernel continues to schedule the process as a unit and assigns a single execution state (Ready, Running, Blocked, etc.) to that process. The following examples should clarify the relationship between thread scheduling and process scheduling. Suppose that process B is executing in its thread 2; the states of the process and two ULTs that are part of the process are shown in Figure 4.6a. Each of the following is a possible occurrence:

1. The application executing in thread 2 makes a system call that blocks B. For example, an I/O call is made. This causes control to transfer to the kernel. The kernel invokes the I/O action, places process B in the Blocked state, and switches to another process. Meanwhile, according to the data structure maintained by

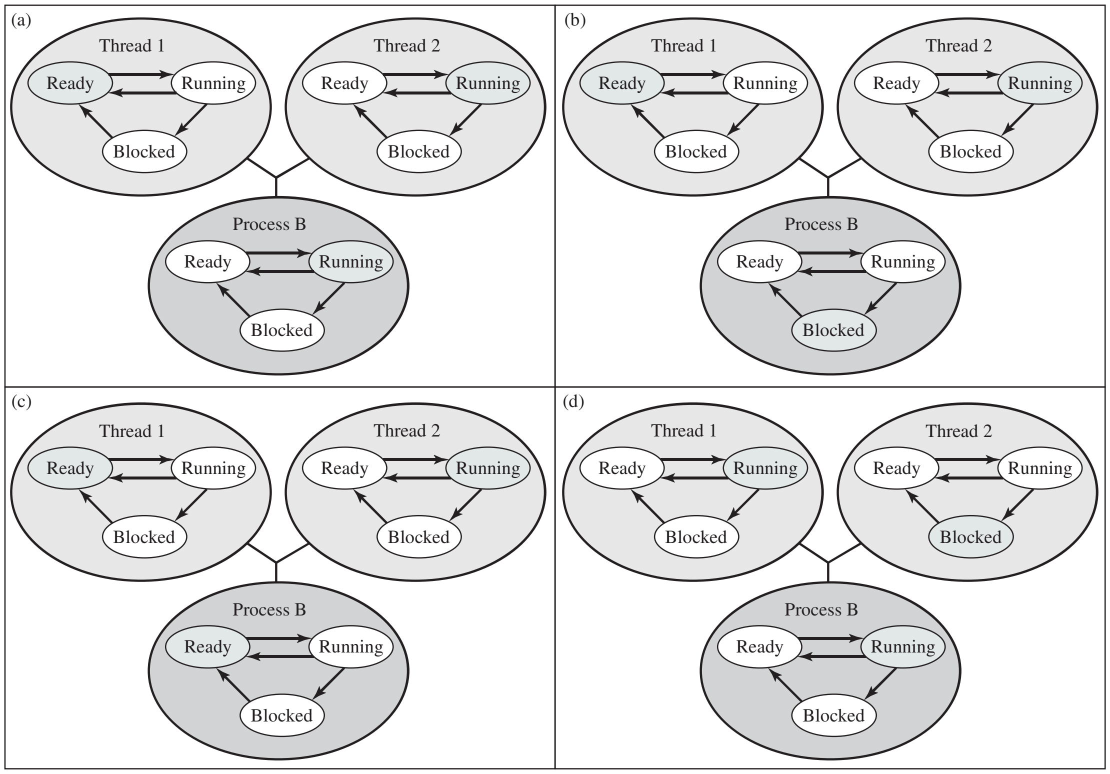

Figure 4.6 **Examples of the Relationships between User-Level Thread States and Process States**

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the threads library, thread 2 of process B is still in the Running state. It is important to note that thread 2 is not actually running in the sense of being executed on a processor; but it is perceived as being in the Running state by the threads library. The corresponding state diagrams are shown in Figure 4.6b.

2. A clock interrupt passes control to the kernel, and the kernel determines that the currently running process (B) has exhausted its time slice. The kernel places process B in the Ready state and switches to another process. Meanwhile, according to the data structure maintained by the threads library, thread 2 of process B is still in the Running state. The corresponding state diagrams are shown in Figure 4.6c.
3. Thread 2 has reached a point where it needs some action performed by thread 1 of process B. Thread 2 enters a Blocked state and thread 1 transitions from Ready to Running. The process itself remains in the Running state. The corresponding state diagrams are shown in Figure 4.6d.

In cases 1 and 2 (Figures 4.6b and 4.6c), when the kernel switches control back to process B, execution resumes in thread 2. Also note that a process can be interrupted, either by exhausting its time slice or by being preempted by a higher-priority process, while it is executing code in the threads library. Thus, a process may be in the midst of a thread switch from one thread to another when interrupted. When that process is resumed, execution continues within the threads library, which completes the thread switch and transfers control to another thread within that process.

There are a number of advantages to the use of ULTs instead of KLTs, including the following:

1. Thread switching does not require kernel mode privileges because all of the thread management data structures are within the user address space of a single process. Therefore, the process does not switch to the kernel mode to do thread management. This saves the overhead of two mode switches (user to kernel; kernel back to user).
2. Scheduling can be application specific. One application may benefit most from a simple round-robin scheduling algorithm, while another might benefit from a priority-based scheduling algorithm. The scheduling algorithm can be tailored to the application without disturbing the underlying OS scheduler.
3. ULTs can run on any OS. No changes are required to the underlying kernel to support ULTs. The threads library is a set of application-level functions shared by all applications.

There are two distinct disadvantages of ULTs compared to KLTs:

1. In a typical OS, many system calls are blocking. As a result, when a ULT executes a system call, not only is that thread blocked, but also all of the threads within the process are blocked.
2. In a pure ULT strategy, a multithreaded application cannot take advantage of multiprocessing. A kernel assigns one process to only one processor at a time. Therefore, only a single thread within a process can execute at a time. In effect, we have application-level multiprogramming within a single process.

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While this multiprogramming can result in a significant speedup of the application, there are applications that would benefit from the ability to execute portions of code simultaneously.

There are ways to work around these two problems. For example, both problems can be overcome by writing an application as multiple processes rather than multiple threads. But this approach eliminates the main advantage of threads: Each switch becomes a process switch rather than a thread switch, resulting in much greater overhead.

Another way to overcome the problem of blocking threads is to use a technique referred to as **jacketing**. The purpose of jacketing is to convert a blocking system call into a nonblocking system call. For example, instead of directly calling a system I/O routine, a thread calls an application-level I/O jacket routine. Within this jacket routine is code that checks to determine if the I/O device is busy. If it is, the thread enters the Blocked state and passes control (through the threads library) to another thread. When this thread later is given control again, the jacket routine checks the I/O device again.

Kernel-Level Threads In a pure KLT facility, all of the work of thread management is done by the kernel. There is no thread management code in the application level, simply an application programming interface (API) to the kernel thread facility. Windows is an example of this approach.

Figure 4.5b depicts the pure KLT approach. The kernel maintains context information for the process as a whole and for individual threads within the process. Scheduling by the kernel is done on a thread basis. This approach overcomes the two principal drawbacks of the ULT approach. First, the kernel can simultaneously schedule multiple threads from the same process on multiple processors. Second, if one thread in a process is blocked, the kernel can schedule another thread of the same process. Another advantage of the KLT approach is that kernel routines themselves can be multithreaded.

The principal disadvantage of the KLT approach compared to the ULT approach is that the transfer of control from one thread to another within the same process requires a mode switch to the kernel. To illustrate the differences, Table 4.1 shows the results of measurements taken on a uniprocessor VAX computer running a UNIX-like OS. The two benchmarks are as follows: Null Fork, the time to create, schedule, execute, and complete a process/thread that invokes the null procedure (i.e., the overhead of forking a process/thread); and Signal-Wait, the time for a process/thread to signal a waiting process/thread and then wait on a condition (i.e., the overhead of synchronizing two processes/threads together). We see that there is an order of magnitude or more of difference between ULTs and KLTs and similarly between KLTs and processes.

Table 4.1 Thread and Process Operation Latencies (μs)

Operation	User-Level Threads	Kernel-Level Threads	Processes
Null Fork	34	948	11,300
Signal Wait	37	441	1,840

Thus, on the face of it, while there is a significant speedup by using KLT multithreading compared to single-threaded processes, there is an additional significant speedup by using ULTs. However, whether or not the additional speedup is realized depends on the nature of the applications involved. If most of the thread switches in an application require kernel mode access, then a ULT-based scheme may not perform much better than a KLT-based scheme.

Combined Approaches Some operating systems provide a combined ULT/KLT facility (Figure 4.5c). In a combined system, thread creation is done completely in user space, as is the bulk of the scheduling and synchronization of threads within an application. The multiple ULTs from a single application are mapped onto some (smaller or equal) number of KLTs. The programmer may adjust the number of KLTs for a particular application and processor to achieve the best overall results.

In a combined approach, multiple threads within the same application can run in parallel on multiple processors, and a blocking system call need not block the entire process. If properly designed, this approach should combine the advantages of the pure ULT and KLT approaches while minimizing the disadvantages.

Solaris is a good example of an OS using this combined approach. The current Solaris version limits the ULT/KLT relationship to be one-to-one.

Other Arrangements

As we have said, the concepts of resource allocation and dispatching unit have traditionally been embodied in the single concept of the process—that is, as a 1 : 1 relationship between threads and processes. Recently, there has been much interest in providing for multiple threads within a single process, which is a many-to-one relationship. However, as Table 4.2 shows, the other two combinations have also been investigated, namely, a many-to-many relationship and a one-to-many relationship.

Many-to-Many Relationship The idea of having a many-to-many relationship between threads and processes has been explored in the experimental operating system TRIX [PAZZ92, WARD80]. In TRIX, there are the concepts of domain

Table 4.2 Relationship between Threads and Processes

Threads: Processes	Description	Example Systems
1:1	Each thread of execution is a unique process with its own address space and resources.	Traditional UNIX implementations
M:1	A process defines an address space and dynamic resource ownership. Multiple threads may be created and executed within that process.	Windows NT, Solaris, Linux, OS/2, OS/390, MACH
1:M	A thread may migrate from one process environment to another. This allows a thread to be easily moved among distinct systems.	Ra (Clouds), Emerald
M:N	Combines attributes of M:1 and 1:M cases.	TRIX

and thread. A domain is a static entity, consisting of an address space and "ports" through which messages may be sent and received. A thread is a single execution path, with an execution stack, processor state, and scheduling information.

As with the multithreading approaches discussed so far, multiple threads may execute in a single domain, providing the efficiency gains discussed earlier. However, it is also possible for a single user activity, or application, to be performed in multiple domains. In this case, a thread exists that can move from one domain to another.

The use of a single thread in multiple domains seems primarily motivated by a desire to provide structuring tools for the programmer. For example, consider a program that makes use of an I/O subprogram. In a multiprogramming environment that allows user-spawned processes, the main program could generate a new process to handle I/O and then continue to execute. However, if the future progress of the main program depends on the outcome of the I/O operation, then the main program will have to wait for the other I/O program to finish. There are several ways to implement this application:

1. The entire program can be implemented as a single process. This is a reasonable and straightforward solution. There are drawbacks related to memory management. The process as a whole may require considerable main memory to execute efficiently, whereas the I/O subprogram requires a relatively small address space to buffer I/O and to handle the relatively small amount of program code. Because the I/O program executes in the address space of the larger program, either the entire process must remain in main memory during the I/O operation or the I/O operation is subject to swapping. This memory management effect would also exist if the main program and the I/O subprogram were implemented as two threads in the same address space.
2. The main program and I/O subprogram can be implemented as two separate processes. This incurs the overhead of creating the subordinate process. If the I/O activity is frequent, one must either leave the subordinate process alive, which consumes management resources, or frequently create and destroy the subprogram, which is inefficient.
3. Treat the main program and the I/O subprogram as a single activity that is to be implemented as a single thread. However, one address space (domain) could be created for the main program and one for the I/O subprogram. Thus, the thread can be moved between the two address spaces as execution proceeds. The OS can manage the two address spaces independently, and no process creation overhead is incurred. Furthermore, the address space used by the I/O subprogram could also be shared by other simple I/O programs.

The experiences of the TRIX developers indicate that the third option has merit and may be the most effective solution for some applications.

One-to-Many Relationship In the field of distributed operating systems (designed to control distributed computer systems), there has been interest in the concept of a thread as primarily an entity that can move among address spaces.[5] A notable example of this research is the Clouds operating system, and especially its kernel, known as Ra [DASG92]. Another example is the Emerald system [STEE95].

A thread in Clouds is a unit of activity from the user's perspective. A process is a virtual address space with an associated process control block. Upon creation, a thread starts executing in a process by invoking an entry point to a program in that process. Threads may move from one address space to another and actually span computer boundaries (i.e., move from one computer to another). As a thread moves, it must carry with it certain information, such as the controlling terminal, global parameters, and scheduling guidance (e.g., priority).

The Clouds approach provides an effective way of insulating both users and programmers from the details of the distributed environment. A user's activity may be represented as a single thread, and the movement of that thread among computers may be dictated by the OS for a variety of system-related reasons, such as the need to access a remote resource, and load balancing.

4.3 MULTICORE AND MULTITHREADING

The use of a multicore system to support a single application with multiple threads, such as might occur on a workstation, a video-game console, or a personal computer running a processor-intense application, raises issues of performance and application design. In this section, we first look at some of the performance implications of a multithreaded application on a multicore system and then describe a specific example of an application designed to exploit multicore capabilities.

Performance of Software on Multicore

The potential performance benefits of a multicore organization depend on the ability to effectively exploit the parallel resources available to the application. Let us focus first on a single application running on a multicore system. Amdahl's law (see Appendix E) states that:

$$\text{Speedup} = \frac{\text{time to execute program on a single processor}}{\text{time to execute program on } N \text{ parallel processors}} = \frac{1}{(1-f) + \dfrac{f}{N}}$$

The law assumes a program in which a fraction $(1 - f)$ of the execution time involves code that is inherently serial and a fraction f that involves code that is infinitely parallelizable with no scheduling overhead.

This law appears to make the prospect of a multicore organization attractive. But as Figure 4.7a shows, even a small amount of serial code has a noticeable impact. If only 10% of the code is inherently serial ($f = 0.9$), running the program on a multicore system with eight processors yields a performance gain of only a factor of 4.7. In addition, software typically incurs overhead as a result of communication

[5]The movement of processes or threads among address spaces, or thread migration, on different machines has become a hot topic in recent years. Chapter 18 explores this topic.

UNIT -3
CONCURRENCY : MUTUAL EXCLUSION AND SYNCHRONIZATION, DEADLOCK AND STARVATION

Designing correct routines for controlling concurrent activities proved to be one of the most difficult aspects of systems programming. The ad hoc techniques used by programmers of early multiprogramming and real-time systems were always vulnerable to subtle programming errors whose effects could be observed only when certain relatively rare sequences of actions occurred. The errors are particularly difficult to locate, since the precise conditions under which they appear are very hard to reproduce.

—*The Computer Science and Engineering Research Study*, MIT Press, 1980

Learning Objectives

After studying this chapter, you should be able to:

- Discuss basic concepts related to concurrency, such as race conditions, OS concerns, and mutual exclusion requirements.
- Understand hardware approaches to supporting mutual exclusion.
- Define and explain semaphores.
- Define and explain monitors.
- Define and explain monitors.
- Explain the readers/writers problem.

The central themes of operating system design are all concerned with the management of processes and threads:

- **Multiprogramming:** The management of multiple processes within a uniprocessor system
- **Multiprocessing**: The management of multiple processes within a multiprocessor
- **Distributed processing:** The management of multiple processes executing on multiple, distributed computer systems. The recent proliferation of clusters is a prime example of this type of system.

Fundamental to all of these areas, and fundamental to OS design, is concurrency. Concurrency encompasses a host of design issues, including communication among processes, sharing of and competing for resources (such as memory, files, and I/O access), synchronization of the activities of multiple processes, and allocation of processor time to processes. We shall see that these issues arise not just in multiprocessing and distributed processing environments but even in single-processor multiprogramming systems.

Concurrency arises in three different contexts:

- **Multiple applications:** Multiprogramming was invented to allow processing time to be dynamically shared among a number of active applications.
- **Structured applications:** As an extension of the principles of modular design and structured programming, some applications can be effectively programmed as a set of concurrent processes.

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- **Operating system structure:** The same structuring advantages apply to systems programs, and we have seen that operating systems are themselves often implemented as a set of processes or threads.

Because of the importance of this topic, four chapters and an appendix focus on concurrency-related issues. Chapters 5 and 6 deal with concurrency in multiprogramming and multiprocessing systems. Chapters 16 and 18 examine concurrency issues related to distributed processing.

This chapter begins with an introduction to the concept of concurrency and the implications of the execution of multiple concurrent processes.[1] We find that the basic requirement for support of concurrent processes is the ability to enforce mutual exclusion; that is, the ability to exclude all other processes from a course of action while one process is granted that ability. Next, we examine some hardware mechanisms that can support mutual exclusion. Then we look at solutions that do not involve busy waiting and that can be supported either by the OS or enforced by language compilers. We examine three approaches: semaphores, monitors, and message passing.

Two classic problems in concurrency are used to illustrate the concepts and compare the approaches presented in this chapter. The producer/consumer problem is introduced in Section 5.3 and used as a running example. The chapter closes with the readers/writers problem.

Our discussion of concurrency continues in Chapter 6, and we defer a discussion of the concurrency mechanisms of our example systems until the end of that chapter. Appendix A covers additional topics on concurrency. Table 5.1 lists some key terms related to concurrency. A set of animations that illustrate concepts in this chapter is available online. Click on the rotating globe at this book's Web site at WilliamStallings.com/OS/OS7e.html for access.

Table 5.1 Some Key Terms Related to Concurrency

atomic operation	A function or action implemented as a sequence of one or more instructions that appears to be indivisible; that is, no other process can see an intermediate state or interrupt the operation. The sequence of instruction is guaranteed to execute as a group, or not execute at all, having no visible effect on system state. Atomicity guarantees isolation from concurrent processes.
critical section	A section of code within a process that requires access to shared resources and that must not be executed while another process is in a corresponding section of code.
deadlock	A situation in which two or more processes are unable to proceed because each is waiting for one of the others to do something.
livelock	A situation in which two or more processes continuously change their states in response to changes in the other process(es) without doing any useful work.
mutual exclusion	The requirement that when one process is in a critical section that accesses shared resources, no other process may be in a critical section that accesses any of those shared resources.
race condition	A situation in which multiple threads or processes read and write a shared data item and the final result depends on the relative timing of their execution.
starvation	A situation in which a runnable process is overlooked indefinitely by the scheduler; although it is able to proceed, it is never chosen.

[1]For simplicity, we generally refer to the concurrent execution of *processes*. In fact, as we have seen in the preceding chapter, in some systems the fundamental unit of concurrency is a thread rather than a process.

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5.1 PRINCIPLES OF CONCURRENCY

In a single-processor multiprogramming system, processes are interleaved in time to yield the appearance of simultaneous execution (Figure 2.12a). Even though actual parallel processing is not achieved, and even though there is a certain amount of overhead involved in switching back and forth between processes, interleaved execution provides major benefits in processing efficiency and in program structuring. In a multiple-processor system, it is possible not only to interleave the execution of multiple processes but also to overlap them (Figure 2.12b).

At first glance, it may seem that interleaving and overlapping represent fundamentally different modes of execution and present different problems. In fact, both techniques can be viewed as examples of concurrent processing, and both present the same problems. In the case of a uniprocessor, the problems stem from a basic characteristic of multiprogramming systems: The relative speed of execution of processes cannot be predicted. It depends on the activities of other processes, the way in which the OS handles interrupts, and the scheduling policies of the OS. The following difficulties arise:

1. The sharing of global resources is fraught with peril. For example, if two processes both make use of the same global variable and both perform reads and writes on that variable, then the order in which the various reads and writes are executed is critical. An example of this problem is shown in the following subsection.
2. It is difficult for the OS to manage the allocation of resources optimally. For example, process A may request use of, and be granted control of, a particular I/O channel and then be suspended before using that channel. It may be undesirable for the OS simply to lock the channel and prevent its use by other processes; indeed this may lead to a deadlock condition, as described in Chapter 6.
3. It becomes very difficult to locate a programming error because results are typically not deterministic and reproducible (e.g., see [LEBL87, CARR89, SHEN02] for a discussion of this point).

All of the foregoing difficulties present themselves in a multiprocessor system as well, because here too the relative speed of execution of processes is unpredictable. A multiprocessor system must also deal with problems arising from the simultaneous execution of multiple processes. Fundamentally, however, the problems are the same as those for uniprocessor systems. This should become clear as the discussion proceeds.

A Simple Example

Consider the following procedure:

```
void echo()
{
  chin = getchar();
  chout = chin;
  putchar(chout);
}
```

This procedure shows the essential elements of a program that will provide a character echo procedure; input is obtained from a keyboard one keystroke at a time. Each input character is stored in variable `chin`. It is then transferred to variable `chout` and sent to the display. Any program can call this procedure repeatedly to accept user input and display it on the user's screen.

Now consider that we have a single-processor multiprogramming system supporting a single user. The user can jump from one application to another, and each application uses the same keyboard for input and the same screen for output. Because each application needs to use the procedure `echo`, it makes sense for it to be a shared procedure that is loaded into a portion of memory global to all applications. Thus, only a single copy of the `echo` procedure is used, saving space.

The sharing of main memory among processes is useful to permit efficient and close interaction among processes. However, such sharing can lead to problems. Consider the following sequence:

1. Process P1 invokes the `echo` procedure and is interrupted immediately after `getchar` returns its value and stores it in `chin`. At this point, the most recently entered character, `x`, is stored in variable `chin`.
2. Process P2 is activated and invokes the `echo` procedure, which runs to conclusion, inputting and then displaying a single character, `y`, on the screen.
3. Process P1 is resumed. By this time, the value `x` has been overwritten in `chin` and therefore lost. Instead, `chin` contains `y`, which is transferred to `chout` and displayed.

Thus, the first character is lost and the second character is displayed twice. The essence of this problem is the shared global variable, `chin`. Multiple processes have access to this variable. If one process updates the global variable and then is interrupted, another process may alter the variable before the first process can use its value. Suppose, however, that we permit only one process at a time to be in that procedure. Then the foregoing sequence would result in the following:

1. Process P1 invokes the `echo` procedure and is interrupted immediately after the conclusion of the input function. At this point, the most recently entered character, `x`, is stored in variable `chin`.
2. Process P2 is activated and invokes the `echo` procedure. However, because P1 is still inside the `echo` procedure, although currently suspended, P2 is blocked from entering the procedure. Therefore, P2 is suspended awaiting the availability of the `echo` procedure.
3. At some later time, process P1 is resumed and completes execution of `echo`. The proper character, `x`, is displayed.
4. When P1 exits `echo`, this removes the block on P2. When P2 is later resumed, the `echo` procedure is successfully invoked.

This example shows that it is necessary to protect shared global variables (and other shared global resources) and that the only way to do that is to control the code that accesses the variable. If we impose the discipline that only one process at a time may enter `echo` and that once in `echo` the procedure must run to completion before it is available for another process, then the type of error just discussed will not occur. How that discipline may be imposed is a major topic of this chapter.

This problem was stated with the assumption that there was a single-processor, multiprogramming OS. The example demonstrates that the problems of concurrency occur even when there is a single processor. In a multiprocessor system, the same problems of protected shared resources arise, and the same solution works. First, suppose that there is no mechanism for controlling access to the shared global variable:

1. Processes P1 and P2 are both executing, each on a separate processor. Both processes invoke the `echo` procedure.
2. The following events occur; events on the same line take place in parallel:

```
      Process P1                  Process P2
•                           •
chin = getchar();           •
•                           chin = getchar();
chout = chin;               chout = chin;
putchar(chout);             •
•                           putchar(chout);
•                           •
```

The result is that the character input to P1 is lost before being displayed, and the character input to P2 is displayed by both P1 and P2. Again, let us add the capability of enforcing the discipline that only one process at a time may be in `echo`. Then the following sequence occurs:

1. Processes P1 and P2 are both executing, each on a separate processor. P1 invokes the `echo` procedure.
2. While P1 is inside the `echo` procedure, P2 invokes `echo`. Because P1 is still inside the `echo` procedure (whether P1 is suspended or executing), P2 is blocked from entering the procedure. Therefore, P2 is suspended awaiting the availability of the `echo` procedure.
3. At a later time, process P1 completes execution of `echo`, exits that procedure, and continues executing. Immediately upon the exit of P1 from `echo`, P2 is resumed and begins executing `echo`.

In the case of a uniprocessor system, the reason we have a problem is that an interrupt can stop instruction execution anywhere in a process. In the case of a multiprocessor system, we have that same condition and, in addition, a problem can be caused because two processes may be executing simultaneously and both trying to access the same global variable. However, the solution to both types of problem is the same: control access to the shared resource.

Race Condition

A race condition occurs when multiple processes or threads read and write data items so that the final result depends on the order of execution of instructions in the multiple processes. Let us consider two simple examples.

As a first example, suppose that two processes, P1 and P2, share the global variable `a`. At some point in its execution, P1 updates `a` to the value 1, and at some point in its execution, P2 updates a to the value 2. Thus, the two tasks are in a race to write variable `a`. In this example, the "loser" of the race (the process that updates last) determines the final value of `a`.

For our second example, consider two process, P3 and P4, that share global variables `b` and `c`, with initial values `b = 1` and `c = 2`. At some point in its execution, P3 executes the assignment `b = b + c`, and at some point in its execution, P4 executes the assignment `c = b + c`. Note that the two processes update different variables. However, the final values of the two variables depend on the order in which the two processes execute these two assignments. If P3 executes its assignment statement first, then the final values are `b = 3` and `c = 5`. If P4 executes its assignment statement first, then the final values are `b = 4` and `c = 3`.

Appendix A includes a discussion of race conditions using semaphores as an example.

Operating System Concerns

What design and management issues are raised by the existence of concurrency? We can list the following concerns:

1. The OS must be able to keep track of the various processes. This is done with the use of process control blocks and was described in Chapter 4.
2. The OS must allocate and deallocate various resources for each active process. At times, multiple processes want access to the same resource. These resources include
   - **Processor time:** This is the scheduling function, discussed in Part Four.
   - **Memory:** Most operating systems use a virtual memory scheme. The topic is addressed in Part Three.
   - **Files:** Discussed in Chapter 12.
   - **I/O devices:** Discussed in Chapter 11.
3. The OS must protect the data and physical resources of each process against unintended interference by other processes. This involves techniques that relate to memory, files, and I/O devices. A general treatment of protection is found in Part Seven.
4. The functioning of a process, and the output it produces, must be independent of the speed at which its execution is carried out relative to the speed of other concurrent processes. This is the subject of this chapter.

To understand how the issue of speed independence can be addressed, we need to look at the ways in which processes can interact.

Process Interaction

We can classify the ways in which processes interact on the basis of the degree to which they are aware of each other's existence. Table 5.2 lists three possible degrees of awareness plus the consequences of each:

- **Processes unaware of each other:** These are independent processes that are not intended to work together. The best example of this situation is the multiprogramming of multiple independent processes. These can either be batch jobs or interactive sessions or a mixture. Although the processes are not working together, the OS needs to be concerned about **competition** for resources. For example, two independent applications may both want to access the same disk or file or printer. The OS must regulate these accesses.
- **Processes indirectly aware of each other:** These are processes that are not necessarily aware of each other by their respective process IDs but that share access to some object, such as an I/O buffer. Such processes exhibit **cooperation** in sharing the common object.
- **Processes directly aware of each other:** These are processes that are able to communicate with each other by process ID and that are designed to work jointly on some activity. Again, such processes exhibit **cooperation**.

Conditions will not always be as clear-cut as suggested in Table 5.2. Rather, several processes may exhibit aspects of both competition and cooperation. Nevertheless, it is productive to examine each of the three items in the preceding list separately and determine their implications for the OS.

Table 5.2 Process Interaction

Degree of Awareness	Relationship	Influence that One Process Has on the Other	Potential Control Problems
Processes unaware of each other	Competition	• Results of one process independent of the action of others • Timing of process may be affected	• Mutual exclusion • Deadlock (renewable resource) • Starvation
Processes indirectly aware of each other (e.g., shared object)	Cooperation by sharing	• Results of one process may depend on information obtained from others • Timing of process may be affected	• Mutual exclusion • Deadlock (renewable resource) • Starvation • Data coherence
Processes directly aware of each other (have communication primitives available to them)	Cooperation by communication	• Results of one process may depend on information obtained from others • Timing of process may be affected	• Deadlock (consumable resource) • Starvation

Competition among Processes for Resources Concurrent processes come into conflict with each other when they are competing for the use of the same resource. In its pure form, we can describe the situation as follows. Two or more processes need to access a resource during the course of their execution. Each process is unaware of the existence of other processes, and each is to be unaffected by the execution of the other processes. It follows from this that each process should leave the state of any resource that it uses unaffected. Examples of resources include I/O devices, memory, processor time, and the clock.

There is no exchange of information between the competing processes. However, the execution of one process may affect the behavior of competing processes. In particular, if two processes both wish access to a single resource, then one process will be allocated that resource by the OS, and the other will have to wait. Therefore, the process that is denied access will be slowed down. In an extreme case, the blocked process may never get access to the resource and hence will never terminate successfully.

In the case of competing processes three control problems must be faced. First is the need for **mutual exclusion**. Suppose two or more processes require access to a single nonsharable resource, such as a printer. During the course of execution, each process will be sending commands to the I/O device, receiving status information, sending data, and/or receiving data. We will refer to such a resource as a **critical resource**, and the portion of the program that uses it as a **critical section** of the program. It is important that only one program at a time be allowed in its critical section. We cannot simply rely on the OS to understand and enforce this restriction because the detailed requirements may not be obvious. In the case of the printer, for example, we want any individual process to have control of the printer while it prints an entire file. Otherwise, lines from competing processes will be interleaved.

The enforcement of mutual exclusion creates two additional control problems. One is that of **deadlock**. For example, consider two processes, P1 and P2, and two resources, R1 and R2. Suppose that each process needs access to both resources to perform part of its function. Then it is possible to have the following situation: the OS assigns R1 to P2, and R2 to P1. Each process is waiting for one of the two resources. Neither will release the resource that it already owns until it has acquired the other resource and performed the function requiring both resources. The two processes are deadlocked.

A final control problem is **starvation**. Suppose that three processes (P1, P2, P3) each require periodic access to resource R. Consider the situation in which P1 is in possession of the resource, and both P2 and P3 are delayed, waiting for that resource. When P1 exits its critical section, either P2 or P3 should be allowed access to R. Assume that the OS grants access to P3 and that P1 again requires access before P3 completes its critical section. If the OS grants access to P1 after P3 has finished, and subsequently alternately grants access to P1 and P3, then P2 may indefinitely be denied access to the resource, even though there is no deadlock situation.

Control of competition inevitably involves the OS because it is the OS that allocates resources. In addition, the processes themselves will need to be able to

```
/* PROCESS 1 */

void P1
{
  while (true) {
    /* preceding code */;
    entercritical (Ra);
    /* critical section */;
    exitcritical (Ra);
    /* following code */;
  }
}
```

```
/* PROCESS 2 */

void P2
{
  while (true) {
    /* preceding code */;
    entercritical (Ra);
    /* critical section */;
    exitcritical (Ra);
    /* following code */;
  }
}
```

• • •

```
/* PROCESS n */

void Pn
{
  while (true) {
    /* preceding code */;
    entercritical (Ra);
    /* critical section */;
    exitcritical (Ra);
    /* following code */;
  }
}
```

Figure 5.1 Illustration of Mutual Exclusion

express the requirement for mutual exclusion in some fashion, such as locking a resource prior to its use. Any solution will involve some support from the OS, such as the provision of the locking facility. Figure 5.1 illustrates the mutual exclusion mechanism in abstract terms. There are *n* processes to be executed concurrently. Each process includes (1) a critical section that operates on some resource Ra, and (2) additional code preceding and following the critical section that does not involve access to Ra. Because all processes access the same resource Ra, it is desired that only one process at a time be in its critical section. To enforce mutual exclusion, two functions are provided: `entercritical` and `exitcritical`. Each function takes as an argument the name of the resource that is the subject of competition. Any process that attempts to enter its critical section while another process is in its critical section, for the same resource, is made to wait.

It remains to examine specific mechanisms for providing the functions `entercritical` and `exitcritical`. For the moment, we defer this issue while we consider the other cases of process interaction.

Cooperation among Processes by Sharing The case of cooperation by sharing covers processes that interact with other processes without being explicitly aware of them. For example, multiple processes may have access to shared variables or to shared files or databases. Processes may use and update the shared data without reference to other processes but know that other processes may have access to the same data. Thus the processes must cooperate to ensure that the data they share are properly managed. The control mechanisms must ensure the integrity of the shared data.

Because data are held on resources (devices, memory), the control problems of mutual exclusion, deadlock, and starvation are again present. The only difference is that data items may be accessed in two different modes, reading and writing, and only writing operations must be mutually exclusive.

However, over and above these problems, a new requirement is introduced: that of data coherence. As a simple example, consider a bookkeeping application in which various data items may be updated. Suppose two items of data *a* and *b* are to be maintained in the relationship $a = b$. That is, any program that updates one value must also update the other to maintain the relationship. Now consider the following two processes:

```
P1:
        a = a + 1;
        b = b + 1;
P2:
        b = 2 * b;
        a = 2 * a;
```

If the state is initially consistent, each process taken separately will leave the shared data in a consistent state. Now consider the following concurrent execution sequence, in which the two processes respect mutual exclusion on each individual data item (*a* and *b*):

```
a = a + 1;
b = 2 * b;
b = b + 1;
a = 2 * a;
```

At the end of this execution sequence, the condition $a = b$ no longer holds. For example, if we start with $a = b = 1$, at the end of this execution sequence we have $a = 4$ and $b = 3$. The problem can be avoided by declaring the entire sequence in each process to be a critical section.

Thus, we see that the concept of critical section is important in the case of cooperation by sharing. The same abstract functions of `entercritical` and `exitcritical` discussed earlier (Figure 5.1) can be used here. In this case, the argument for the functions could be a variable, a file, or any other shared object. Furthermore, if critical sections are used to provide data integrity, then there may be no specific resource or variable that can be identified as an argument. In that case, we can think of the argument as being an identifier that is shared among concurrent processes to identify critical sections that must be mutually exclusive.

Cooperation among Processes by Communication In the first two cases that we have discussed, each process has its own isolated environment that does not include the other processes. The interactions among processes are indirect. In both cases, there is a sharing. In the case of competition, they are sharing resources without being aware of the other processes. In the second case, they are sharing values, and although each process is not explicitly aware of the other processes, it is aware of the need to maintain data integrity. When processes cooperate by communication, however, the various processes participate in a common effort that links all of the processes. The communication provides a way to synchronize, or coordinate, the various activities.

Typically, communication can be characterized as consisting of messages of some sort. Primitives for sending and receiving messages may be provided as part of the programming language or provided by the OS kernel.

Because nothing is shared between processes in the act of passing messages, mutual exclusion is not a control requirement for this sort of cooperation. However, the problems of deadlock and starvation are still present. As an example of deadlock, two processes may be blocked, each waiting for a communication from the other. As an example of starvation, consider three processes, P1, P2, and P3, that exhibit the following behavior. P1 is repeatedly attempting to communicate with either P2 or P3, and P2 and P3 are both attempting to communicate with P1. A sequence could arise in which P1 and P2 exchange information repeatedly, while P3 is blocked waiting for a communication from P1. There is no deadlock, because P1 remains active, but P3 is starved.

Requirements for Mutual Exclusion

Any facility or capability that is to provide support for mutual exclusion should meet the following requirements:

1. Mutual exclusion must be enforced: Only one process at a time is allowed into its critical section, among all processes that have critical sections for the same resource or shared object.
2. A process that halts in its noncritical section must do so without interfering with other processes.
3. It must not be possible for a process requiring access to a critical section to be delayed indefinitely: no deadlock or starvation.
4. When no process is in a critical section, any process that requests entry to its critical section must be permitted to enter without delay.
5. No assumptions are made about relative process speeds or number of processors.
6. A process remains inside its critical section for a finite time only.

There are a number of ways in which the requirements for mutual exclusion can be satisfied. One approach is to leave the responsibility with the processes that wish to execute concurrently. Processes, whether they are system programs or application programs, would be required to coordinate with one another to enforce mutual exclusion, with no support from the programming language or the OS. We can refer to these as software approaches. Although this approach is prone to high processing overhead and bugs, it is nevertheless useful to examine such approaches to gain a better understanding of the complexity of concurrent processing. This topic is covered in Appendix A. A second approach involves the use of special-purpose machine instructions. These have the advantage of reducing overhead but nevertheless will be shown to be unattractive as a general-purpose solution; they are covered in Section 5.2. A third approach is to provide some level of support within the OS or a programming language. Three of the most important such approaches are examined in Sections 5.3 through 5.5.

5.2 MUTUAL EXCLUSION: HARDWARE SUPPORT

In this section, we look at several interesting hardware approaches to mutual exclusion.

When two trains approach each other at a crossing, both shall come to a full stop and neither shall start up again until the other has gone.

STATUTE PASSED BY THE KANSAS STATE LEGISLATURE, EARLY IN THE 20TH CENTURY
—A TREASURY OF RAILROAD FOLKLORE,
B. A. BOTKIN AND ALVIN F. HARLOW

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- List and explain the conditions for deadlock.
- Define deadlock prevention and describe deadlock prevention strategies related to each of the conditions for deadlock.
- Explain the difference between deadlock prevention and deadlock avoidance.
- Understand two approaches to deadlock avoidance.
- Explain the fundamental difference in approach between deadlock detection and deadlock prevention or avoidance.
- Understand how an integrated deadlock strategy can be designed.
- Analyze the dining philosophers problem.
- Explain the concurrency and synchronization methods used in UNIX, Linux, Solaris, and Windows 7.

This chapter examines two problems that plague all efforts to support concurrent processing: deadlock and starvation. We begin with a discussion of the underlying principles of deadlock and the related problem of starvation. Then we examine the three common approaches to dealing with deadlock: prevention, detection, and avoidance. We then look at one of the classic problems used to illustrate both synchronization and deadlock issues: the dining philosophers problem.

As with Chapter 5, the discussion in this chapter is limited to a consideration of concurrency and deadlock on a single system. Measures to deal with distributed deadlock problems are assessed in Chapter 18. An animation illustrating deadlock is available online. Click on the rotating globe at WilliamStallings.com/OS/OS7e.html for access.

6.1 PRINCIPLES OF DEADLOCK

Deadlock can be defined as the *permanent* blocking of a set of processes that either compete for system resources or communicate with each other. A set of processes is deadlocked when each process in the set is blocked awaiting an event (typically the freeing up of some requested resource) that can only be triggered by another blocked process in the set. Deadlock is permanent because none of the events is ever triggered. Unlike other problems in concurrent process management, there is no efficient solution in the general case.

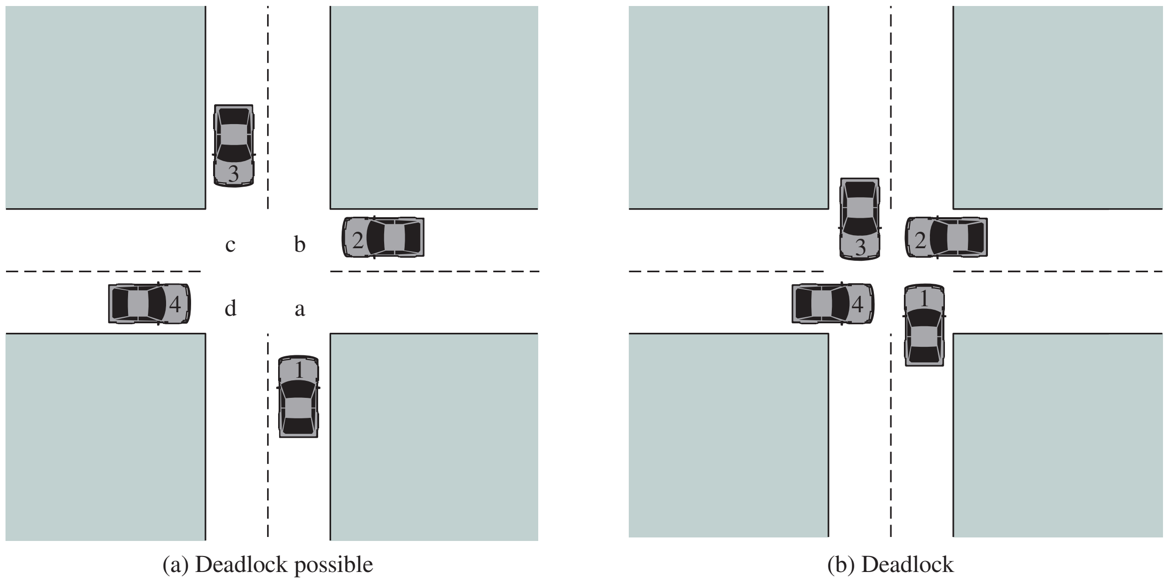

Figure 6.1 Illustration of Deadlock

All deadlocks involve conflicting needs for resources by two or more processes. A common example is the traffic deadlock. Figure 6.1a shows a situation in which four cars have arrived at a four-way stop intersection at approximately the same time. The four quadrants of the intersection are the resources over which control is needed. In particular, if all four cars wish to go straight through the intersection, the resource requirements are as follows:

- Car 1, traveling north, needs quadrants a and b.
- Car 2 needs quadrants b and c.
- Car 3 needs quadrants c and d.
- Car 4 needs quadrants d and a.

The rule of the road in the United States is that a car at a four-way stop should defer to a car immediately to its right. This rule works if there are only two or three cars at the intersection. For example, if only the northbound and westbound cars arrive at the intersection, the northbound car will wait and the westbound car proceeds. However, if all four cars arrive at about the same time and all four follow the rule, each will refrain from entering the intersection. This causes a potential deadlock. It is only a potential deadlock, because the necessary resources are available for any of the cars to proceed. If one car eventually chooses to proceed, it can do so.

However, if all four cars ignore the rules and proceed (cautiously) into the intersection at the same time, then each car seizes one resource (one quadrant) but cannot proceed because the required second resource has already been seized by another car. This is an actual deadlock.

Let us now look at a depiction of deadlock involving processes and computer resources. Figure 6.2 (based on one in [BACO03]), which we refer to as a **joint progress diagram**, illustrates the progress of two processes competing for two

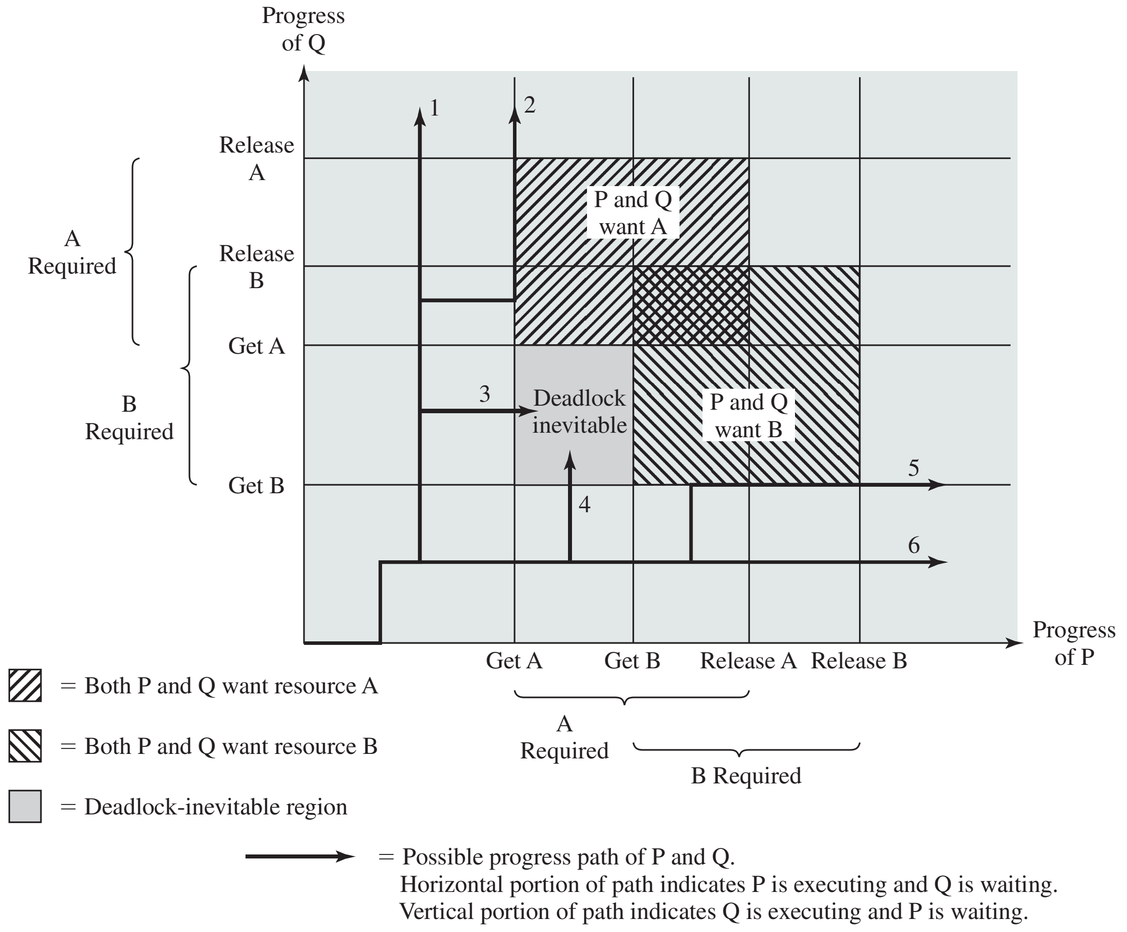
Progress of Q
Release A
Release B
Get A
Get B
A Required
B Required
1
2
3
4
5
6
P and Q want A
Deadlock inevitable
P and Q want B
Get A
Get B
Release A
Release B
Progress of P
A Required
B Required
= Both P and Q want resource A
= Both P and Q want resource B
= Deadlock-inevitable region
= Possible progress path of P and Q.
Horizontal portion of path indicates P is executing and Q is waiting.
Vertical portion of path indicates Q is executing and P is waiting.

Figure 6.2 **Example of Deadlock**

resources. Each process needs exclusive use of both resources for a certain period of time. Two processes, P and Q, have the following general form:

Process P	**Process Q**
• • •	• • •
Get A	Get B
• • •	• • •
Get B	Get A
• • •	• • •
Release A	Release B
• • •	• • •
Release B	Release A
• • •	• • •

In Figure 6.2, the *x*-axis represents progress in the execution of P and the *y*-axis represents progress in the execution of Q. The joint progress of the two processes is therefore represented by a path that progresses from the origin in a northeasterly direction. For a uniprocessor system, only one process at a time may execute, and the path consists of alternating horizontal and vertical segments, with a horizontal segment representing a period when P executes and Q waits and a vertical segment representing a period when Q executes and P waits. The figure indicates areas in which both P and Q require resource A (upward slanted lines); both P and Q require resource B (downward slanted lines); and both P and Q require both resources. Because we assume that each process requires exclusive control of any resource, these are all forbidden regions; that is, it is impossible for any path representing the joint execution progress of P and Q to enter these regions.

The figure shows six different execution paths. These can be summarized as follows:

1. Q acquires B and then A and then releases B and A. When P resumes execution, it will be able to acquire both resources.
2. Q acquires B and then A. P executes and blocks on a request for A. Q releases B and A. When P resumes execution, it will be able to acquire both resources.
3. Q acquires B and then P acquires A. Deadlock is inevitable, because as execution proceeds, Q will block on A and P will block on B.
4. P acquires A and then Q acquires B. Deadlock is inevitable, because as execution proceeds, Q will block on A and P will block on B.
5. P acquires A and then B. Q executes and blocks on a request for B. P releases A and B. When Q resumes execution, it will be able to acquire both resources.
6. P acquires A and then B and then releases A and B. When Q resumes execution, it will be able to acquire both resources.

The gray-shaded area of Figure 6.2, which can be referred to as a **fatal region**, applies to the commentary on paths 3 and 4. If an execution path enters this fatal region, then deadlock is inevitable. Note that the existence of a fatal region depends on the logic of the two processes. However, deadlock is only inevitable if the joint progress of the two processes creates a path that enters the fatal region.

Whether or not deadlock occurs depends on both the dynamics of the execution and on the details of the application. For example, suppose that P does not need both resources at the same time so that the two processes have the following form:

Process P	**Process Q**
• • •	• • •
Get A	Get B
• • •	• • •
Release A	Get A
• • •	• • •
Get B	Release B
• • •	• • •
Release B	Release A
• • •	• • •

This situation is reflected in Figure 6.3. Some thought should convince you that regardless of the relative timing of the two processes, deadlock cannot occur.

As shown, the joint progress diagram can be used to record the execution history of two processes that share resources. In cases where more than two processes

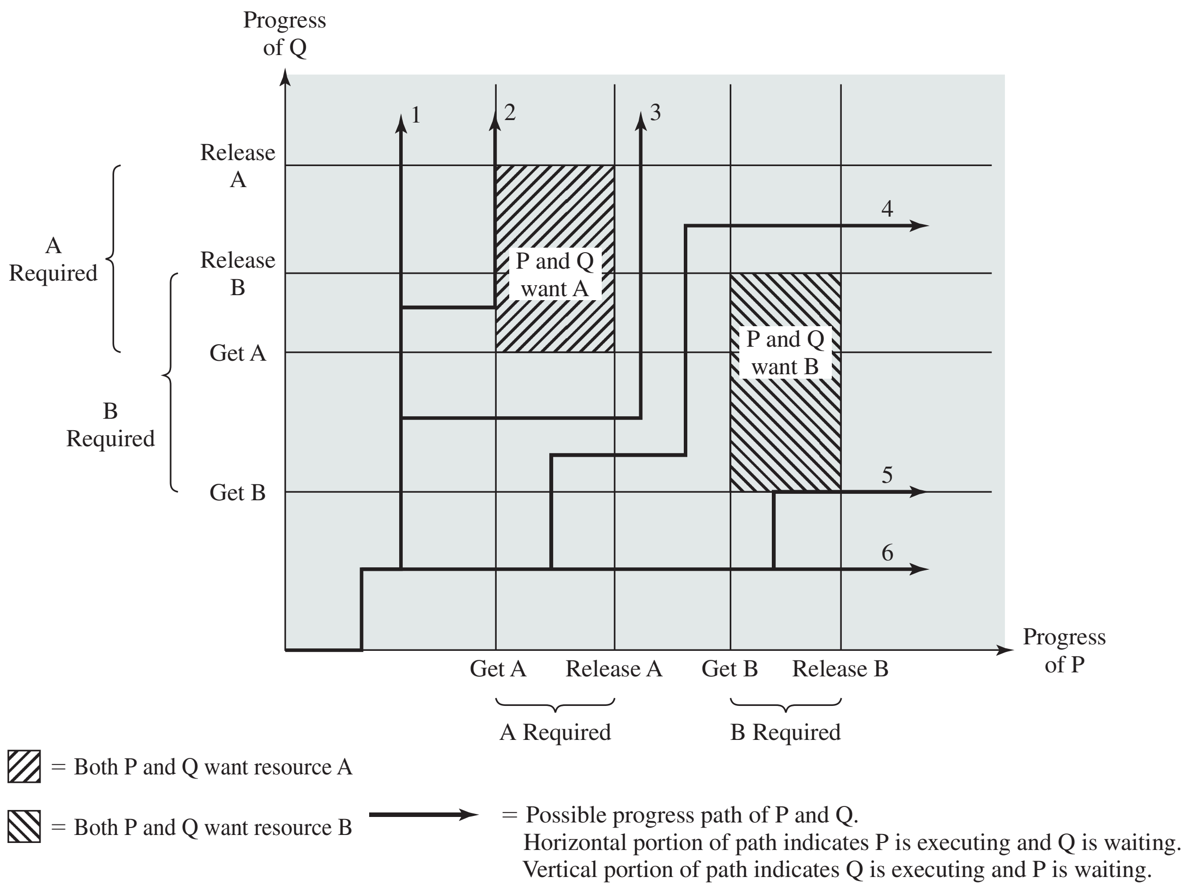
Progress of Q
Release A
Release B
Get A
Get B
A Required
B Required
1
2
3
4
5
6
P and Q want A
P and Q want B
Progress of P
Get A
Release A
Get B
Release B
A Required
B Required
= Both P and Q want resource A
= Both P and Q want resource B
= Possible progress path of P and Q.
Horizontal portion of path indicates P is executing and Q is waiting.
Vertical portion of path indicates Q is executing and P is waiting.

Figure 6.3 Example of No Deadlock [BACO03]

may compete for the same resource, a higher-dimensional diagram would be required. The principles concerning fatal regions and deadlock would remain the same.

Reusable Resources

Two general categories of resources can be distinguished: reusable and consumable. A reusable resource is one that can be safely used by only one process at a time and is not depleted by that use. Processes obtain resource units that they later release for reuse by other processes. Examples of reusable resources include processors; I/O channels; main and secondary memory; devices; and data structures such as files, databases, and semaphores.

As an example of deadlock involving reusable resources, consider two processes that compete for exclusive access to a disk file D and a tape drive T. The programs engage in the operations depicted in Figure 6.4. Deadlock occurs if each process holds one resource and requests the other. For example, deadlock occurs if the multiprogramming system interleaves the execution of the two processes as follows:

$$p_0\ p_1\ q_0\ q_1\ p_2\ q_2$$

Step	Process P Action	Step	Process Q Action
p_0	Request (D)	q_0	Request (T)
p_1	Lock (D)	q_1	Lock (T)
p_2	Request (T)	q_2	Request (D)
p_3	Lock (T)	q_3	Lock (D)
p_4	Perform function	q_4	Perform function
p_5	Unlock (D)	q_5	Unlock (T)
p_6	Unlock (T)	q_6	Unlock (D)

Figure 6.4 Example of Two Processes Competing for Reusable Resources

It may appear that this is a programming error rather than a problem for the OS designer. However, we have seen that concurrent program design is challenging. Such deadlocks do occur, and the cause is often embedded in complex program logic, making detection difficult. One strategy for dealing with such a deadlock is to impose system design constraints concerning the order in which resources can be requested.

Another example of deadlock with a reusable resource has to do with requests for main memory. Suppose the space available for allocation is 200 Kbytes, and the following sequence of requests occurs:

P1	**P2**
…	…
Request 80 Kbytes;	Request 70 Kbytes;
…	…
Request 60 Kbytes;	Request 80 Kbytes;

Deadlock occurs if both processes progress to their second request. If the amount of memory to be requested is not known ahead of time, it is difficult to deal with this type of deadlock by means of system design constraints. The best way to deal with this particular problem is, in effect, to eliminate the possibility by using virtual memory, which is discussed in Chapter 8.

Consumable Resources

A consumable resource is one that can be created (produced) and destroyed (consumed). Typically, there is no limit on the number of consumable resources of a particular type. An unblocked producing process may create any number of such resources. When a resource is acquired by a consuming process, the resource ceases to exist. Examples of consumable resources are interrupts, signals, messages, and information in I/O buffers.

As an example of deadlock involving consumable resources, consider the following pair of processes, in which each process attempts to receive a message from the other process and then send a message to the other process:

```
        P1                              P2
…                               …
Receive (P2);                   Receive (P1);
…                               …
Send (P2, M1);                  Send (P1, M2);
```

Deadlock occurs if the Receive is blocking (i.e., the receiving process is blocked until the message is received). Once again, a design error is the cause of the deadlock. Such errors may be quite subtle and difficult to detect. Furthermore, it may take a rare combination of events to cause the deadlock; thus a program

Table 6.1 Summary of Deadlock Detection, Prevention, and Avoidance Approaches for Operating Systems [ISLO80]

Approach	Resource Allocation Policy	Different Schemes	Major Advantages	Major Disadvantages
Prevention	Conservative; undercommits resources	Requesting all resources at once	• Works well for processes that perform a single burst of activity • No preemption necessary	• Inefficient • Delays process initiation • Future resource requirements must be known by processes
		Preemption	• Convenient when applied to resources whose state can be saved and restored easily	• Preempts more often than necessary
		Resource ordering	• Feasible to enforce via compile-time checks • Needs no run-time computation since problem is solved in system design	• Disallows incremental resource requests
Avoidance	Midway between that of detection and prevention	Manipulate to find at least one safe path	• No preemption necessary	• Future resource requirements must be known by OS • Processes can be blocked for long periods
Detection	Very liberal; requested resources are granted where possible	Invoke periodically to test for deadlock	• Never delays process initiation • Facilitates online handling	• Inherent preemption losses

could be in use for a considerable period of time, even years, before the deadlock actually occurs.

There is no single effective strategy that can deal with all types of deadlock. Table 6.1 summarizes the key elements of the most important approaches that have been developed: prevention, avoidance, and detection. We examine each of these in turn, after first introducing resource allocation graphs and then discussing the conditions for deadlock.

Resource Allocation Graphs

A useful tool in characterizing the allocation of resources to processes is the **resource allocation graph**, introduced by Holt [HOLT72]. The resource allocation graph is a directed graph that depicts a state of the system of resources and processes, with each process and each resource represented by a node. A graph edge directed from a process to a resource indicates a resource that has been requested by the process but not yet granted (Figure 6.5a). Within a resource node, a dot is shown for each instance of that resource. Examples of resource types that may have multiple instances are I/O devices that are allocated by a resource management module in the OS. A graph edge directed from a reusable resource node dot to a process indicates a request that has been granted (Figure 6.5b); that is, the process

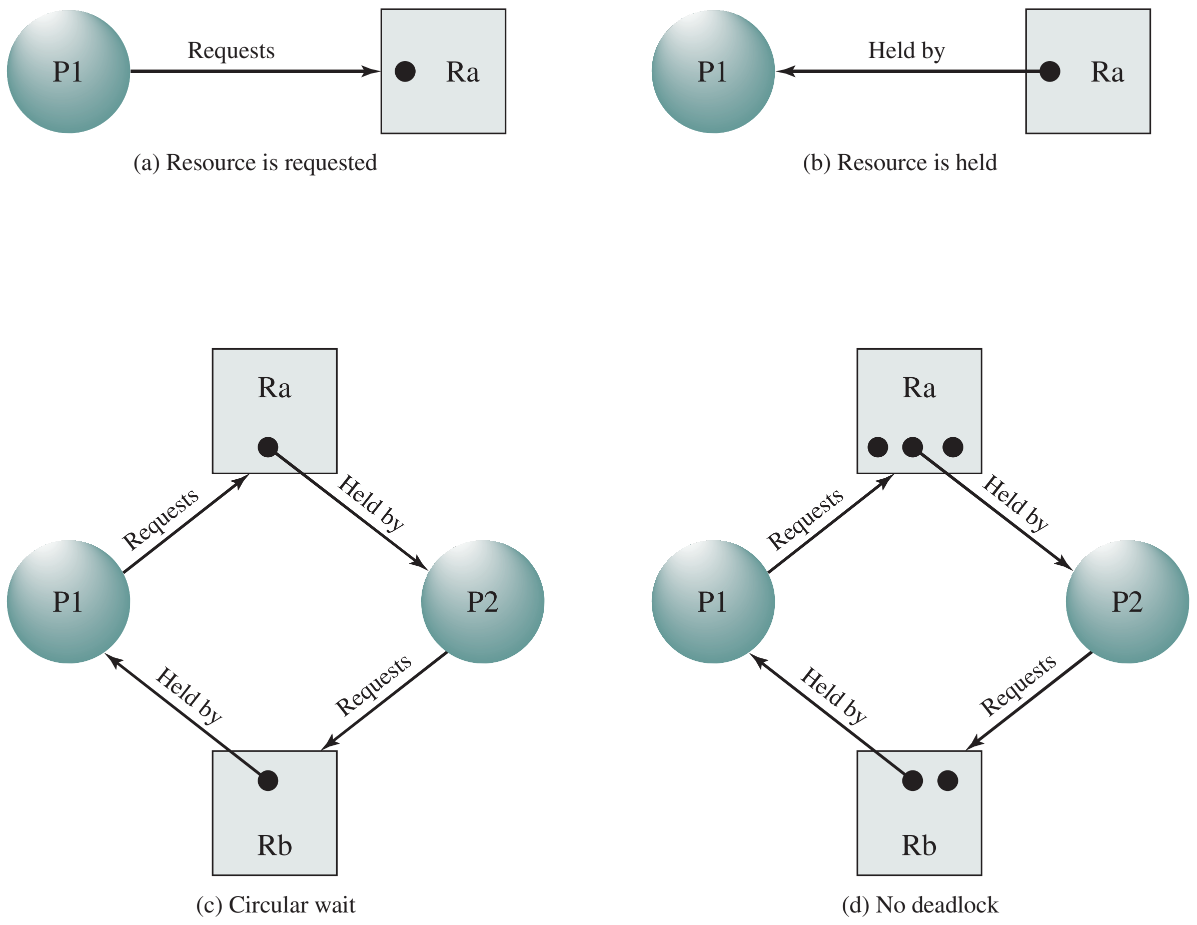

Figure 6.5 Examples of Resource Allocation Graphs

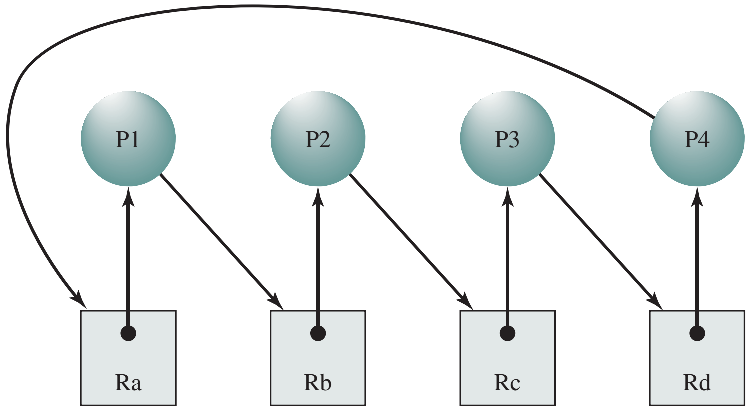

Figure 6.6 Resource Allocation Graph for Figure 6.1b

has been assigned one unit of that resource. A graph edge directed from a consumable resource node dot to a process indicates that the process is the producer of that resource.

Figure 6.5c shows an example deadlock. There is only one unit each of resources Ra and Rb. Process P1 holds Rb and requests Ra, while P2 holds Ra but requests Rb. Figure 6.5d has the same topology as Figure 6.5c, but there is no deadlock because multiple units of each resource are available.

The resource allocation graph of Figure 6.6 corresponds to the deadlock situation in Figure 6.1b. Note that in this case, we do not have a simple situation in which two processes each have one resource the other needs. Rather, in this case, there is a circular chain of processes and resources that results in deadlock.

The Conditions for Deadlock

Three conditions of policy must be present for a deadlock to be possible:

1. **Mutual exclusion.** Only one process may use a resource at a time. No process may access a resource unit that has been allocated to another process.
2. **Hold and wait.** A process may hold allocated resources while awaiting assignment of other resources.
3. **No preemption.** No resource can be forcibly removed from a process holding it.

In many ways these conditions are quite desirable. For example, mutual exclusion is needed to ensure consistency of results and the integrity of a database. Similarly, preemption should not be done arbitrarily. For example, when data resources are involved, preemption must be supported by a rollback recovery mechanism, which restores a process and its resources to a suitable previous state from which the process can eventually repeat its actions.

The first three conditions are necessary but not sufficient for a deadlock to exist. For deadlock to actually take place, a fourth condition is required:

4. **Circular wait.** A closed chain of processes exists, such that each process holds at least one resource needed by the next process in the chain (e.g., Figure 6.5c and Figure 6.6).

The fourth condition is, actually, a potential consequence of the first three. That is, given that the first three conditions exist, a sequence of events may occur that lead to an unresolvable circular wait. The unresolvable circular wait is in fact the definition of deadlock. The circular wait listed as condition 4 is unresolvable because the first three conditions hold. Thus, the four conditions, taken together, constitute necessary and sufficient conditions for deadlock.[1]

To clarify this discussion, it is useful to return to the concept of the joint progress diagram, such as the one shown in Figure 6.2. Recall that we defined a fatal region as one such that once the processes have progressed into that region, those processes will deadlock. A fatal region exists only if all of the first three conditions listed above are met. If one or more of these conditions are not met, there is no fatal region and deadlock cannot occur. Thus, these are necessary conditions for deadlock. For deadlock to occur, there must not only be a fatal region, but also a sequence of resource requests that has led into the fatal region. If a circular wait condition occurs, then in fact the fatal region has been entered. Thus, all four conditions listed above are sufficient for deadlock. To summarize,

Possibility of Deadlock	**Existence of Deadlock**
1. Mutual exclusion	**1.** Mutual exclusion
2. No preemption	**2.** No preemption
3. Hold and wait	**3.** Hold and wait
	4. Circular wait

Three general approaches exist for dealing with deadlock. First, one can **prevent** deadlock by adopting a policy that eliminates one of the conditions (conditions 1 through 4). Second, one can **avoid** deadlock by making the appropriate dynamic choices based on the current state of resource allocation. Third, one can attempt to **detect** the presence of deadlock (conditions 1 through 4 hold) and take action to recover. We discuss each of these approaches in turn.

6.2 DEADLOCK PREVENTION

The strategy of deadlock prevention is, simply put, to design a system in such a way that the possibility of deadlock is excluded. We can view deadlock prevention methods as falling into two classes. An indirect method of deadlock prevention is to prevent the occurrence of one of the three necessary conditions listed previously (items 1 through 3). A direct method of deadlock prevention is to prevent the occurrence of a circular wait (item 4). We now examine techniques related to each of the four conditions.

[1]Virtually all textbooks simply list these four conditions as the conditions needed for deadlock, but such a presentation obscures some of the subtler issues. Item 4, the circular wait condition, is fundamentally different from the other three conditions. Items 1 through 3 are policy decisions, while item 4 is a circumstance that might occur depending on the sequencing of requests and releases by the involved processes. Linking circular wait with the three necessary conditions leads to inadequate distinction between prevention and avoidance. See [SHUB90] and [SHUB03] for a discussion.

Mutual Exclusion

In general, the first of the four listed conditions cannot be disallowed. If access to a resource requires mutual exclusion, then mutual exclusion must be supported by the OS. Some resources, such as files, may allow multiple accesses for reads but only exclusive access for writes. Even in this case, deadlock can occur if more than one process requires write permission.

Hold and Wait

The hold-and-wait condition can be prevented by requiring that a process request all of its required resources at one time and blocking the process until all requests can be granted simultaneously. This approach is inefficient in two ways. First, a process may be held up for a long time waiting for all of its resource requests to be filled, when in fact it could have proceeded with only some of the resources. Second, resources allocated to a process may remain unused for a considerable period, during which time they are denied to other processes. Another problem is that a process may not know in advance all of the resources that it will require.

There is also the practical problem created by the use of modular programming or a multithreaded structure for an application. An application would need to be aware of all resources that will be requested at all levels or in all modules to make the simultaneous request.

No Preemption

This condition can be prevented in several ways. First, if a process holding certain resources is denied a further request, that process must release its original resources and, if necessary, request them again together with the additional resource. Alternatively, if a process requests a resource that is currently held by another process, the OS may preempt the second process and require it to release its resources. This latter scheme would prevent deadlock only if no two processes possessed the same priority.

This approach is practical only when applied to resources whose state can be easily saved and restored later, as is the case with a processor.

Circular Wait

The circular-wait condition can be prevented by defining a linear ordering of resource types. If a process has been allocated resources of type R, then it may subsequently request only those resources of types following R in the ordering.

To see that this strategy works, let us associate an index with each resource type. Then resource R_i precedes R_j in the ordering if $i < j$. Now suppose that two processes, A and B, are deadlocked because A has acquired R_i and requested R_j, and B has acquired R_j and requested R_i. This condition is impossible because it implies $i < j$ and $j < i$.

As with hold-and-wait prevention, circular-wait prevention may be inefficient, slowing down processes and denying resource access unnecessarily.

6.3 DEADLOCK AVOIDANCE

An approach to solving the deadlock problem that differs subtly from deadlock prevention is deadlock avoidance.[2] In **deadlock prevention**, we constrain resource requests to prevent at least one of the four conditions of deadlock. This is either done indirectly, by preventing one of the three necessary policy conditions (mutual exclusion, hold and wait, no preemption), or directly, by preventing circular wait. This leads to inefficient use of resources and inefficient execution of processes. **Deadlock avoidance**, on the other hand, allows the three necessary conditions but makes judicious choices to assure that the deadlock point is never reached. As such, avoidance allows more concurrency than prevention. With deadlock avoidance, a decision is made dynamically whether the current resource allocation request will, if granted, potentially lead to a deadlock. Deadlock avoidance thus requires knowledge of future process resource requests.

In this section, we describe two approaches to deadlock avoidance:

- Do not start a process if its demands might lead to deadlock.
- Do not grant an incremental resource request to a process if this allocation might lead to deadlock.

Process Initiation Denial

Consider a system of n processes and m different types of resources. Let us define the following vectors and matrices:

Resource $= \mathbf{R} = (R_1, R_2, \ldots, R_m)$	Total amount of each resource in the system
Available $= \mathbf{V} = (V_1, V_2, \ldots, V_m)$	Total amount of each resource not allocated to any process
Claim $= \mathbf{C} = \begin{pmatrix} C_{11} & C_{12} & \ldots & C_{1m} \\ C_{21} & C_{22} & \ldots & C_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ C_{n1} & C_{n2} & \ldots & C_{nm} \end{pmatrix}$	C_{ij} = requirement of process i for resource j
Allocation $= \mathbf{A} = \begin{pmatrix} A_{11} & A_{12} & \ldots & A_{1m} \\ A_{21} & A_{22} & \ldots & A_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1} & A_{n2} & \ldots & A_{nm} \end{pmatrix}$	A_{ij} = current allocation to process i of resource j

The matrix Claim gives the maximum requirement of each process for each resource, with one row dedicated to each process. This information must be

[2]The term *avoidance* is a bit confusing. In fact, one could consider the strategies discussed in this section to be examples of deadlock prevention because they indeed prevent the occurrence of a deadlock.

declared in advance by a process for deadlock avoidance to work. Similarly, the matrix Allocation gives the current allocation to each process. The following relationships hold:

1. $R_j = V_j + \sum_{i=1}^{n} A_{ij}$, for all j	All resources are either available or allocated.
2. $C_{ij} \leq R_j$, for all i,j	No process can claim more than the total amount of resources in the system.
3. $A_{ij} \leq C_{ij}$, for all i,j	No process is allocated more resources of any type than the process originally claimed to need.

With these quantities defined, we can define a deadlock avoidance policy that refuses to start a new process if its resource requirements might lead to deadlock. Start a new process P_{n+1} only if

$$R_j \geq C_{(n+1)j} + \sum_{i=1}^{n} C_{ij} \quad \text{for all } j$$

That is, a process is only started if the maximum claim of all current processes plus those of the new process can be met. This strategy is hardly optimal, because it assumes the worst: that all processes will make their maximum claims together.

Resource Allocation Denial

The strategy of resource allocation denial, referred to as the **banker's algorithm**,[3] was first proposed in [DIJK65]. Let us begin by defining the concepts of state and safe state. Consider a system with a fixed number of processes and a fixed number of resources. At any time a process may have zero or more resources allocated to it. The **state** of the system reflects the current allocation of resources to processes. Thus, the state consists of the two vectors, Resource and Available, and the two matrices, Claim and Allocation, defined earlier. A **safe state** is one in which there is at least one sequence of resource allocations to processes that does not result in a deadlock (i.e., all of the processes can be run to completion). An **unsafe state** is, of course, a state that is not safe.

The following example illustrates these concepts. Figure 6.7a shows the state of a system consisting of four processes and three resources. The total amount of resources R1, R2, and R3 are 9, 3, and 6 units, respectively. In the current state allocations have been made to the four processes, leaving 1 unit of R2

[3]Dijkstra used this name because of the analogy of this problem to one in banking, with customers who wish to borrow money corresponding to processes and the money to be borrowed corresponding to resources. Stated as a banking problem, the bank has a limited reserve of money to lend and a list of customers, each with a line of credit. A customer may choose to borrow against the line of credit a portion at a time, and there is no guarantee that the customer will make any repayment until after having taken out the maximum amount of loan. The banker can refuse a loan to a customer if there is a risk that the bank will have insufficient funds to make further loans that will permit the customers to repay eventually.

	R1	R2	R3
P1	3	2	2
P2	6	1	3
P3	3	1	4
P4	4	2	2

Claim matrix C

	R1	R2	R3
P1	1	0	0
P2	6	1	2
P3	2	1	1
P4	0	0	2

Allocation matrix A

	R1	R2	R3
P1	2	2	2
P2	0	0	1
P3	1	0	3
P4	4	2	0

C – A

R1	R2	R3
9	3	6

Resource vector R

R1	R2	R3
0	1	1

Available vector V

(a) Initial state

	R1	R2	R3
P1	3	2	2
P2	0	0	0
P3	3	1	4
P4	4	2	2

Claim matrix C

	R1	R2	R3
P1	1	0	0
P2	0	0	0
P3	2	1	1
P4	0	0	2

Allocation matrix A

	R1	R2	R3
P1	2	2	2
P2	0	0	0
P3	1	0	3
P4	4	2	0

C – A

R1	R2	R3
9	3	6

Resource vector R

R1	R2	R3
6	2	3

Available vector V

(b) P2 runs to completion

	R1	R2	R3
P1	0	0	0
P2	0	0	0
P3	3	1	4
P4	4	2	2

Claim matrix C

	R1	R2	R3
P1	0	0	0
P2	0	0	0
P3	2	1	1
P4	0	0	2

Allocation matrix A

	R1	R2	R3
P1	0	0	0
P2	0	0	0
P3	1	0	3
P4	4	2	0

C – A

R1	R2	R3
9	3	6

Resource vector R

R1	R2	R3
7	2	3

Available vector V

(c) P1 runs to completion

	R1	R2	R3
P1	0	0	0
P2	0	0	0
P3	0	0	0
P4	4	2	2

Claim matrix C

	R1	R2	R3
P1	0	0	0
P2	0	0	0
P3	0	0	0
P4	0	0	2

Allocation matrix A

	R1	R2	R3
P1	0	0	0
P2	0	0	0
P3	0	0	0
P4	4	2	0

C – A

R1	R2	R3
9	3	6

Resource vector R

R1	R2	R3
9	3	4

Available vector V

(d) P3 runs to completion

Figure 6.7 Determination of a Safe State

and 1 unit of R3 available. Is this a safe state? To answer this question, we ask an intermediate question: Can any of the four processes be run to completion with the resources available? That is, can the difference between the maximum requirement and current allocation for any process be met with the available resources? In terms of the matrices and vectors introduced earlier, the condition to be met for process *i* is:

$$C_{ij} - A_{ij} \leq V_j, \quad \text{for all } j$$

Clearly, this is not possible for P1, which has only 1 unit of R1 and requires 2 more units of R1, 2 units of R2, and 2 units of R3. However, by assigning one unit of R3 to process P2, P2 has its maximum required resources allocated and can run to completion. Let us assume that this is accomplished. When P2 completes, its resources can be returned to the pool of available resources. The resulting state is shown in Figure 6.7b. Now we can ask again if any of the remaining processes can be completed. In this case, each of the remaining processes could be completed. Suppose we choose P1, allocate the required resources, complete P1, and return all of P1's resources to the available pool. We are left in the state shown in Figure 6.7c. Next, we can complete P3, resulting in the state of Figure 6.7d. Finally, we can complete P4. At this point, all of the processes have been run to completion. Thus, the state defined by Figure 6.7a is a safe state.

These concepts suggest the following deadlock avoidance strategy, which ensures that the system of processes and resources is always in a safe state. When a process makes a request for a set of resources, assume that the request is granted, update the system state accordingly, and then determine if the result is a safe state. If so, grant the request and, if not, block the process until it is safe to grant the request.

Consider the state defined in Figure 6.8a. Suppose P2 makes a request for one additional unit of R1 and one additional unit of R3. If we assume the request is granted, then the resulting state is that of Figure 6.7a. We have already seen that this is a safe state; therefore, it is safe to grant the request. Now let us return to the state of Figure 6.8a and suppose that P1 makes the request for one additional unit each of R1 and R3; if we assume that the request is granted, we are left in the state of Figure 6.8b. Is this a safe state? The answer is no, because each process will need at least one additional unit of R1, and there are none available. Thus, on the basis of deadlock avoidance, the request by P1 should be denied and P1 should be blocked.

It is important to point out that Figure 6.8b is not a deadlocked state. It merely has the potential for deadlock. It is possible, for example, that if P1 were run from this state it would subsequently release one unit of R1 and one unit of R3 prior to needing these resources again. If that happened, the system would return to a safe state. Thus, the deadlock avoidance strategy does not predict deadlock with certainty; it merely anticipates the possibility of deadlock and assures that there is never such a possibility.

	R1	R2	R3
P1	3	2	2
P2	6	1	3
P3	3	1	4
P4	4	2	2

Claim matrix C

	R1	R2	R3
P1	1	0	0
P2	5	1	1
P3	2	1	1
P4	0	0	2

Allocation matrix A

	R1	R2	R3
P1	2	2	2
P2	1	0	2
P3	1	0	3
P4	4	2	0

C – A

R1	R2	R3
9	3	6

Resource vector R

R1	R2	R3
1	1	2

Available vector V

(a) Initial state

	R1	R2	R3
P1	3	2	2
P2	6	1	3
P3	3	1	4
P4	4	2	2

Claim matrix C

	R1	R2	R3
P1	2	0	1
P2	5	1	1
P3	2	1	1
P4	0	0	2

Allocation matrix A

	R1	R2	R3
P1	1	2	1
P2	1	0	2
P3	1	0	3
P4	4	2	0

C – A

R1	R2	R3
9	3	6

Resource vector R

R1	R2	R3
0	1	1

Available vector V

(b) P1 requests one unit each of R1 and R3

Figure 6.8 Determination of an Unsafe State

Figure 6.9 gives an abstract version of the deadlock avoidance logic. The main algorithm is shown in part (b). With the state of the system defined by the data structure `state`, `request[*]` is a vector defining the resources requested by process *i*. First, a check is made to assure that the request does not exceed the original claim of the process. If the request is valid, the next step is to determine if it is possible to fulfill the request (i.e., there are sufficient resources available). If it is not possible, then the process is suspended. If it is possible, the final step is to determine if it is safe to fulfill the request. To do this, the resources are tentatively assigned to process *i* to form `newstate`. Then a test for safety is made using the algorithm in Figure 6.9c.

Deadlock avoidance has the advantage that it is not necessary to preempt and rollback processes, as in deadlock detection, and is less restrictive than deadlock prevention. However, it does have a number of restrictions on its use:

- The maximum resource requirement for each process must be stated in advance.
- The processes under consideration must be independent; that is, the order in which they execute must be unconstrained by any synchronization requirements.
- There must be a fixed number of resources to allocate.
- No process may exit while holding resources.

```
struct state {
       int resource[m];
       int available[m];
       int claim[n][m];
       int alloc[n][m];
}
```

(a) Global data structures

```
if (alloc [i,*] + request [*] > claim [i,*])
     <error>;                        /* total request > claim*/
else if (request [*] > available [*])
     <suspend process>;
else  {                                    /* simulate alloc */
     <define newstate by:
     alloc [i,*] = alloc [i,*] + request [*];
     available [*] = available [*] - request [*]>;
}
if (safe (newstate))
     <carry out allocation>;
else {
     <restore original state>;
     <suspend process>;
}
```

(b) Resource alloc algorithm

```
boolean safe (state S) {
    int currentavail[m];
    process rest[<number of processes>];
    currentavail = available;
    rest = {all processes};
    possible = true;
    while (possible) {
        <find a process Pk in rest such that
           claim [k,*] - alloc [k,*]<= currentavail;
        if (found) {              /* simulate execution of Pk */
           currentavail = currentavail + alloc [k,*];
           rest = rest - {Pk};
        }
        else possible = false;
    }
    return (rest == null);
}
```

(c) Test for safety algorithm (banker's algorithm)

Figure 6.9 Deadlock Avoidance Logic

6.4 DEADLOCK DETECTION

Deadlock prevention strategies are very conservative; they solve the problem of deadlock by limiting access to resources and by imposing restrictions on processes. At the opposite extreme, deadlock detection strategies do not limit resource access or restrict process actions. With deadlock detection, requested resources are granted to processes whenever possible. Periodically, the OS performs an algorithm that allows it to detect the circular wait condition described earlier in condition (4) and illustrated in Figure 6.6.

Deadlock Detection Algorithm

A check for deadlock can be made as frequently as each resource request or, less frequently, depending on how likely it is for a deadlock to occur. Checking at each resource request has two advantages: It leads to early detection, and the algorithm is relatively simple because it is based on incremental changes to the state of the system. On the other hand, such frequent checks consume considerable processor time.

A common algorithm for deadlock detection is one described in [COFF71]. The Allocation matrix and Available vector described in the previous section are used. In addition, a request matrix **Q** is defined such that *Qij* represents the amount of resources of type *j* requested by process *i*. The algorithm proceeds by marking processes that are not deadlocked. Initially, all processes are unmarked. Then the following steps are performed:

1. Mark each process that has a row in the Allocation matrix of all zeros.
2. Initialize a temporary vector **W** to equal the Available vector.
3. Find an index *i* such that process *i* is currently unmarked and the *i*th row of **Q** is less than or equal to **W**. That is, $Q_{ik} \leq W_k$, for $1 \leq k \leq m$. If no such row is found, terminate the algorithm.
4. If such a row is found, mark process *i* and add the corresponding row of the allocation matrix to **W**. That is, set $W_k = W_k + A_{ik}$, for $1 \leq k \leq m$. Return to step 3.

A deadlock exists if and only if there are unmarked processes at the end of the algorithm. Each unmarked process is deadlocked. The strategy in this algorithm is to find a process whose resource requests can be satisfied with the available resources, and then assume that those resources are granted and that the process runs to completion and releases all of its resources. The algorithm then looks for another process to satisfy. Note that this algorithm does not guarantee to prevent deadlock; that will depend on the order in which future requests are granted. All that it does is determine if deadlock currently exists.

We can use Figure 6.10 to illustrate the deadlock detection algorithm. The algorithm proceeds as follows:

1. Mark P4, because P4 has no allocated resources.
2. Set **W** = (0 0 0 0 1).

	R1	R2	R3	R4	R5
P1	0	1	0	0	1
P2	0	0	1	0	1
P3	0	0	0	0	1
P4	1	0	1	0	1

Request matrix Q

	R1	R2	R3	R4	R5
P1	1	0	1	1	0
P2	1	1	0	0	0
P3	0	0	0	1	0
P4	0	0	0	0	0

Allocation matrix A

R1	R2	R3	R4	R5
2	1	1	2	1

Resource vector

R1	R2	R3	R4	R5
0	0	0	0	1

Available vector

Figure 6.10 Example for Deadlock Detection

3. The request of process P3 is less than or equal to **W**, so mark P3 and set

$$\mathbf{W} = \mathbf{W} + (0\ 0\ 0\ 1\ 0) = (0\ 0\ 0\ 1\ 1).$$

4. No other unmarked process has a row in **Q** that is less than or equal to **W**. Therefore, terminate the algorithm.

The algorithm concludes with P1 and P2 unmarked, indicating that these processes are deadlocked.

Recovery

Once deadlock has been detected, some strategy is needed for recovery. The following are possible approaches, listed in order of increasing sophistication:

1. Abort all deadlocked processes. This is, believe it or not, one of the most common, if not the most common, solution adopted in operating systems.
2. Back up each deadlocked process to some previously defined checkpoint, and restart all processes. This requires that rollback and restart mechanisms be built in to the system. The risk in this approach is that the original deadlock may recur. However, the nondeterminancy of concurrent processing may ensure that this does not happen.
3. Successively abort deadlocked processes until deadlock no longer exists. The order in which processes are selected for abortion should be on the basis of some criterion of minimum cost. After each abortion, the detection algorithm must be reinvoked to see whether deadlock still exists.
4. Successively preempt resources until deadlock no longer exists. As in (3), a cost-based selection should be used, and reinvocation of the detection algorithm is required after each preemption. A process that has a resource preempted from it must be rolled back to a point prior to its acquisition of that resource.

For (3) and (4), the selection criteria could be one of the following. Choose the process with the

- least amount of processor time consumed so far
- least amount of output produced so far
- most estimated time remaining

- least total resources allocated so far
- lowest priority

Some of these quantities are easier to measure than others. Estimated time remaining is particularly suspect. Also, other than by means of the priority measure, there is no indication of the "cost" to the user, as opposed to the cost to the system as a whole.

6.5 AN INTEGRATED DEADLOCK STRATEGY

As Table 6.1 suggests, there are strengths and weaknesses to all of the strategies for dealing with deadlock. Rather than attempting to design an OS facility that employs only one of these strategies, it might be more efficient to use different strategies in different situations. [HOWA73] suggests one approach:

- Group resources into a number of different resource classes.
- Use the linear ordering strategy defined previously for the prevention of circular wait to prevent deadlocks between resource classes.
- Within a resource class, use the algorithm that is most appropriate for that class.

As an example of this technique, consider the following classes of resources:

- **Swappable space:** Blocks of memory on secondary storage for use in swapping processes
- **Process resources:** Assignable devices, such as tape drives, and files
- **Main memory:** Assignable to processes in pages or segments
- **Internal resources:** Such as I/O channels

The order of the preceding list represents the order in which resources are assigned. The order is a reasonable one, considering the sequence of steps that a process may follow during its lifetime. Within each class, the following strategies could be used:

- **Swappable space:** Prevention of deadlocks by requiring that all of the required resources that may be used be allocated at one time, as in the hold-and-wait prevention strategy. This strategy is reasonable if the maximum storage requirements are known, which is often the case. Deadlock avoidance is also a possibility.
- **Process resources:** Avoidance will often be effective in this category, because it is reasonable to expect processes to declare ahead of time the resources that they will require in this class. Prevention by means of resource ordering within this class is also possible.
- **Main memory:** Prevention by preemption appears to be the most appropriate strategy for main memory. When a process is preempted, it is simply swapped to secondary memory, freeing space to resolve the deadlock.
- **Internal resources:** Prevention by means of resource ordering can be used.

UNIT - 4
MEMORY MANAGEMENT, VIRTUAL MEMORY

I cannot guarantee that I carry all the facts in my mind. Intense mental concentration has a curious way of blotting out what has passed. Each of my cases displaces the last, and Mlle. Carère has blurred my recollection of Baskerville Hall. Tomorrow some other little problem may be submitted to my notice which will in turn dispossess the fair French lady and the infamous Upwood.

—*The Hound of the Baskervilles*,
Arthur Conan Doyle.

Learning Objectives

After studying this chapter, you should be able to:

- Discuss the principal requirements for memory management.
- Understand the reason for memory partitioning and explain the various techniques that are used.
- Understand and explain the concept of paging.
- Understand and explain the concept of segmentation.
- Assess the relative advantages of paging and segmentation.
- Summarize key security issues related to memory management.
- Describe the concepts of loading and linking.

In a uniprogramming system, main memory is divided into two parts: one part for the operating system (resident monitor, kernel) and one part for the program currently being executed. In a multiprogramming system, the "user" part of memory must be further subdivided to accommodate multiple processes. The task of subdivision is carried out dynamically by the operating system and is known as **memory management**.

Effective memory management is vital in a multiprogramming system. If only a few processes are in memory, then for much of the time all of the processes will be waiting for I/O and the processor will be idle. Thus memory needs to be allocated to ensure a reasonable supply of ready processes to consume available processor time.

We begin with the requirements that memory management is intended to satisfy. Next, we discuss a variety of simple schemes that have been used for memory management

Table 7.1 introduces some key terms for our discussion. A set of animations that illustrate concepts in this chapter is available online. Click on the rotating globe at WilliamStallings.com/OS/OS7e.html for access.

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Table 7.1 Memory Management Terms

Frame	A fixed-length block of main memory.
Page	A fixed-length block of data that resides in secondary memory (such as disk). A page of data may temporarily be copied into a frame of main memory.
Segment	A variable-length block of data that resides in secondary memory. An entire segment may temporarily be copied into an available region of main memory (segmentation) or the segment may be divided into pages which can be individually copied into main memory (combined segmentation and paging).

7.1 MEMORY MANAGEMENT REQUIREMENTS

While surveying the various mechanisms and policies associated with memory management, it is helpful to keep in mind the requirements that memory management is intended to satisfy. These requirements include the following:

- Relocation
- Protection
- Sharing
- Logical organization
- Physical organization

Relocation

In a multiprogramming system, the available main memory is generally shared among a number of processes. Typically, it is not possible for the programmer to know in advance which other programs will be resident in main memory at the time of execution of his or her program. In addition, we would like to be able to swap active processes in and out of main memory to maximize processor utilization by providing a large pool of ready processes to execute. Once a program is swapped out to disk, it would be quite limiting to specify that when it is next swapped back in, it must be placed in the same main memory region as before. Instead, we may need to **relocate** the process to a different area of memory.

Thus, we cannot know ahead of time where a program will be placed, and we must allow for the possibility that the program may be moved about in main memory due to swapping. These facts raise some technical concerns related to addressing, as illustrated in Figure 7.1. The figure depicts a process image. For simplicity, let us assume that the process image occupies a contiguous region of main memory. Clearly, the operating system will need to know the location of process control information and of the execution stack, as well as the entry point to begin execution of the program for this process. Because the operating system is managing memory and is responsible for bringing this process into main memory, these addresses are easy to come by. In addition, however, the processor must deal with memory

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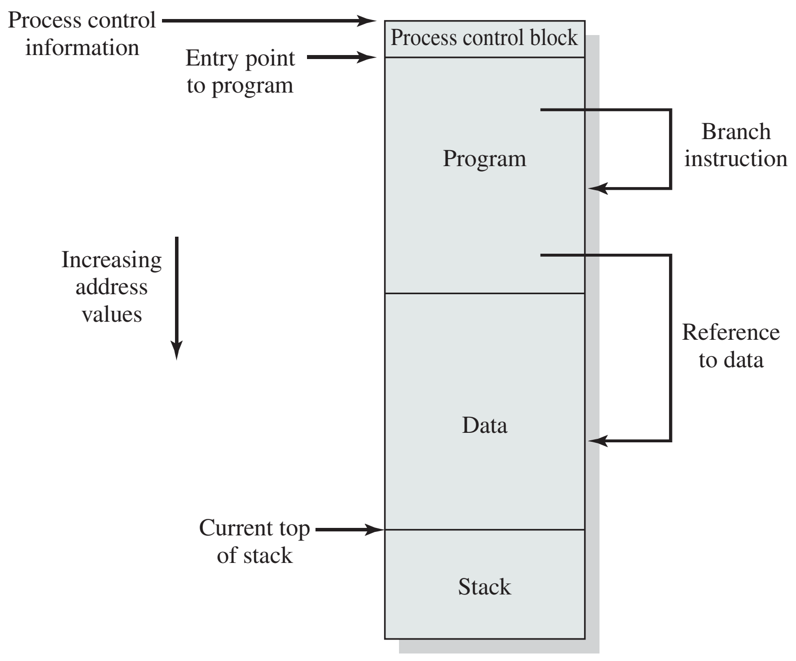

Figure 7.1 Addressing Requirements for a Process

references within the program. Branch instructions contain an address to reference the instruction to be executed next. Data reference instructions contain the address of the byte or word of data referenced. Somehow, the processor hardware and operating system software must be able to translate the memory references found in the code of the program into actual physical memory addresses, reflecting the current location of the program in main memory.

Protection

Each process should be protected against unwanted interference by other processes, whether accidental or intentional. Thus, programs in other processes should not be able to reference memory locations in a process for reading or writing purposes without permission. In one sense, satisfaction of the relocation requirement increases the difficulty of satisfying the protection requirement. Because the location of a program in main memory is unpredictable, it is impossible to check absolute addresses at compile time to assure protection. Furthermore, most programming languages allow the dynamic calculation of addresses at run time (e.g., by computing an array subscript or a pointer into a data structure). Hence all memory references generated by a process must be checked at run time to ensure that they refer only to the memory space allocated to that process. Fortunately, we shall see that mechanisms that support relocation also support the protection requirement.

Normally, a user process cannot access any portion of the operating system, neither program nor data. Again, usually a program in one process cannot branch to an instruction in another process. Without special arrangement, a program in one process cannot access the data area of another process. The processor must be able to abort such instructions at the point of execution.

Note that the memory protection requirement must be satisfied by the processor (hardware) rather than the operating system (software). This is because the OS cannot anticipate all of the memory references that a program will make. Even if such anticipation were possible, it would be prohibitively time consuming to screen each program in advance for possible memory-reference violations. Thus, it is only possible to assess the permissibility of a memory reference (data access or branch) at the time of execution of the instruction making the reference. To accomplish this, the processor hardware must have that capability.

Sharing

Any protection mechanism must have the flexibility to allow several processes to access the same portion of main memory. For example, if a number of processes are executing the same program, it is advantageous to allow each process to access the same copy of the program rather than have its own separate copy. Processes that are cooperating on some task may need to share access to the same data structure. The memory management system must therefore allow controlled access to shared areas of memory without compromising essential protection. Again, we will see that the mechanisms used to support relocation support sharing capabilities.

Logical Organization

Almost invariably, main memory in a computer system is organized as a linear, or one-dimensional, address space, consisting of a sequence of bytes or words. Secondary memory, at its physical level, is similarly organized. While this organization closely mirrors the actual machine hardware, it does not correspond to the way in which programs are typically constructed. Most programs are organized into modules, some of which are unmodifiable (read only, execute only) and some of which contain data that may be modified. If the operating system and computer hardware can effectively deal with user programs and data in the form of modules of some sort, then a number of advantages can be realized:

1. Modules can be written and compiled independently, with all references from one module to another resolved by the system at run time.
2. With modest additional overhead, different degrees of protection (read only, execute only) can be given to different modules.
3. It is possible to introduce mechanisms by which modules can be shared among processes. The advantage of providing sharing on a module level is that this corresponds to the user's way of viewing the problem, and hence it is easy for the user to specify the sharing that is desired.

The tool that most readily satisfies these requirements is segmentation, which is one of the memory management techniques explored in this chapter.

Physical Organization

As we discussed in Section 1.5, computer memory is organized into at least two levels, referred to as main memory and secondary memory. Main memory provides fast access at relatively high cost. In addition, main memory is volatile; that is, it does not provide permanent storage. Secondary memory is slower and cheaper than main memory and is usually not volatile. Thus secondary memory of large capacity can be provided for long-term storage of programs and data, while a smaller main memory holds programs and data currently in use.

In this two-level scheme, the organization of the flow of information between main and secondary memory is a major system concern. The responsibility for this flow could be assigned to the individual programmer, but this is impractical and undesirable for two reasons:

1. The main memory available for a program plus its data may be insufficient. In that case, the programmer must engage in a practice known as **overlaying**, in which the program and data are organized in such a way that various modules can be assigned the same region of memory, with a main program responsible for switching the modules in and out as needed. Even with the aid of compiler tools, overlay programming wastes programmer time.
2. In a multiprogramming environment, the programmer does not know at the time of coding how much space will be available or where that space will be.

It is clear, then, that the task of moving information between the two levels of memory should be a system responsibility. This task is the essence of memory management.

7.2 MEMORY PARTITIONING

The principal operation of memory management is to bring processes into main memory for execution by the processor. In almost all modern multiprogramming systems, this involves a sophisticated scheme known as virtual memory. Virtual memory is, in turn, based on the use of one or both of two basic techniques: segmentation and paging. Before we can look at these virtual memory techniques, we must prepare the ground by looking at simpler techniques that do not involve virtual memory (Table 7.2 summarizes all the techniques examined in this chapter and the next). One of these techniques, partitioning, has been used in several variations in some now-obsolete operating systems. The other two techniques, simple paging and simple segmentation, are not used by themselves. However, it will clarify the discussion of virtual memory if we look first at these two techniques in the absence of virtual memory considerations.

Fixed Partitioning

In most schemes for memory management, we can assume that the OS occupies some fixed portion of main memory and that the rest of main memory is available for use by multiple processes. The simplest scheme for managing this available memory is to partition it into regions with fixed boundaries.

Partition Sizes Figure 7.2 shows examples of two alternatives for fixed partitioning. One possibility is to make use of equal-size partitions. In this case, any process whose size is less than or equal to the partition size can be loaded into

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Table 7.2 Memory Management Techniques

Technique	Description	Strengths	Weaknesses
Fixed Partitioning	Main memory is divided into a number of static partitions at system generation time. A process may be loaded into a partition of equal or greater size.	Simple to implement; little operating system overhead.	Inefficient use of memory due to internal fragmentation; maximum number of active processes is fixed.
Dynamic Partitioning	Partitions are created dynamically, so that each process is loaded into a partition of exactly the same size as that process.	No internal fragmentation; more efficient use of main memory.	Inefficient use of processor due to the need for compaction to counter external fragmentation.
Simple Paging	Main memory is divided into a number of equal-size frames. Each process is divided into a number of equal-size pages of the same length as frames. A process is loaded by loading all of its pages into available, not necessarily contiguous, frames.	No external fragmentation.	A small amount of internal fragmentation.
Simple Segmentation	Each process is divided into a number of segments. A process is loaded by loading all of its segments into dynamic partitions that need not be contiguous.	No internal fragmentation; improved memory utilization and reduced overhead compared to dynamic partitioning.	External fragmentation.
Virtual Memory Paging	As with simple paging, except that it is not necessary to load all of the pages of a process. Nonresident pages that are needed are brought in later automatically.	No external fragmentation; higher degree of multiprogramming; large virtual address space.	Overhead of complex memory management.
Virtual Memory Segmentation	As with simple segmentation, except that it is not necessary to load all of the segments of a process. Nonresident segments that are needed are brought in later automatically.	No internal fragmentation, higher degree of multiprogramming; large virtual address space; protection and sharing support.	Overhead of complex memory management.

any available partition. If all partitions are full and no process is in the Ready or Running state, the operating system can swap a process out of any of the partitions and load in another process, so that there is some work for the processor.

There are two difficulties with the use of equal-size fixed partitions:

- A program may be too big to fit into a partition. In this case, the programmer must design the program with the use of overlays so that only a portion of the program need be in main memory at any one time. When a module is needed

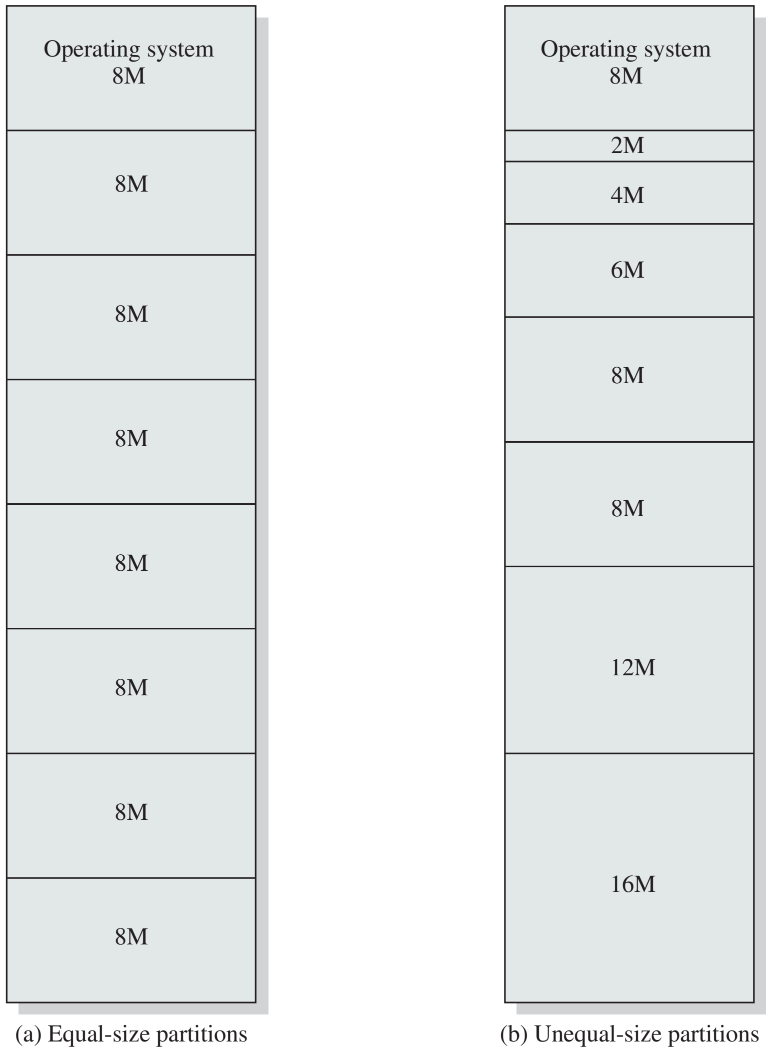

Figure 7.2 Example of Fixed Partitioning of a 64-Mbyte Memory

that is not present, the user's program must load that module into the program's partition, overlaying whatever programs or data are there.

- Main memory utilization is extremely inefficient. Any program, no matter how small, occupies an entire partition. In our example, there may be a program whose length is less than 2 Mbytes; yet it occupies an 8-Mbyte partition whenever it is swapped in. This phenomenon, in which there is wasted space internal to a partition due to the fact that the block of data loaded is smaller than the partition, is referred to as **internal fragmentation**.

Both of these problems can be lessened, though not solved, by using unequal-size partitions (Figure 7.2b). In this example, programs as large as 16 Mbytes can be accommodated without overlays. Partitions smaller than 8 Mbytes allow smaller programs to be accommodated with less internal fragmentation.

Placement Algorithm With equal-size partitions, the placement of processes in memory is trivial. As long as there is any available partition, a process can be loaded into that partition. Because all partitions are of equal size, it does not matter which partition is used. If all partitions are occupied with processes that are not ready to run, then one of these processes must be swapped out to make room for a new process. Which one to swap out is a scheduling decision; this topic is explored in Part Four.

With unequal-size partitions, there are two possible ways to assign processes to partitions. The simplest way is to assign each process to the smallest partition within which it will fit.[1] In this case, a scheduling queue is needed for each partition, to hold swapped-out processes destined for that partition (Figure 7.3a). The advantage of this approach is that processes are always assigned in such a way as to minimize wasted memory within a partition (internal fragmentation).

Although this technique seems optimum from the point of view of an individual partition, it is not optimum from the point of view of the system as a whole. In Figure 7.2b, for example, consider a case in which there are no processes with a size between 12 and 16M at a certain point in time. In that case, the 16M partition will remain unused, even though some smaller process could have been assigned to it. Thus, a preferable approach would be to employ a single queue for all processes (Figure 7.3b). When it is time to load a process into main memory, the smallest available partition that will hold the process is selected. If all partitions are occupied, then a swapping decision must be made. Preference might be given to swapping out of the smallest partition that will hold the incoming process. It is also possible to

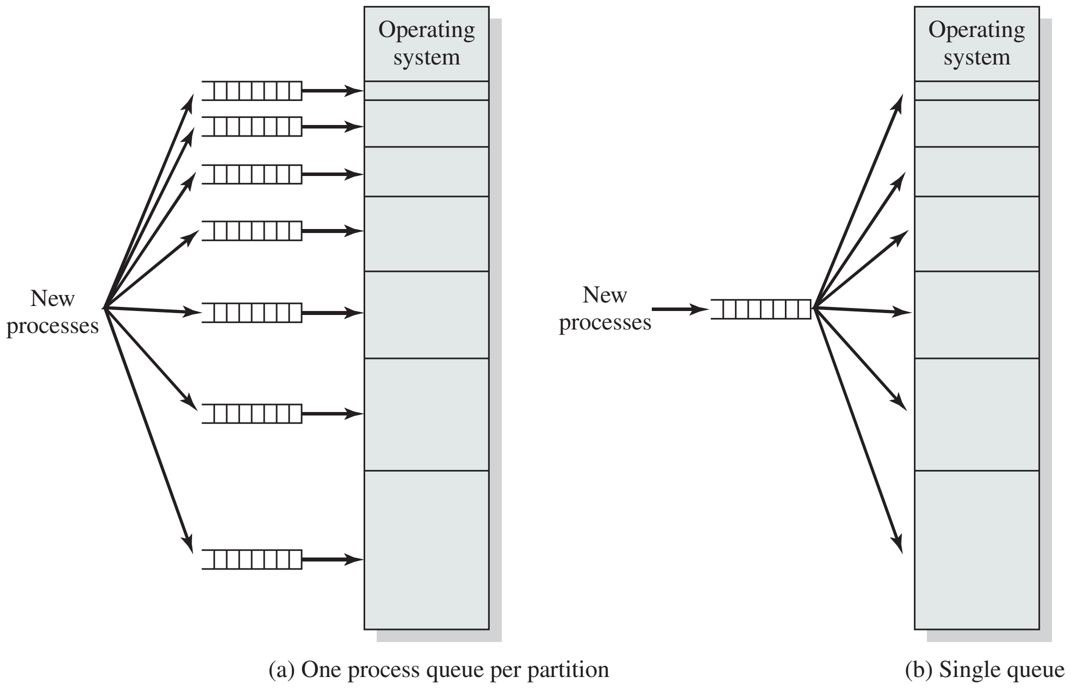

Figure 7.3 Memory Assignment for Fixed Partitioning

[1]This assumes that one knows the maximum amount of memory that a process will require. This is not always the case. If it is not known how large a process may become, the only alternatives are an overlay scheme or the use of virtual memory.

consider other factors, such as priority, and a preference for swapping out blocked processes versus ready processes.

The use of unequal-size partitions provides a degree of flexibility to fixed partitioning. In addition, it can be said that fixed-partitioning schemes are relatively simple and require minimal OS software and processing overhead. However, there are disadvantages:

- The number of partitions specified at system generation time limits the number of active (not suspended) processes in the system.
- Because partition sizes are preset at system generation time, small jobs will not utilize partition space efficiently. In an environment where the main storage requirement of all jobs is known beforehand, this may be reasonable, but in most cases, it is an inefficient technique.

The use of fixed partitioning is almost unknown today. One example of a successful operating system that did use this technique was an early IBM mainframe operating system, OS/MFT (Multiprogramming with a Fixed Number of Tasks).

Dynamic Partitioning

To overcome some of the difficulties with fixed partitioning, an approach known as dynamic partitioning was developed. Again, this approach has been supplanted by more sophisticated memory management techniques. An important operating system that used this technique was IBM's mainframe operating system, OS/MVT (Multiprogramming with a Variable Number of Tasks).

With dynamic partitioning, the partitions are of variable length and number. When a process is brought into main memory, it is allocated exactly as much memory as it requires and no more. An example, using 64 Mbytes of main memory, is shown in Figure 7.4. Initially, main memory is empty, except for the OS (a). The first three processes are loaded in, starting where the operating system ends and occupying just enough space for each process (b, c, d). This leaves a "hole" at the end of memory that is too small for a fourth process. At some point, none of the processes in memory is ready. The operating system swaps out process 2 (e), which leaves sufficient room to load a new process, process 4 (f). Because process 4 is smaller than process 2, another small hole is created. Later, a point is reached at which none of the processes in main memory is ready, but process 2, in the Ready-Suspend state, is available. Because there is insufficient room in memory for process 2, the operating system swaps process 1 out (g) and swaps process 2 back in (h).

As this example shows, this method starts out well, but eventually it leads to a situation in which there are a lot of small holes in memory. As time goes on, memory becomes more and more fragmented, and memory utilization declines. This phenomenon is referred to as **external fragmentation**, indicating that the memory that is external to all partitions becomes increasingly fragmented. This is in contrast to internal fragmentation, referred to earlier.

One technique for overcoming external fragmentation is **compaction**: From time to time, the OS shifts the processes so that they are contiguous and so that all of the free memory is together in one block. For example, in Figure 7.4h, compaction

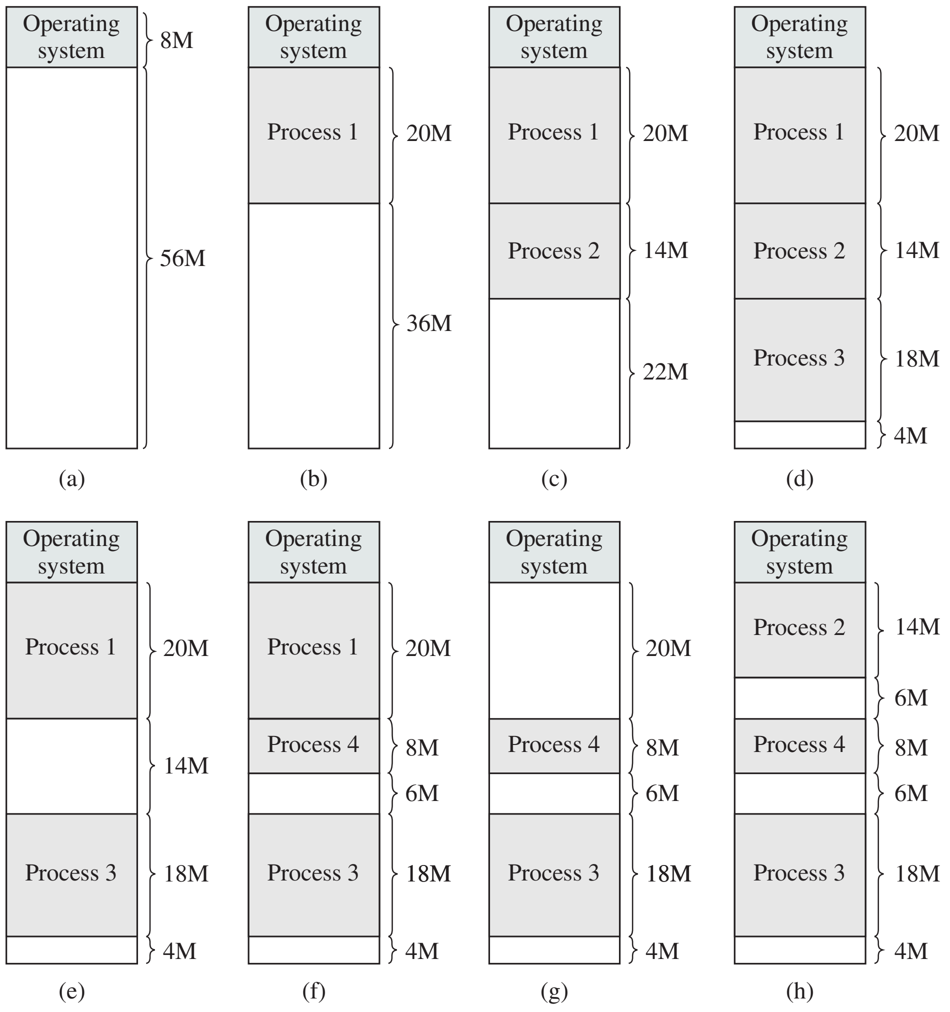

Figure 7.4 The Effect of Dynamic Partitioning

will result in a block of free memory of length 16M. This may well be sufficient to load in an additional process. The difficulty with compaction is that it is a time-consuming procedure and wasteful of processor time. Note that compaction implies the need for a dynamic relocation capability. That is, it must be possible to move a program from one region to another in main memory without invalidating the memory references in the program (see Appendix 7A).

Placement Algorithm Because memory compaction is time consuming, the OS designer must be clever in deciding how to assign processes to memory (how to plug the holes). When it is time to load or swap a process into main memory, and if there is more than one free block of memory of sufficient size, then the operating system must decide which free block to allocate.

Three placement algorithms that might be considered are best-fit, first-fit, and next-fit. All, of course, are limited to choosing among free blocks of main memory that are equal to or larger than the process to be brought in. **Best-fit** chooses the block that is closest in size to the request. **First-fit** begins to scan memory from the

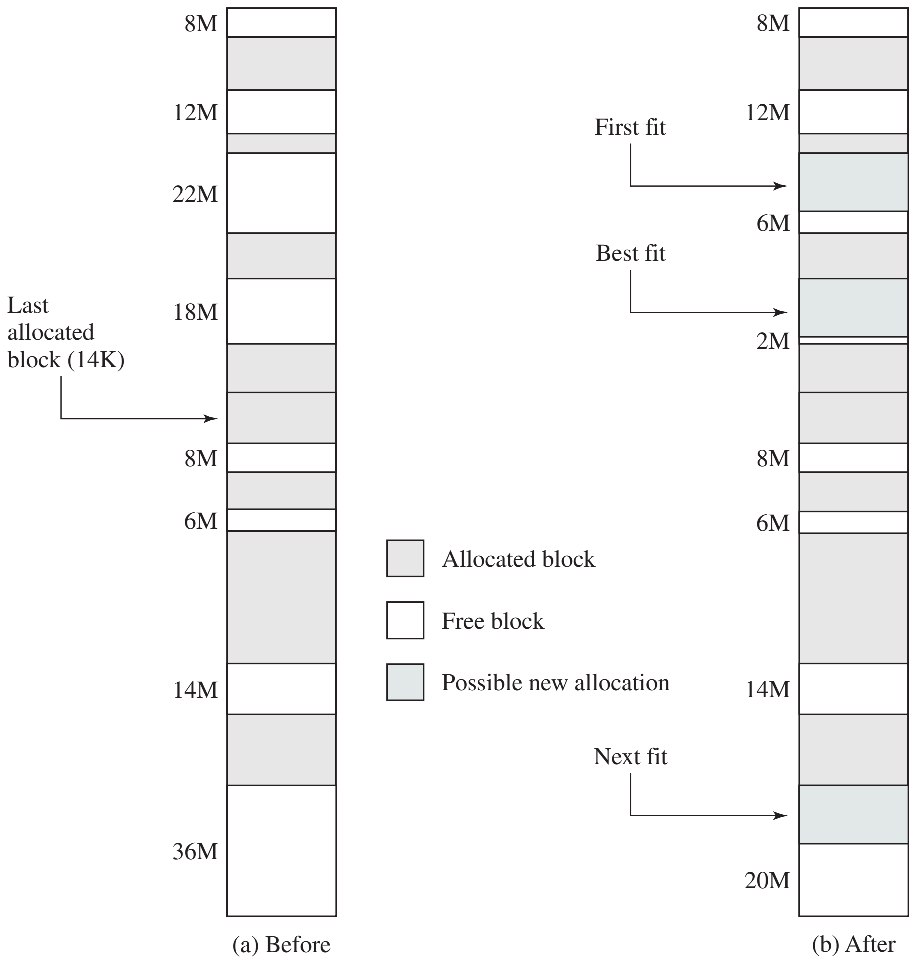

Figure 7.5 Example Memory Configuration before and after Allocation of 16-Mbyte Block

beginning and chooses the first available block that is large enough. **Next-fit** begins to scan memory from the location of the last placement, and chooses the next available block that is large enough.

Figure 7.5a shows an example memory configuration after a number of placement and swapping-out operations. The last block that was used was a 22-Mbyte block from which a 14-Mbyte partition was created. Figure 7.5b shows the difference between the best-, first-, and next-fit placement algorithms in satisfying a 16-Mbyte allocation request. Best-fit will search the entire list of available blocks and make use of the 18-Mbyte block, leaving a 2-Mbyte fragment. First-fit results in a 6-Mbyte fragment, and next-fit results in a 20-Mbyte fragment.

Which of these approaches is best will depend on the exact sequence of process swappings that occurs and the size of those processes. However, some general comments can be made (see also [BREN89], [SHOR75], and [BAYS77]). The first-fit algorithm is not only the simplest but usually the best and fastest as well. The next-fit algorithm tends to produce slightly worse results than the first-fit. The next-fit algorithm will more frequently lead to an allocation from a free block at the end of memory. The result is that the largest block of free memory, which usually appears at the end of the memory space, is quickly broken up into small fragments. Thus, compaction may be required more frequently with next-fit. On the other hand, the first-fit algorithm may litter the front end with small free partitions that need to be searched over on each subsequent first-fit pass. The best-fit algorithm, despite its name, is usually the worst performer. Because this algorithm looks for the smallest block that will satisfy the requirement, it guarantees that the fragment left behind is as small as possible. Although each memory request always wastes the smallest amount of memory, the result is that main memory is quickly littered by blocks too small to satisfy memory allocation requests. Thus, memory compaction must be done more frequently than with the other algorithms.

Replacement Algorithm In a multiprogramming system using dynamic partitioning, there will come a time when all of the processes in main memory are in a blocked state and there is insufficient memory, even after compaction, for an additional process. To avoid wasting processor time waiting for an active process to become unblocked, the OS will swap one of the processes out of main memory to make room for a new process or for a process in a Ready-Suspend state. Therefore, the operating system must choose which process to replace. Because the topic of replacement algorithms will be covered in some detail with respect to various virtual memory schemes, we defer a discussion of replacement algorithms until then.

Buddy System

Both fixed and dynamic partitioning schemes have drawbacks. A fixed partitioning scheme limits the number of active processes and may use space inefficiently if there is a poor match between available partition sizes and process sizes. A dynamic partitioning scheme is more complex to maintain and includes the overhead of compaction. An interesting compromise is the buddy system ([KNUT97], [PETE77]).

In a buddy system, memory blocks are available of size 2^K words, $L \leq K \leq U$, where

2^L = smallest size block that is allocated

2^U = largest size block that is allocated; generally 2^U is the size of the entire memory available for allocation

To begin, the entire space available for allocation is treated as a single block of size 2^U. If a request of size s such that $2^{U-1} < s \leq 2^U$ is made, then the entire block is allocated. Otherwise, the block is split into two equal buddies of size 2^{U-1}. If $2^{U-2} < s \leq 2^{U-1}$, then the request is allocated to one of the two buddies. Otherwise, one of the buddies is split in half again. This process continues until the smallest block greater than or equal to s is generated and allocated to the request. At any time, the buddy system maintains a list of holes (unallocated blocks) of each size 2^i. A hole may be removed from the $(i + 1)$ list by splitting it in half to create two buddies of size 2^i in the i list. Whenever a pair of buddies on the i list both become unallocated, they are removed from that list and coalesced into a single block on the $(i + 1)$

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list. Presented with a request for an allocation of size k such that $2^{i-1} < k \leqslant 2^i$, the following recursive algorithm is used to find a hole of size 2^i:

```
void get_hole(int i)
{
  if (i == (U + 1)) <failure>;
  if (<i_list empty>) {
     get_hole(i + 1);
     <split hole into buddies>;
     <put buddies on i_list>;
  }
  <take first hole on i_list>;
}
```

Figure 7.6 gives an example using a 1-Mbyte initial block. The first request, A, is for 100 Kbytes, for which a 128K block is needed. The initial block is divided into two 512K buddies. The first of these is divided into two 256K buddies, and the first of these is divided into two 128K buddies, one of which is allocated to A. The next request, B, requires a 256K block. Such a block is already available and is allocated. The process continues with splitting and coalescing occurring as needed. Note that when E is released, two 128K buddies are coalesced into a 256K block, which is immediately coalesced with its buddy.

Figure 7.7 shows a binary tree representation of the buddy allocation immediately after the Release B request. The leaf nodes represent the current partitioning of the memory. If two buddies are leaf nodes, then at least one must be allocated; otherwise they would be coalesced into a larger block.

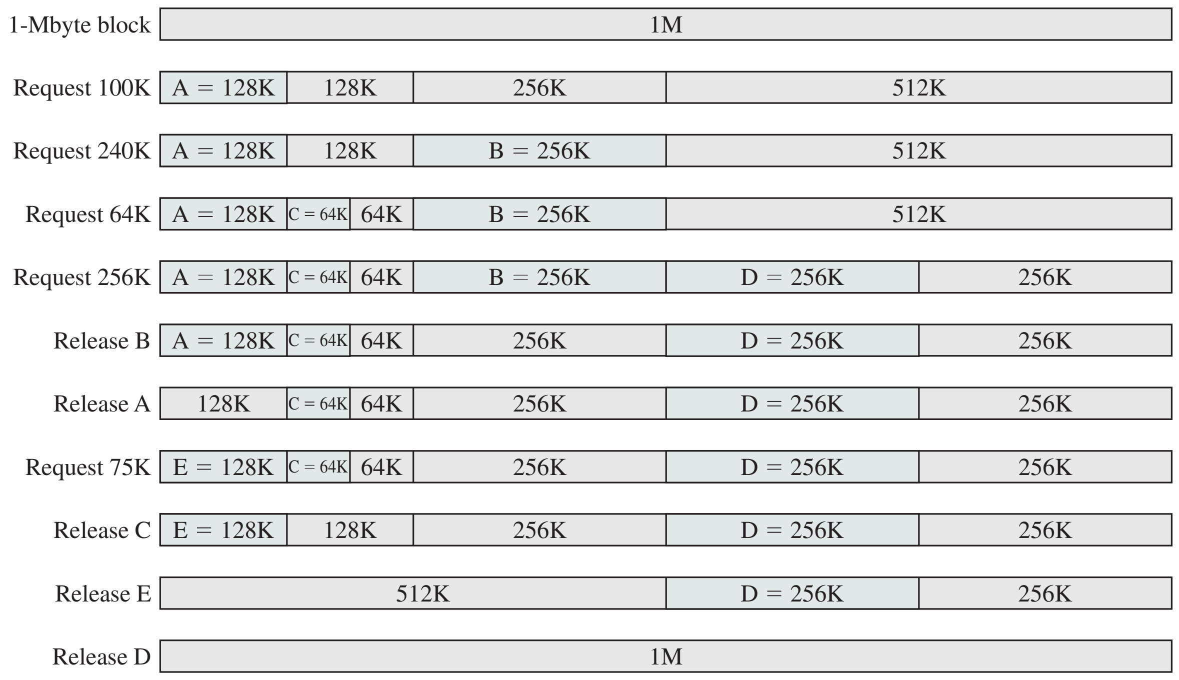


Figure 7.6 Example of Buddy System

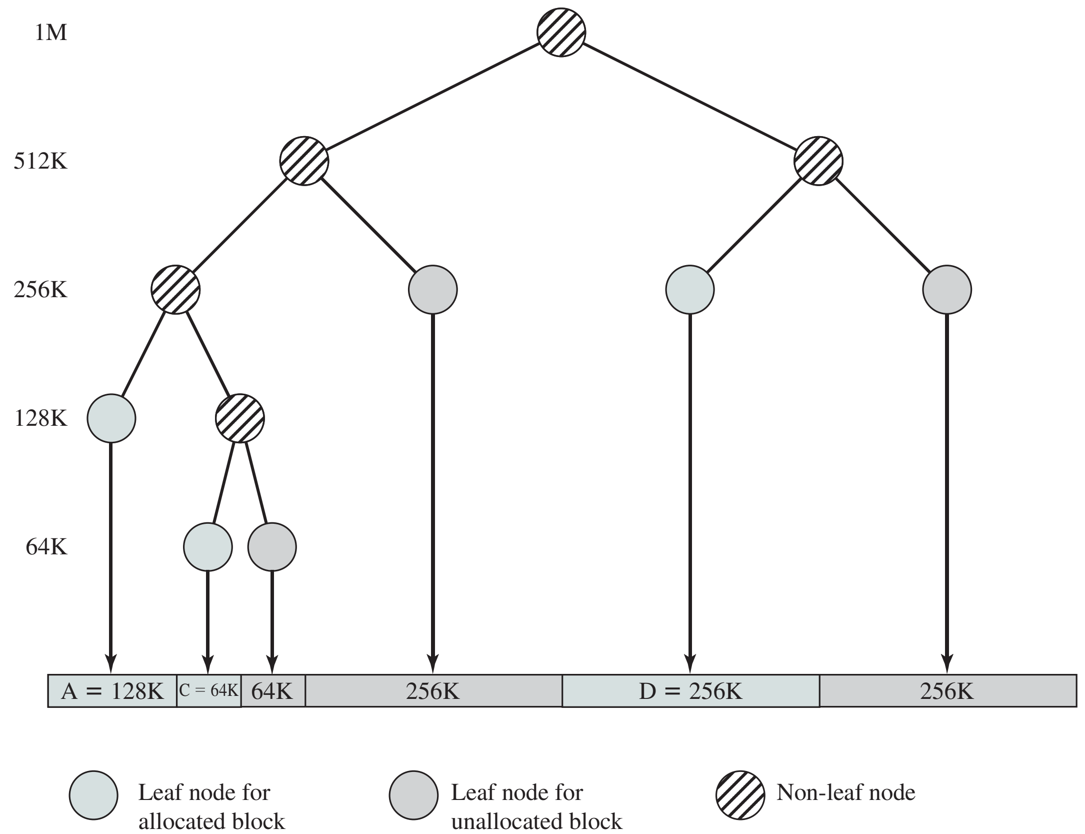


Figure 7.7 Tree Representation of Buddy System

The buddy system is a reasonable compromise to overcome the disadvantages of both the fixed and variable partitioning schemes, but in contemporary operating systems, virtual memory based on paging and segmentation is superior. However, the buddy system has found application in parallel systems as an efficient means of allocation and release for parallel programs (e.g., see [JOHN92]). A modified form of the buddy system is used for UNIX kernel memory allocation (described in Chapter 8).

Relocation

Before we consider ways of dealing with the shortcomings of partitioning, we must clear up one loose end, which relates to the placement of processes in memory. When the fixed partition scheme of Figure 7.3a is used, we can expect that a process will always be assigned to the same partition. That is, whichever partition is selected when a new process is loaded will always be used to swap that process back into memory after it has been swapped out. In that case, a simple relocating loader, such as is described in Appendix 7A, can be used: When the process is first loaded, all relative memory references in the code are replaced by absolute main memory addresses, determined by the base address of the loaded process.

In the case of equal-size partitions (Figure 7.2), and in the case of a single process queue for unequal-size partitions (Figure 7.3b), a process may occupy different partitions during the course of its life. When a process image is first created, it is loaded into some partition in main memory. Later, the process may be swapped out; when it is subsequently swapped back in, it may be assigned to a different partition than the last time. The same is true for dynamic partitioning. Observe in Figure 7.4c and Figure 7.4h that process 2 occupies two different regions of memory on the two occasions when it is brought in. Furthermore, when compaction is used, processes are shifted while they are in main memory. Thus, the locations (of instructions and data) referenced by a process are not fixed. They will change each time a process is swapped in or shifted. To solve this problem, a distinction is made among several types of addresses. A **logical address** is a reference to a memory location independent of the current assignment of data to memory; a translation must be made to a physical address before the memory access can be achieved. A **relative address** is a particular example of logical address, in which the address is expressed as a location relative to some known point, usually a value in a processor register. A **physical address**, or absolute address, is an actual location in main memory.

Programs that employ relative addresses in memory are loaded using dynamic run-time loading (see Appendix 7A for a discussion). Typically, all of the memory references in the loaded process are relative to the origin of the program. Thus a hardware mechanism is needed for translating relative addresses to physical main memory addresses at the time of execution of the instruction that contains the reference.

Figure 7.8 shows the way in which this address translation is typically accomplished. When a process is assigned to the Running state, a special processor register, sometimes called the base register, is loaded with the starting address in main memory of the program. There is also a "bounds" register that indicates the ending location

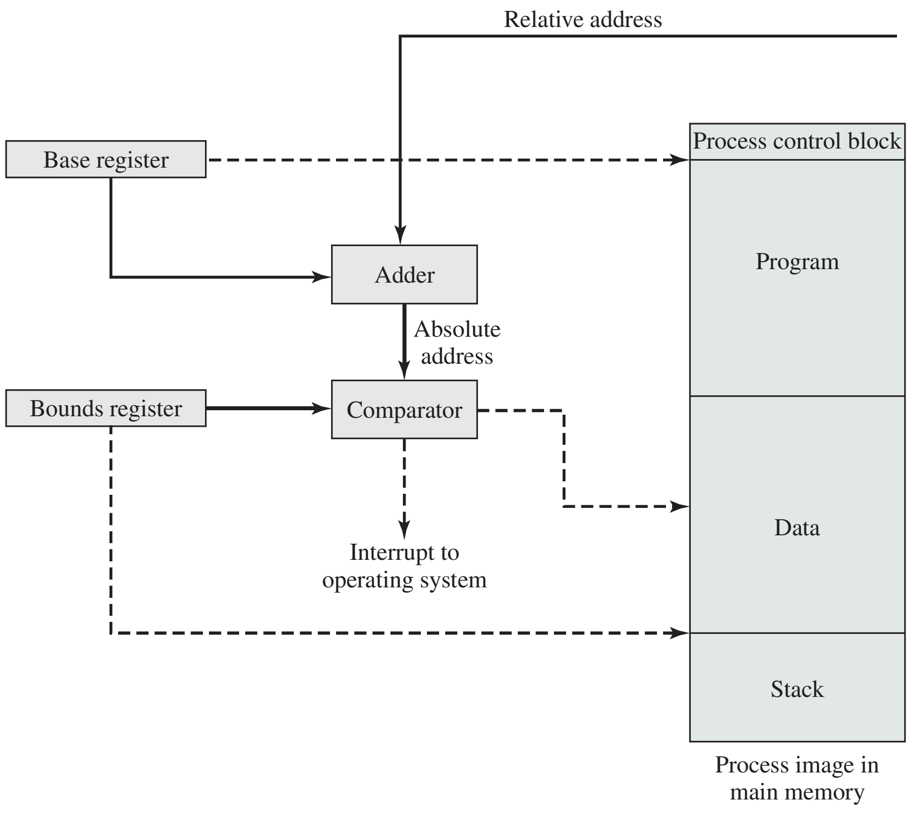


Figure 7.8 Hardware Support for Relocation

of the program; these values must be set when the program is loaded into memory or when the process image is swapped in. During the course of execution of the process, relative addresses are encountered. These include the contents of the instruction register, instruction addresses that occur in branch and call instructions, and data addresses that occur in load and store instructions. Each such relative address goes through two steps of manipulation by the processor. First, the value in the base register is added to the relative address to produce an absolute address. Second, the resulting address is compared to the value in the bounds register. If the address is within bounds, then the instruction execution may proceed. Otherwise, an interrupt is generated to the operating system, which must respond to the error in some fashion.

The scheme of Figure 7.8 allows programs to be swapped in and out of memory during the course of execution. It also provides a measure of protection: Each process image is isolated by the contents of the base and bounds registers and safe from unwanted accesses by other processes.

7.3 PAGING

Both unequal fixed-size and variable-size partitions are inefficient in the use of memory; the former results in internal fragmentation, the latter in external fragmentation. Suppose, however, that main memory is partitioned into equal fixed-size chunks that are relatively small, and that each process is also divided into small fixed-size chunks of the same size. Then the chunks of a process, known as **pages,** could be assigned to available chunks of memory, known as **frames,** or page frames. We show in this section that the wasted space in memory for each process is due to internal fragmentation consisting of only a fraction of the last page of a process. There is no external fragmentation.

Figure 7.9 illustrates the use of pages and frames. At a given point in time, some of the frames in memory are in use and some are free. A list of free frames is maintained by the OS. Process A, stored on disk, consists of four pages. When it is time to load this process, the OS finds four free frames and loads the four pages of process A into the four frames (Figure 7.9b). Process B, consisting of three pages, and process C, consisting of four pages, are subsequently loaded. Then process B is suspended and is swapped out of main memory. Later, all of the processes in main memory are blocked, and the OS needs to bring in a new process, process D, which consists of five pages.

Now suppose, as in this example, that there are not sufficient unused contiguous frames to hold the process. Does this prevent the operating system from loading D? The answer is no, because we can once again use the concept of logical address. A simple base address register will no longer suffice. Rather, the operating system maintains a **page table** for each process. The page table shows the frame location for each page of the process. Within the program, each logical address consists of a page number and an offset within the page. Recall that in the case of simple partition, a logical address is the location of a word relative to the beginning of the program; the processor translates that into a physical address. With paging, the logical-to-physical address translation is still done by processor hardware. Now the processor must know how to access the page table of the current process. Presented with a logical

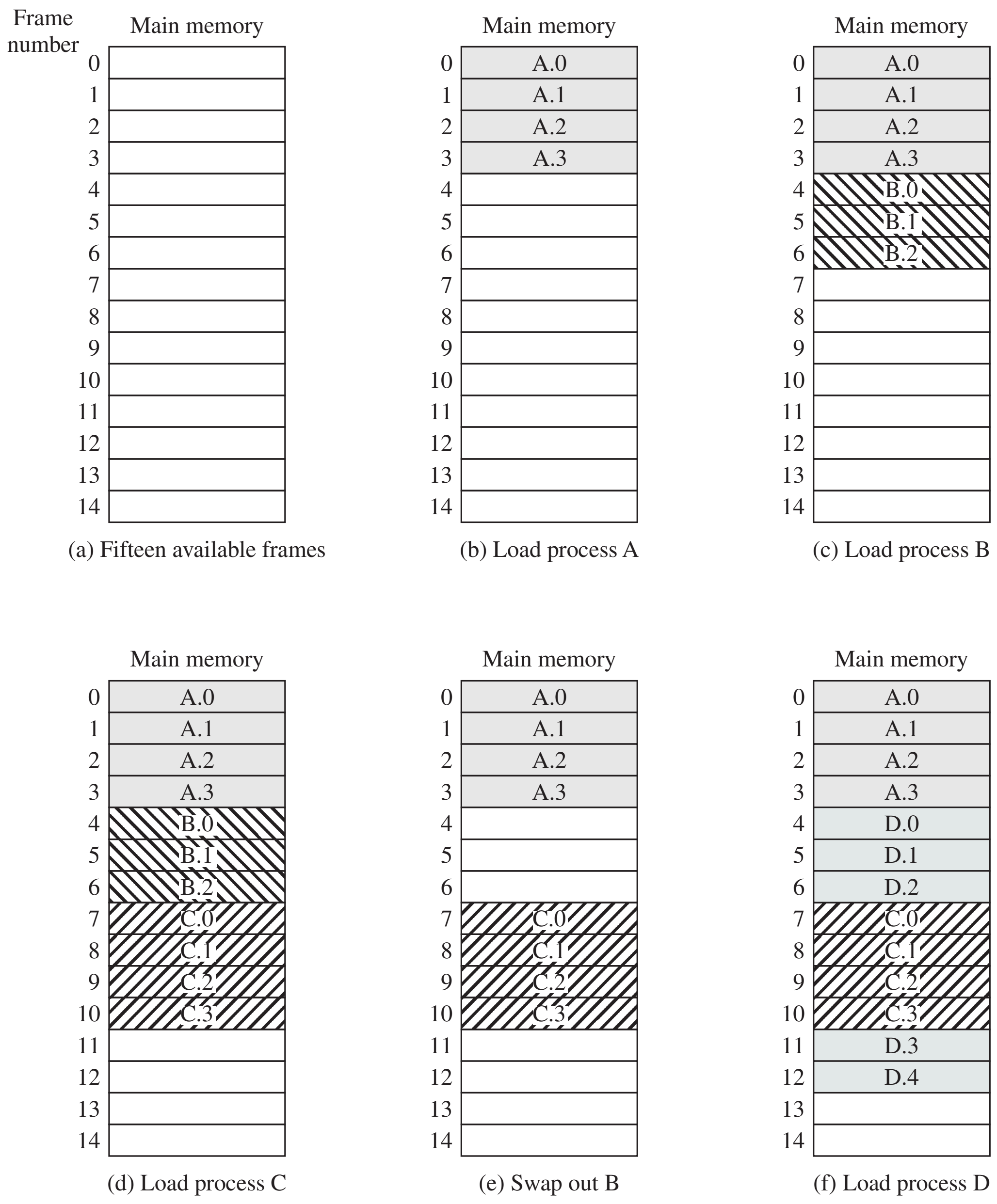
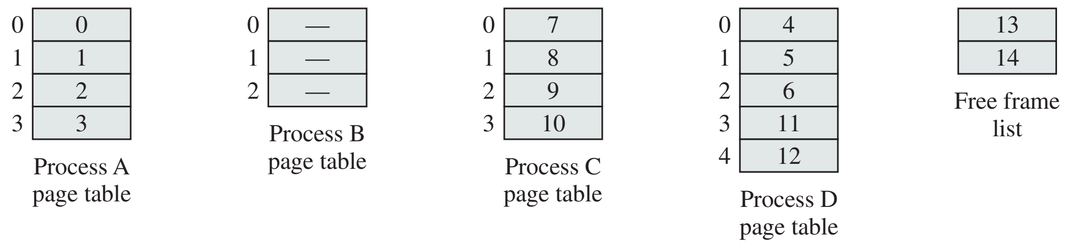


Figure 7.9 Assignment of Process to Free Frames

address (page number, offset), the processor uses the page table to produce a physical address (frame number, offset).

Continuing our example, the five pages of process D are loaded into frames 4, 5, 6, 11, and 12. Figure 7.10 shows the various page tables at this time. A page table contains one entry for each page of the process, so that the table is easily indexed by the page number (starting at page 0). Each page table entry contains the number of the frame in main memory, if any, that holds the corresponding page. In addition, the OS maintains a single free-frame list of all the frames in main memory that are currently unoccupied and available for pages.

Thus we see that simple paging, as described here, is similar to fixed partitioning. The differences are that, with paging, the partitions are rather small; a



Process A page table
Process B page table
Process C page table
Process D page table
Free frame list

Figure 7.10 Data Structures for the Example of Figure 7.9 at Time Epoch (f)

program may occupy more than one partition; and these partitions need not be contiguous.

To make this paging scheme convenient, let us dictate that the page size, hence the frame size, must be a power of 2. With the use of a page size that is a power of 2, it is easy to demonstrate that the relative address, which is defined with reference to the origin of the program, and the logical address, expressed as a page number and offset, are the same. An example is shown in Figure 7.11. In this example, 16-bit addresses are used, and the page size is 1K = 1,024 bytes. The relative address 1502, in binary form, is 0000010111011110. With a page size of 1K, an offset field of 10 bits is needed, leaving 6 bits for the page number. Thus a program can consist of a maximum of 2^6 = 64 pages of 1K bytes each. As Figure 7.11b shows, relative address 1502 corresponds to an offset of 478 (0111011110) on page 1 (000001), which yields the same 16-bit number, 0000010111011110.

The consequences of using a page size that is a power of 2 are twofold. First, the logical addressing scheme is transparent to the programmer, the assembler, and

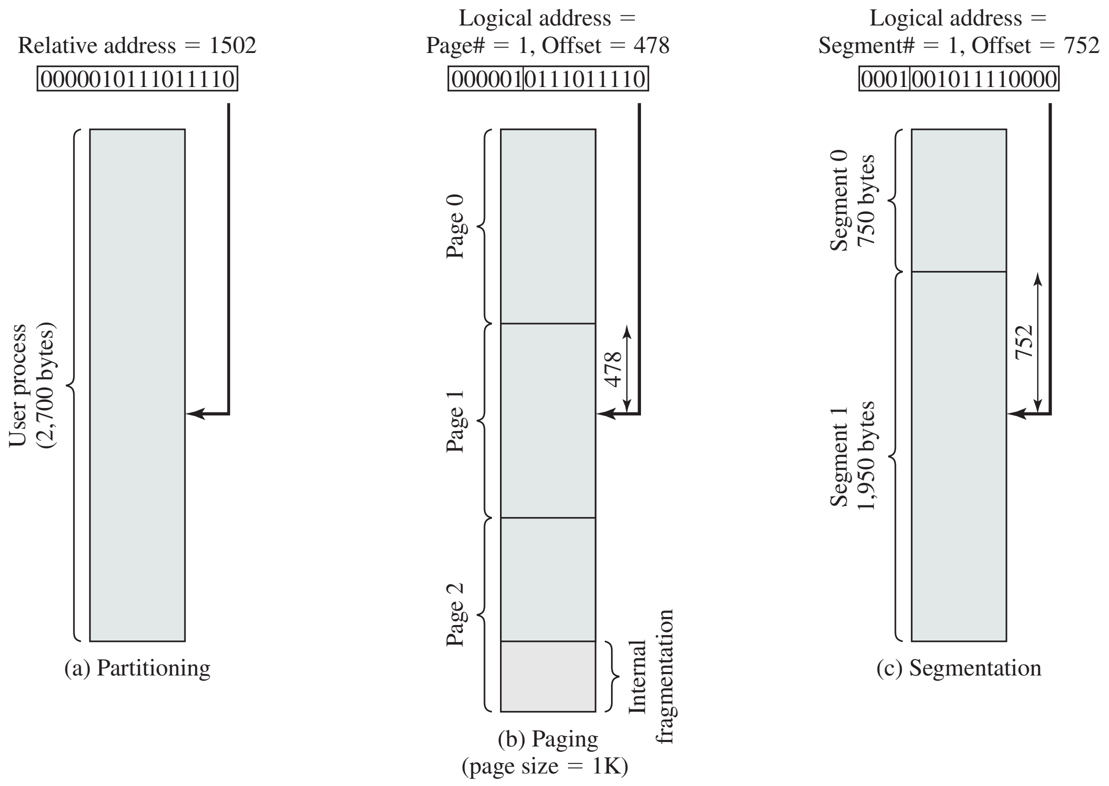


Figure 7.11 Logical Addresses

the linker. Each logical address (page number, offset) of a program is identical to its relative address. Second, it is a relatively easy matter to implement a function in hardware to perform dynamic address translation at run time. Consider an address of $n + m$ bits, where the leftmost n bits are the page number and the rightmost m bits are the offset. In our example (Figure 7.11b), $n = 6$ and $m = 10$. The following steps are needed for address translation:

- Extract the page number as the leftmost n bits of the logical address.
- Use the page number as an index into the process page table to find the frame number, k.
- The starting physical address of the frame is $k \times 2_m$, and the physical address of the referenced byte is that number plus the offset. This physical address need not be calculated; it is easily constructed by appending the frame number to the offset.

In our example, we have the logical address 0000010111011110, which is page number 1, offset 478. Suppose that this page is residing in main memory frame 6 = binary 000110. Then the physical address is frame number 6, offset 478 = 0001100111011110 (Figure 7.12a).

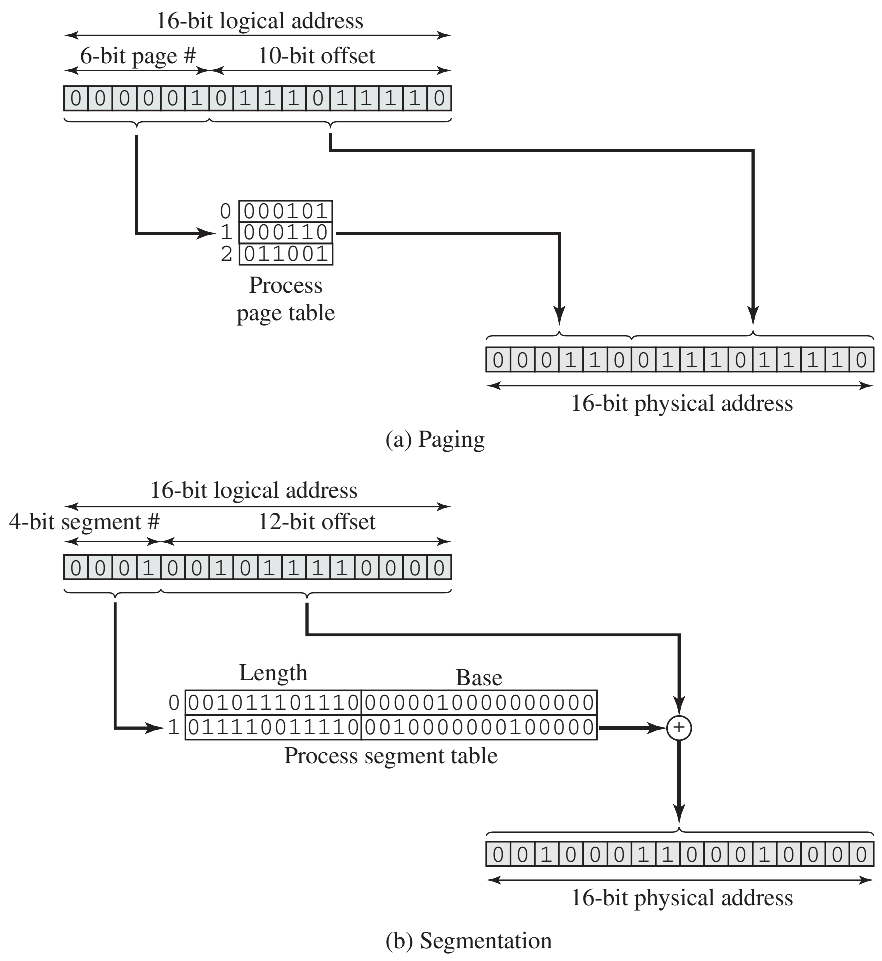


Figure 7.12 Examples of Logical-to-Physical Address Translation

To summarize, with simple paging, main memory is divided into many small equal-size frames. Each process is divided into frame-size pages. Smaller processes require fewer pages; larger processes require more. When a process is brought in, all of its pages are loaded into available frames, and a page table is set up. This approach solves many of the problems inherent in partitioning.

7.4 SEGMENTATION

A user program can be subdivided using segmentation, in which the program and its associated data are divided into a number of **segments**. It is not required that all segments of all programs be of the same length, although there is a maximum segment length. As with paging, a logical address using segmentation consists of two parts, in this case a segment number and an offset.

Because of the use of unequal-size segments, segmentation is similar to dynamic partitioning. In the absence of an overlay scheme or the use of virtual memory, it would be required that all of a program's segments be loaded into memory for execution. The difference, compared to dynamic partitioning, is that with segmentation a program may occupy more than one partition, and these partitions need not be contiguous. Segmentation eliminates internal fragmentation but, like dynamic partitioning, it suffers from external fragmentation. However, because a process is broken up into a number of smaller pieces, the external fragmentation should be less.

Whereas paging is invisible to the programmer, segmentation is usually visible and is provided as a convenience for organizing programs and data. Typically, the programmer or compiler will assign programs and data to different segments. For purposes of modular programming, the program or data may be further broken down into multiple segments. The principal inconvenience of this service is that the programmer must be aware of the maximum segment size limitation.

Another consequence of unequal-size segments is that there is no simple relationship between logical addresses and physical addresses. Analogous to paging, a simple segmentation scheme would make use of a segment table for each process and a list of free blocks of main memory. Each segment table entry would have to give the starting address in main memory of the corresponding segment. The entry should also provide the length of the segment, to assure that invalid addresses are not used. When a process enters the Running state, the address of its segment table is loaded into a special register used by the memory management hardware. Consider an address of $n + m$ bits, where the leftmost n bits are the segment number and the rightmost m bits are the offset. In our example (Figure 7.11c), $n = 4$ and $m = 12$. Thus the maximum segment size is $2^{12} = 4096$. The following steps are needed for address translation:

- Extract the segment number as the leftmost n bits of the logical address.
- Use the segment number as an index into the process segment table to find the starting physical address of the segment.
- Compare the offset, expressed in the rightmost m bits, to the length of the segment. If the offset is greater than or equal to the length, the address is invalid.

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- The desired physical address is the sum of the starting physical address of the segment plus the offset.

In our example, we have the logical address 0001001011110000, which is segment number 1, offset 752. Suppose that this segment is residing in main memory starting at physical address 0010000000100000. Then the physical address is 0010000000100000 + 001011110000 = 0010001100010000 (Figure 7.12b).

To summarize, with simple segmentation, a process is divided into a number of segments that need not be of equal size. When a process is brought in, all of its segments are loaded into available regions of memory, and a segment table is set up.

7.5 SECURITY ISSUES

Main memory and virtual memory are system resources subject to security threats and for which security countermeasures need to be taken. The most obvious security requirement is the prevention of unauthorized access to the memory contents of processes. If a process has not declared a portion of its memory to be sharable, then no other process should have access to the contents of that portion of memory. If a process declares that a portion of memory may be shared by other designated processes, then the security service of the OS must ensure that only the designated processes have access. The security threats and countermeasures discussed in Chapter 3 are relevant to this type of memory protection.

In this section, we summarize another threat that involves memory protection. Part Seven provides more detail.

Buffer Overflow Attacks

One serious security threat related to memory management remains to be introduced: **buffer overflow**, also known as a **buffer overrun**, which is defined in the NIST (National Institute of Standards and Technology) *Glossary of Key Information Security Terms* as follows:

> **buffer overrun:** A condition at an interface under which more input can be placed into a buffer or data-holding area than the capacity allocated, overwriting other information. Attackers exploit such a condition to crash a system or to insert specially crafted code that allows them to gain control of the system.

A buffer overflow can occur as a result of a programming error when a process attempts to store data beyond the limits of a fixed-sized buffer and consequently overwrites adjacent memory locations. These locations could hold other program variables or parameters or program control flow data such as return addresses and pointers to previous stack frames. The buffer could be located on the stack, in the heap, or in the data section of the process. The consequences of this error include corruption of data used by the program, unexpected transfer of control in the program, possibly memory access violations, and very likely eventual program

You're gonna need a bigger boat.

—STEVEN SPIELBERG, *JAWS*, 1975

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Define virtual memory.
- Describe the hardware and control structures that support virtual memory.
- Describe the various OS mechanisms used to implement virtual memory.
- Describe the virtual memory management mechanisms in UNIX, Linux, and Windows 7.

Chapter 7 introduced the concepts of paging and segmentation and analyzed their shortcomings. We now move to a discussion of virtual memory. An analysis of this topic is complicated by the fact that memory management is a complex interrelationship between processor hardware and operating system software. We focus first on the hardware aspect of virtual memory, looking at the use of paging, segmentation, and combined paging and segmentation. Then we look at the issues involved in the design of a virtual memory facility in operating systems.

Table 8.1 defines some key terms related to virtual memory. A set of animations that illustrate concepts in this chapter is available online. Click on the rotating globe at WilliamStallings.com/OS/OS7e.html for access.

8.1 HARDWARE AND CONTROL STRUCTURES

Comparing simple paging and simple segmentation, on the one hand, with fixed and dynamic partitioning, on the other, we see the foundation for a fundamental breakthrough in memory management. Two characteristics of paging and segmentation are the keys to this breakthrough:

Table 8.1 Virtual Memory Terminology

Virtual memory	A storage allocation scheme in which secondary memory can be addressed as though it were part of main memory. The addresses a program may use to reference memory are distinguished from the addresses the memory system uses to identify physical storage sites, and program-generated addresses are translated automatically to the corresponding machine addresses. The size of virtual storage is limited by the addressing scheme of the computer system and by the amount of secondary memory available and not by the actual number of main storage locations.
Virtual address	The address assigned to a location in virtual memory to allow that location to be accessed as though it were part of main memory.
Virtual address space	The virtual storage assigned to a process.
Address space	The range of memory addresses available to a process.
Real address	The address of a storage location in main memory.

1. All memory references within a process are logical addresses that are dynamically translated into physical addresses at run time. This means that a process may be swapped in and out of main memory such that it occupies different regions of main memory at different times during the course of execution.
2. A process may be broken up into a number of pieces (pages or segments) and these pieces need not be contiguously located in main memory during execution. The combination of dynamic run-time address translation and the use of a page or segment table permits this.

Now we come to the breakthrough. *If the preceding two characteristics are present, then it is not necessary that all of the pages or all of the segments of a process be in main memory during execution.* If the piece (segment or page) that holds the next instruction to be fetched and the piece that holds the next data location to be accessed are in main memory, then at least for a time execution may proceed.

Let us consider how this may be accomplished. For now, we can talk in general terms, and we will use the term *piece* to refer to either page or segment, depending on whether paging or segmentation is employed. Suppose that it is time to bring a new process into memory. The OS begins by bringing in only one or a few pieces, to include the initial program piece and the initial data piece to which those instructions refer. The portion of a process that is actually in main memory at any time is called the **resident set** of the process. As the process executes, things proceed smoothly as long as all memory references are to locations that are in the resident set. Using the segment or page table, the processor always is able to determine whether this is so. If the processor encounters a logical address that is not in main memory, it generates an interrupt indicating a memory access fault. The OS puts the interrupted process in a blocking state. For the execution of this process to proceed later, the OS must bring into main memory the piece of the process that contains the logical address that caused the access fault. For this purpose, the OS issues a disk I/O read request. After the I/O request has been issued, the OS can dispatch another process to run while the disk I/O is performed. Once the desired piece has been brought into main memory, an I/O interrupt is issued, giving control back to the OS, which places the affected process back into a Ready state.

It may immediately occur to you to question the efficiency of this maneuver, in which a process may be executing and have to be interrupted for no other reason than that you have failed to load in all of the needed pieces of the process. For now, let us defer consideration of this question with the assurance that efficiency is possible. Instead, let us ponder the implications of our new strategy. There are two implications, the second more startling than the first, and both lead to improved system utilization:

1. **More processes may be maintained in main memory.** Because we are only going to load some of the pieces of any particular process, there is room for more processes. This leads to more efficient utilization of the processor because it is more likely that at least one of the more numerous processes will be in a Ready state at any particular time.
2. **A process may be larger than all of main memory.** One of the most fundamental restrictions in programming is lifted. Without the scheme we have been discussing, a programmer must be acutely aware of how much memory is available. If the program being written is too large, the programmer must devise ways to

structure the program into pieces that can be loaded separately in some sort of overlay strategy. With virtual memory based on paging or segmentation, that job is left to the OS and the hardware. As far as the programmer is concerned, he or she is dealing with a huge memory, the size associated with disk storage. The OS automatically loads pieces of a process into main memory as required.

Because a process executes only in main memory, that memory is referred to as **real memory.** But a programmer or user perceives a potentially much larger memory—that which is allocated on disk. This latter is referred to as **virtual memory.** Virtual memory allows for very effective multiprogramming and relieves the user of the unnecessarily tight constraints of main memory. Table 8.2 summarizes characteristics of paging and segmentation, with and without the use of virtual memory.

Table 8.2 Characteristics of Paging and Segmentation

Simple Paging	**Virtual Memory Paging**	**Simple Segmentation**	**Virtual Memory Segmentation**
Main memory partitioned into small fixed-size chunks called frames	Main memory partitioned into small fixed-size chunks called frames	Main memory not partitioned	Main memory not partitioned
Program broken into pages by the compiler or memory management system	Program broken into pages by the compiler or memory management system	Program segments specified by the programmer to the compiler (i.e., the decision is made by the programmer)	Program segments specified by the programmer to the compiler (i.e., the decision is made by the programmer)
Internal fragmentation within frames	Internal fragmentation within frames	No internal fragmentation	No internal fragmentation
No external fragmentation	No external fragmentation	External fragmentation	External fragmentation
Operating system must maintain a page table for each process showing which frame each page occupies	Operating system must maintain a page table for each process showing which frame each page occupies	Operating system must maintain a segment table for each process showing the load address and length of each segment	Operating system must maintain a segment table for each process showing the load address and length of each segment
Operating system must maintain a free frame list	Operating system must maintain a free frame list	Operating system must maintain a list of free holes in main memory	Operating system must maintain a list of free holes in main memory
Processor uses page number, offset to calculate absolute address	Processor uses page number, offset to calculate absolute address	Processor uses segment number, offset to calculate absolute address	Processor uses segment number, offset to calculate absolute address
All the pages of a process must be in main memory for process to run, unless overlays are used	Not all pages of a process need be in main memory frames for the process to run. Pages may be read in as needed	All the segments of a process must be in main memory for process to run, unless overlays are used	Not all segments of a process need be in main memory for the process to run. Segments may be read in as needed
	Reading a page into main memory may require writing a page out to disk		Reading a segment into main memory may require writing one or more segments out to disk

Locality and Virtual Memory

The benefits of virtual memory are attractive, but is the scheme practical? At one time, there was considerable debate on this point, but experience with numerous operating systems has demonstrated beyond doubt that virtual memory does work. Accordingly, virtual memory, based on either paging or paging plus segmentation, has become an essential component of contemporary operating systems.

To understand the key issue and why virtual memory was a matter of much debate, let us examine again the task of the OS with respect to virtual memory. Consider a large process, consisting of a long program plus a number of arrays of data. Over any short period of time, execution may be confined to a small section of the program (e.g., a subroutine) and access to perhaps only one or two arrays of data. If this is so, then it would clearly be wasteful to load in dozens of pieces for that process when only a few pieces will be used before the program is suspended and swapped out. We can make better use of memory by loading in just a few pieces. Then, if the program branches to an instruction or references a data item on a piece not in main memory, a fault is triggered. This tells the OS to bring in the desired piece.

Thus, at any one time, only a few pieces of any given process are in memory, and therefore more processes can be maintained in memory. Furthermore, time is saved because unused pieces are not swapped in and out of memory. However, the OS must be clever about how it manages this scheme. In the steady state, practically all of main memory will be occupied with process pieces, so that the processor and OS have direct access to as many processes as possible. Thus, when the OS brings one piece in, it must throw another out. If it throws out a piece just before it is used, then it will just have to go get that piece again almost immediately. Too much of this leads to a condition known as **thrashing**: The system spends most of its time swapping pieces rather than executing instructions. The avoidance of thrashing was a major research area in the 1970s and led to a variety of complex but effective algorithms. In essence, the OS tries to guess, based on recent history, which pieces are least likely to be used in the near future.

This reasoning is based on belief in the **principle of locality**, which was introduced in Chapter 1 (see especially Appendix 1A). To summarize, the principle of locality states that program and data references within a process tend to cluster. Hence, the assumption that only a few pieces of a process will be needed over a short period of time is valid. Also, it should be possible to make intelligent guesses about which pieces of a process will be needed in the near future, which avoids thrashing.

One way to confirm the principle of locality is to look at the performance of processes in a virtual memory environment. Figure 8.1 is a rather famous diagram that dramatically illustrates the principle of locality [HATF72]. Note that, during the lifetime of the process, references are confined to a subset of pages.

Thus we see that the principle of locality suggests that a virtual memory scheme may work. For virtual memory to be practical and effective, two ingredients are needed. First, there must be hardware support for the paging and/or segmentation scheme to be employed. Second, the OS must include software for managing the movement of pages and/or segments between secondary memory and main memory. In this section, we examine the hardware aspect and look at the

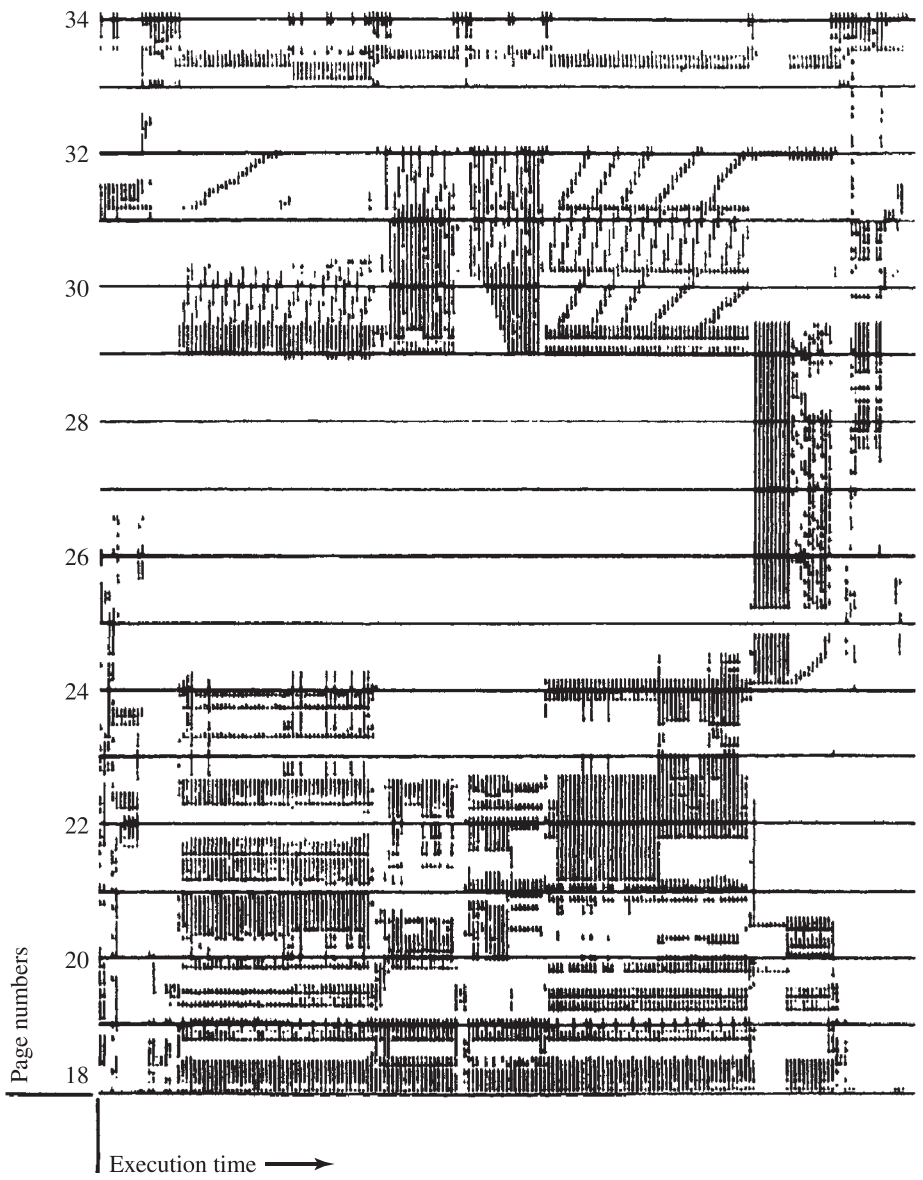


Figure 8.1 Paging Behavior

necessary control structures, which are created and maintained by the OS but are used by the memory management hardware. An examination of the OS issues is provided in the next section.

Paging

The term *virtual memory* is usually associated with systems that employ paging, although virtual memory based on segmentation is also used and is discussed next. The use of paging to achieve virtual memory was first reported for the Atlas computer [KILB62] and soon came into widespread commercial use.

In the discussion of simple paging, we indicated that each process has its own page table, and when all of its pages are loaded into main memory, the page table for a process is created and loaded into main memory. Each page table entry (PTE) contains the frame number of the corresponding page in main memory. A page table is also needed for a virtual memory scheme based on paging. Again, it is typical to associate a unique page table with each process. In this case, however, the page table entries become more complex (Figure 8.2a). Because only some of the pages of a process may be in main memory, a bit is needed in each page table entry to indicate whether the corresponding page is present (P) in main memory or not. If the bit indicates that the page is in memory, then the entry also includes the frame number of that page.

The page table entry includes a modify (M) bit, indicating whether the contents of the corresponding page have been altered since the page was last loaded into main memory. If there has been no change, then it is not necessary to write the page out when it comes time to replace the page in the frame that it currently occupies. Other control bits may also be present. For example, if protection or sharing is managed at the page level, then bits for that purpose will be required.

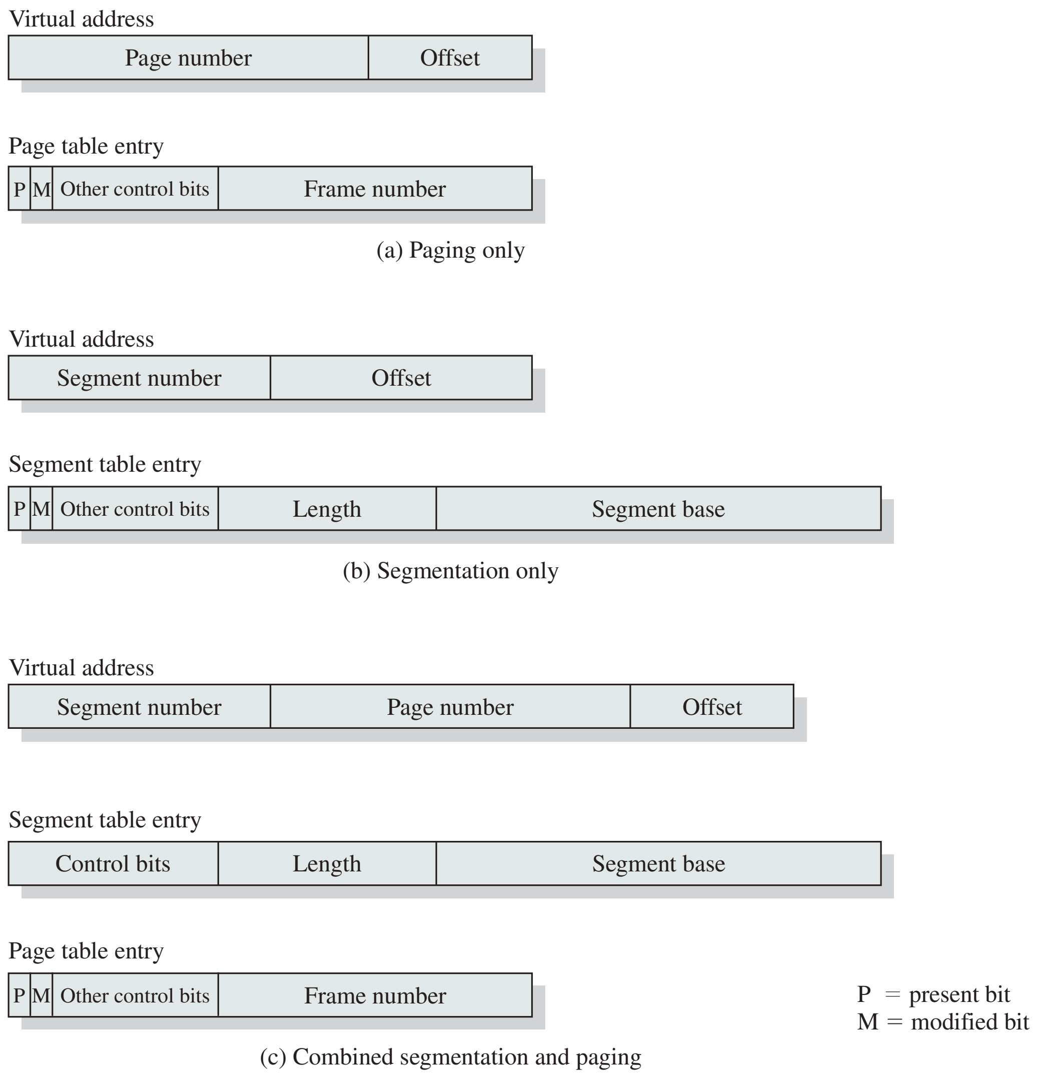


Figure 8.2 Typical Memory Management Formats

Page Table Structure The basic mechanism for reading a word from memory involves the translation of a virtual, or logical, address, consisting of page number and offset, into a physical address, consisting of frame number and offset, using a page table. Because the page table is of variable length, depending on the size of the process, we cannot expect to hold it in registers. Instead, it must be in main memory to be accessed. Figure 8.3 suggests a hardware implementation. When a particular process is running, a register holds the starting address of the page table for that process. The page number of a virtual address is used to index that table and look up the corresponding frame number. This is combined with the offset portion of the virtual address to produce the desired real address. Typically, the page number field is longer than the frame number field ($n > m$).

In most systems, there is one page table per process. But each process can occupy huge amounts of virtual memory. For example, in the VAX architecture, each process can have up to $2^{31} = 2$ Gbytes of virtual memory. Using $2^9 = 512$-byte pages means that as many as 2^{22} page table entries are required *per process*. Clearly, the amount of memory devoted to page tables alone could be unacceptably high. To overcome this problem, most virtual memory schemes store page tables in virtual memory rather than real memory. This means that page tables are subject to paging just as other pages are. When a process is running, at least a part of its page table must be in main memory, including the page table entry of the currently executing page. Some processors make use of a two-level scheme to organize large page tables. In this scheme, there is a page directory, in which each entry points to a page table. Thus, if the length of the page directory is X, and if the maximum length of a page table is Y, then a process can

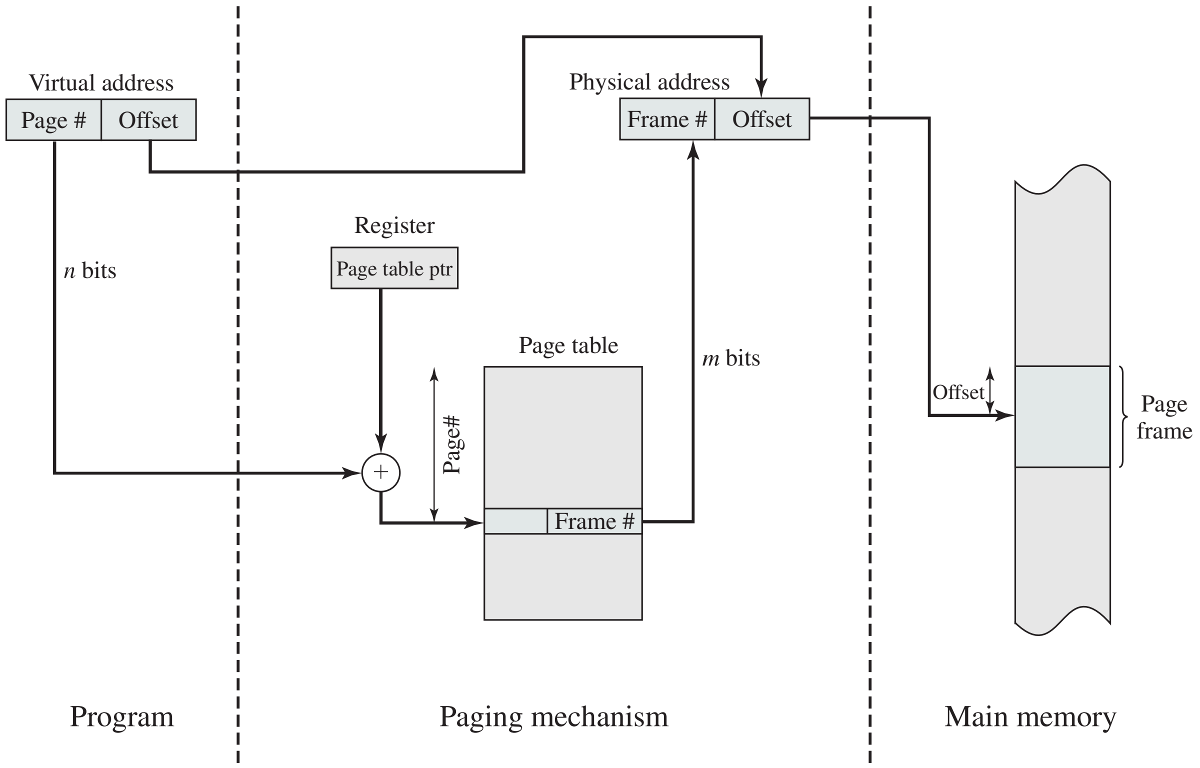


Figure 8.3 Address Translation in a Paging System

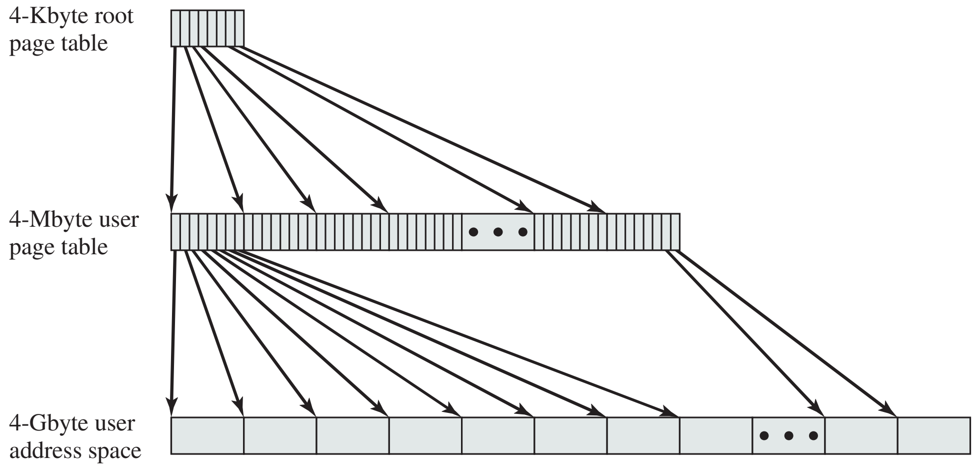


Figure 8.4 A Two-Level Hierarchical Page Table

consist of up to $X \times Y$ pages. Typically, the maximum length of a page table is restricted to be equal to one page. For example, the Pentium processor uses this approach.

Figure 8.4 shows an example of a two-level scheme typical for use with a 32-bit address. If we assume byte-level addressing and 4-Kbyte (2^{12}) pages, then the 4-Gbyte (2^{32}) virtual address space is composed of 2^{20} pages. If each of these pages is mapped by a 4-byte page table entry, we can create a user page table composed of 2^{20} PTEs requiring 4 Mbytes (2^{22}). This huge user page table, occupying 2^{10} pages, can be kept in virtual memory and mapped by a root page table with 2^{10} PTEs occupying 4 Kbytes (2^{12}) of main memory. Figure 8.5 shows the steps involved in address

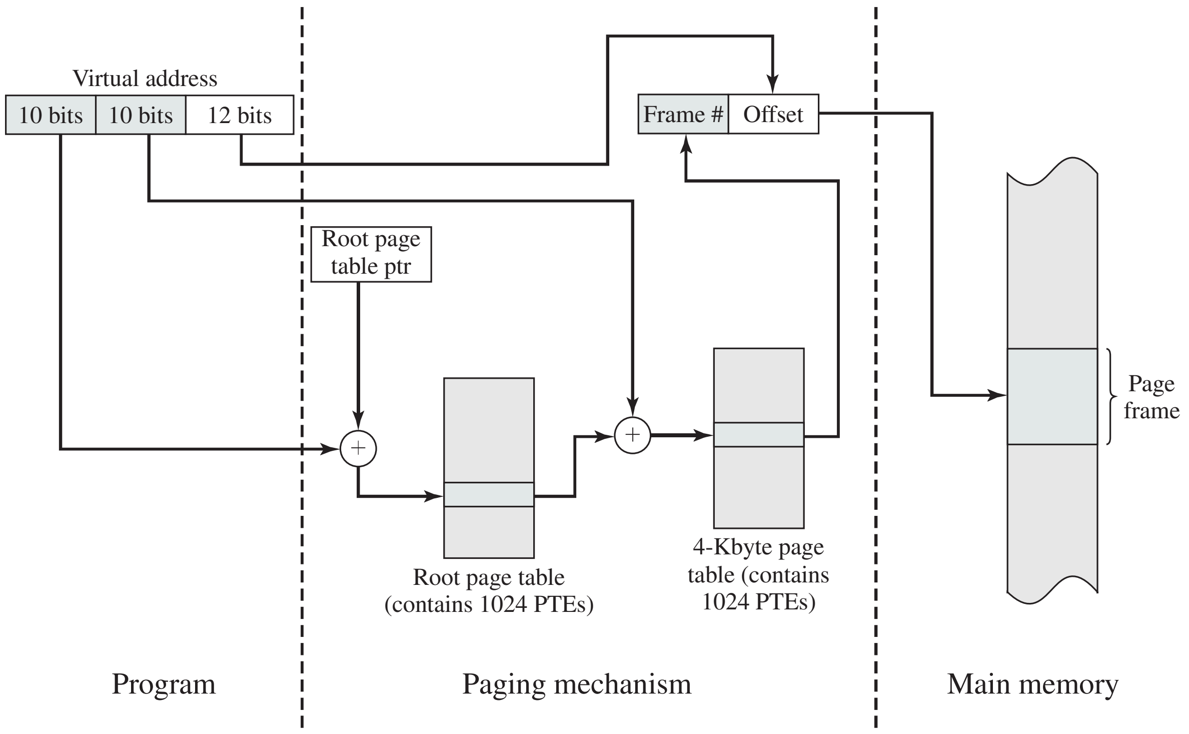


Figure 8.5 Address Translation in a Two-Level Paging System

translation for this scheme. The root page always remains in main memory. The first 10 bits of a virtual address are used to index into the root page to find a PTE for a page of the user page table. If that page is not in main memory, a page fault occurs. If that page is in main memory, then the next 10 bits of the virtual address index into the user PTE page to find the PTE for the page that is referenced by the virtual address.

Inverted Page Table A drawback of the type of page tables that we have been discussing is that their size is proportional to that of the virtual address space.

An alternative approach to the use of one or multiple-level page tables is the use of an **inverted page table** structure. Variations on this approach are used on the PowerPC, UltraSPARC, and the IA-64 architecture. An implementation of the Mach operating system on the RT-PC also uses this technique.

In this approach, the page number portion of a virtual address is mapped into a hash value using a simple hashing function.[1] The hash value is a pointer to the inverted page table, which contains the page table entries. There is one entry in the inverted page table for each real memory page frame rather than one per virtual page. Thus, a fixed proportion of real memory is required for the tables regardless of the number of processes or virtual pages supported. Because more than one virtual address may map into the same hash table entry, a chaining technique is used for managing the overflow. The hashing technique results in chains that are typically short—between one and two entries. The page table's structure is called *inverted* because it indexes page table entries by frame number rather than by virtual page number.

Figure 8.6 shows a typical implementation of the inverted page table approach. For a physical memory size of 2^m frames, the inverted page table contains 2^m entries, so that the ith entry refers to frame i. Each entry in the page table includes the following:

- **Page number:** This is the page number portion of the virtual address.
- **Process identifier:** The process that owns this page. The combination of page number and process identifier identify a page within the virtual address space of a particular process.
- **Control bits:** This field includes flags, such as valid, referenced, and modified; and protection and locking information.
- **Chain pointer:** This field is null (perhaps indicated by a separate bit) if there are no chained entries for this entry. Otherwise, the field contains the index value (number between 0 and $2^m - 1$) of the next entry in the chain.

In this example, the virtual address includes an n-bit page number, with $n > m$. The hash function maps the n-bit page number into an m-bit quantity, which is used to index into the inverted page table.

Translation Lookaside Buffer In principle, every virtual memory reference can cause two physical memory accesses: one to fetch the appropriate page table entry and one to fetch the desired data. Thus, a straightforward virtual memory

[1]See Appendix F for a discussion of hashing.

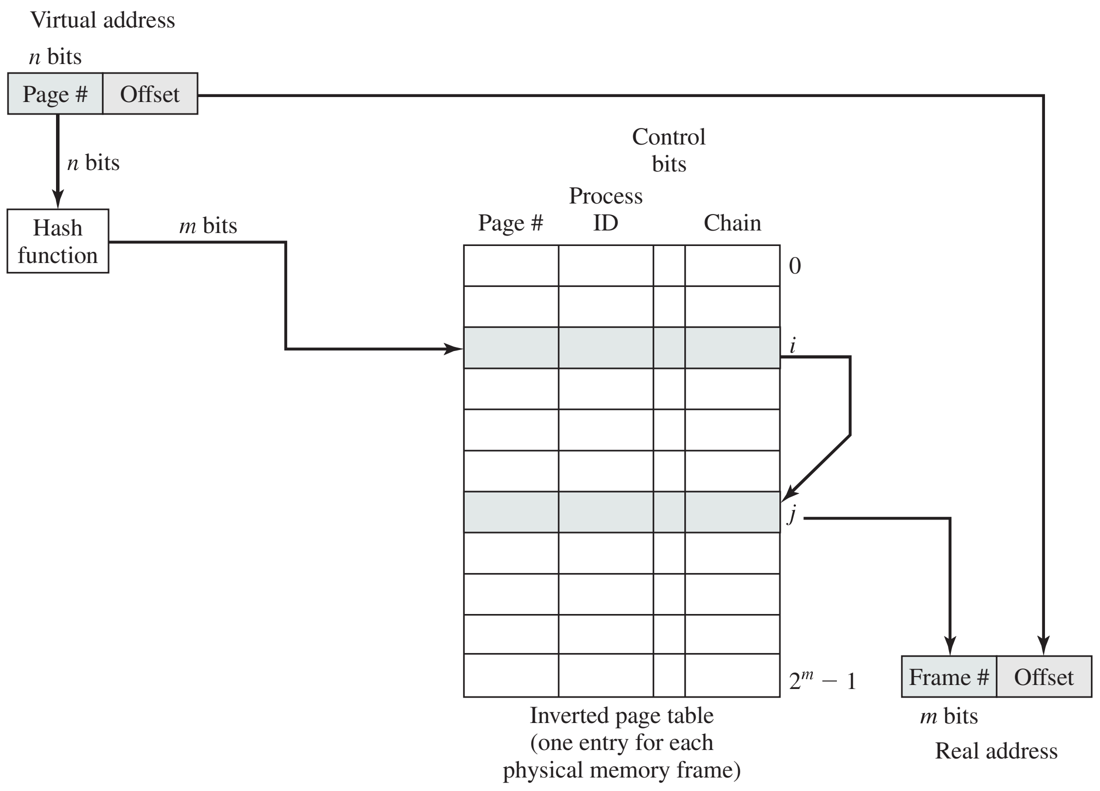


Figure 8.6 Inverted Page Table Structure

scheme would have the effect of doubling the memory access time. To overcome this problem, most virtual memory schemes make use of a special high-speed cache for page table entries, usually called a **translation lookaside buffer (TLB)**. This cache functions in the same way as a memory cache (see Chapter 1) and contains those page table entries that have been most recently used. The organization of the resulting paging hardware is illustrated in Figure 8.7. Given a virtual address, the processor will first examine the TLB. If the desired page table entry is present (*TLB hit*), then the frame number is retrieved and the real address is formed. If the desired page table entry is not found (*TLB miss*), then the processor uses the page number to index the process page table and examine the corresponding page table entry. If the "present bit" is set, then the page is in main memory, and the processor can retrieve the frame number from the page table entry to form the real address. The processor also updates the TLB to include this new page table entry. Finally, if the present bit is not set, then the desired page is not in main memory and a memory access fault, called a **page fault**, is issued. At this point, we leave the realm of hardware and invoke the OS, which loads the needed page and updates the page table.

Figure 8.8 is a flowchart that shows the use of the TLB. The flowchart shows that if the desired page is not in main memory, a page fault interrupt causes the page fault handling routine to be invoked. To keep the flowchart simple, the fact that the OS may dispatch another process while disk I/O is underway is not shown. By the principle of locality, most virtual memory references will be to locations in

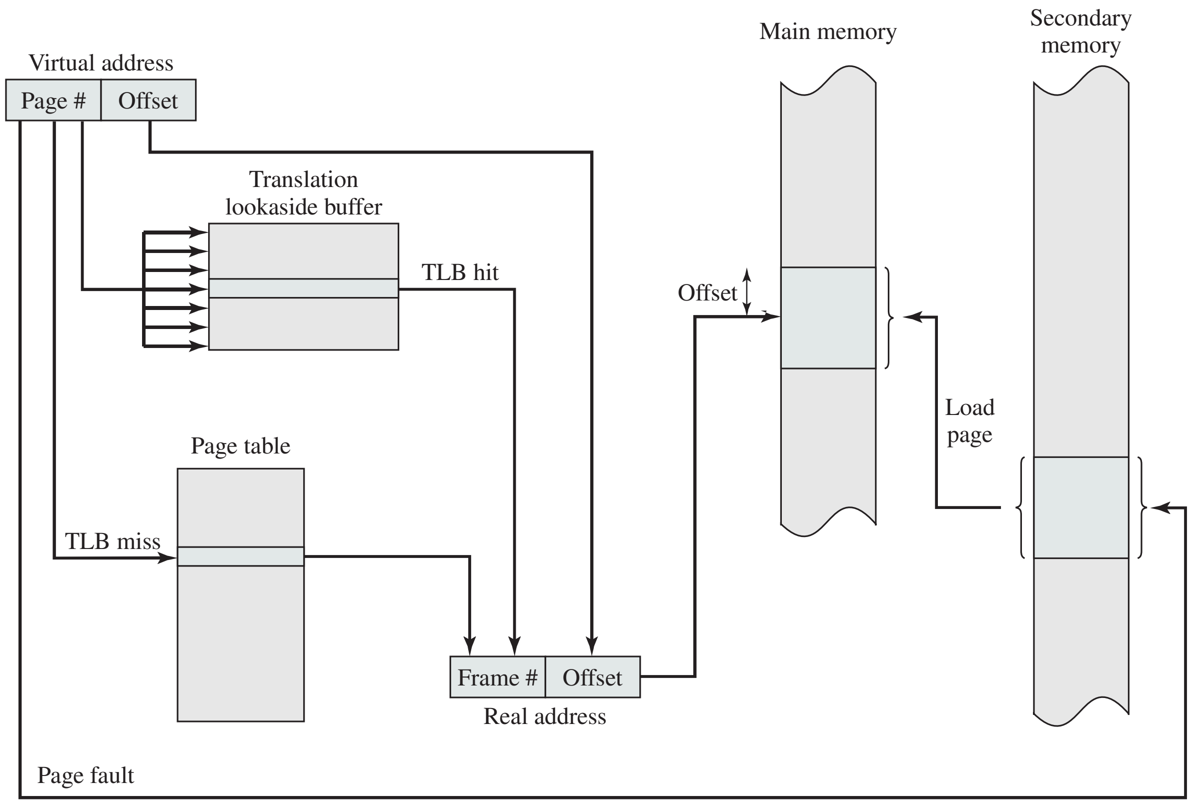


Figure 8.7 Use of a Translation Lookaside Buffer

recently used pages. Therefore, most references will involve page table entries in the cache. Studies of the VAX TLB have shown that this scheme can significantly improve performance [CLAR85, SATY81].

There are a number of additional details concerning the actual organization of the TLB. Because the TLB contains only some of the entries in a full page table, we cannot simply index into the TLB based on page number. Instead, each entry in the TLB must include the page number as well as the complete page table entry. The processor is equipped with hardware that allows it to interrogate simultaneously a number of TLB entries to determine if there is a match on page number. This technique is referred to as **associative mapping** and is contrasted with the direct mapping, or indexing, used for lookup in the page table in Figure 8.9. The design of the TLB also must consider the way in which entries are organized in the TLB and which entry to replace when a new entry is brought in. These issues must be considered in any hardware cache design. This topic is not pursued here; the reader may consult a treatment of cache design for further details (e.g., [STAL10]).

Finally, the virtual memory mechanism must interact with the cache system (not the TLB cache, but the main memory cache). This is illustrated in Figure 8.10. A virtual address will generally be in the form of a page number, offset. First, the memory system consults the TLB to see if the matching page table entry is present. If it is, the real (physical) address is generated by combining the frame number with the offset. If not, the entry is accessed from a page table. Once the real address is

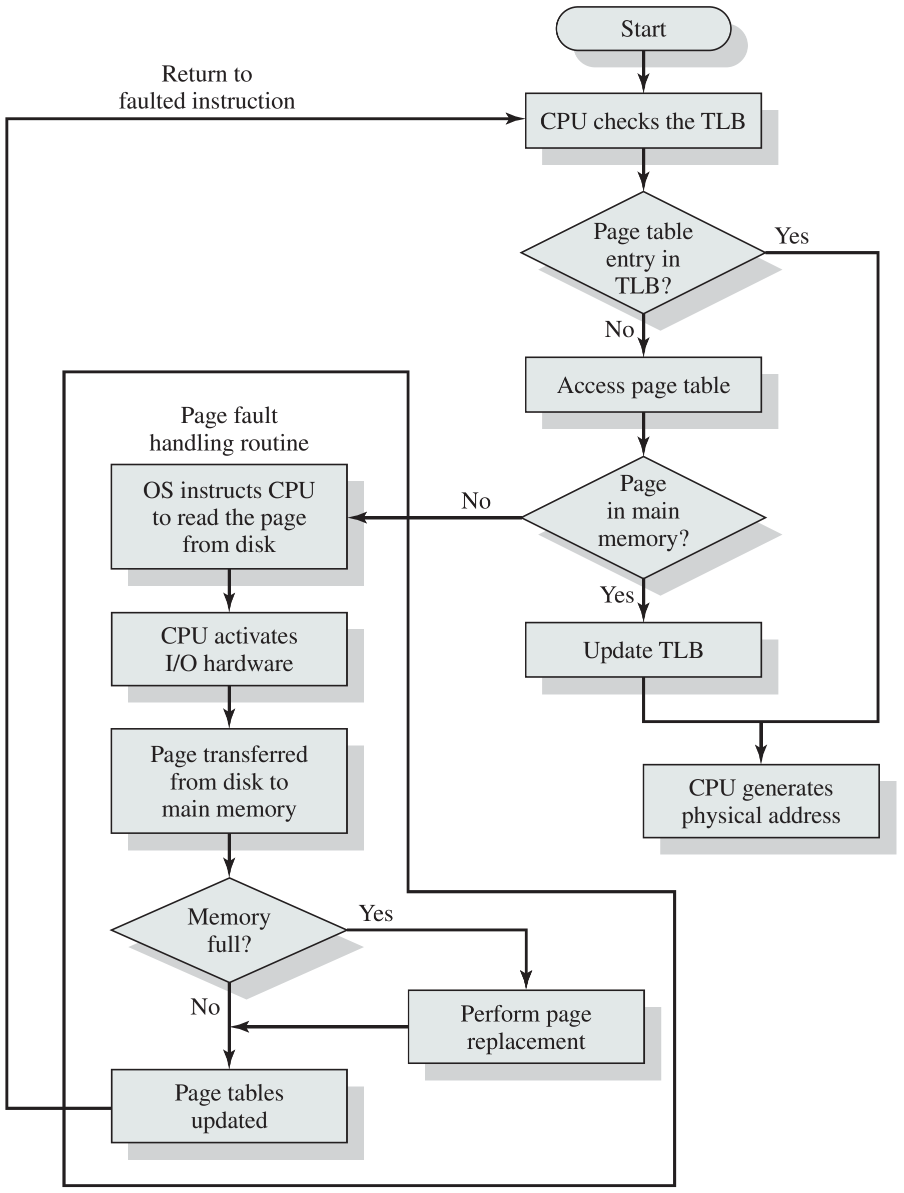

Start
CPU checks the TLB
Return to faulted instruction
Page table entry in TLB?
Yes
No
Access page table
Page in main memory?
No
Yes
Update TLB
CPU generates physical address
Page fault handling routine
OS instructs CPU to read the page from disk
CPU activates I/O hardware
Page transferred from disk to main memory
Memory full?
Yes
No
Perform page replacement
Page tables updated

Figure 8.8 Operation of Paging and Translation Lookaside Buffer (TLB)

generated, which is in the form of a tag[2] and a remainder, the cache is consulted to see if the block containing that word is present. If so, it is returned to the CPU. If not, the word is retrieved from main memory.

The reader should be able to appreciate the complexity of the CPU hardware involved in a single memory reference. The virtual address is translated into a real address. This involves reference to a page table entry, which may be in the TLB, in main memory, or on disk. The referenced word may be in cache, main memory, or on disk. If the referenced word is only on disk, the page containing the word must

[2]See Figure 1.17. Typically, a tag is just the leftmost bits of the real address. Again, for a more detailed discussion of caches, see [STAL10].

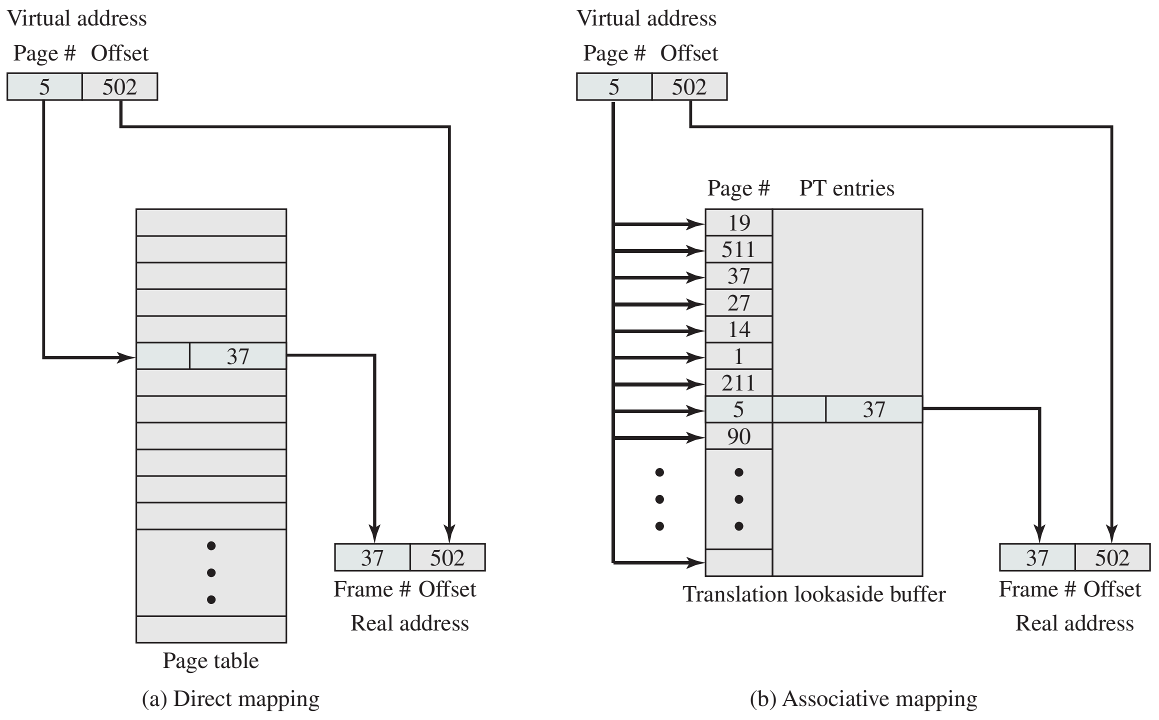


Figure 8.9 Direct versus Associative Lookup for Page Table Entries

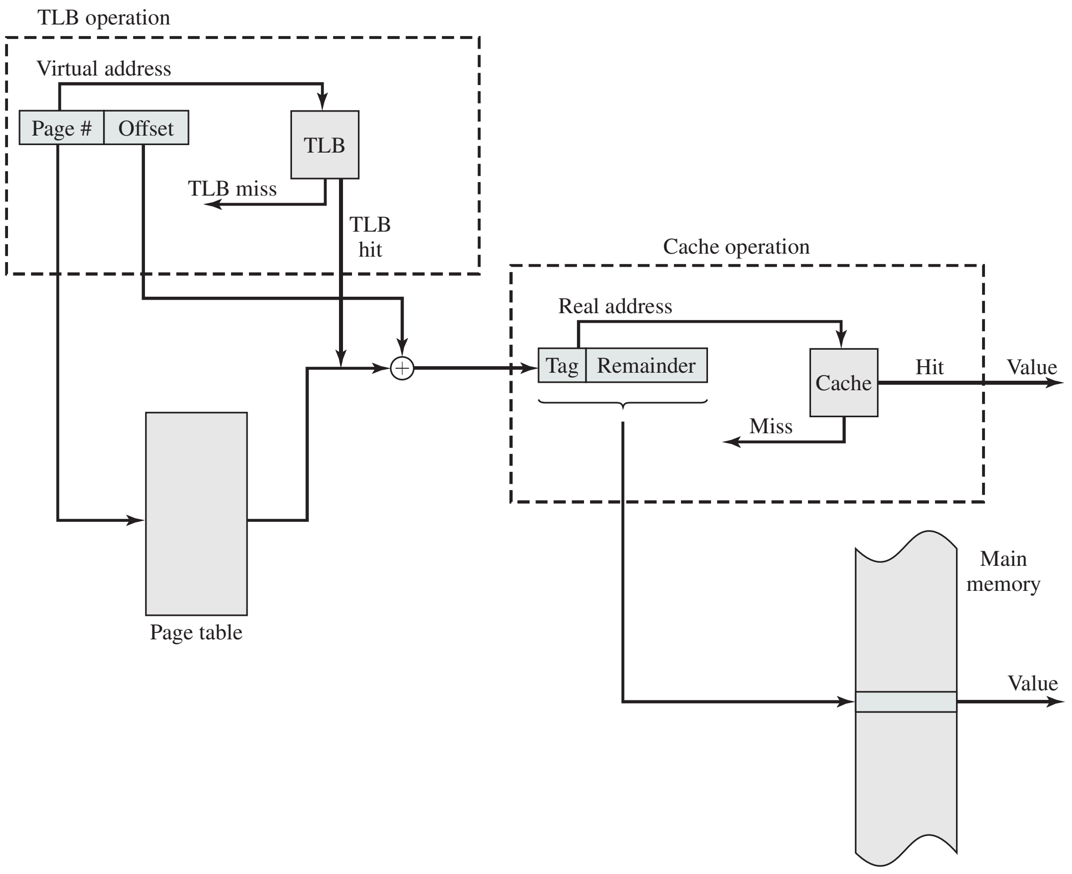


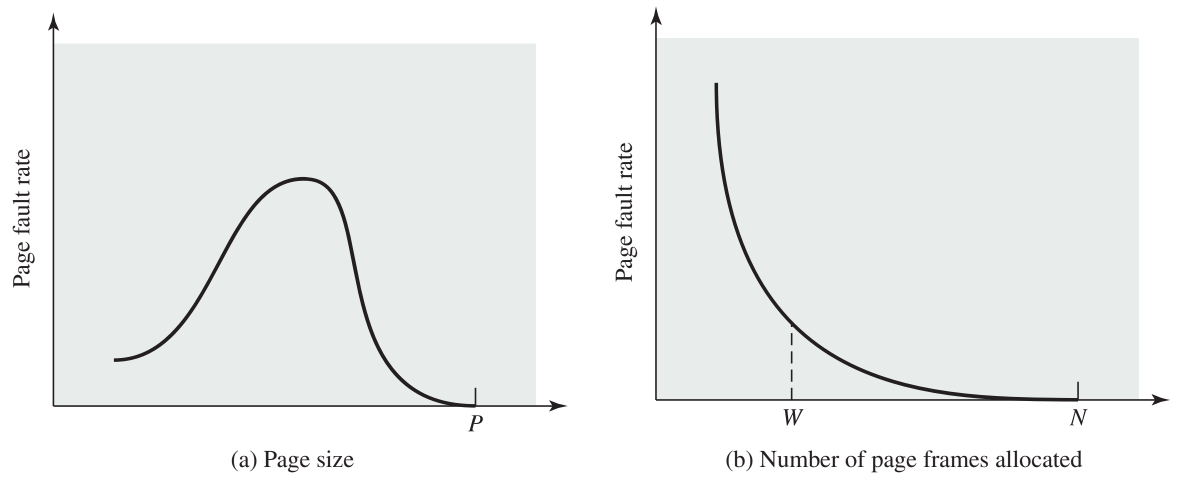
Figure 8.10 Translation Lookaside Buffer and Cache Operation

be loaded into main memory and its block loaded into the cache. In addition, the page table entry for that page must be updated.

Page Size An important hardware design decision is the size of page to be used. There are several factors to consider. One is internal fragmentation. Clearly, the smaller the page size, the lesser is the amount of internal fragmentation. To optimize the use of main memory, we would like to reduce internal fragmentation. On the other hand, the smaller the page, the greater is the number of pages required per process. More pages per process means larger page tables. For large programs in a heavily multiprogrammed environment, this may mean that some portion of the page tables of active processes must be in virtual memory, not in main memory. Thus, there may be a double page fault for a single reference to memory: first to bring in the needed portion of the page table and second to bring in the process page. Another factor is that the physical characteristics of most secondary-memory devices, which are rotational, favor a larger page size for more efficient block transfer of data.

Complicating these matters is the effect of page size on the rate at which page faults occur. This behavior, in general terms, is depicted in Figure 8.11a and is based on the principle of locality. If the page size is very small, then ordinarily a relatively large number of pages will be available in main memory for a process. After a time, the pages in memory will all contain portions of the process near recent references. Thus, the page fault rate should be low. As the size of the page is increased, each individual page will contain locations further and further from any particular recent reference. Thus the effect of the principle of locality is weakened and the page fault rate begins to rise. Eventually, however, the page fault rate will begin to fall as the size of a page approaches the size of the entire process (point *P* in the diagram). When a single page encompasses the entire process, there will be no page faults.

A further complication is that the page fault rate is also determined by the number of frames allocated to a process. Figure 8.11b shows that, for a fixed page



P = size of entire process
W = working set size
N = total number of pages in process

Figure 8.11 Typical Paging Behavior of a Program

Table 8.3 Example Page Sizes

Computer	Page Size
Atlas	512 48-bit words
Honeywell-Multics	1,024 36-bit words
IBM 370/XA and 370/ESA	4 Kbytes
VAX family	512 bytes
IBM AS/400	512 bytes
DEC Alpha	8 Kbytes
MIPS	4 Kbytes to 16 Mbytes
UltraSPARC	8 Kbytes to 4 Mbytes
Pentium	4 Kbytes or 4 Mbytes
Intel Itanium	4 Kbytes to 256 Mbytes
Intel core i7	4 Kbytes to 1 Gbyte

size, the fault rate drops as the number of pages maintained in main memory grows.[3] Thus, a software policy (the amount of memory to allocate to each process) interacts with a hardware design decision (page size).

Table 8.3 lists the page sizes used on some machines.

Finally, the design issue of page size is related to the size of physical main memory and program size. At the same time that main memory is getting larger, the address space used by applications is also growing. The trend is most obvious on personal computers and workstations, where applications are becoming increasingly complex. Furthermore, contemporary programming techniques used in large programs tend to decrease the locality of references within a process [HUCK93]. For example,

- Object-oriented techniques encourage the use of many small program and data modules with references scattered over a relatively large number of objects over a relatively short period of time.
- Multithreaded applications may result in abrupt changes in the instruction stream and in scattered memory references.

For a given size of TLB, as the memory size of processes grows and as locality decreases, the hit ratio on TLB accesses declines. Under these circumstances, the TLB can become a performance bottleneck (e.g., see [CHEN92]).

One way to improve TLB performance is to use a larger TLB with more entries. However, TLB size interacts with other aspects of the hardware design, such as the main memory cache and the number of memory accesses per instruction cycle [TALL92]. The upshot is that TLB size is unlikely to grow as rapidly as main memory size. An alternative is to use larger page sizes so that each page table entry in the TLB refers to a larger block of memory. But we have just seen that the use of large page sizes can lead to performance degradation.

[3]The parameter W represents working set size, a concept discussed in Section 8.2.

Accordingly, a number of designers have investigated the use of multiple page sizes [TALL92, KHAL93], and several microprocessor architectures support multiple pages sizes, including MIPS R4000, Alpha, UltraSPARC, Pentium, and IA-64. Multiple page sizes provide the flexibility needed to use a TLB effectively. For example, large contiguous regions in the address space of a process, such as program instructions, may be mapped using a small number of large pages rather than a large number of small pages, while thread stacks may be mapped using the small page size. However, most commercial operating systems still support only one page size, regardless of the capability of the underlying hardware. The reason for this is that page size affects many aspects of the OS; thus, a change to multiple page sizes is a complex undertaking (see [GANA98] for a discussion).

Segmentation

Virtual Memory Implications Segmentation allows the programmer to view memory as consisting of multiple address spaces or segments. Segments may be of unequal, indeed dynamic, size. Memory references consist of a (segment number, offset) form of address.

This organization has a number of advantages to the programmer over a nonsegmented address space:

1. It simplifies the handling of growing data structures. If the programmer does not know ahead of time how large a particular data structure will become, it is necessary to guess unless dynamic segment sizes are allowed. With segmented virtual memory, the data structure can be assigned its own segment, and the OS will expand or shrink the segment as needed. If a segment that needs to be expanded is in main memory and there is insufficient room, the OS may move the segment to a larger area of main memory, if available, or swap it out. In the latter case, the enlarged segment would be swapped back in at the next opportunity.
2. It allows programs to be altered and recompiled independently, without requiring the entire set of programs to be relinked and reloaded. Again, this is accomplished using multiple segments.
3. It lends itself to sharing among processes. A programmer can place a utility program or a useful table of data in a segment that can be referenced by other processes.
4. It lends itself to protection. Because a segment can be constructed to contain a well-defined set of programs or data, the programmer or system administrator can assign access privileges in a convenient fashion.

Organization In the discussion of simple segmentation, we indicated that each process has its own segment table, and when all of its segments are loaded into main memory, the segment table for a process is created and loaded into main memory. Each segment table entry contains the starting address of the corresponding segment in main memory, as well as the length of the segment. The same device, a segment table, is needed when we consider a virtual memory scheme based on segmentation. Again, it is typical to associate a unique segment table with each process. In this case, however, the segment table entries become more complex (Figure 8.2b). Because only some of the segments of a process may be in main memory, a bit is needed in each segment table entry to indicate whether the corresponding segment is present in main memory or not. If the bit indicates that the segment is in memory, then the entry also includes the starting address and length of that segment.

Another control bit in the segmentation table entry is a modify bit, indicating whether the contents of the corresponding segment have been altered since the segment was last loaded into main memory. If there has been no change, then it is not necessary to write the segment out when it comes time to replace the segment in the frame that it currently occupies. Other control bits may also be present. For example, if protection or sharing is managed at the segment level, then bits for that purpose will be required.

The basic mechanism for reading a word from memory involves the translation of a virtual, or logical, address, consisting of segment number and offset, into a physical address, using a segment table. Because the segment table is of variable length, depending on the size of the process, we cannot expect to hold it in registers. Instead, it must be in main memory to be accessed. Figure 8.12 suggests a hardware implementation of this scheme (note similarity to Figure 8.3). When a particular process is running, a register holds the starting address of the segment table for that process. The segment number of a virtual address is used to index that table and look up the corresponding main memory address for the start of the segment. This is added to the offset portion of the virtual address to produce the desired real address.

Combined Paging and Segmentation

Both paging and segmentation have their strengths. Paging, which is transparent to the programmer, eliminates external fragmentation and thus provides efficient use of main memory. In addition, because the pieces that are moved in and out of

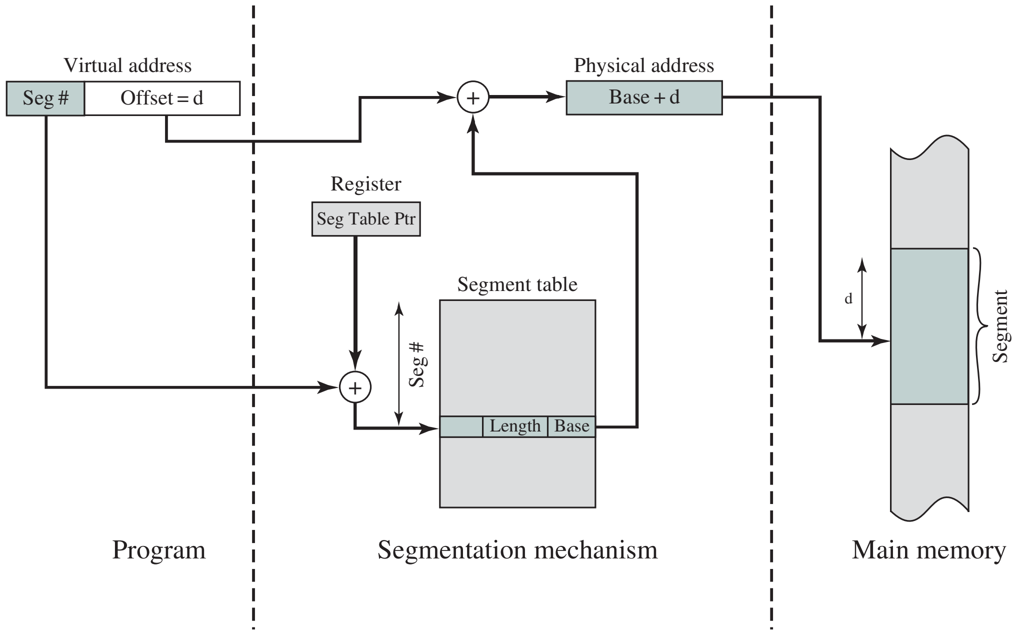


Figure 8.12 **Address Translation in a Segmentation System**

main memory are of fixed, equal size, it is possible to develop sophisticated memory management algorithms that exploit the behavior of programs, as we shall see. Segmentation, which is visible to the programmer, has the strengths listed earlier, including the ability to handle growing data structures, modularity, and support for sharing and protection. To combine the advantages of both, some systems are equipped with processor hardware and OS software to provide both.

In a combined paging/segmentation system, a user's address space is broken up into a number of segments, at the discretion of the programmer. Each segment is, in turn, broken up into a number of fixed-size pages, which are equal in length to a main memory frame. If a segment has length less than that of a page, the segment occupies just one page. From the programmer's point of view, a logical address still consists of a segment number and a segment offset. From the system's point of view, the segment offset is viewed as a page number and page offset for a page within the specified segment.

Figure 8.13 suggests a structure to support combined paging/segmentation (note similarity to Figure 8.5). Associated with each process is a segment table and a number of page tables, one per process segment. When a particular process is running, a register holds the starting address of the segment table for that process. Presented with a virtual address, the processor uses the segment number portion to index into the process segment table to find the page table for that segment. Then the page number portion of the virtual address is used to index the page table and look up the corresponding frame number. This is combined with the offset portion of the virtual address to produce the desired real address.

Figure 8.2c suggests the segment table entry and page table entry formats. As before, the segment table entry contains the length of the segment. It also contains

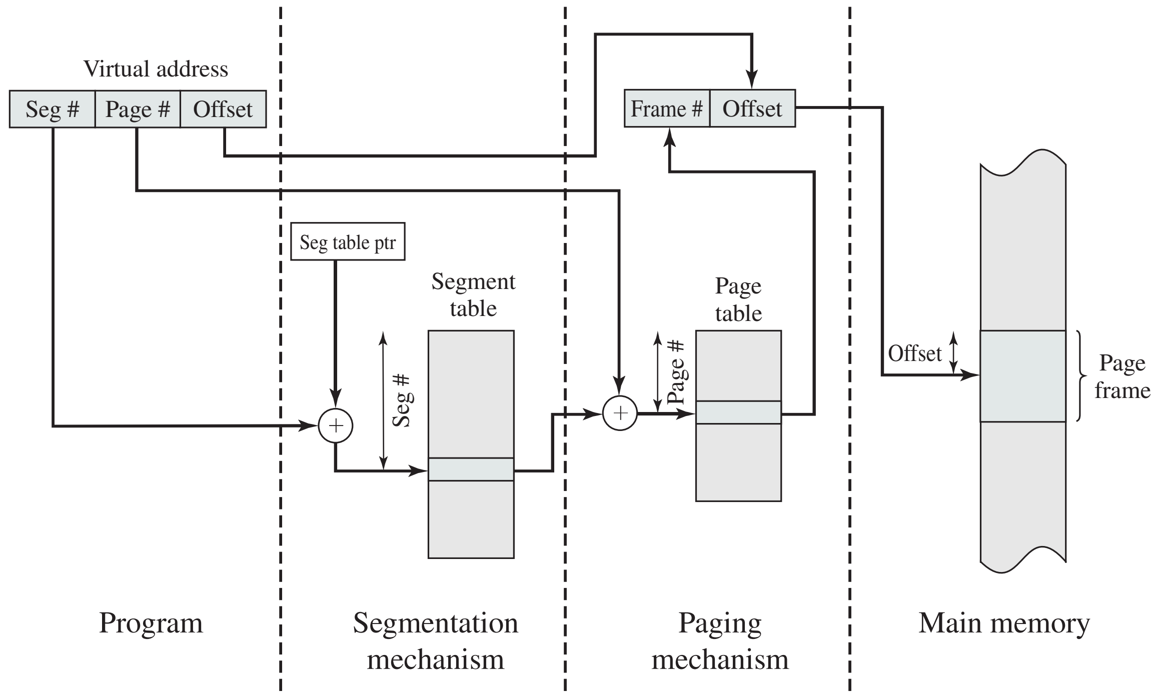


Figure 8.13 **Address Translation in a Segmentation/Paging System**

a base field, which now refers to a page table. The present and modified bits are not needed because these matters are handled at the page level. Other control bits may be used, for purposes of sharing and protection. The page table entry is essentially the same as is used in a pure paging system. Each page number is mapped into a corresponding frame number if the page is present in main memory. The modified bit indicates whether this page needs to be written back out when the frame is allocated to another page. There may be other control bits dealing with protection or other aspects of memory management.

Protection and Sharing

Segmentation lends itself to the implementation of protection and sharing policies. Because each segment table entry includes a length as well as a base address, a program cannot inadvertently access a main memory location beyond the limits of a segment. To achieve sharing, it is possible for a segment to be referenced in the segment tables of more than one process. The same mechanisms are, of course, available in a paging system. However, in this case the page structure of programs and data is not visible to the programmer, making the specification of protection and sharing requirements more awkward. Figure 8.14 illustrates the types of protection relationships that can be enforced in such a system.

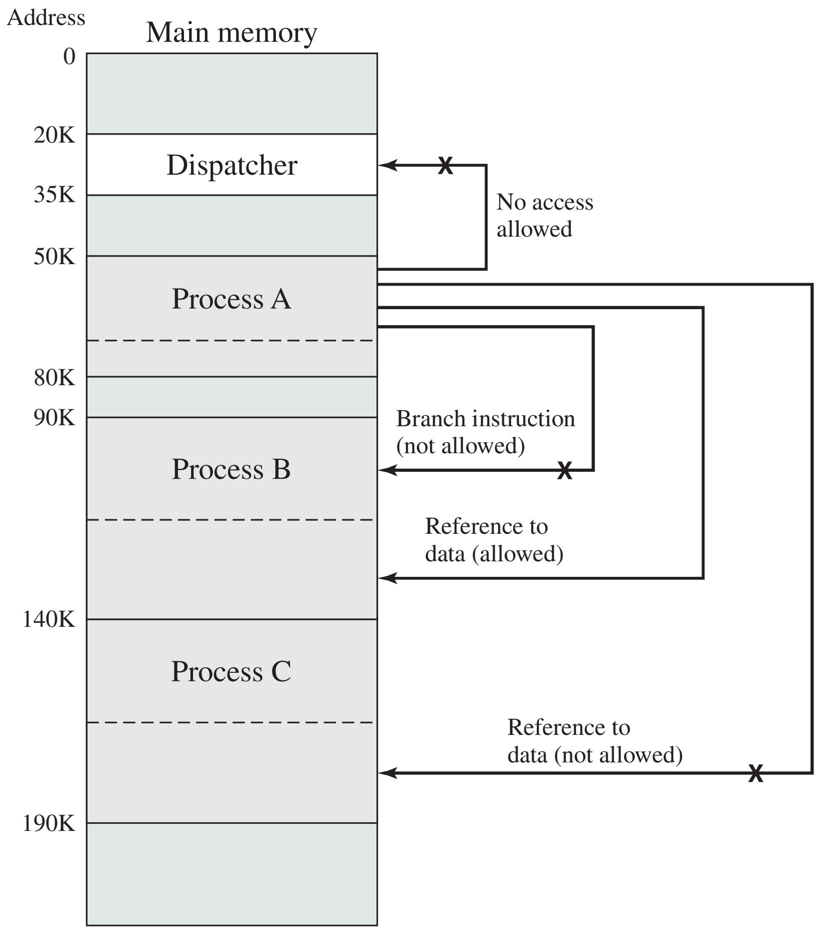


Figure 8.14 Protection Relationships between Segments

More sophisticated mechanisms can also be provided. A common scheme is to use a ring-protection structure, of the type we referred to in Chapter 3 (Figure 3.18). In this scheme, lower-numbered, or inner, rings enjoy greater privilege than higher-numbered, or outer, rings. Typically, ring 0 is reserved for kernel functions of the OS, with applications at a higher level. Some utilities or OS services may occupy an intermediate ring. Basic principles of the ring system are as follows:

1. A program may access only data that reside on the same ring or a less privileged ring.
2. A program may call services residing on the same or a more privileged ring.

8.2 OPERATING SYSTEM SOFTWARE

The design of the memory management portion of an OS depends on three fundamental areas of choice:

- Whether or not to use virtual memory techniques
- The use of paging or segmentation or both
- The algorithms employed for various aspects of memory management

The choices made in the first two areas depend on the hardware platform available. Thus, earlier UNIX implementations did not provide virtual memory because the processors on which the system ran did not support paging or segmentation. Neither of these techniques is practical without hardware support for address translation and other basic functions.

Two additional comments about the first two items in the preceding list: First, with the exception of operating systems for some of the older personal computers, such as MS-DOS, and specialized systems, all important operating systems provide virtual memory. Second, pure segmentation systems are becoming increasingly rare. When segmentation is combined with paging, most of the memory management issues confronting the OS designer are in the area of paging.[4] Thus, we can concentrate in this section on the issues associated with paging.

The choices related to the third item are the domain of operating system software and are the subject of this section. Table 8.4 lists the key design elements that we examine. In each case, the key issue is one of performance: We would like to minimize the rate at which page faults occur, because page faults cause considerable software overhead. At a minimum, the overhead includes deciding which resident page or pages to replace, and the I/O of exchanging pages. Also, the OS must schedule another process to run during the page I/O, causing a process switch. Accordingly, we would like to arrange matters so that, during the time that a process is executing, the probability of referencing a word on a missing page is minimized. In all of the areas referred to in Table 8.4, there is no definitive policy that works best.

[4]Protection and sharing are usually dealt with at the segment level in a combined segmentation/paging system. We will deal with these issues in later chapters.

Table 8.4 Operating System Policies for Virtual Memory

Fetch Policy	**Resident Set Management**
Demand paging	Resident set size
Prepaging	Fixed
	Variable
Placement Policy	Replacement Scope
	Global
Replacement Policy	Local
Basic Algorithms	
Optimal	**Cleaning Policy**
Least recently used (LRU)	Demand
First-in-first-out (FIFO)	Precleaning
Clock	
Page Buffering	**Load Control**
	Degree of multiprogramming

As we shall see, the task of memory management in a paging environment is fiendishly complex. Furthermore, the performance of any particular set of policies depends on main memory size, the relative speed of main and secondary memory, the size and number of processes competing for resources, and the execution behavior of individual programs. This latter characteristic depends on the nature of the application, the programming language and compiler employed, the style of the programmer who wrote it, and, for an interactive program, the dynamic behavior of the user. Thus, the reader must expect no final answers here or anywhere. For smaller systems, the OS designer should attempt to choose a set of policies that seems "good" over a wide range of conditions, based on the current state of knowledge. For larger systems, particularly mainframes, the operating system should be equipped with monitoring and control tools that allow the site manager to tune the operating system to get "good" results based on site conditions.

Fetch Policy

The fetch policy determines when a page should be brought into main memory. The two common alternatives are demand paging and prepaging. With **demand paging**, a page is brought into main memory only when a reference is made to a location on that page. If the other elements of memory management policy are good, the following should happen. When a process is first started, there will be a flurry of page faults. As more and more pages are brought in, the principle of locality suggests that most future references will be to pages that have recently been brought in. Thus, after a time, matters should settle down and the number of page faults should drop to a very low level.

With **prepaging,** pages other than the one demanded by a page fault are brought in. Prepaging exploits the characteristics of most secondary memory devices, such as disks, which have seek times and rotational latency. If the pages of a process are stored contiguously in secondary memory, then it is more efficient to bring in a number of contiguous pages at one time rather than bringing them in one at a time over an extended period. Of course, this policy is ineffective if most of the extra pages that are brought in are not referenced.

The prepaging policy could be employed either when a process first starts up, in which case the programmer would somehow have to designate desired pages, or every time a page fault occurs. This latter course would seem preferable because it is invisible to the programmer. However, the utility of prepaging has not been established [MAEK87].

Prepaging should not be confused with swapping. When a process is swapped out of memory and put in a suspended state, all of its resident pages are moved out. When the process is resumed, all of the pages that were previously in main memory are returned to main memory.

Placement Policy

The placement policy determines where in real memory a process piece is to reside. In a pure segmentation system, the placement policy is an important design issue; policies such as best-fit, first-fit, and so on, which were discussed in Chapter 7, are possible alternatives. However, for a system that uses either pure paging or paging combined with segmentation, placement is usually irrelevant because the address translation hardware and the main memory access hardware can perform their functions for any page-frame combination with equal efficiency.

There is one area in which placement does become a concern, and this is a subject of research and development. On a so-called nonuniform memory access (NUMA) multiprocessor, the distributed, shared memory of the machine can be referenced by any processor on the machine, but the time for accessing a particular physical location varies with the distance between the processor and the memory module. Thus, performance depends heavily on the extent to which data reside close to the processors that use them [LARO92, BOLO89, COX89]. For NUMA systems, an automatic placement strategy is desirable to assign pages to the memory module that provides the best performance.

Replacement Policy

In most operating system texts, the treatment of memory management includes a section entitled "replacement policy," which deals with the selection of a page in main memory to be replaced when a new page must be brought in. This topic is sometimes difficult to explain because several interrelated concepts are involved:

- How many page frames are to be allocated to each active process
- Whether the set of pages to be considered for replacement should be limited to those of the process that caused the page fault or encompass all the page frames in main memory
- Among the set of pages considered, which particular page should be selected for replacement

We shall refer to the first two concepts as *resident set management*, which is dealt with in the next subsection, and reserve the term *replacement policy* for the third concept, which is discussed in this subsection.

The area of replacement policy is probably the most studied of any area of memory management. When all of the frames in main memory are occupied and it is necessary to bring in a new page to satisfy a page fault, the replacement policy determines which page currently in memory is to be replaced. All of the policies have as their objective that the page that is removed should be the page least likely to be referenced in the near future. Because of the principle of locality, there is often a high correlation between recent referencing history and near-future referencing patterns. Thus, most policies try to predict future behavior on the basis of past behavior. One trade-off that must be considered is that the more elaborate and sophisticated the replacement policy, the greater will be the hardware and software overhead to implement it.

Frame Locking One restriction on replacement policy needs to be mentioned before looking at various algorithms: Some of the frames in main memory may be locked. When a frame is locked, the page currently stored in that frame may not be replaced. Much of the kernel of the OS, as well as key control structures, are held in locked frames. In addition, I/O buffers and other time-critical areas may be locked into main memory frames. Locking is achieved by associating a lock bit with each frame. This bit may be kept in a frame table as well as being included in the current page table.

Basic Algorithms Regardless of the resident set management strategy (discussed in the next subsection), there are certain basic algorithms that are used for the selection of a page to replace. Replacement algorithms that have been discussed in the literature include

- Optimal
- Least recently used (LRU)
- First-in-first-out (FIFO)
- Clock

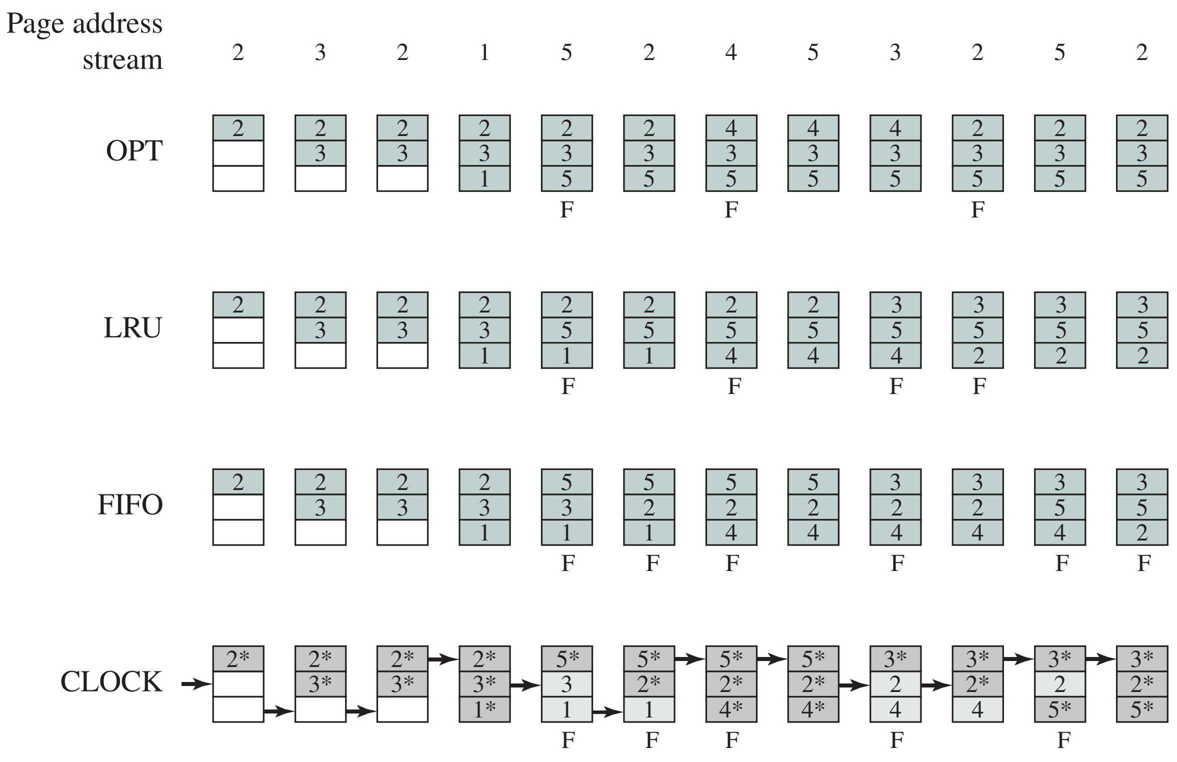
The **optimal** policy selects for replacement that page for which the time to the next reference is the longest. It can be shown that this policy results in the fewest number of page faults [BELA66]. Clearly, this policy is impossible to implement, because it would require the OS to have perfect knowledge of future events. However, it does serve as a standard against which to judge real-world algorithms.

Figure 8.15 gives an example of the optimal policy. The example assumes a fixed frame allocation (fixed resident set size) for this process of three frames. The execution of the process requires reference to five distinct pages. The page address stream formed by executing the program is

2 3 2 1 5 2 4 5 3 2 5 2

which means that the first page referenced is 2, the second page referenced is 3, and so on. The optimal policy produces three page faults after the frame allocation has been filled.

The **least recently used (LRU)** policy replaces the page in memory that has not been referenced for the longest time. By the principle of locality, this should be the page least likely to be referenced in the near future. And, in fact, the LRU policy does nearly as well as the optimal policy. The problem with this approach is the difficulty in implementation. One approach would be to tag each page with the



F = page fault occurring after the frame allocation is initially filled

Figure 8.15 Behavior of Four Page Replacement Algorithms

time of its last reference; this would have to be done at each memory reference, both instruction and data. Even if the hardware would support such a scheme, the overhead would be tremendous. Alternatively, one could maintain a stack of page references, again an expensive prospect.

Figure 8.15 shows an example of the behavior of LRU, using the same page address stream as for the optimal policy example. In this example, there are four page faults.

The **first-in-first-out (FIFO)** policy treats the page frames allocated to a process as a circular buffer, and pages are removed in round-robin style. All that is required is a pointer that circles through the page frames of the process. This is therefore one of the simplest page replacement policies to implement. The logic behind this choice, other than its simplicity, is that one is replacing the page that has been in memory the longest: A page fetched into memory a long time ago may have now fallen out of use. This reasoning will often be wrong, because there will often be regions of program or data that are heavily used throughout the life of a program. Those pages will be repeatedly paged in and out by the FIFO algorithm.

Continuing our example in Figure 8.15, the FIFO policy results in six page faults. Note that LRU recognizes that pages 2 and 5 are referenced more frequently than other pages, whereas FIFO does not.

Although the LRU policy does nearly as well as an optimal policy, it is difficult to implement and imposes significant overhead. On the other hand, the FIFO policy is very simple to implement but performs relatively poorly. Over the years, OS designers have tried a number of other algorithms to approximate the performance of LRU while imposing little overhead. Many of these algorithms are variants of a scheme referred to as the **clock policy**.

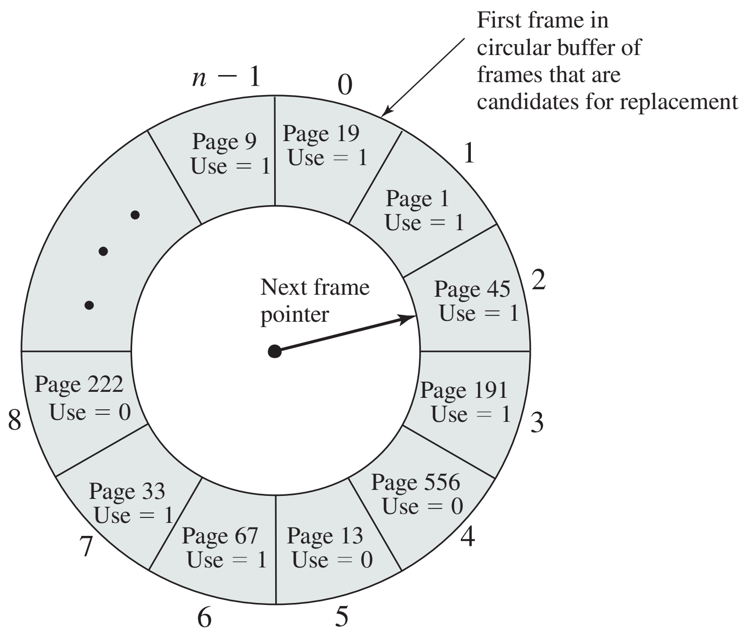
The simplest form of clock policy requires the association of an additional bit with each frame, referred to as the use bit. When a page is first loaded into a frame in memory, the use bit for that frame is set to 1. Whenever the page is subsequently referenced (after the reference that generated the page fault), its use bit is set to 1. For the page replacement algorithm, the set of frames that are candidates for replacement (this process: local scope; all of main memory: global scope[5]) is considered to be a circular buffer, with which a pointer is associated. When a page is replaced, the pointer is set to indicate the next frame in the buffer after the one just updated. When it comes time to replace a page, the OS scans the buffer to find a frame with a use bit set to 0. Each time it encounters a frame with a use bit of 1, it resets that bit to 0 and continues on. If any of the frames in the buffer have a use bit of 0 at the beginning of this process, the first such frame encountered is chosen for replacement. If all of the frames have a use bit of 1, then the pointer will make one complete cycle through the buffer, setting all the use bits to 0, and stop at its original position, replacing the page in that frame. We can see that this policy is similar to FIFO, except that, in the clock policy, any frame with a use bit of 1 is passed over by the algorithm. The policy is referred to as a clock policy because we can visualize the page frames as laid out in a circle. A number of operating systems have employed some variation of this simple clock policy (e.g., Multics [CORB68]).

Figure 8.16 provides an example of the simple clock policy mechanism. A circular buffer of n main memory frames is available for page replacement. Just prior to the replacement of a page from the buffer with incoming page 727, the next frame pointer points at frame 2, which contains page 45. The clock policy is now executed. Because the use bit for page 45 in frame 2 is equal to 1, this page is not replaced. Instead, the use bit is set to 0 and the pointer advances. Similarly, page 191 in frame 3 is not replaced; its use bit is set to 0 and the pointer advances. In the next frame, frame 4, the use bit is set to 0. Therefore, page 556 is replaced with page 727. The use bit is set to 1 for this frame and the pointer advances to frame 5, completing the page replacement procedure.

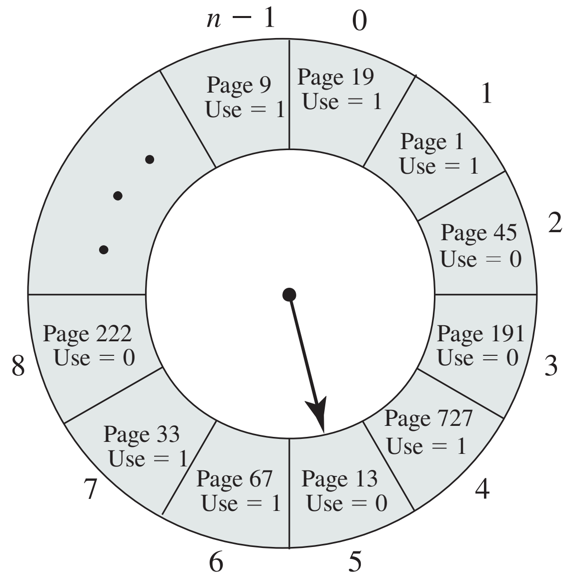
The behavior of the clock policy is illustrated in Figure 8.15. The presence of an asterisk indicates that the corresponding use bit is equal to 1, and the arrow indicates the current position of the pointer. Note that the clock policy is adept at protecting frames 2 and 5 from replacement.

Figure 8.17 shows the results of an experiment reported in [BAER80], which compares the four algorithms that we have been discussing; it is assumed that the number of page frames assigned to a process is fixed. The results are based on the execution of 0.25×10^6 references in a FORTRAN program, using a page size of 256 words. Baer ran the experiment with frame allocations of 6, 8, 10, 12, and 14 frames. The differences among the four policies are most striking at small allocations, with

[5]The concept of scope is discussed in the subsection "Replacement Scope," subsequently.



(a) State of buffer just prior to a page replacement



(b) State of buffer just after the next page replacement

Figure 8.16 Example of Clock Policy Operation

FIFO being over a factor of 2 worse than optimal. All four curves have the same shape as the idealized behavior shown in Figure 8.11b. In order to run efficiently, we would like to be to the right of the knee of the curve (with a small page fault rate) while keeping a small frame allocation (to the left of the knee of the curve). These two constraints indicate that a desirable mode of operation would be at the knee of the curve.

Almost identical results have been reported in [FINK88], again showing a maximum spread of about a factor of 2. Finkel's approach was to simulate the effects of various policies on a synthesized page-reference string of 10,000 references selected

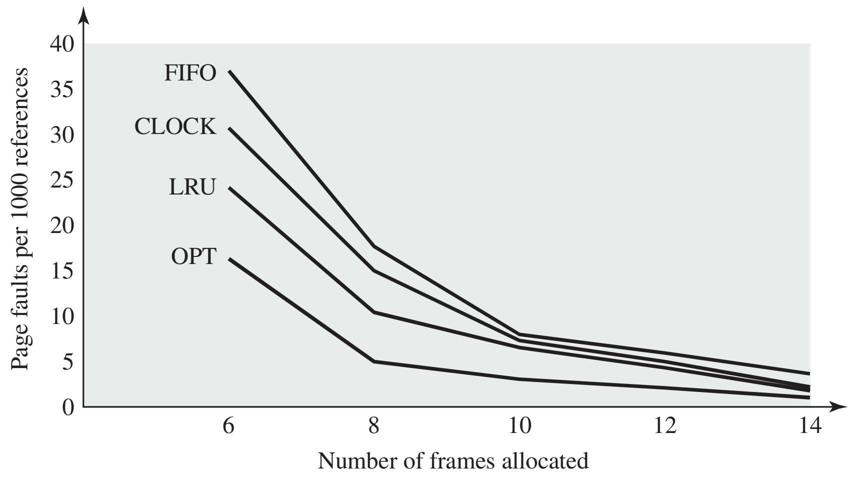


Figure 8.17 Comparison of Fixed-Allocation, Local Page Replacement Algorithms

from a virtual space of 100 pages. To approximate the effects of the principle of locality, an exponential distribution for the probability of referencing a particular page was imposed. Finkel observes that some might be led to conclude that there is little point in elaborate page replacement algorithms when only a factor of 2 is at stake. But he notes that this difference will have a noticeable effect either on main memory requirements (to avoid degrading operating system performance) or operating system performance (to avoid enlarging main memory).

The clock algorithm has also been compared to these other algorithms when a variable allocation and either global or local replacement scope (see the following discussion of replacement policy) is used [CARR81, CARR84]. The clock algorithm was found to approximate closely the performance of LRU.

The clock algorithm can be made more powerful by increasing the number of bits that it employs.[6] In all processors that support paging, a modify bit is associated with every page in main memory and hence with every frame of main memory. This bit is needed so that, when a page has been modified, it is not replaced until it has been written back into secondary memory. We can exploit this bit in the clock algorithm in the following way. If we take the use and modify bits into account, each frame falls into one of four categories:

- Not accessed recently, not modified ($u = 0; m = 0$)
- Accessed recently, not modified ($u = 1; m = 0$)
- Not accessed recently, modified ($u = 0; m = 1$)
- Accessed recently, modified ($u = 1; m = 1$)

With this classification, the clock algorithm performs as follows:

1. Beginning at the current position of the pointer, scan the frame buffer. During this scan, make no changes to the use bit. The first frame encountered with ($u = 0; m = 0$) is selected for replacement.

[6]On the other hand, if we reduce the number of bits employed to zero, the clock algorithm degenerates to FIFO.

2. If step 1 fails, scan again, looking for the frame with ($u = 0; m = 1$). The first such frame encountered is selected for replacement. During this scan, set the use bit to 0 on each frame that is bypassed.
3. If step 2 fails, the pointer should have returned to its original position and all of the frames in the set will have a use bit of 0. Repeat step 1 and, if necessary, step 2. This time, a frame will be found for the replacement.

In summary, the page replacement algorithm cycles through all of the pages in the buffer looking for one that has not been modified since being brought in and has not been accessed recently. Such a page is a good bet for replacement and has the advantage that, because it is unmodified, it does not need to be written back out to secondary memory. If no candidate page is found in the first sweep, the algorithm cycles through the buffer again, looking for a modified page that has not been accessed recently. Even though such a page must be written out to be replaced, because of the principle of locality, it may not be needed again anytime soon. If this second pass fails, all of the frames in the buffer are marked as having not been accessed recently and a third sweep is performed.

This strategy was used on an earlier version of the Macintosh virtual memory scheme [GOLD89], illustrated in Figure 8.18. The advantage of this algorithm over

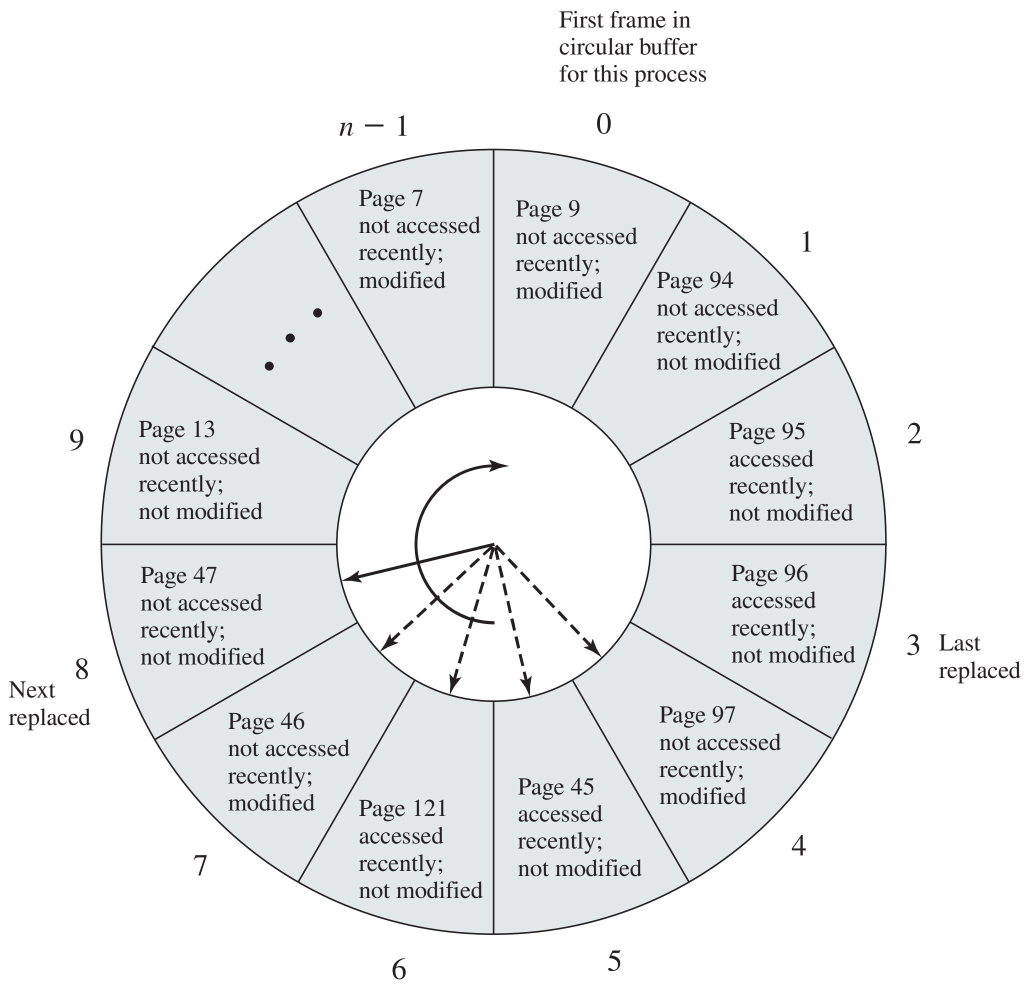

First frame in circular buffer for this process
0
$n - 1$
1
2
3
4
5
6
7
8
9
Page 7 not accessed recently; modified
Page 9 not accessed recently; modified
Page 94 not accessed recently; not modified
Page 95 accessed recently; not modified
Page 96 accessed recently; not modified
Page 97 not accessed recently; modified
Page 45 accessed recently; not modified
Page 121 accessed recently; not modified
Page 46 not accessed recently; modified
Page 47 not accessed recently; not modified
Page 13 not accessed recently; not modified
Last replaced
Next replaced

Figure 8.18 The Clock Page Replacement Algorithm [GOLD89]

the simple clock algorithm is that pages that are unchanged are given preference for replacement. Because a page that has been modified must be written out before being replaced, there is an immediate saving of time.

Page Buffering Although LRU and the clock policies are superior to FIFO, they both involve complexity and overhead not suffered with FIFO. In addition, there is the related issue that the cost of replacing a page that has been modified is greater than for one that has not, because the former must be written back out to secondary memory.

An interesting strategy that can improve paging performance and allow the use of a simpler page replacement policy is page buffering. The VAX VMS approach is representative. The page replacement algorithm is simple FIFO. To improve performance, a replaced page is not lost but rather is assigned to one of two lists: the free page list if the page has not been modified, or the modified page list if it has. Note that the page is not physically moved about in main memory; instead, the entry in the page table for this page is removed and placed in either the free or modified page list.

The free page list is a list of page frames available for reading in pages. VMS tries to keep some small number of frames free at all times. When a page is to be read in, the page frame at the head of the list is used, destroying the page that was there. When an unmodified page is to be replaced, it remains in memory and its page frame is added to the tail of the free page list. Similarly, when a modified page is to be written out and replaced, its page frame is added to the tail of the modified page list.

The important aspect of these maneuvers is that the page to be replaced remains in memory. Thus if the process references that page, it is returned to the resident set of that process at little cost. In effect, the free and modified page lists act as a cache of pages. The modified page list serves another useful function: Modified pages are written out in clusters rather than one at a time. This significantly reduces the number of I/O operations and therefore the amount of disk access time.

A simpler version of page buffering is implemented in the Mach operating system [RASH88]. In this case, no distinction is made between modified and unmodified pages.

Replacement Policy and Cache Size As discussed earlier, main memory size is getting larger and the locality of applications is decreasing. In compensation, cache sizes have been increasing. Large cache sizes, even multimegabyte ones, are now feasible design alternatives [BORG90]. With a large cache, the replacement of virtual memory pages can have a performance impact. If the page frame selected for replacement is in the cache, then that cache block is lost as well as the page that it holds.

In systems that use some form of page buffering, it is possible to improve cache performance by supplementing the page replacement policy with a policy for page placement in the page buffer. Most operating systems place pages by selecting an arbitrary page frame from the page buffer; typically a first-in-first-out discipline is used. A study reported in [KESS92] shows that a careful page placement strategy can result in 10–20% fewer cache misses than naive placement.

Several page placement algorithms are examined in [KESS92]. The details are beyond the scope of this book, as they depend on the details of cache structure and policies. The essence of these strategies is to bring consecutive pages into main memory in such a way as to minimize the number of page frames that are mapped into the same cache slots.

Resident Set Management

Resident Set Size With paged virtual memory, it is not necessary and indeed may not be possible to bring all of the pages of a process into main memory to prepare it for execution. Thus, the OS must decide how many pages to bring in, that is, how much main memory to allocate to a particular process. Several factors come into play:

- The smaller the amount of memory allocated to a process, the more processes that can reside in main memory at any one time. This increases the probability that the OS will find at least one ready process at any given time and hence reduces the time lost due to swapping.
- If a relatively small number of pages of a process are in main memory, then, despite the principle of locality, the rate of page faults will be rather high (see Figure 8.11b).
- Beyond a certain size, additional allocation of main memory to a particular process will have no noticeable effect on the page fault rate for that process because of the principle of locality.

With these factors in mind, two sorts of policies are to be found in contemporary operating systems. A **fixed-allocation** policy gives a process a fixed number of frames in main memory within which to execute. That number is decided at initial load time (process creation time) and may be determined based on the type of process (interactive, batch, type of application) or may be based on guidance from the programmer or system manager. With a fixed-allocation policy, whenever a page fault occurs in the execution of a process, one of the pages of that process must be replaced by the needed page.

A **variable-allocation** policy allows the number of page frames allocated to a process to be varied over the lifetime of the process. Ideally, a process that is suffering persistently high levels of page faults, indicating that the principle of locality only holds in a weak form for that process, will be given additional page frames to reduce the page fault rate; whereas a process with an exceptionally low page fault rate, indicating that the process is quite well behaved from a locality point of view, will be given a reduced allocation, with the hope that this will not noticeably increase the page fault rate. The use of a variable-allocation policy relates to the concept of replacement scope, as explained in the next subsection.

The variable-allocation policy would appear to be the more powerful one. However, the difficulty with this approach is that it requires the OS to assess the behavior of active processes. This inevitably requires software overhead in the OS and is dependent on hardware mechanisms provided by the processor platform.

Replacement Scope The scope of a replacement strategy can be categorized as global or local. Both types of policies are activated by a page fault when there are no free page frames. A **local replacement policy** chooses only among the resident pages of the process that generated the page fault in selecting a page to replace. A **global replacement policy** considers all unlocked pages in main memory as candidates for replacement, regardless of which process owns a particular page. While it happens that local policies are easier to analyze, there is no convincing evidence that they perform better than global policies, which are attractive because of their simplicity of implementation and minimal overhead [CARR84, MAEK87].

There is a correlation between replacement scope and resident set size (Table 8.5). A fixed resident set implies a local replacement policy: To hold the size of a resident set fixed, a page that is removed from main memory must be replaced by another page from the same process. A variable-allocation policy can clearly employ a global replacement policy: The replacement of a page from one process in main memory with that of another causes the allocation of one process to grow by one page and that of the other to shrink by one page. We shall also see that variable allocation and local replacement is a valid combination. We now examine these three combinations.

Fixed Allocation, Local Scope For this case, we have a process that is running in main memory with a fixed number of frames. When a page fault occurs, the OS must choose which page from among the currently resident pages for this process is to be replaced. Replacement algorithms such as those discussed in the preceding subsection can be used.

With a fixed-allocation policy, it is necessary to decide ahead of time the amount of allocation to give to a process. This could be decided on the basis of the type of application and the amount requested by the program. The drawback to this approach is twofold: If allocations tend to be too small, then there will be a high page fault rate, causing the entire multiprogramming system to run slowly. If allocations tend to be unnecessarily large, then there will be too few programs in main memory and there will be either considerable processor idle time or considerable time spent in swapping.

Table 8.5 Resident Set Management

	Local Replacement	**Global Replacement**
Fixed Allocation	• Number of frames allocated to a process is fixed. • Page to be replaced is chosen from among the frames allocated to that process.	• Not possible.
Variable Allocation	• The number of frames allocated to a process may be changed from time to time to maintain the working set of the process. • Page to be replaced is chosen from among the frames allocated to that process.	• Page to be replaced is chosen from all available frames in main memory; this causes the size of the resident set of processes to vary.

Variable Allocation, Global Scope This combination is perhaps the easiest to implement and has been adopted in a number of operating systems. At any given time, there are a number of processes in main memory, each with a certain number of frames allocated to it. Typically, the OS also maintains a list of free frames. When a page fault occurs, a free frame is added to the resident set of a process and the page is brought in. Thus, a process experiencing page faults will gradually grow in size, which should help reduce overall page faults in the system.

The difficulty with this approach is in the replacement choice. When there are no free frames available, the OS must choose a page currently in memory to replace. The selection is made from among all of the frames in memory, except for locked frames such as those of the kernel. Using any of the policies discussed in the preceding subsection, the page selected for replacement can belong to any of the resident processes; there is no discipline to determine which process should lose a page from its resident set. Therefore, the process that suffers the reduction in resident set size may not be optimum.

One way to counter the potential performance problems of a variable-allocation, global-scope policy is to use page buffering. In this way, the choice of which page to replace becomes less significant, because the page may be reclaimed if it is referenced before the next time that a block of pages are overwritten.

Variable Allocation, Local Scope The variable-allocation, local-scope strategy attempts to overcome the problems with a global-scope strategy. It can be summarized as follows:

1. When a new process is loaded into main memory, allocate to it a certain number of page frames as its resident set, based on application type, program request, or other criteria. Use either prepaging or demand paging to fill up the allocation.
2. When a page fault occurs, select the page to replace from among the resident set of the process that suffers the fault.
3. From time to time, reevaluate the allocation provided to the process, and increase or decrease it to improve overall performance.

With this strategy, the decision to increase or decrease a resident set size is a deliberate one and is based on an assessment of the likely future demands of active processes. Because of this evaluation, such a strategy is more complex than a simple global replacement policy. However, it may yield better performance.

The key elements of the variable-allocation, local-scope strategy are the criteria used to determine resident set size and the timing of changes. One specific strategy that has received much attention in the literature is known as the **working set strategy.** Although a true working set strategy would be difficult to implement, it is useful to examine it as a baseline for comparison.

The working set is a concept introduced and popularized by Denning [DENN68, DENN70, DENN80b]; it has had a profound impact on virtual memory management design. The working set with parameter Δ for a process at virtual time t, which we designate as $W(t, \Delta)$, is the set of pages of that process that have been referenced in the last Δ virtual time units.

Sequence of Page References	Window Size, Δ			
W	2	3	4	5
24	24	24	24	24
15	24 15	24 15	24 15	24 15
18	15 18	24 15 18	24 15 18	24 15 18
23	18 23	15 18 23	24 15 18 23	24 15 18 23
24	23 24	18 23 24	•	•
17	24 17	23 24 17	18 23 24 17	15 18 23 24 17
18	17 18	24 17 18	•	18 23 24 17
24	18 24	•	24 17 18	•
18	•	18 24	•	24 17 18
17	18 17	24 18 17	•	•
17	17	18 17	•	•
15	17 15	17 15	18 17 15	24 18 17 15
24	15 24	17 15 24	17 15 24	•
17	24 17	•	•	17 15 24
24	•	24 17	•	•
18	24 18	17 24 18	17 24 18	15 17 24 18

Figure 8.19 Working Set of Process as Defined by Window Size

Virtual time is defined as follows. Consider a sequence of memory references, $r(1)$, $r(2)$, ..., in which $r(i)$ is the page that contains the ith virtual address generated by a given process. Time is measured in memory references; thus $t = 1, 2, 3, \ldots$ measures the process's internal virtual time.

Let us consider each of the two variables of W. The variable Δ is a window of virtual time over which the process is observed. The working set size will be a nondecreasing function of the window size. The result is illustrated in Figure 8.19 (based on [BACH86]), which shows a sequence of page references for a process. The dots indicate time units in which the working set does not change. Note that the larger the window size, the larger is the working set. This can be expressed in the following relationship:

$$W(t,\Delta + 1) \supseteq W(t,\Delta)$$

The working set is also a function of time. If a process executes over Δ time units and uses only a single page, then $|W(t,\Delta)| = 1$. A working set can also grow as large as the number of pages N of the process if many different pages are rapidly addressed and if the window size allows. Thus,

$$1 \leq |W(t,\Delta)| \leq \min(\Delta,N)$$

Figure 8.20 indicates the way in which the working set size can vary over time for a fixed value of Δ. For many programs, periods of relatively stable working set

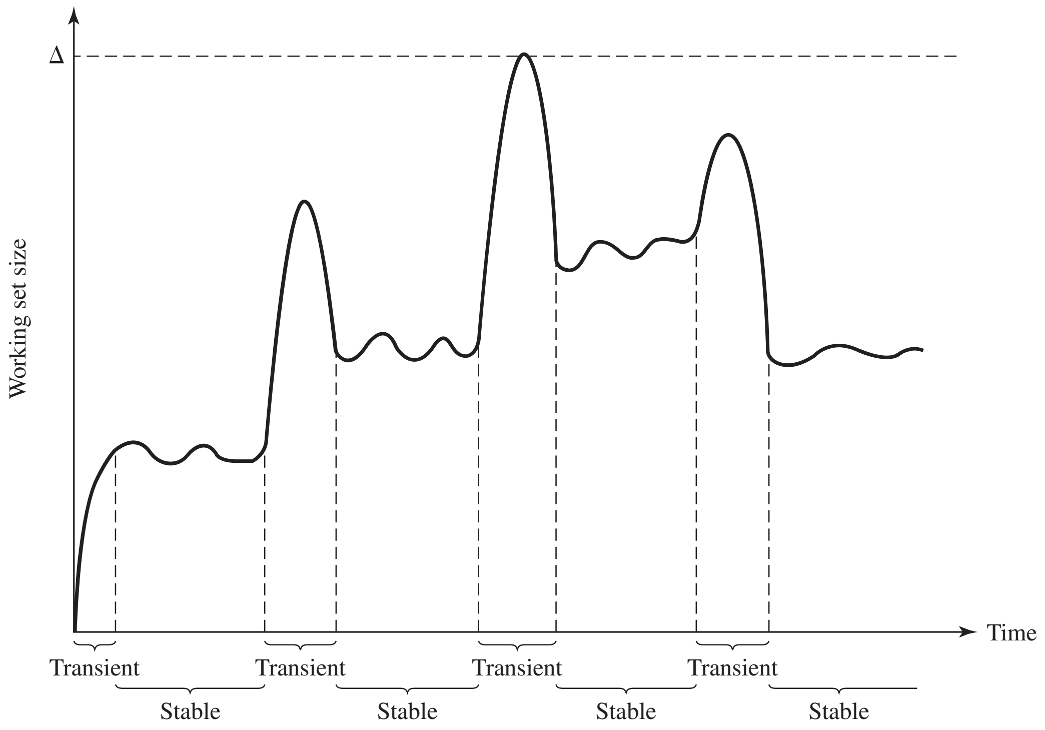


Figure 8.20 Typical Graph of Working Set Size [MAEK87]

sizes alternate with periods of rapid change. When a process first begins executing, it gradually builds up to a working set as it references new pages. Eventually, by the principle of locality, the process should stabilize on a certain set of pages. Subsequent transient periods reflect a shift of the program to a new locality. During the transition phase, some of the pages from the old locality remain within the window, Δ, causing a surge in the size of the working set as new pages are referenced. As the window slides past these page references, the working set size declines until it contains only those pages from the new locality.

This concept of a working set can be used to guide a strategy for resident set size:

1. Monitor the working set of each process.
2. Periodically remove from the resident set of a process those pages that are not in its working set. This is essentially an LRU policy.
3. A process may execute only if its working set is in main memory (i.e., if its resident set includes its working set).

This strategy is appealing because it takes an accepted principle, the principle of locality, and exploits it to achieve a memory management strategy that should minimize page faults. Unfortunately, there are a number of problems with the working set strategy:

1. The past does not always predict the future. Both the size and the membership of the working set will change over time (e.g., see Figure 8.20).
2. A true measurement of working set for each process is impractical. It would be necessary to time-stamp every page reference for every process using the

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virtual time of that process and then maintain a time-ordered queue of pages for each process.

3. The optimal value of Δ is unknown and in any case would vary.

Nevertheless, the spirit of this strategy is valid, and a number of operating systems attempt to approximate a working set strategy. One way to do this is to focus not on the exact page references but on the page fault rate of a process. As Figure 8.11b illustrates, the page fault rate falls as we increase the resident set size of a process. The working set size should fall at a point on this curve such as indicated by W in the figure. Therefore, rather than monitor the working set size directly, we can achieve comparable results by monitoring the page fault rate. The line of reasoning is as follows: If the page fault rate for a process is below some minimum threshold, the system as a whole can benefit by assigning a smaller resident set size to this process (because more page frames are available for other processes) without harming the process (by causing it to incur increased page faults). If the page fault rate for a process is above some maximum threshold, the process can benefit from an increased resident set size (by incurring fewer faults) without degrading the system.

An algorithm that follows this strategy is the **page fault frequency (PFF)** algorithm [CHU72, GUPT78]. It requires a use bit to be associated with each page in memory. The bit is set to 1 when that page is accessed. When a page fault occurs, the OS notes the virtual time since the last page fault for that process; this could be done by maintaining a counter of page references. A threshold *F* is defined. If the amount of time since the last page fault is less than *F*, then a page is added to the resident set of the process. Otherwise, discard all pages with a use bit of 0, and shrink the resident set accordingly. At the same time, reset the use bit on the remaining pages of the process to 0. The strategy can be refined by using two thresholds: an upper threshold that is used to trigger a growth in the resident set size, and a lower threshold that is used to trigger a contraction in the resident set size.

The time between page faults is the reciprocal of the page fault rate. Although it would seem to be better to maintain a running average of the page fault rate, the use of a single time measurement is a reasonable compromise that allows decisions about resident set size to be based on the page fault rate. If such a strategy is supplemented with page buffering, the resulting performance should be quite good.

Nevertheless, there is a major flaw in the PFF approach, which is that it does not perform well during the transient periods when there is a shift to a new locality. With PFF, no page ever drops out of the resident set before *F* virtual time units have elapsed since it was last referenced. During interlocality transitions, the rapid succession of page faults causes the resident set of a process to swell before the pages of the old locality are expelled; the sudden peaks of memory demand may produce unnecessary process deactivations and reactivations, with the corresponding undesirable switching and swapping overheads.

An approach that attempts to deal with the phenomenon of interlocality transition with a similar relatively low overhead to that of PFF is the **variable-interval sampled working set (VSWS)** policy [FERR83]. The VSWS policy evaluates the working set of a process at sampling instances based on elapsed virtual time. At the beginning of a sampling interval, the use bits of all the resident pages for the process are reset; at the end, only the pages that have been referenced during the interval will have their use bit set; these pages are retained in the resident set of the process throughout the next interval, while the others are discarded. Thus the resident set size can only decrease at the end of an interval. During each interval, any faulted pages are added to the resident set; thus the resident set remains fixed or grows during the interval.

The VSWS policy is driven by three parameters:

M:	The minimum duration of the sampling interval
L:	The maximum duration of the sampling interval
Q:	The number of page faults that are allowed to occur between sampling instances

The VSWS policy is as follows:

1. If the virtual time since the last sampling instance reaches *L*, then suspend the process and scan the use bits.
2. If, prior to an elapsed virtual time of *L*, *Q* page faults occur,
   a. If the virtual time since the last sampling instance is less than *M*, then wait until the elapsed virtual time reaches *M* to suspend the process and scan the use bits.
   b. If the virtual time since the last sampling instance is greater than or equal to *M*, suspend the process and scan the use bits.

The parameter values are to be selected so that the sampling will normally be triggered by the occurrence of the *Q*th page fault after the last scan (case 2b). The other two parameters (*M* and *L*) provide boundary protection for exceptional conditions. The VSWS policy tries to reduce the peak memory demands caused by abrupt interlocality transitions by increasing the sampling frequency, and hence the rate at which unused pages drop out of the resident set, when the page fault rate increases. Experience with this technique in the Bull mainframe operating system, GCOS 8, indicates that this approach is as simple to implement as PFF and more effective [PIZZ89].

Cleaning Policy

A cleaning policy is the opposite of a fetch policy; it is concerned with determining when a modified page should be written out to secondary memory. Two common alternatives are demand cleaning and precleaning. With **demand cleaning**, a page is written out to secondary memory only when it has been selected for replacement. A **precleaning** policy writes modified pages before their page frames are needed so that pages can be written out in batches.

There is a danger in following either policy to the full. With precleaning, a page is written out but remains in main memory until the page replacement algorithm dictates that it be removed. Precleaning allows the writing of pages in batches, but it makes little sense to write out hundreds or thousands of pages only to find that the majority of them have been modified again before they are replaced. The transfer capacity of secondary memory is limited and should not be wasted with unnecessary cleaning operations.

On the other hand, with demand cleaning, the writing of a dirty page is coupled to, and precedes, the reading in of a new page. This technique may minimize page writes, but it means that a process that suffers a page fault may have to wait for two page transfers before it can be unblocked. This may decrease processor utilization.

A better approach incorporates page buffering. This allows the adoption of the following policy: Clean only pages that are replaceable, but decouple the cleaning and replacement operations. With page buffering, replaced pages can be placed on two lists: modified and unmodified. The pages on the modified list can periodically be written out in batches and moved to the unmodified list. A page on the unmodified list is either reclaimed if it is referenced or lost when its frame is assigned to another page.

Load Control

Load control is concerned with determining the number of processes that will be resident in main memory, which has been referred to as the multiprogramming level. The load control policy is critical in effective memory management. If too few processes are resident at any one time, then there will be many occasions when all processes are blocked, and much time will be spent in swapping. On the other hand, if too many processes are resident, then, on average, the size of the resident set of each process will be inadequate and frequent faulting will occur. The result is thrashing.

Multiprogramming Level Thrashing is illustrated in Figure 8.21. As the multiprogramming level increases from a small value, one would expect to see processor utilization rise, because there is less chance that all resident processes are blocked. However, a point is reached at which the average resident set is inadequate. At this point, the number of page faults rises dramatically, and processor utilization collapses.

There are a number of ways to approach this problem. A working set or PFF algorithm implicitly incorporates load control. Only those processes whose resident set is sufficiently large are allowed to execute. In providing the required resident set

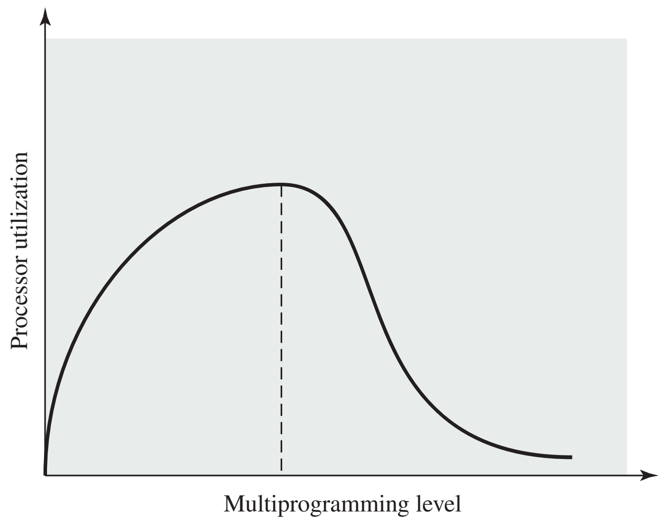

Figure 8.21 Multiprogramming Effects

size for each active process, the policy automatically and dynamically determines the number of active programs.

Another approach, suggested by Denning and his colleagues [DENN80b], is known as the *$L = S$ criterion*, which adjusts the multiprogramming level so that the mean time between faults equals the mean time required to process a page fault. Performance studies indicate that this is the point at which processor utilization attained a maximum. A policy with a similar effect, proposed in [LERO76], is the *50% criterion*, which attempts to keep utilization of the paging device at approximately 50%. Again, performance studies indicate that this is a point of maximum processor utilization.

Another approach is to adapt the clock page replacement algorithm described earlier (Figure 8.16). [CARR84] describes a technique, using a global scope, that involves monitoring the rate at which the pointer scans the circular buffer of frames. If the rate is below a given lower threshold, this indicates one or both of two circumstances:

1. Few page faults are occurring, resulting in few requests to advance the pointer.
2. For each request, the average number of frames scanned by the pointer is small, indicating that there are many resident pages not being referenced and are readily replaceable.

In both cases, the multiprogramming level can safely be increased. On the other hand, if the pointer scan rate exceeds an upper threshold, this indicates either a high fault rate or difficulty in locating replaceable pages, which implies that the multiprogramming level is too high.

Process Suspension If the degree of multiprogramming is to be reduced, one or more of the currently resident processes must be suspended (swapped out). [CARR84] lists six possibilities:

- **Lowest-priority process:** This implements a scheduling policy decision and is unrelated to performance issues.
- **Faulting process:** The reasoning is that there is a greater probability that the faulting task does not have its working set resident, and performance would suffer least by suspending it. In addition, this choice has an immediate payoff because it blocks a process that is about to be blocked anyway and it eliminates the overhead of a page replacement and I/O operation.
- **Last process activated:** This is the process least likely to have its working set resident.
- **Process with the smallest resident set:** This will require the least future effort to reload. However, it penalizes programs with strong locality.
- **Largest process:** This obtains the most free frames in an overcommitted memory, making additional deactivations unlikely soon.
- **Process with the largest remaining execution window:** In most process scheduling schemes, a process may only run for a certain quantum of time before being interrupted and placed at the end of the Ready queue. This approximates a shortest-processing-time-first scheduling discipline.

UNIT - 5
UNIPROCESSOR SCHEDULING
FILE MANAGEMENT

I take a two hour nap, from one o'clock to four.

—Yogi Berra

Learning Objectives

After studying this chapter, you should be able to:

- Explain the differences among long-, medium-, and short-term scheduling.
- Assess the performance of different scheduling policies.
- Understand the scheduling technique used in traditional UNIX.

In a multiprogramming system, multiple processes exist concurrently in main memory. Each process alternates between using a processor and waiting for some event to occur, such as the completion of an I/O operation. The processor or processors are kept busy by executing one process while the others wait.

The key to multiprogramming is scheduling. In fact, four types of scheduling are typically involved (Table 9.1). One of these, I/O scheduling, is more conveniently addressed in Chapter 11, where I/O is discussed. The remaining three types of scheduling, which are types of processor scheduling, are addressed in this chapter and the next.

This chapter begins with an examination of the three types of processor scheduling, showing how they are related. We see that long-term scheduling and medium-term scheduling are driven primarily by performance concerns related to the degree of multiprogramming. These issues are dealt with to some extent in Chapter 3 and in more detail in Chapters 7 and 8. Thus, the remainder of this chapter concentrates on short-term scheduling and is limited to a consideration of scheduling on a uniprocessor system. Because the use of multiple processors adds additional complexity, it is best to focus on the uniprocessor case first, so that the differences among scheduling algorithms can be clearly seen.

Section 9.2 looks at the various algorithms that may be used to make short-term scheduling decisions. A set of animations that illustrate concepts in this chapter is available online. Click on the rotating globe at WilliamStallings.com/OS/OS7e.html for access.

Table 9.1 Types of Scheduling

Long-term scheduling	The decision to add to the pool of processes to be executed
Medium-term scheduling	The decision to add to the number of processes that are partially or fully in main memory
Short-term scheduling	The decision as to which available process will be executed by the processor
I/O scheduling	The decision as to which process's pending I/O request shall be handled by an available I/O device

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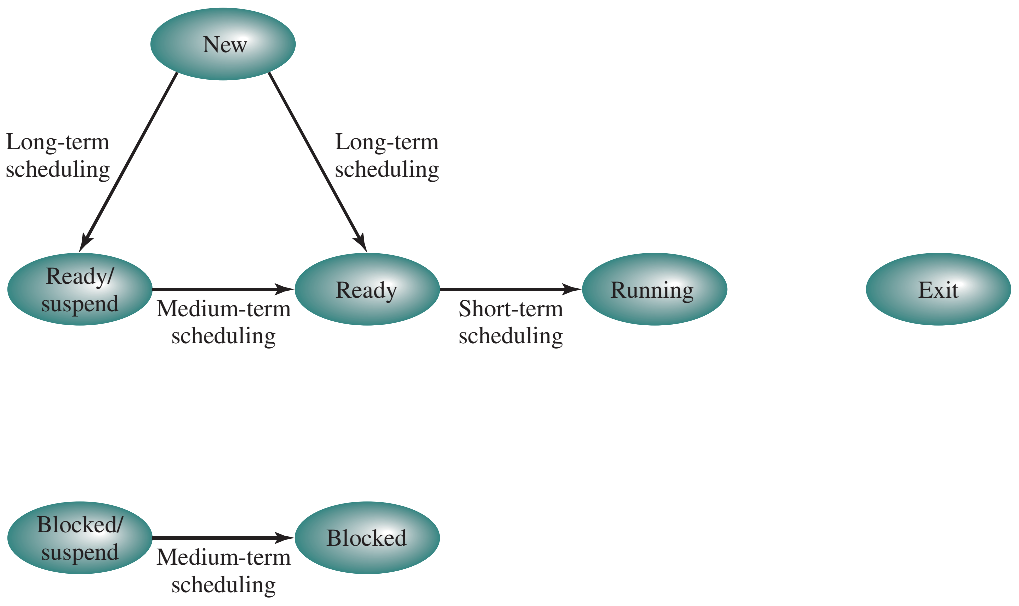

Figure 9.1 Scheduling and Process State Transitions

9.1 TYPES OF PROCESSOR SCHEDULING

The aim of processor scheduling is to assign processes to be executed by the processor or processors over time, in a way that meets system objectives, such as response time, throughput, and processor efficiency. In many systems, this scheduling activity is broken down into three separate functions: long-, medium-, and short-term scheduling. The names suggest the relative time scales with which these functions are performed.

Figure 9.1 relates the scheduling functions to the process state transition diagram (first shown in Figure 3.9b). Long-term scheduling is performed when a new process is created. This is a decision whether to add a new process to the set of processes that are currently active. Medium-term scheduling is a part of the swapping function. This is a decision whether to add a process to those that are at least partially in main memory and therefore available for execution. Short-term scheduling is the actual decision of which ready process to execute next. Figure 9.2 reorganizes the state transition diagram of Figure 3.9b to suggest the nesting of scheduling functions.

Scheduling affects the performance of the system because it determines which processes will wait and which will progress. This point of view is presented in Figure 9.3, which shows the queues involved in the state transitions of a process.[1] Fundamentally, scheduling is a matter of managing queues to minimize queueing delay and to optimize performance in a queueing environment.

Long-Term Scheduling

The long-term scheduler determines which programs are admitted to the system for processing. Thus, it controls the degree of multiprogramming. Once admitted, a job

[1]For simplicity, Figure 9.3 shows new processes going directly to the Ready state, whereas Figures 9.1 and 9.2 show the option of either the Ready state or the Ready/Suspend state.

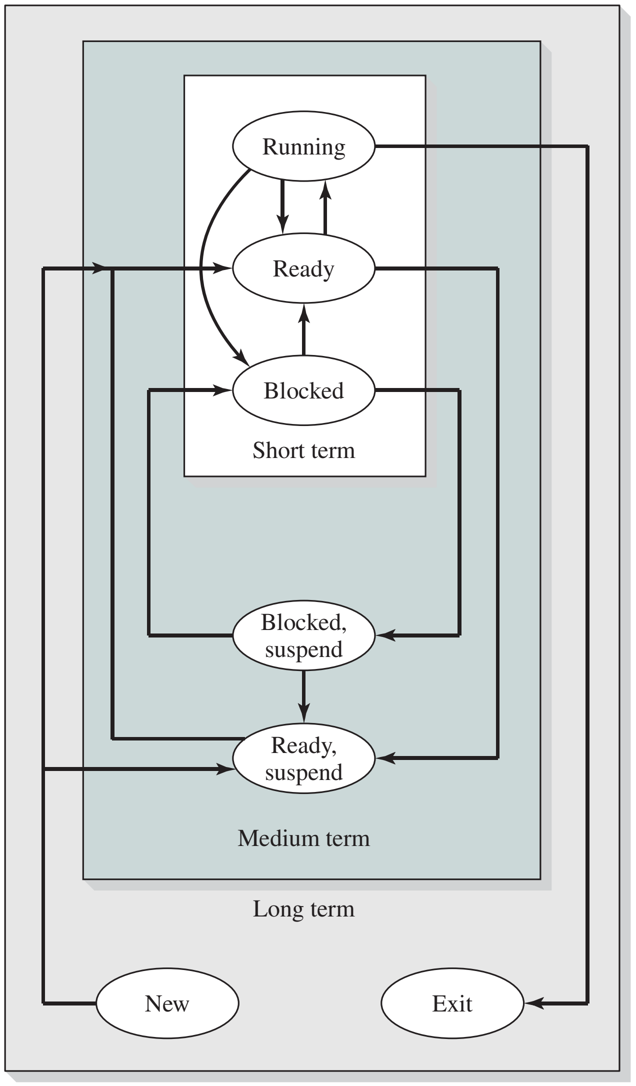

Figure 9.2 Levels of Scheduling

or user program becomes a process and is added to the queue for the short-term scheduler. In some systems, a newly created process begins in a swapped-out condition, in which case it is added to a queue for the medium-term scheduler.

In a batch system, or for the batch portion of an OS, newly submitted jobs are routed to disk and held in a batch queue. The long-term scheduler creates processes from the queue when it can. There are two decisions involved. The scheduler must decide when the OS can take on one or more additional processes. And the scheduler must decide which job or jobs to accept and turn into processes. We briefly consider these two decisions.

The decision as to when to create a new process is generally driven by the desired degree of multiprogramming. The more processes that are created, the smaller is the percentage of time that each process can be executed (i.e., more processes are competing for the same amount of processor time). Thus, the long-term scheduler may limit the degree of multiprogramming to provide satisfactory service

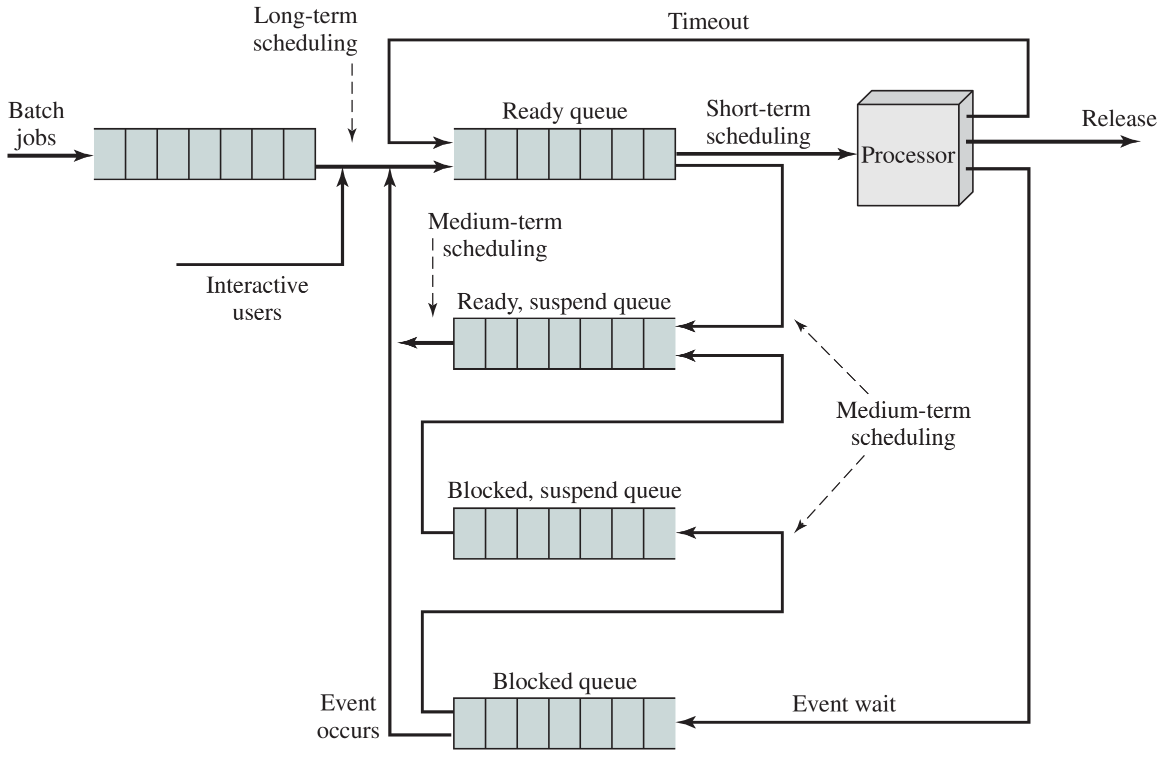

Figure 9.3 Queueing Diagram for Scheduling

to the current set of processes. Each time a job terminates, the scheduler may decide to add one or more new jobs. Additionally, if the fraction of time that the processor is idle exceeds a certain threshold, the long-term scheduler may be invoked.

The decision as to which job to admit next can be on a simple first-come-first-served (FCFS) basis, or it can be a tool to manage system performance. The criteria used may include priority, expected execution time, and I/O requirements. For example, if the information is available, the scheduler may attempt to keep a mix of processor-bound and I/O-bound processes.[2] Also, the decision can depend on which I/O resources are to be requested, in an attempt to balance I/O usage.

For interactive programs in a time-sharing system, a process creation request can be generated by the act of a user attempting to connect to the system. Time-sharing users are not simply queued up and kept waiting until the system can accept them. Rather, the OS will accept all authorized comers until the system is saturated, using some predefined measure of saturation. At that point, a connection request is met with a message indicating that the system is full and the user should try again later.

Medium-Term Scheduling

Medium-term scheduling is part of the swapping function. The issues involved are discussed in Chapters 3, 7, and 8. Typically, the swapping-in decision is based on the need to manage the degree of multiprogramming. On a system that does not

[2]A process is regarded as *processor bound* if it mainly performs computational work and occasionally uses I/O devices. A process is regarded as *I/O bound* if the time it takes to execute the process depends primarily on the time spent waiting for I/O operations.

use virtual memory, memory management is also an issue. Thus, the swapping-in decision will consider the memory requirements of the swapped-out processes.

Short-Term Scheduling

In terms of frequency of execution, the long-term scheduler executes relatively infrequently and makes the coarse-grained decision of whether or not to take on a new process and which one to take. The medium-term scheduler is executed somewhat more frequently to make a swapping decision. The short-term scheduler, also known as the dispatcher, executes most frequently and makes the fine-grained decision of which process to execute next.

The short-term scheduler is invoked whenever an event occurs that may lead to the blocking of the current process or that may provide an opportunity to preempt a currently running process in favor of another. Examples of such events include:

- Clock interrupts
- I/O interrupts
- Operating system calls
- Signals (e.g., semaphores)

9.2 SCHEDULING ALGORITHMS

Short-Term Scheduling Criteria

The main objective of short-term scheduling is to allocate processor time in such a way as to optimize one or more aspects of system behavior. Generally, a set of criteria is established against which various scheduling policies may be evaluated.

The commonly used criteria can be categorized along two dimensions. First, we can make a distinction between user-oriented and system-oriented criteria. User-oriented criteria relate to the behavior of the system as perceived by the individual user or process. An example is response time in an interactive system. Response time is the elapsed time between the submission of a request until the response begins to appear as output. This quantity is visible to the user and is naturally of interest to the user. We would like a scheduling policy that provides "good" service to various users. In the case of response time, a threshold may be defined, say two seconds. Then a goal of the scheduling mechanism should be to maximize the number of users who experience an average response time of two seconds or less.

Other criteria are system oriented. That is, the focus is on effective and efficient utilization of the processor. An example is throughput, which is the rate at which processes are completed. This is certainly a worthwhile measure of system performance and one that we would like to maximize. However, it focuses on system performance rather than service provided to the user. Thus, throughput is of concern to a system administrator but not to the user population.

Whereas user-oriented criteria are important on virtually all systems, system-oriented criteria are generally of minor importance on single-user systems. On a single-user system, it probably is not important to achieve high processor utilization

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or high throughput as long as the responsiveness of the system to user applications is acceptable.

Another dimension along which criteria can be classified is those that are performance related and those that are not directly performance related. Performance-related criteria are quantitative and generally can be readily measured. Examples include response time and throughput. Criteria that are not performance related are either qualitative in nature or do not lend themselves readily to measurement and analysis. An example of such a criterion is predictability. We would like for the service provided to users to exhibit the same characteristics over time, independent of other work being performed by the system. To some extent, this criterion can be measured by calculating variances as a function of workload. However, this is not nearly as straightforward as measuring throughput or response time as a function of workload.

Table 9.2 summarizes key scheduling criteria. These are interdependent, and it is impossible to optimize all of them simultaneously. For example, providing good

Table 9.2 Scheduling Criteria

User Oriented, Performance Related

Turnaround time This is the interval of time between the submission of a process and its completion. Includes actual execution time plus time spent waiting for resources, including the processor. This is an appropriate measure for a batch job.

Response time For an interactive process, this is the time from the submission of a request until the response begins to be received. Often a process can begin producing some output to the user while continuing to process the request. Thus, this is a better measure than turnaround time from the user's point of view. The scheduling discipline should attempt to achieve low response time and to maximize the number of interactive users receiving acceptable response time.

Deadlines When process completion deadlines can be specified, the scheduling discipline should subordinate other goals to that of maximizing the percentage of deadlines met.

User Oriented, Other

Predictability A given job should run in about the same amount of time and at about the same cost regardless of the load on the system. A wide variation in response time or turnaround time is distracting to users. It may signal a wide swing in system workloads or the need for system tuning to cure instabilities.

System Oriented, Performance Related

Throughput The scheduling policy should attempt to maximize the number of processes completed per unit of time. This is a measure of how much work is being performed. This clearly depends on the average length of a process but is also influenced by the scheduling policy, which may affect utilization.

Processor utilization This is the percentage of time that the processor is busy. For an expensive shared system, this is a significant criterion. In single-user systems and in some other systems, such as real-time systems, this criterion is less important than some of the others.

System Oriented, Other

Fairness In the absence of guidance from the user or other system-supplied guidance, processes should be treated the same, and no process should suffer starvation.

Enforcing priorities When processes are assigned priorities, the scheduling policy should favor higher-priority processes.

Balancing resources The scheduling policy should keep the resources of the system busy. Processes that will underutilize stressed resources should be favored. This criterion also involves medium-term and long-term scheduling.

response time may require a scheduling algorithm that switches between processes frequently. This increases the overhead of the system, reducing throughput. Thus, the design of a scheduling policy involves compromising among competing requirements; the relative weights given the various requirements will depend on the nature and intended use of the system.

In most interactive operating systems, whether single user or time shared, adequate response time is the critical requirement. Because of the importance of this requirement, and because the definition of adequacy will vary from one application to another, the topic is explored further in Appendix G.

The Use of Priorities

In many systems, each process is assigned a priority and the scheduler will always choose a process of higher priority over one of lower priority. Figure 9.4 illustrates the use of priorities. For clarity, the queueing diagram is simplified, ignoring the existence of multiple blocked queues and of suspended states (compare Figure 3.8a). Instead of a single ready queue, we provide a set of queues, in descending order of priority: RQ0, RQ1, . . . , RQn, with priority[RQi] > priority[RQj] for $i > j$.[3] When a scheduling selection is to be made, the scheduler will start at the highest-priority ready queue (RQ0). If there are one or more processes in the queue, a process is selected using some scheduling policy. If RQ0 is empty, then RQ1 is examined, and so on.

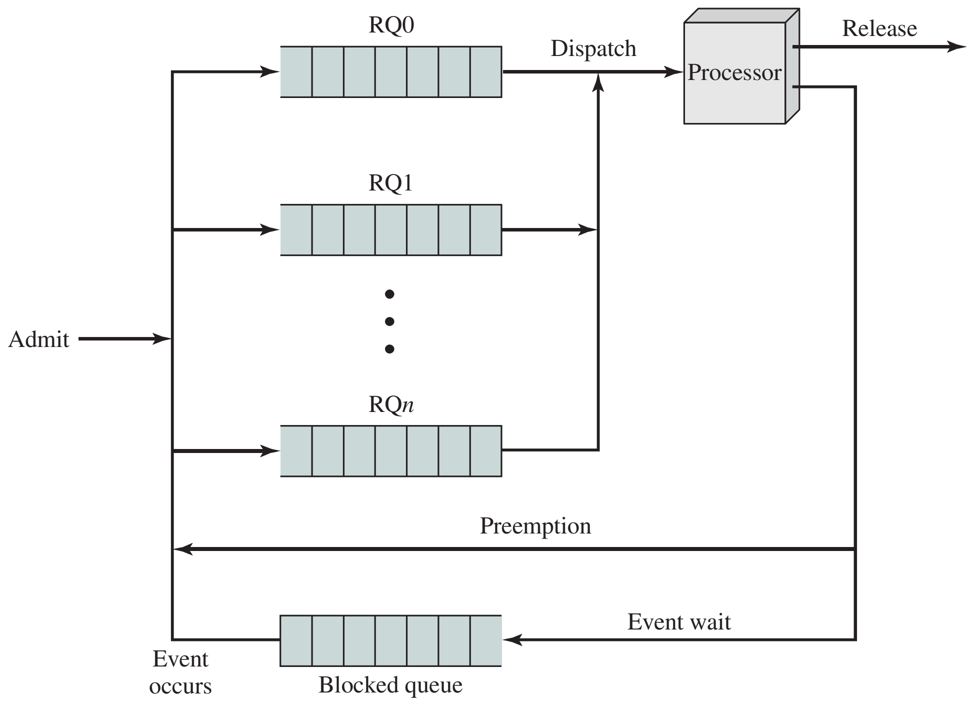

Figure 9.4 Priority Queueing

[3]In UNIX and many other systems, larger priority values represent lower priority processes; unless otherwise stated we follow that convention. Some systems, such as Windows, use the opposite convention: a higher number means a higher priority.

One problem with a pure priority scheduling scheme is that lower-priority processes may suffer starvation. This will happen if there is always a steady supply of higher-priority ready processes. If this behavior is not desirable, the priority of a process can change with its age or execution history. We will give one example of this subsequently.

Alternative Scheduling Policies

Table 9.3 presents some summary information about the various scheduling policies that are examined in this subsection. The **selection function** determines which process, among ready processes, is selected next for execution. The function may be based on priority, resource requirements, or the execution characteristics of the process. In the latter case, three quantities are significant:

w = time spent in system so far, waiting

e = time spent in execution so far

s = total service time required by the process, including e; generally, this quantity must be estimated or supplied by the user

For example, the selection function max[w] indicates an FCFS discipline.

Table 9.3 Characteristics of Various Scheduling Policies

	FCFS	**Round Robin**	**SPN**	**SRT**	**HRRN**	**Feedback**
Selection Function	max[w]	constant	min[s]	min[$s - e$]	$\max\left(\frac{w+s}{s}\right)$	(see text)
Decision Mode	Non-preemptive	Preemptive (at time quantum)	Non-preemptive	Preemptive (at arrival)	Non-preemptive	Preemptive (at time quantum)
Throughput	Not emphasized	May be low if quantum is too small	High	High	High	Not emphasized
Response Time	May be high, especially if there is a large variance in process execution times	Provides good response time for short processes	Provides good response time for short processes	Provides good response time	Provides good response time	Not emphasized
Overhead	Minimum	Minimum	Can be high	Can be high	Can be high	Can be high
Effect on Processes	Penalizes short processes; penalizes I/O bound processes	Fair treatment	Penalizes long processes	Penalizes long processes	Good balance	May favor I/O bound processes
Starvation	No	No	Possible	Possible	No	Possible

The **decision mode** specifies the instants in time at which the selection function is exercised. There are two general categories:

- **Nonpreemptive:** In this case, once a process is in the Running state, it continues to execute until (a) it terminates or (b) it blocks itself to wait for I/O or to request some OS service.
- **Preemptive:** The currently running process may be interrupted and moved to the Ready state by the OS. The decision to preempt may be performed when a new process arrives; when an interrupt occurs that places a blocked process in the Ready state; or periodically, based on a clock interrupt.

Preemptive policies incur greater overhead than nonpreemptive ones but may provide better service to the total population of processes, because they prevent any one process from monopolizing the processor for very long. In addition, the cost of preemption may be kept relatively low by using efficient process-switching mechanisms (as much help from hardware as possible) and by providing a large main memory to keep a high percentage of programs in main memory.

As we describe the various scheduling policies, we will use the set of processes in Table 9.4 as a running example. We can think of these as batch jobs, with the service time being the total execution time required. Alternatively, we can consider these to be ongoing processes that require alternate use of the processor and I/O in a repetitive fashion. In this latter case, the service times represent the processor time required in one cycle. In either case, in terms of a queueing model, this quantity corresponds to the service time.[4]

For the example of Table 9.4, Figure 9.5 shows the execution pattern for each policy for one cycle, and Table 9.5 summarizes some key results. First, the finish time of each process is determined. From this, we can determine the turnaround time. In terms of the queueing model, **turnaround time (TAT)** is the residence time T_r, or total time that the item spends in the system (waiting time plus service time). A more useful figure is the normalized turnaround time, which is the ratio of turnaround time to service time. This value indicates the relative

Table 9.4 Process Scheduling Example

Process	Arrival Time	Service Time
A	0	3
B	2	6
C	4	4
D	6	5
E	8	2

[4]See Appendix H for a summary of queueing model terminology, and Chapter 20 for a more detailed discussion of queueing analysis.

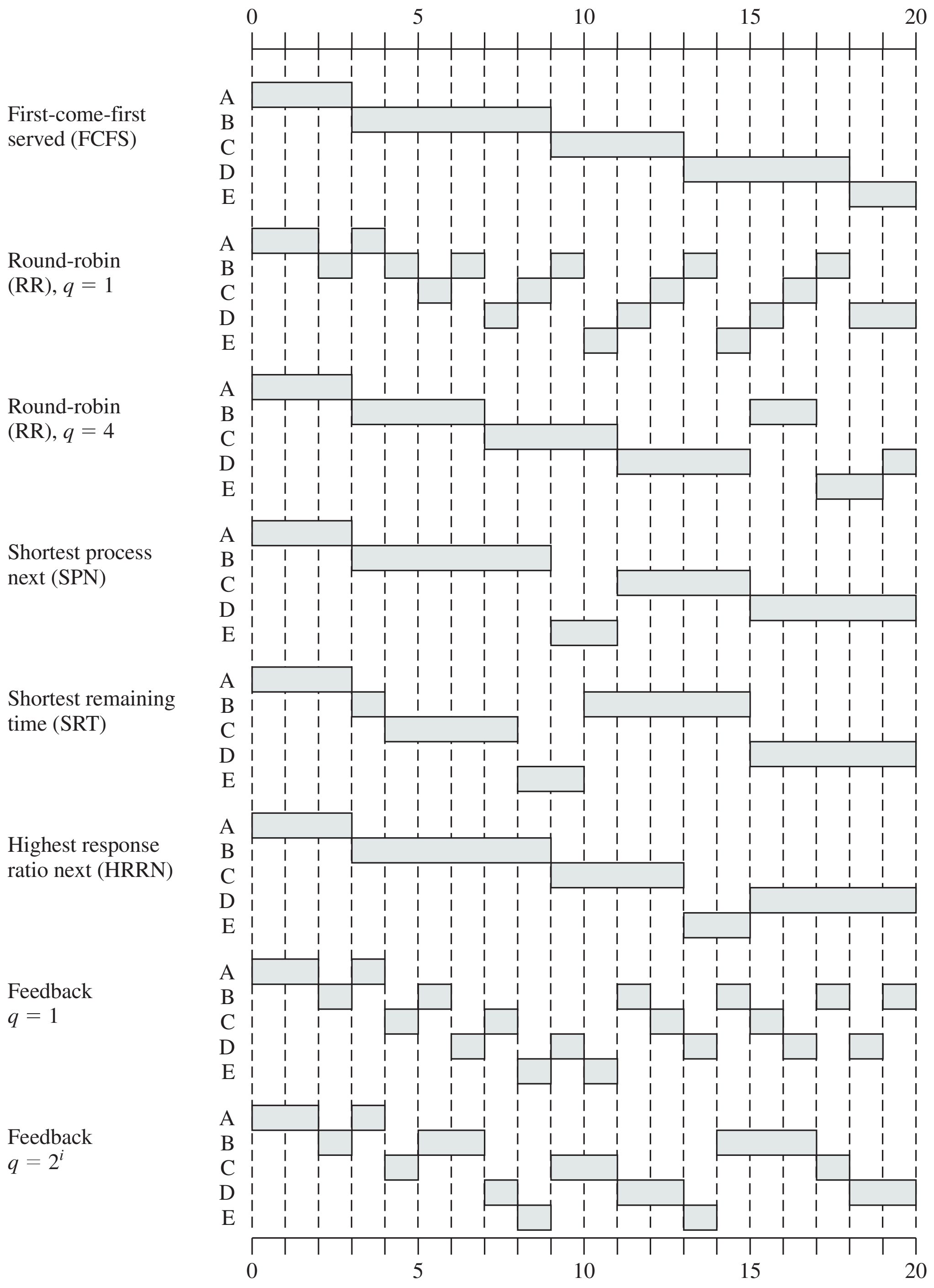

Figure 9.5 A Comparison of Scheduling Policies

delay experienced by a process. Typically, the longer the process execution time, the greater is the absolute amount of delay that can be tolerated. The minimum possible value for this ratio is 1.0; increasing values correspond to a decreasing level of service.

Table 9.5 A Comparison of Scheduling Policies

Process	A	B	C	D	E	
Arrival Time	0	2	4	6	8	
Service Time (T_s)	3	6	4	5	2	Mean
FCFS						
Finish Time	3	9	13	18	20	
Turnaround Time (T_r)	3	7	9	12	12	8.60
T_r/T_s	1.00	1.17	2.25	2.40	6.00	2.56
RR $q = 1$						
Finish Time	4	18	17	20	15	
Turnaround Time (T_r)	4	16	13	14	7	10.80
T_r/T_s	1.33	2.67	3.25	2.80	3.50	2.71
RR $q = 4$						
Finish Time	3	17	11	20	19	
Turnaround Time (T_r)	3	15	7	14	11	10.00
T_r/T_s	1.00	2.5	1.75	2.80	5.50	2.71
SPN						
Finish Time	3	9	15	20	11	
Turnaround Time (T_r)	3	7	11	14	3	7.60
T_r/T_s	1.00	1.17	2.75	2.80	1.50	1.84
SRT						
Finish Time	3	15	8	20	10	
Turnaround Time (T_r)	3	13	4	14	2	7.20
T_r/T_s	1.00	2.17	1.00	2.80	1.00	1.59
HRRN						
Finish Time	3	9	13	20	15	
Turnaround Time (T_r)	3	7	9	14	7	8.00
T_r/T_s	1.00	1.17	2.25	2.80	3.5	2.14
FB $q = 1$						
Finish Time	4	20	16	19	11	
Turnaround Time (T_r)	4	18	12	13	3	10.00
T_r/T_s	1.33	3.00	3.00	2.60	1.5	2.29
FB $q = 2^i$						
Finish Time	4	17	18	20	14	
Turnaround Time (T_r)	4	15	14	14	6	10.60
T_r/T_s	1.33	2.50	3.50	2.80	3.00	2.63

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First-Come-First-Served The simplest scheduling policy is first-come-first-served (FCFS), also known as first-in-first-out (FIFO) or a strict queueing scheme. As each process becomes ready, it joins the ready queue. When the currently running process ceases to execute, the process that has been in the ready queue the longest is selected for running.

FCFS performs much better for long processes than short ones. Consider the following example, based on one in [FINK88]:

Process	Arrival Time	Service Time (T_s)	Start Time	Finish Time	Turnaround Time (T_r)	T_r/T_s
W	0	1	0	1	1	1
X	1	100	1	101	100	1
Y	2	1	101	102	100	100
Z	3	100	102	202	199	1.99
Mean					100	26

The normalized turnaround time for process Y is way out of line compared to the other processes: the total time that it is in the system is 100 times the required processing time. This will happen whenever a short process arrives just after a long process. On the other hand, even in this extreme example, long processes do not fare poorly. Process Z has a turnaround time that is almost double that of Y, but its normalized residence time is under 2.0.

Another difficulty with FCFS is that it tends to favor processor-bound processes over I/O-bound processes. Consider that there is a collection of processes, one of which mostly uses the processor (processor bound) and a number of which favor I/O (I/O bound). When a processor-bound process is running, all of the I/O bound processes must wait. Some of these may be in I/O queues (blocked state) but may move back to the ready queue while the processor-bound process is executing. At this point, most or all of the I/O devices may be idle, even though there is potentially work for them to do. When the currently running process leaves the Running state, the ready I/O-bound processes quickly move through the Running state and become blocked on I/O events. If the processor-bound process is also blocked, the processor becomes idle. Thus, FCFS may result in inefficient use of both the processor and the I/O devices.

FCFS is not an attractive alternative on its own for a uniprocessor system. However, it is often combined with a priority scheme to provide an effective scheduler. Thus, the scheduler may maintain a number of queues, one for each priority level, and dispatch within each queue on a first-come-first-served basis. We see one example of such a system later, in our discussion of feedback scheduling.

Round Robin A straightforward way to reduce the penalty that short jobs suffer with FCFS is to use preemption based on a clock. The simplest such policy is round robin. A clock interrupt is generated at periodic intervals. When the interrupt occurs, the currently running process is placed in the ready queue, and the next ready job is selected on a FCFS basis. This technique is also known as **time slicing**, because each process is given a slice of time before being preempted.

With round robin, the principal design issue is the length of the time quantum, or slice, to be used. If the quantum is very short, then short processes will move through the system relatively quickly. On the other hand, there is processing overhead involved in handling the clock interrupt and performing the scheduling and dispatching function. Thus, very short time quanta should be avoided. One useful guide is that the time quantum should be slightly greater than the time required for a typical interaction or process function. If it is less, then most processes will require at least two time quanta. Figure 9.6 illustrates the effect this has on response time. Note that in the limiting case of a time quantum that is longer than the longest-running process, round robin degenerates to FCFS.

Figure 9.5 and Table 9.5 show the results for our example using time quanta q of 1 and 4 time units. Note that process E, which is the shortest job, enjoys significant improvement for a time quantum of 1.

Round robin is particularly effective in a general-purpose time-sharing system or transaction processing system. One drawback to round robin is its relative

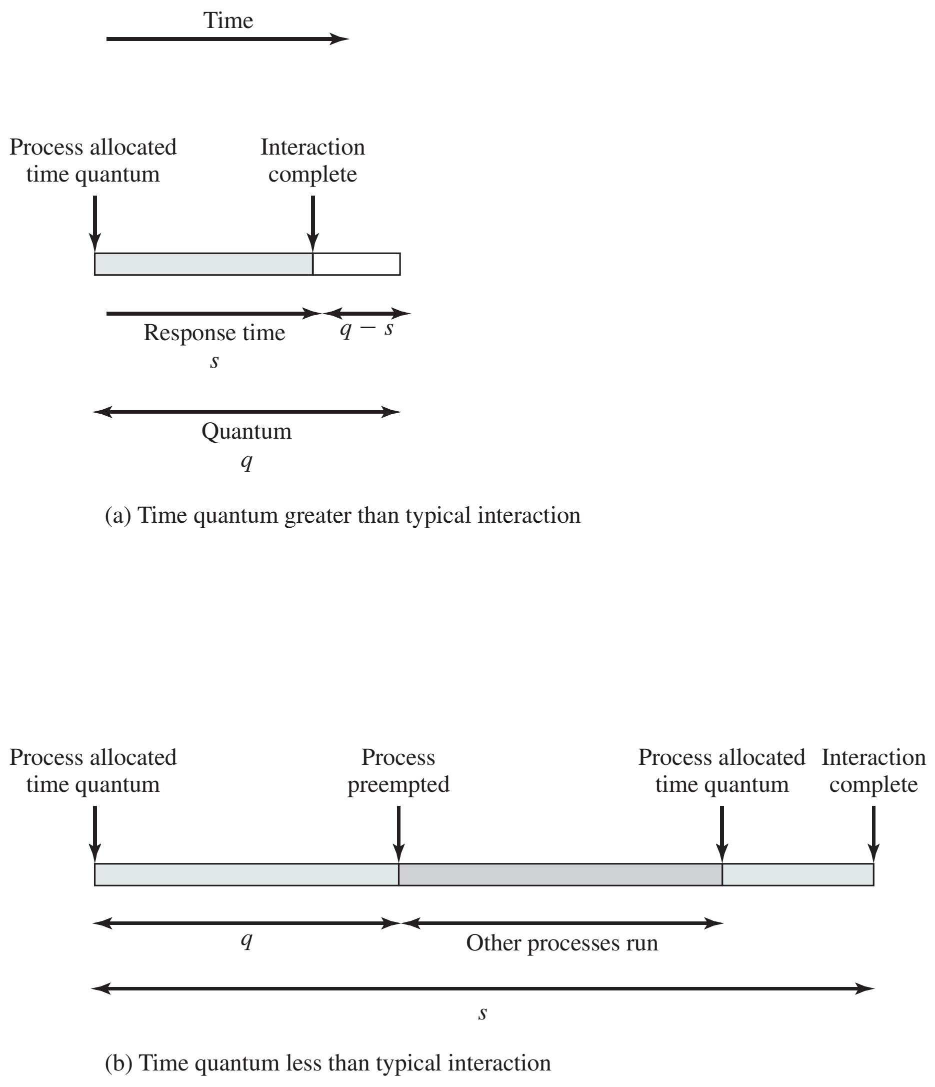

Time
Process allocated time quantum
Interaction complete
Response time s
$q - s$
Quantum q
(a) Time quantum greater than typical interaction
Process allocated time quantum
Process preempted
Process allocated time quantum
Interaction complete
q
Other processes run
s
(b) Time quantum less than typical interaction

Figure 9.6 Effect of Size of Preemption Time Quantum

treatment of processor-bound and I/O-bound processes. Generally, an I/O-bound process has a shorter processor burst (amount of time spent executing between I/O operations) than a processor-bound process. If there is a mix of processor-bound and I/O-bound processes, then the following will happen: An I/O-bound process uses a processor for a short period and then is blocked for I/O; it waits for the I/O operation to complete and then joins the ready queue. On the other hand, a processor-bound process generally uses a complete time quantum while executing and immediately returns to the ready queue. Thus, processor-bound processes tend to receive an unfair portion of processor time, which results in poor performance for I/O-bound processes, inefficient use of I/O devices, and an increase in the variance of response time.

[HALD91] suggests a refinement to round robin that he refers to as a virtual round robin (VRR) and that avoids this unfairness. Figure 9.7 illustrates the scheme. New processes arrive and join the ready queue, which is managed on an FCFS basis. When a running process times out, it is returned to the ready queue. When a process is blocked for I/O, it joins an I/O queue. So far, this is as usual. The new feature is an FCFS auxiliary queue to which processes are moved after being released from an I/O block. When a dispatching decision is to be made, processes in the auxiliary queue get preference over those in the main ready queue. When a process is dispatched from the auxiliary queue, it runs no longer than a time equal to the basic time quantum minus the total time spent running since it was last selected from the

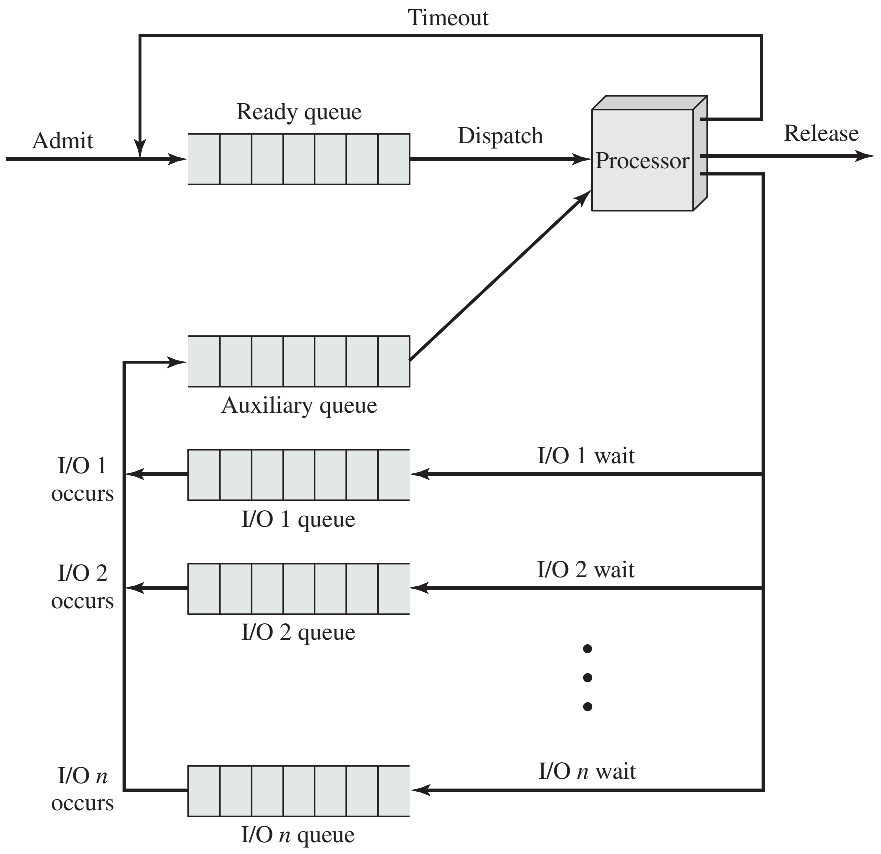


Figure 9.7 Queueing Diagram for Virtual Round-Robin Scheduler

main ready queue. Performance studies by the authors indicate that this approach is indeed superior to round robin in terms of fairness.

Shortest Process Next Another approach to reducing the bias in favor of long processes inherent in FCFS is the shortest process next (SPN) policy. This is a nonpreemptive policy in which the process with the shortest expected processing time is selected next. Thus, a short process will jump to the head of the queue past longer jobs.

Figure 9.5 and Table 9.5 show the results for our example. Note that process E receives service much earlier than under FCFS. Overall performance is also significantly improved in terms of response time. However, the variability of response times is increased, especially for longer processes, and thus predictability is reduced.

One difficulty with the SPN policy is the need to know or at least estimate the required processing time of each process. For batch jobs, the system may require the programmer to estimate the value and supply it to the OS. If the programmer's estimate is substantially under the actual running time, the system may abort the job. In a production environment, the same jobs run frequently, and statistics may be gathered. For interactive processes, the OS may keep a running average of each "burst" for each process. The simplest calculation would be the following:

$$S_{n+1} = \frac{1}{n}\sum_{i=1}^{n} T_i \qquad \textbf{(9.1)}$$

where

T_i = processor execution time for the ith instance of this process (total execution time for batch job; processor burst time for interactive job)

S_i = predicted value for the ith instance

S_1 = predicted value for first instance; not calculated

To avoid recalculating the entire summation each time, we can rewrite Equation (9.1) as

$$S_{n+1} = \frac{1}{n} T_n + \frac{n-1}{n} S_n \qquad \textbf{(9.2)}$$

Note that each term in this summation is given equal weight; that is, each term is multiplied by the same constant $1/(n)$. Typically, we would like to give greater weight to more recent instances, because these are more likely to reflect future behavior. A common technique for predicting a future value on the basis of a time series of past values is **exponential averaging**:

$$S_{n+1} = \alpha T_n + (1 - \alpha) S_n \qquad \textbf{(9.3)}$$

where α is a constant weighting factor ($0 > \alpha > 1$) that determines the relative weight given to more recent observations relative to older observations. Compare with Equation (9.2). By using a constant value of α, independent of the number of past observations, Equation (9.3) considers all past values, but the less recent ones have less weight. To see this more clearly, consider the following expansion of Equation (9.3):

$$S_{n+1} = \alpha T_n + (1 - \alpha)\alpha T_{n-1} + \ldots + (1 - \alpha)^i \alpha T_{n-i} + \ldots + (1 - \alpha)^n S_1 \qquad \textbf{(9.4)}$$

Because both α and (1 – α) are less than 1, each successive term in the preceding equation is smaller. For example, for α = 0.8, Equation (9.4) becomes

$$S_{n+1} = 0.8T_n + 0.16T_{n-1} + 0.032T_{n-2} + 0.0064T_{n-3} + \ \ldots \ + (0.2)^n S_1$$

The older the observation, the less it is counted in to the average.

The size of the coefficient as a function of its position in the expansion is shown in Figure 9.8. The larger the value of , the greater is the weight given to the more recent observations. For α = 0.8, virtually all of the weight is given to the four most recent observations, whereas for α = 0.2, the averaging is effectively spread out over the eight or so most recent observations. The advantage of using a value of α close to 1 is that the average will quickly reflect a rapid change in the observed quantity. The disadvantage is that if there is a brief surge in the value of the observed quantity and it then settles back to some average value, the use of a large value of α will result in jerky changes in the average.

Figure 9.9 compares simple averaging with exponential averaging (for two different values of α). In Figure 9.9a, the observed value begins at 1, grows gradually to a value of 10, and then stays there. In Figure 9.9b, the observed value begins at 20, declines gradually to 10, and then stays there. In both cases, we start out with an estimate of $S_1 = 0$. This gives greater priority to new processes. Note that exponential averaging tracks changes in process behavior faster than does simple averaging and that the larger value of α results in a more rapid reaction to the change in the observed value.

A risk with SPN is the possibility of starvation for longer processes, as long as there is a steady supply of shorter processes. On the other hand, although SPN reduces the bias in favor of longer jobs, it still is not desirable for a time-sharing or transaction processing environment because of the lack of preemption. Looking back at our worst-case analysis described under FCFS, processes W, X, Y, and Z will still execute in the same order, heavily penalizing the short process Y.

Shortest Remaining Time The shortest remaining time (SRT) policy is a preemptive version of SPN. In this case, the scheduler always chooses the process

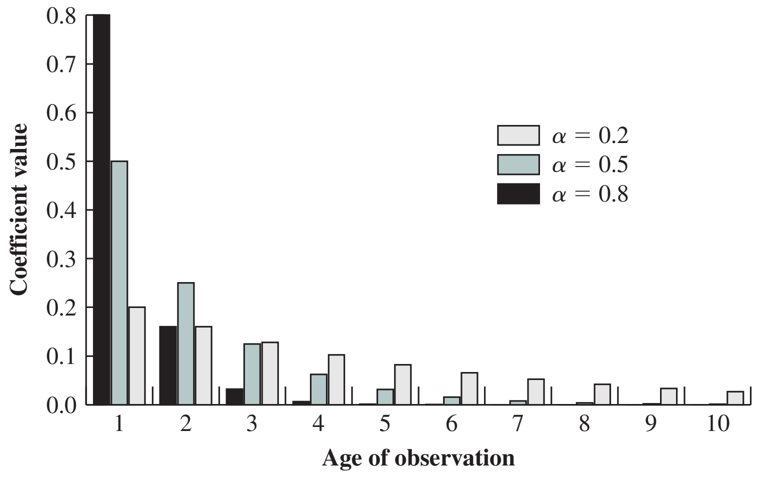
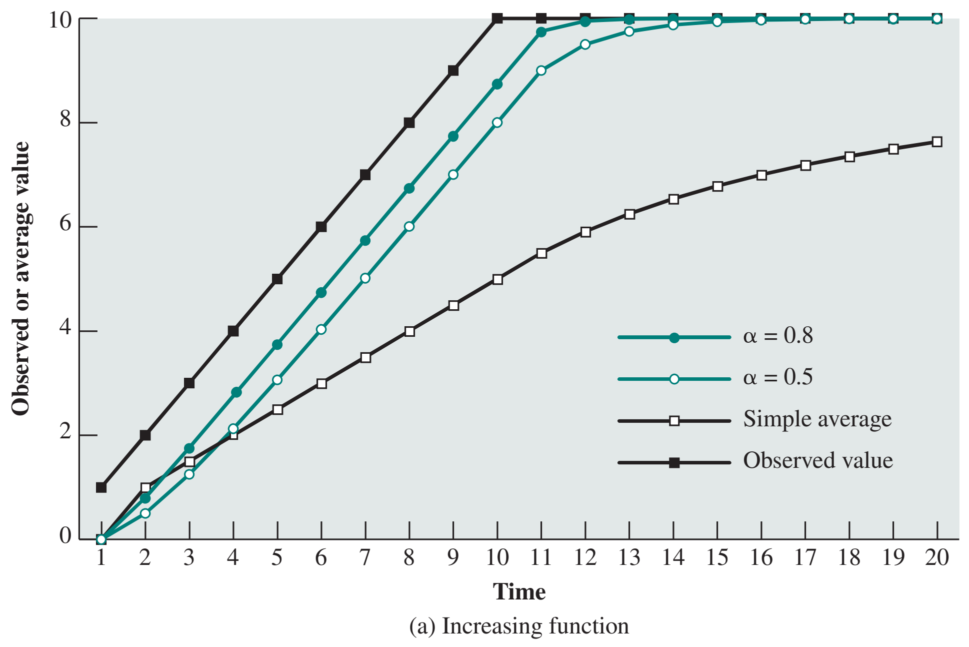
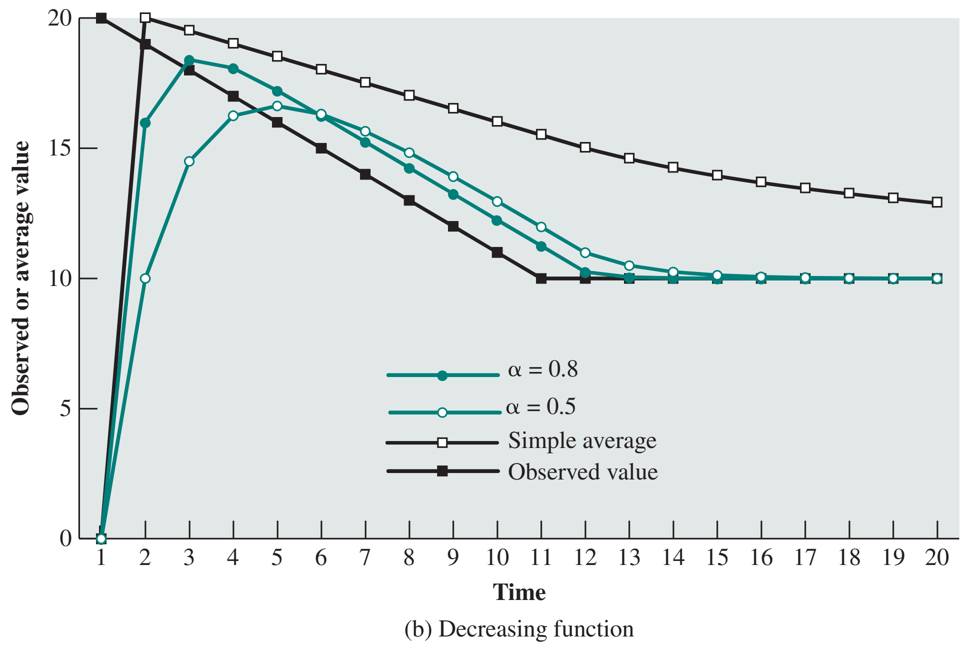


Figure 9.8 Exponential Smoothing Coefficients



(a) Increasing function



(b) Decreasing function

Figure 9.9 Use of Exponential Averaging

that has the shortest expected remaining processing time. When a new process joins the ready queue, it may in fact have a shorter remaining time than the currently running process. Accordingly, the scheduler may preempt the current process when a new process becomes ready. As with SPN, the scheduler must have an estimate of processing time to perform the selection function, and there is a risk of starvation of longer processes.

SRT does not have the bias in favor of long processes found in FCFS. Unlike round robin, no additional interrupts are generated, reducing overhead. On the other hand, elapsed service times must be recorded, contributing to overhead. SRT should also give superior turnaround time performance to SPN, because a short job is given immediate preference to a running longer job.

Note that in our example (Table 9.5), the three shortest processes all receive immediate service, yielding a normalized turnaround time for each of 1.0.

Highest Response Ratio Next In Table 9.5, we have used the normalized turnaround time, which is the ratio of turnaround time to actual service time, as a figure of merit. For each individual process, we would like to minimize this ratio, and we would like to minimize the average value over all processes. In general, we cannot know ahead of time what the service time is going to be, but we can approximate it, either based on past history or some input from the user or a configuration manager. Consider the following ratio:

$$R = \frac{w + s}{s}$$

where

R = response ratio

w = time spent waiting for the processor

s = expected service time

If the process with this value is dispatched immediately, R is equal to the normalized turnaround time. Note that the minimum value of R is 1.0, which occurs when a process first enters the system.

Thus, our scheduling rule becomes the following: when the current process completes or is blocked, choose the ready process with the greatest value of R. This approach is attractive because it accounts for the age of the process. While shorter jobs are favored (a smaller denominator yields a larger ratio), aging without service increases the ratio so that a longer process will eventually get past competing shorter jobs.

As with SRT and SPN, the expected service time must be estimated to use highest response ratio next (HRRN).

Feedback If we have no indication of the relative length of various processes, then none of SPN, SRT, and HRRN can be used. Another way of establishing a preference for shorter jobs is to penalize jobs that have been running longer. In other words, if we cannot focus on the time remaining to execute, let us focus on the time spent in execution so far.

The way to do this is as follows. Scheduling is done on a preemptive (at time quantum) basis, and a dynamic priority mechanism is used. When a process first enters the system, it is placed in RQ0 (see Figure 9.4). After its first preemption, when it returns to the Ready state, it is placed in RQ1. Each subsequent time that it is preempted, it is demoted to the next lower-priority queue. A short process will complete quickly, without migrating very far down the hierarchy of ready queues. A longer process will gradually drift downward. Thus, newer, shorter processes are favored over older, longer processes. Within each queue, except the lowest-priority queue, a simple FCFS mechanism is used. Once in the lowest-priority queue, a

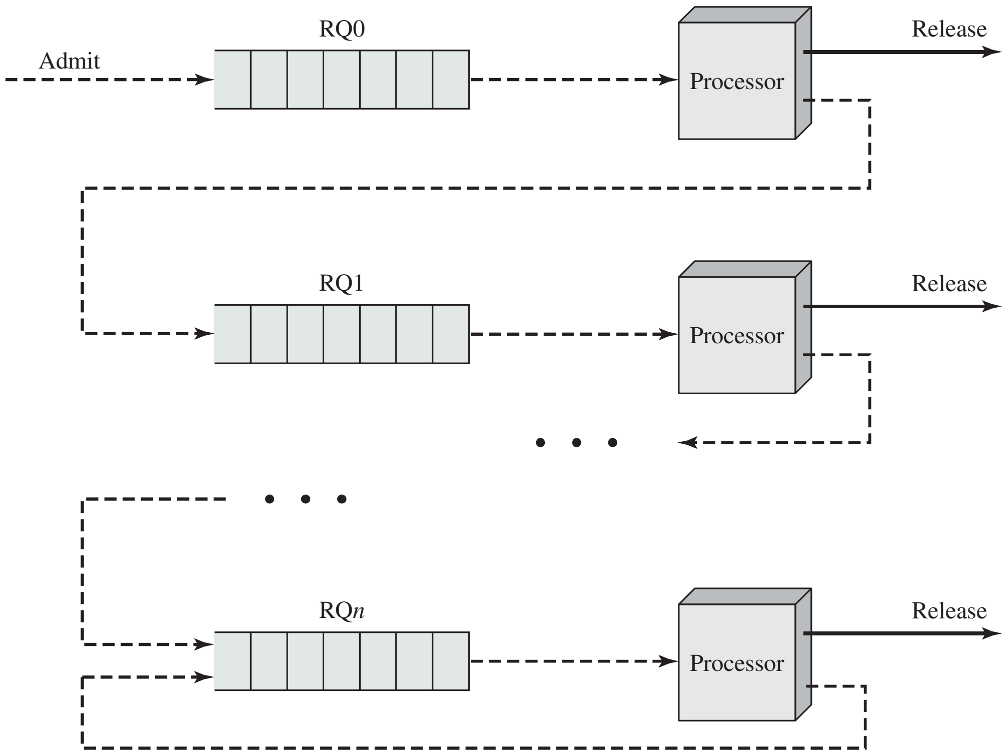


Figure 9.10 Feedback Scheduling

process cannot go lower, but is returned to this queue repeatedly until it completes execution. Thus, this queue is treated in round-robin fashion.

Figure 9.10 illustrates the feedback scheduling mechanism by showing the path that a process will follow through the various queues.[5] This approach is known as **multilevel feedback**, meaning that the OS allocates the processor to a process and, when the process blocks or is preempted, feeds it back into one of several priority queues.

There are a number of variations on this scheme. A simple version is to perform preemption in the same fashion as for round robin: at periodic intervals. Our example shows this (Figure 9.5 and Table 9.5) for a quantum of one time unit. Note that in this case, the behavior is similar to round robin with a time quantum of 1.

One problem with the simple scheme just outlined is that the turnaround time of longer processes can stretch out alarmingly. Indeed, it is possible for starvation to occur if new jobs are entering the system frequently. To compensate for this, we can vary the preemption times according to the queue: A process scheduled from RQ0 is allowed to execute for one time unit and then is preempted; a process scheduled from RQ1 is allowed to execute two time units, and so on. In general, a process scheduled from RQi is allowed to execute 2^i time units before preemption. This scheme is illustrated for our example in Figure 9.5 and Table 9.5.

[5]Dotted lines are used to emphasize that this is a time sequence diagram rather than a static depiction of possible transitions, such as Figure 9.4.

Even with the allowance for greater time allocation at lower priority, a longer process may still suffer starvation. A possible remedy is to promote a process to a higher-priority queue after it spends a certain amount of time waiting for service in its current queue.

Performance Comparison

Clearly, the performance of various scheduling policies is a critical factor in the choice of a scheduling policy. However, it is impossible to make definitive comparisons because relative performance will depend on a variety of factors, including the probability distribution of service times of the various processes, the efficiency of the scheduling and context switching mechanisms, and the nature of the I/O demand and the performance of the I/O subsystem. Nevertheless, we attempt in what follows to draw some general conclusions.

Queueing Analysis In this section, we make use of basic queueing formulas, with the common assumptions of Poisson arrivals and exponential service times.[6]

First, we make the observation that any such scheduling discipline that chooses the next item to be served independent of service time obeys the following relationship:

$$\frac{T_r}{T_s} = \frac{1}{1 - \rho}$$

where

T_r = turnaround time or residence time; total time in system, waiting plus execution

T_s = average service time; average time spent in Running state

ρ = processor utilization

In particular, a priority-based scheduler, in which the priority of each process is assigned independent of expected service time, provides the same average turnaround time and average normalized turnaround time as a simple FCFS discipline. Furthermore, the presence or absence of preemption makes no differences in these averages.

With the exception of round robin and FCFS, the various scheduling disciplines considered so far do make selections on the basis of expected service time. Unfortunately, it turns out to be quite difficult to develop closed analytic models of these disciplines. However, we can get an idea of the relative performance of such scheduling algorithms, compared to FCFS, by considering priority scheduling in which priority is based on service time.

If scheduling is done on the basis of priority and if processes are assigned to a priority class on the basis of service time, then differences do emerge. Table 9.6 shows the formulas that result when we assume two priority classes, with different service times for each class. In the table,   refers to the arrival rate. These results can

[6]The queueing terminology used in this chapter is summarized in Appendix H. Poisson arrivals essentially means random arrivals, as explained in Appendix H.

Table 9.6 Formulas for Single-Server Queues with Two Priority Categories

Assumptions:
1. Poisson arrival rate.
2. Priority 1 items are serviced before priority 2 items.
3. First-come-first-served dispatching for items of equal priority.
4. No item is interrupted while being served.
5. No items leave the queue (lost calls delayed).

(a) General formulas

$$\lambda = \lambda_1 + \lambda_2$$

$$\rho_1 = \lambda_1 T_{s1};\ \rho_2 = \lambda_2 T_{s2}$$

$$\rho = \rho_1 + \rho_2$$

$$T_s = \frac{\lambda_1}{\lambda} T_{s1} + \frac{\lambda_2}{\lambda} T_{s2}$$

$$T_r = \frac{\lambda_1}{\lambda} T_{r1} + \frac{\lambda_2}{\lambda} T_{r2}$$

(b) No interrupts; exponential service times	**(c) Preemptive-resume queueing discipline; exponential service times**
$T_{r1} = T_{s1} + \frac{\rho_1 T_{s1} + \rho_2 T_{s2}}{1 + \rho_1}$	$T_{r1} = T_{s1} + \frac{\rho_1 T_{s1}}{1 - \rho_1}$
$T_{r2} = T_{s2} + \frac{T_{r1} - T_{s1}}{1 - \rho}$	$T_{r2} = T_{s2} + \frac{1}{1 - \rho_1}\left(\rho_1 T_{s2} + \frac{\rho T_s}{1 - \rho}\right)$

be generalized to any number of priority classes. Note that the formulas differ for nonpreemptive versus preemptive scheduling. In the latter case, it is assumed that a lower-priority process is immediately interrupted when a higher-priority process becomes ready.

As an example, let us consider the case of two priority classes, with an equal number of process arrivals in each class and with the average service time for the lower-priority class being five times that of the upper priority class. Thus, we wish to give preference to shorter processes. Figure 9.11 shows the overall result. By giving preference to shorter jobs, the average normalized turnaround time is improved at higher levels of utilization. As might be expected, the improvement is greatest with the use of preemption. Notice, however, that overall performance is not much affected.

However, significant differences emerge when we consider the two priority classes separately. Figure 9.12 shows the results for the higher-priority, shorter processes. For comparison, the upper line on the graph assumes that priorities are not used but that we are simply looking at the relative performance of that half of all processes that have the shorter processing time. The other two lines assume that these processes are assigned a higher priority. When the system is run using priority scheduling without preemption, the improvements are significant. They are even more significant when preemption is used.

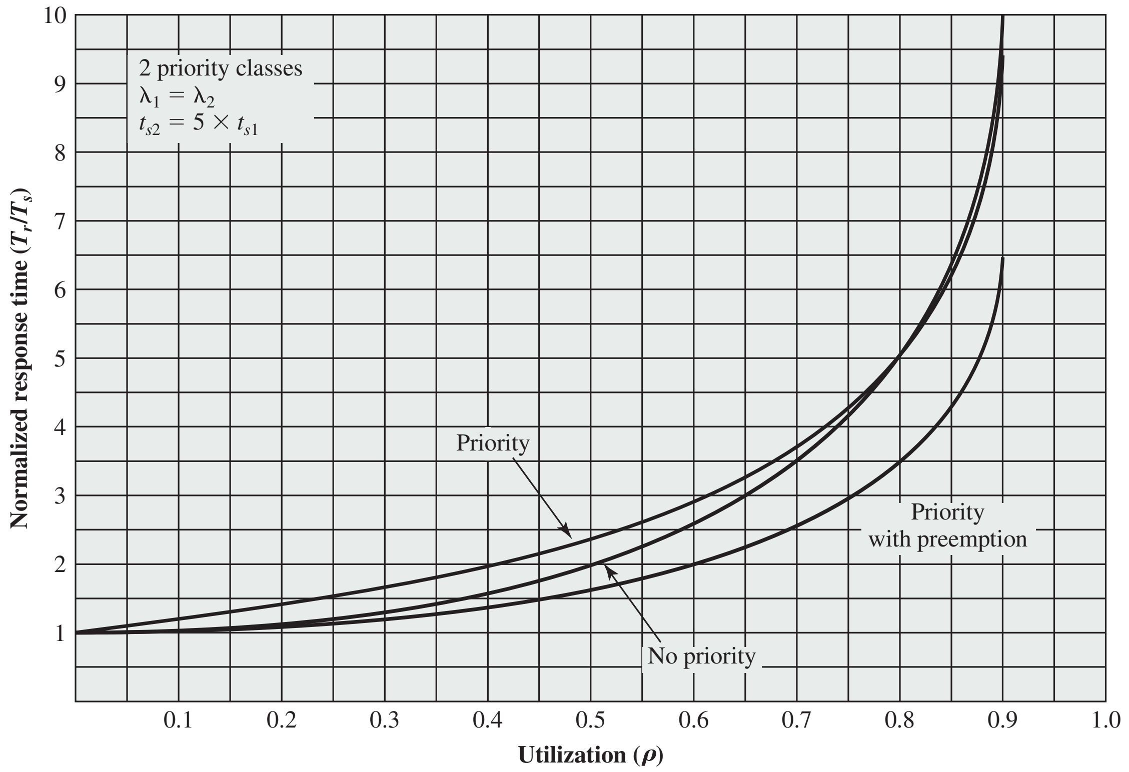


Figure 9.11 **Overall Normalized Response Time**

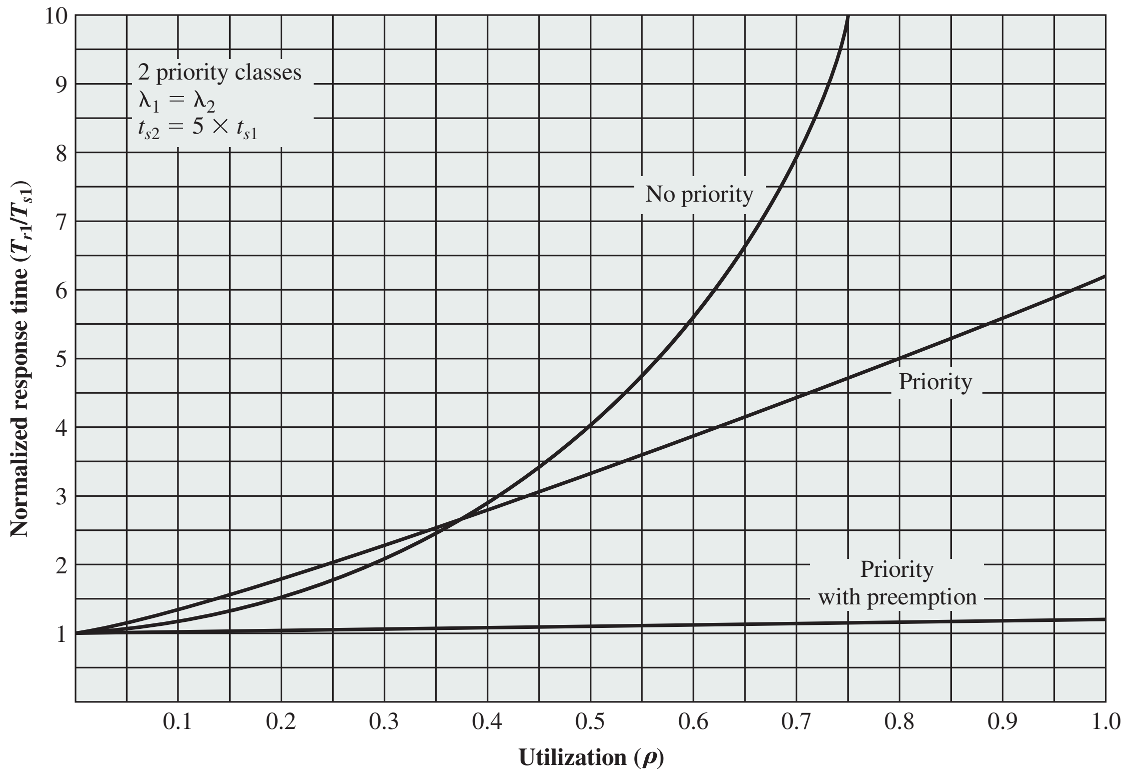


Figure 9.12 **Normalized Response Time for Shorter Processes**

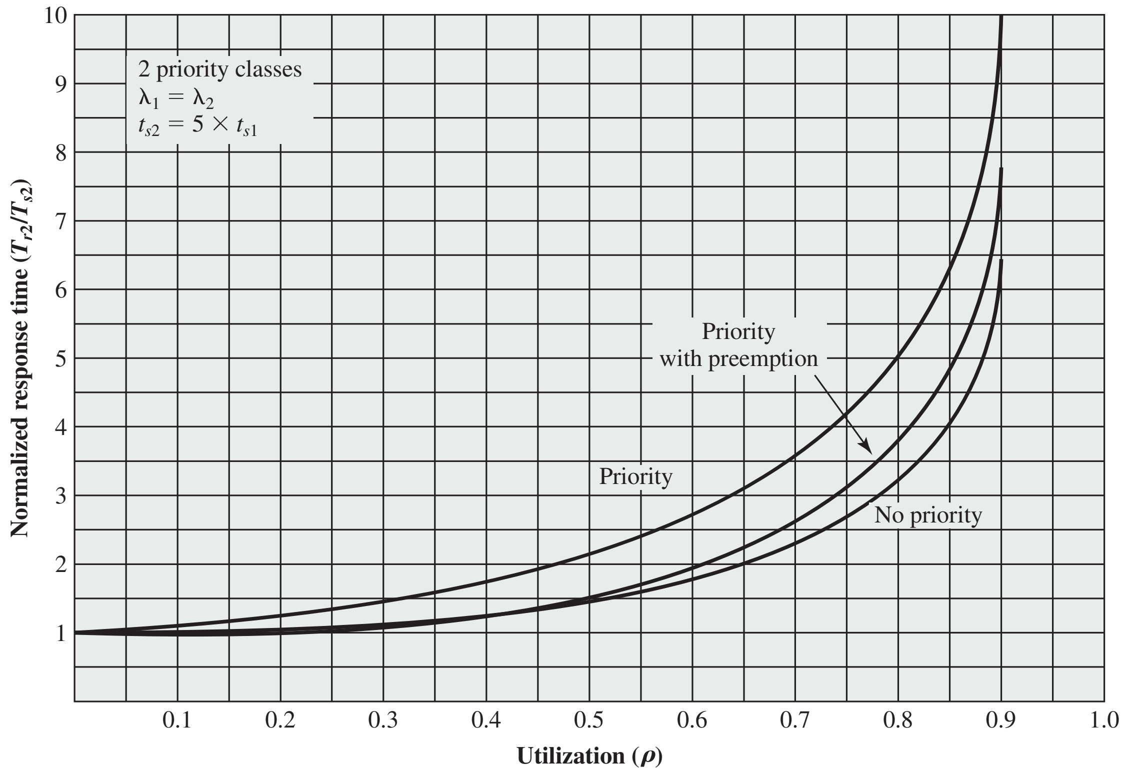


Figure 9.13 Normalized Response Time for Longer Processes

Figure 9.13 shows the same analysis for the lower-priority, longer processes. As expected, such processes suffer a performance degradation under priority scheduling.

Simulation Modeling Some of the difficulties of analytic modeling are overcome by using discrete-event simulation, which allows a wide range of policies to be modeled. The disadvantage of simulation is that the results for a given "run" only apply to that particular collection of processes under that particular set of assumptions. Nevertheless, useful insights can be gained.

The results of one such study are reported in [FINK88]. The simulation involved 50,000 processes with an arrival rate of $\lambda = 0.8$ and an average service time of $T_s = 1$. Thus, the assumption is that the processor utilization is $\rho = \lambda T_s = 0.8$. Note, therefore, that we are only measuring one utilization point.

To present the results, processes are grouped into service-time percentiles, each of which has 500 processes. Thus, the 500 processes with the shortest service time are in the first percentile; with these eliminated, the 500 remaining processes with the shortest service time are in the second percentile; and so on. This allows us to view the effect of various policies on processes as a function of the length of the process.

Figure 9.14 shows the normalized turnaround time, and Figure 9.15 shows the average waiting time. Looking at the turnaround time, we can see that the performance of FCFS is very unfavorable, with one-third of the processes having

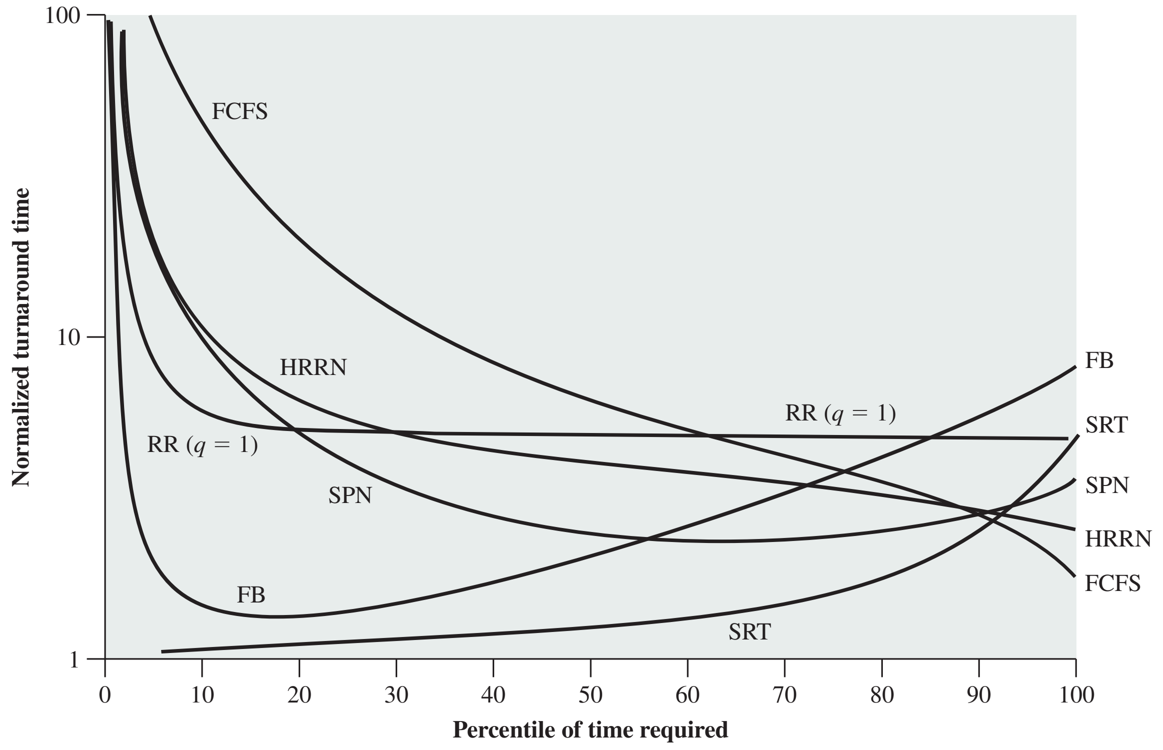


Figure 9.14 Simulation Result for Normalized Turnaround Time

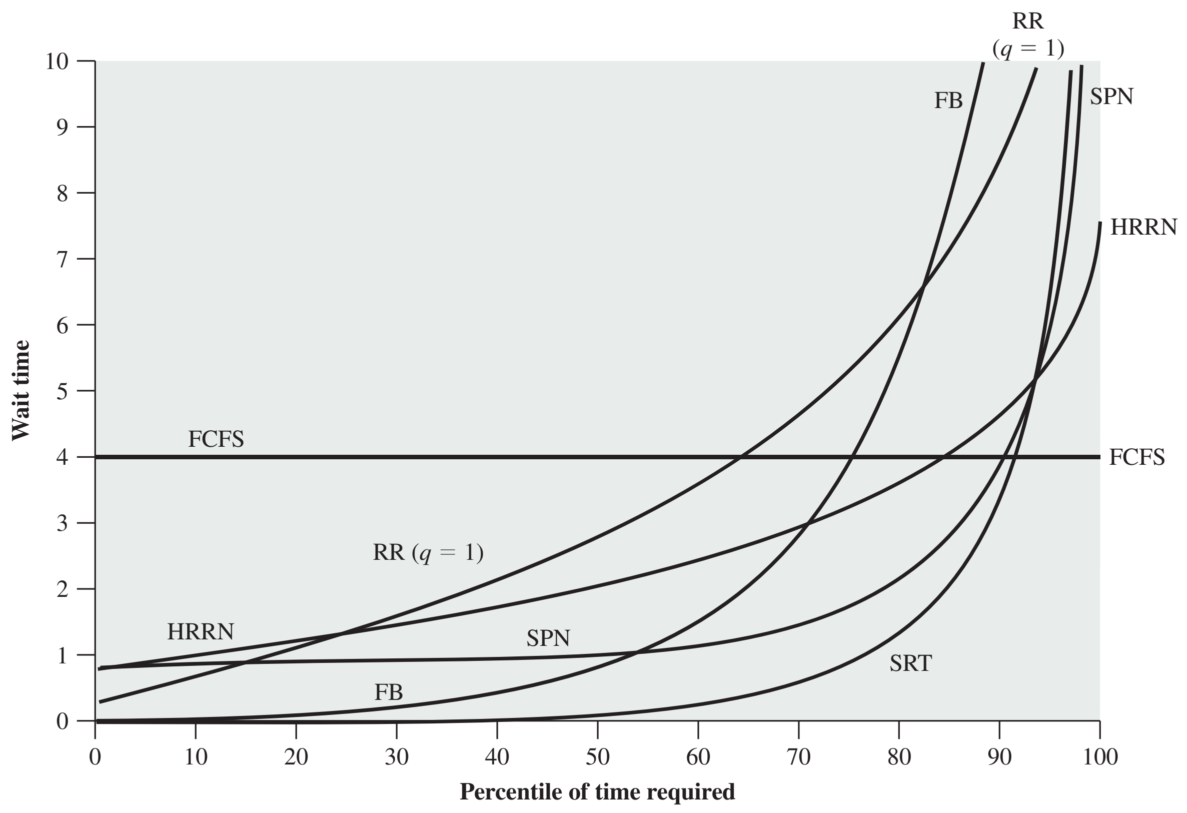


Figure 9.15 Simulation Result for Waiting Time

a normalized turnaround time greater than 10 times the service time; furthermore, these are the shortest processes. On the other hand, the absolute waiting time is uniform, as is to be expected because scheduling is independent of service time. The figures show round robin using a quantum of one time unit. Except for the shortest processes, which execute in less than one quantum, round robin yields a normalized turnaround time of about five for all processes, treating all fairly. Shortest process next performs better than round robin, except for the shortest processes. Shortest remaining time, the preemptive version of SPN, performs better than SPN except for the longest 7% of all processes. We have seen that, among nonpreemptive policies, FCFS favors long processes and SPN favors short ones. Highest response ratio next is intended to be a compromise between these two effects, and this is indeed confirmed in the figures. Finally, the figure shows feedback scheduling with fixed, uniform quanta in each priority queue. As expected, FB performs quite well for short processes.

Fair-Share Scheduling

All of the scheduling algorithms discussed so far treat the collection of ready processes as a single pool of processes from which to select the next running process. This pool may be broken down by priority but is otherwise homogeneous.

However, in a multiuser system, if individual user applications or jobs may be organized as multiple processes (or threads), then there is a structure to the collection of processes that is not recognized by a traditional scheduler. From the user's point of view, the concern is not how a particular process performs but rather how his or her set of processes, which constitute a single application, performs. Thus, it would be attractive to make scheduling decisions on the basis of these process sets. This approach is generally known as fair-share scheduling. Further, the concept can be extended to groups of users, even if each user is represented by a single process. For example, in a time-sharing system, we might wish to consider all of the users from a given department to be members of the same group. Scheduling decisions could then be made that attempt to give each group similar service. Thus, if a large number of people from one department log onto the system, we would like to see response time degradation primarily affect members of that department rather than users from other departments.

The term *fair share* indicates the philosophy behind such a scheduler. Each user is assigned a weighting of some sort that defines that user's share of system resources as a fraction of the total usage of those resources. In particular, each user is assigned a share of the processor. Such a scheme should operate in a more or less linear fashion, so that if user A has twice the weighting of user B, then in the long run, user A should be able to do twice as much work as user B. The objective of a fair-share scheduler is to monitor usage to give fewer resources to users who have had more than their fair share and more to those who have had less than their fair share.

A number of proposals have been made for fair-share schedulers [HENR84, KAY88, WOOD86]. In this section, we describe the scheme proposed in [HENR84] and implemented on a number of UNIX systems. The scheme is simply referred to as the fair-share scheduler (FSS). FSS considers the execution history of a related group of processes, along with the individual execution history of each process in making scheduling decisions. The system divides the user community into a set of fair-share groups and allocates a fraction of the processor resource to each group. Thus, there might be four groups, each with 25% of the processor usage. In effect, each fair-share group is provided with a virtual system that runs proportionally slower than a full system.

Scheduling is done on the basis of priority, which takes into account the underlying priority of the process, its recent processor usage, and the recent processor usage of the group to which the process belongs. The higher the numerical value of the priority, the lower is the priority. The following formulas apply for process *j* in group *k*:

$$CPU_j(i) = \frac{CPU_j(i-1)}{2}$$

$$GCPU_k(i) = \frac{GCPU_k(i-1)}{2}$$

$$P_j(i) = Base_j + \frac{CPU_j(i)}{2} + \frac{GCPU_k(i)}{4 \times W_k}$$

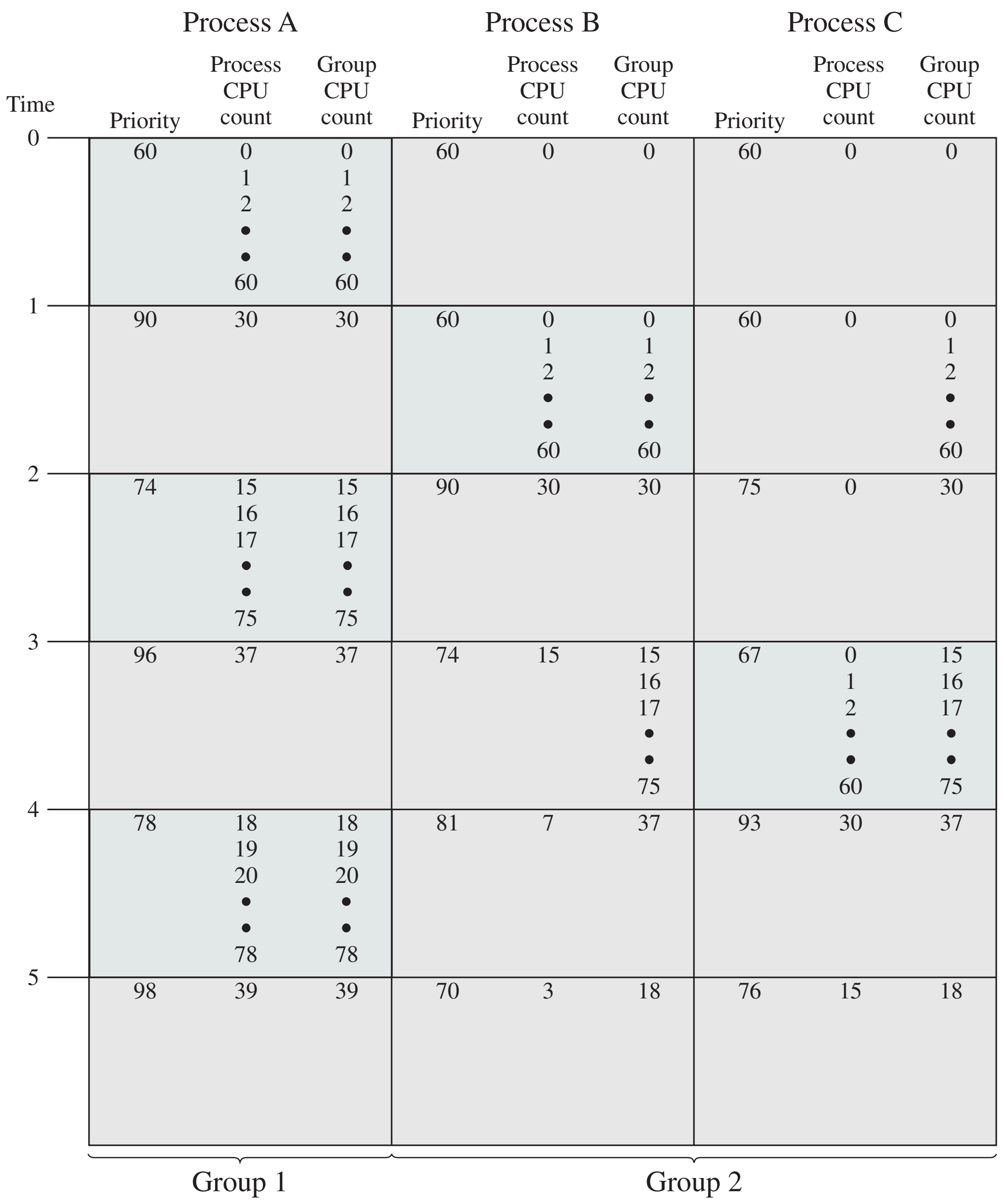
where

$CPU_j(i)$	= measure of processor utilization by process j through interval i
$GCPU_k(i)$	= measure of processor utilization of group k through interval i
$P_j(i)$	= priority of process j at beginning of interval i; lower values equal higher priorities
$Base_j$	= base priority of process j
W_k	= weighting assigned to group k, with the constraint that $0 < W_k \leq 1$ and $\sum_k W_k = 1$

Each process is assigned a base priority. The priority of a process drops as the process uses the processor and as the group to which the process belongs uses the processor. In the case of the group utilization, the average is normalized by dividing by the weight of that group. The greater the weight assigned to the group, the less its utilization will affect its priority.

Figure 9.16 is an example in which process A is in one group and processes B and C are in a second group, with each group having a weighting of 0.5. Assume that all processes are processor bound and are usually ready to run. All processes have a base priority of 60. Processor utilization is measured as follows: The processor is interrupted 60 times per second; during each interrupt, the processor usage field of the currently running process is incremented, as is the corresponding group processor field. Once per second, priorities are recalculated.

In the figure, process A is scheduled first. At the end of one second, it is preempted. Processes B and C now have the higher priority, and process B is scheduled. At the end of the second time unit, process A has the highest priority. Note that the pattern repeats: the kernel schedules the processes in order: A, B, A, C, A, B, and so on. Thus, 50% of the processor is allocated to process A, which constitutes one group, and 50% to processes B and C, which constitute another group.



Time	Process A Priority	Process A Process CPU count	Process A Group CPU count	Process B Priority	Process B Process CPU count	Process B Group CPU count	Process C Priority	Process C Process CPU count	Process C Group CPU count
0	60	0 1 2 • • 60	0 1 2 • • 60	60	0	0	60	0	0
1	90	30	30	60	0 1 2 • • 60	0 1 2 • • 60	60	0	0 1 2 • • 60
2	74	15 16 17 • • 75	15 16 17 • • 75	90	30	30	75	0	30
3	96	37	37	74	15	15 16 17 • • 75	67	0 1 2 • • 60	15 16 17 • • 75
4	78	18 19 20 • • 78	18 19 20 • • 78	81	7	37	93	30	37
5	98	39	39	70	3	18	76	15	18

Figure 9.16 Example of Fair-Share Scheduler—Three Processes, Two Groups

9.3 TRADITIONAL UNIX SCHEDULING

In this section we examine traditional UNIX scheduling, which is used in both SVR3 and 4.3 BSD UNIX. These systems are primarily targeted at the time-sharing interactive environment. The scheduling algorithm is designed to provide good response time for interactive users while ensuring that low-priority background jobs do not starve. Although this algorithm has been replaced in modern UNIX systems, it is worthwhile to examine the approach because it is representative of

If there is one singular characteristic that makes squirrels unique among small mammals it is their natural instinct to hoard food. Squirrels have developed sophisticated capabilities in their hoarding. Different types of food are stored in different ways to maintain quality. Mushrooms, for instance, are usually dried before storing. This is done by impaling them on branches or leaving them in the forks of trees for later retrieval. Pine cones, on the other hand, are often harvested while green and cached in damp conditions that keep seeds from ripening. Gray squirrels usually strip outer husks from walnuts before storing.

—*Squirrels: A Wildlife Handbook*, Kim Long

Learning Objectives

After studying this chapter, you should be able to:

- Describe the basic concepts of files and file systems.
- Understand the principal techniques for file organization and access.
- Define B-trees.
- Explain file directories.
- Understand the requirements for file sharing.
- Understand the concept of record blocking.
- Describe the principal design issues for secondary storage management.
- Understand the design issues for file system security.
- Explain the OS file systems used in Linux, UNIX, and Windows 7.

In most applications, the file is the central element. With the exception of real-time applications and some other specialized applications, the input to the application is by means of a file; and in virtually all applications, output is saved in a file for long-term storage and for later access by the user and by other programs.

Files have a life outside of any individual application that uses them for input and/or output. Users wish to be able to access files, save them, and maintain the integrity of their contents. To aid in these objectives, virtually all operating systems provide file management systems. Typically, a file management system consists of system utility programs that run as privileged applications. However, at the very least, a file management system needs special services from the operating system; at the most, the entire file management system is considered part of the operating system. Thus, it is appropriate to consider the basic elements of file management in this book.

We begin with an overview, followed by a look at various file organization schemes. Although file organization is generally beyond the scope of the operating system, it is essential to have a general understanding of the common alternatives to appreciate some of the design trade-offs involved in file management. The remainder of this chapter looks at other topics in file management.

12.1 OVERVIEW

Files and File Systems

From the user's point of view, one of the most important parts of an operating system is the file system. The file system provides the resource abstractions typically associated with secondary storage. The file system permits users to create data collections, called files, with desirable properties, such as:

- **Long-term existence:** Files are stored on disk or other secondary storage and do not disappear when a user logs off.
- **Sharable between processes:** Files have names and can have associated access permissions that permit controlled sharing.
- **Structure:** Depending on the file system, a file can have an internal structure that is convenient for particular applications. In addition, files can be organized into hierarchical or more complex structure to reflect the relationships among files.

Any file system provides not only a means to store data organized as files, but a collection of functions that can be performed on files. Typical operations include the following:

- **Create:** A new file is defined and positioned within the structure of files.
- **Delete:** A file is removed from the file structure and destroyed.
- **Open:** An existing file is declared to be "opened" by a process, allowing the process to perform functions on the file.
- **Close:** The file is closed with respect to a process, so that the process no longer may perform functions on the file, until the process opens the file again.
- **Read:** A process reads all or a portion of the data in a file.
- **Write:** A process updates a file, either by adding new data that expands the size of the file or by changing the values of existing data items in the file.

Typically, a file system maintains a set of attributes associated with the file. These include owner, creation time, time last modified, access privileges, and so on.

File Structure

Four terms are in common use when discussing files:

- Field
- Record
- File
- Database

A **field** is the basic element of data. An individual field contains a single value, such as an employee's last name, a date, or the value of a sensor reading. It is characterized by its length and data type (e.g., ASCII string, decimal). Depending on the file design, fields may be fixed length or variable length. In the latter case, the field often consists of two or three subfields: the actual value to be stored, the name of the field, and, in some cases, the length of the field. In other cases of variable-length fields, the length of the field is indicated by the use of special demarcation symbols between fields.

A **record** is a collection of related fields that can be treated as a unit by some application program. For example, an employee record would contain such fields as name, social security number, job classification, date of hire, and so on. Again, depending on design, records may be of fixed length or variable length. A record will be of variable length if some of its fields are of variable length or if the number of fields may vary. In the latter case, each field is usually accompanied by a field name. In either case, the entire record usually includes a length field.

A **file** is a collection of similar records. The file is treated as a single entity by users and applications and may be referenced by name. Files have file names and may be created and deleted. Access control restrictions usually apply at the file level. That is, in a shared system, users and programs are granted or denied access to entire files. In some more sophisticated systems, such controls are enforced at the record or even the field level.

Some file systems are structured only in terms of fields, not records. In that case, a file is a collection of fields.

A **database** is a collection of related data. The essential aspects of a database are that the relationships that exist among elements of data are explicit and that the database is designed for use by a number of different applications. A database may contain all of the information related to an organization or project, such as a business or a scientific study. The database itself consists of one or more types of files. Usually, there is a separate database management system that is independent of the operating system, although that system may make use of some file management programs.

Users and applications wish to make use of files. Typical operations that must be supported include the following:

- `Retrieve_All`: Retrieve all the records of a file. This will be required for an application that must process all of the information in the file at one time. For example, an application that produces a summary of the information in the file would need to retrieve all records. This operation is often equated with the term *sequential processing*, because all of the records are accessed in sequence.
- `Retrieve_One`: This requires the retrieval of just a single record. Interactive, transaction-oriented applications need this operation.
- `Retrieve_Next`: This requires the retrieval of the record that is "next" in some logical sequence to the most recently retrieved record. Some interactive applications, such as filling in forms, may require such an operation. A program that is performing a search may also use this operation.
- `Retrieve_Previous`: Similar to `Retrieve_Next`, but in this case the record that is "previous" to the currently accessed record is retrieved.
- `Insert_One`: Insert a new record into the file. It may be necessary that the new record fit into a particular position to preserve a sequencing of the file.

- `Delete_One`: Delete an existing record. Certain linkages or other data structures may need to be updated to preserve the sequencing of the file.
- `Update_One`: Retrieve a record, update one or more of its fields, and rewrite the updated record back into the file. Again, it may be necessary to preserve sequencing with this operation. If the length of the record has changed, the update operation is generally more difficult than if the length is preserved.
- `Retrieve_Few`: Retrieve a number of records. For example, an application or user may wish to retrieve all records that satisfy a certain set of criteria.

The nature of the operations that are most commonly performed on a file will influence the way the file is organized, as discussed in Section 12.2.

It should be noted that not all file systems exhibit the sort of structure discussed in this subsection. On UNIX and UNIX-like systems, the basic file structure is just a stream of bytes. For example, a C program is stored as a file but does not have physical fields, records, and so on.

File Management Systems

A file management system is that set of system software that provides services to users and applications in the use of files. Typically, the only way that a user or application may access files is through the file management system. This relieves the user or programmer of the necessity of developing special-purpose software for each application and provides the system with a consistent, well-defined means of controlling its most important asset. [GROS86] suggests the following objectives for a file management system:

- To meet the data management needs and requirements of the user, which include storage of data and the ability to perform the aforementioned operations
- To guarantee, to the extent possible, that the data in the file are valid
- To optimize performance, both from the system point of view in terms of overall throughput and from the user's point of view in terms of response time
- To provide I/O support for a variety of storage device types
- To minimize or eliminate the potential for lost or destroyed data
- To provide a standardized set of I/O interface routines to user processes
- To provide I/O support for multiple users, in the case of multiple-user systems

With respect to the first point, meeting user requirements, the extent of such requirements depends on the variety of applications and the environment in which the computer system will be used. For an interactive, general-purpose system, the following constitute a minimal set of requirements:

1. Each user should be able to create, delete, read, write, and modify files.
2. Each user may have controlled access to other users' files.
3. Each user may control what types of accesses are allowed to the user's files.
4. Each user should be able to restructure the user's files in a form appropriate to the problem.

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5. Each user should be able to move data between files.
6. Each user should be able to back up and recover the user's files in case of damage.
7. Each user should be able to access his or her files by name rather than by numeric identifier.

These objectives and requirements should be kept in mind throughout our discussion of file management systems.

File System Architecture One way of getting a feel for the scope of file management is to look at a depiction of a typical software organization, as suggested in Figure 12.1. Of course, different systems will be organized differently, but this organization is reasonably representative. At the lowest level, **device drivers** communicate directly with peripheral devices or their controllers or channels. A device driver is responsible for starting I/O operations on a device and processing the completion of an I/O request. For file operations, the typical devices controlled are disk and tape drives. Device drivers are usually considered to be part of the operating system.

The next level is referred to as the **basic file system**, or the **physical I/O** level. This is the primary interface with the environment outside of the computer system. It deals with blocks of data that are exchanged with disk or tape systems. Thus, it is concerned with the placement of those blocks on the secondary storage device and on the buffering of those blocks in main memory. It does not understand the content of the data or the structure of the files involved. The basic file system is often considered part of the operating system.

The **basic I/O supervisor** is responsible for all file I/O initiation and termination. At this level, control structures are maintained that deal with device I/O, scheduling, and file status. The basic I/O supervisor selects the device on which file I/O is to be performed, based on the particular file selected. It is also concerned with scheduling disk and tape accesses to optimize performance. I/O buffers are

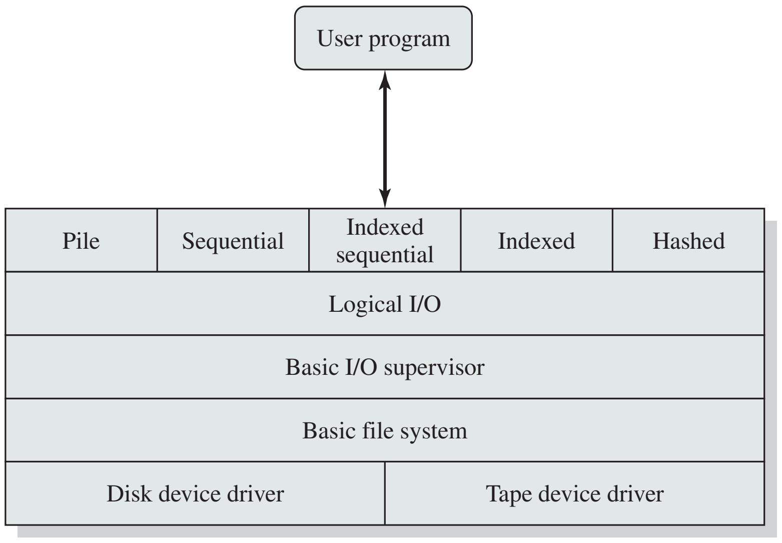


Figure 12.1 File System Software Architecture

assigned and secondary memory is allocated at this level. The basic I/O supervisor is part of the operating system.

Logical I/O enables users and applications to access records. Thus, whereas the basic file system deals with blocks of data, the logical I/O module deals with file records. Logical I/O provides a general-purpose record I/O capability and maintains basic data about files.

The level of the file system closest to the user is often termed the **access method.** It provides a standard interface between applications and the file systems and devices that hold the data. Different access methods reflect different file structures and different ways of accessing and processing the data. Some of the most common access methods are shown in Figure 12.1, and these are briefly described in Section 12.2.

File Management Functions Another way of viewing the functions of a file system is shown in Figure 12.2. Let us follow this diagram from left to right. Users and application programs interact with the file system by means of commands for creating and deleting files and for performing operations on files. Before performing any operation, the file system must identify and locate the selected file. This requires the use of some sort of directory that serves to describe the location of all files, plus their attributes. In addition, most shared systems enforce user access control: Only authorized users are allowed to access particular files in particular ways. The basic operations that a user or application may perform on a file are performed at the record level. The user or application views the file as having some structure that organizes the records, such as a sequential structure (e.g., personnel records are stored alphabetically by last name). Thus, to translate user commands into specific

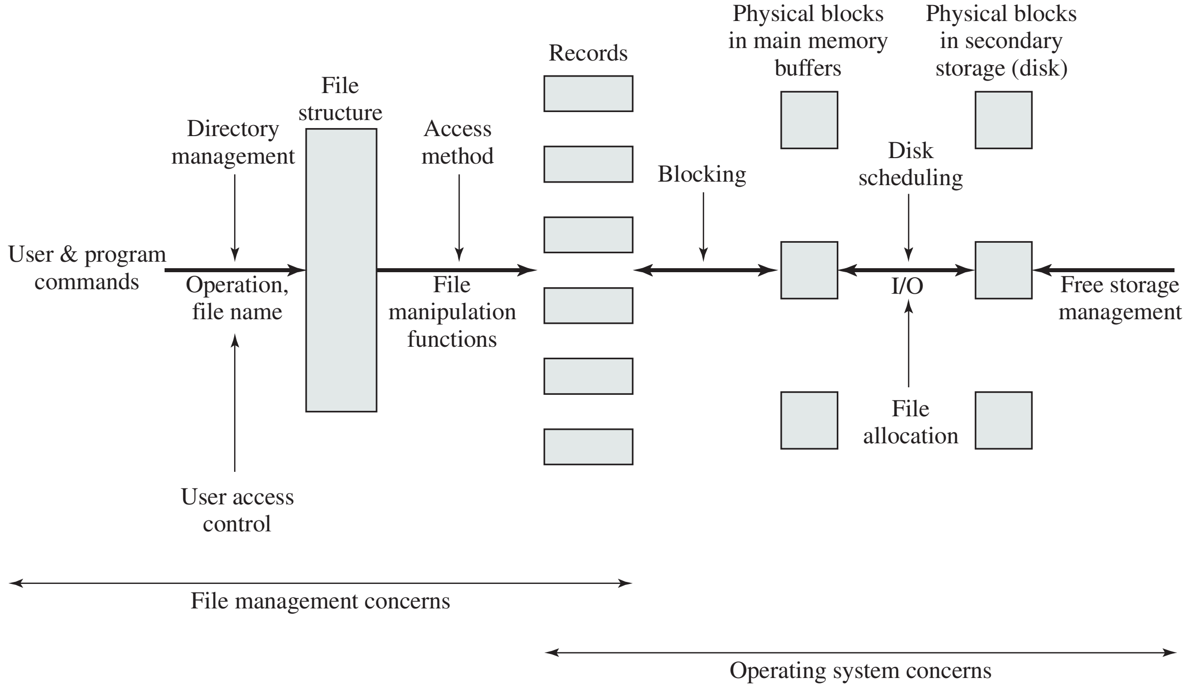


Figure 12.2 Elements of File Management

file manipulation commands, the access method appropriate to this file structure must be employed.

Whereas users and applications are concerned with records or fields, I/O is done on a block basis. Thus, the records or fields of a file must be organized as a sequence of blocks for output and unblocked after input. To support block I/O of files, several functions are needed. The secondary storage must be managed. This involves allocating files to free blocks on secondary storage and managing free storage so as to know what blocks are available for new files and growth in existing files. In addition, individual block I/O requests must be scheduled; this issue was dealt with in Chapter 11. Both disk scheduling and file allocation are concerned with optimizing performance. As might be expected, these functions therefore need to be considered together. Furthermore, the optimization will depend on the structure of the files and the access patterns. Accordingly, developing an optimum file management system from the point of view of performance is an exceedingly complicated task.

Figure 12.2 suggests a division between what might be considered the concerns of the file management system as a separate system utility and the concerns of the operating system, with the point of intersection being record processing. This division is arbitrary; various approaches are taken in various systems.

In the remainder of this chapter, we look at some of the design issues suggested in Figure 12.2. We begin with a discussion of file organizations and access methods. Although this topic is beyond the scope of what is usually considered the concerns of the operating system, it is impossible to assess the other file-related design issues without an appreciation of file organization and access. Next, we look at the concept of file directories. These are often managed by the operating system on behalf of the file management system. The remaining topics deal with the physical I/O aspects of file management and are properly treated as aspects of OS design. One such issue is the way in which logical records are organized into physical blocks. Finally, there are the related issues of file allocation on secondary storage and the management of free secondary storage.

12.2 FILE ORGANIZATION AND ACCESS

In this section, we use the term *file organization* to refer to the logical structuring of the records as determined by the way in which they are accessed. The physical organization of the file on secondary storage depends on the blocking strategy and the file allocation strategy, issues dealt with later in this chapter.

In choosing a file organization, several criteria are important:

- Short access time
- Ease of update
- Economy of storage
- Simple maintenance
- Reliability

The relative priority of these criteria will depend on the applications that will use the file. For example, if a file is only to be processed in batch mode, with all of the records accessed every time, then rapid access for retrieval of a single record is of minimal concern. A file stored on CD-ROM will never be updated, and so ease of update is not an issue.

These criteria may conflict. For example, for economy of storage, there should be minimum redundancy in the data. On the other hand, redundancy is a primary means of increasing the speed of access to data. An example of this is the use of indexes.

The number of alternative file organizations that have been implemented or just proposed is unmanageably large, even for a book devoted to file systems. In this brief survey, we will outline five fundamental organizations. Most structures used in actual systems either fall into one of these categories or can be implemented with a combination of these organizations. The five organizations, the first four of which are depicted in Figure 12.3, are as follows:

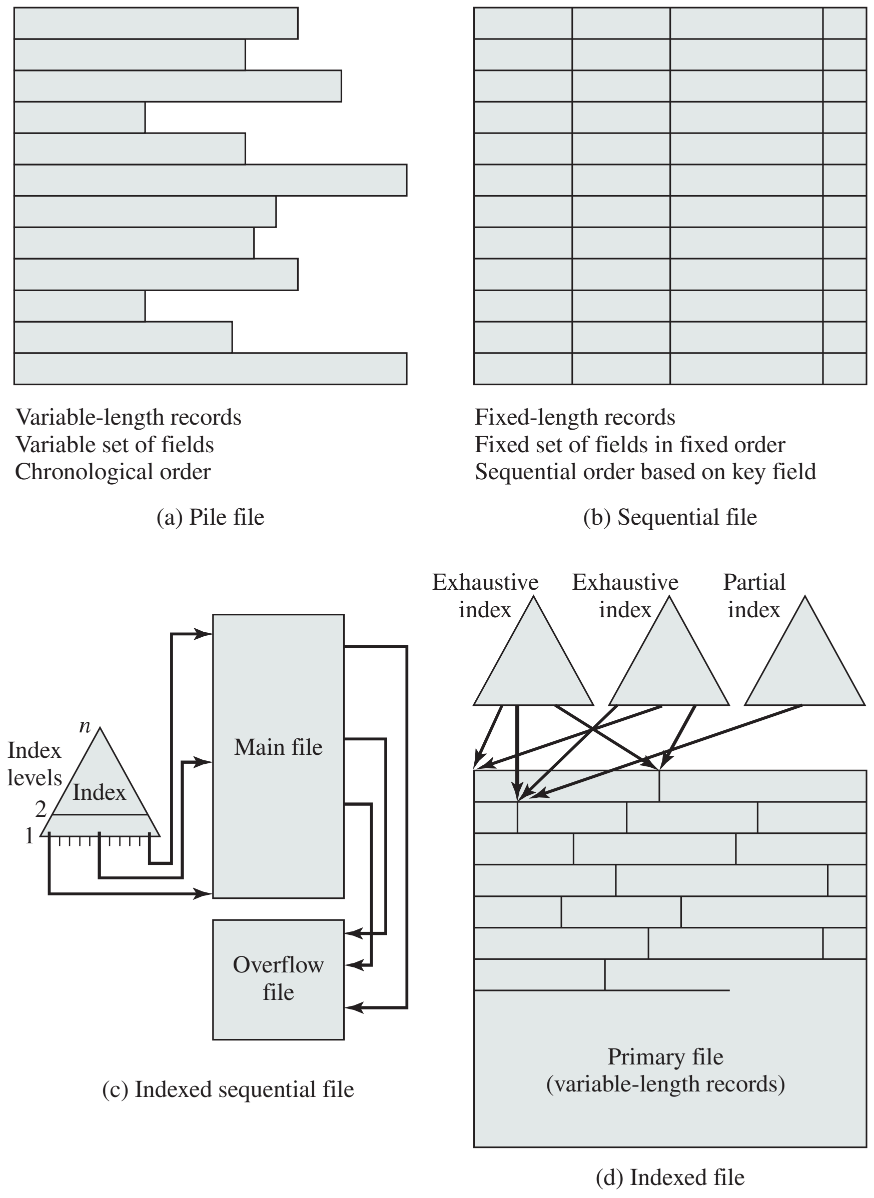


Figure 12.3 Common File Organizations

- The pile
- The sequential file
- The indexed sequential file
- The indexed file
- The direct, or hashed, file

Table 12.1 summarizes relative performance aspects of these five organizations.[1]

The Pile

The least-complicated form of file organization may be termed the *pile*. Data are collected in the order in which they arrive. Each record consists of one burst of data. The purpose of the pile is simply to accumulate the mass of data and save it. Records may have different fields, or similar fields in different orders. Thus, each field should be self-describing, including a field name as well as a value. The length of each field must be implicitly indicated by delimiters, explicitly included as a subfield, or known as default for that field type.

Because there is no structure to the pile file, record access is by exhaustive search. That is, if we wish to find a record that contains a particular field with a particular value, it is necessary to examine each record in the pile until the desired

Table 12.1 Grades of Performance for Five Basic File Organizations [WIED87]

	Space Attributes		Update Record Size		Retrieval		
File Method	**Variable**	**Fixed**	**Equal**	**Greater**	**Single record**	**Subset**	**Exhaustive**
Pile	A	B	A	E	E	D	B
Sequential	F	A	D	F	F	D	A
Indexed sequential	F	B	B	D	B	D	B
Indexed	B	C	C	C	A	B	D
Hashed	F	B	B	F	B	F	E

A = Excellent, well suited to this purpose	$\approx O(r)$
B = Good	$\approx O(o \times r)$
C = Adequate	$\approx O(r \log n)$
D = Requires some extra effort	$\approx O(n)$
E = Possible with extreme effort	$\approx O(r \times n)$
F = Not reasonable for this purpose	$\approx O(n > 1)$

where
r = size of the result
o = number of records that overflow
n = number of records in file

[1]The table employs the "big-O" notation, used for characterizing the time complexity of algorithms. Appendix I explains this notation.

record is found or the entire file has been searched. If we wish to find all records that contain a particular field or contain that field with a particular value, then the entire file must be searched.

Pile files are encountered when data are collected and stored prior to processing or when data are not easy to organize. This type of file uses space well when the stored data vary in size and structure, is perfectly adequate for exhaustive searches, and is easy to update. However, beyond these limited uses, this type of file is unsuitable for most applications.

The Sequential File

The most common form of file structure is the sequential file. In this type of file, a fixed format is used for records. All records are of the same length, consisting of the same number of fixed-length fields in a particular order. Because the length and position of each field are known, only the values of fields need to be stored; the field name and length for each field are attributes of the file structure.

One particular field, usually the first field in each record, is referred to as the **key field**. The key field uniquely identifies the record; thus key values for different records are always different. Further, the records are stored in key sequence: alphabetical order for a text key, and numerical order for a numerical key.

Sequential files are typically used in batch applications and are generally optimum for such applications if they involve the processing of all the records (e.g., a billing or payroll application). The sequential file organization is the only one that is easily stored on tape as well as disk.

For interactive applications that involve queries and/or updates of individual records, the sequential file provides poor performance. Access requires the sequential search of the file for a key match. If the entire file, or a large portion of the file, can be brought into main memory at one time, more efficient search techniques are possible. Nevertheless, considerable processing and delay are encountered to access a record in a large sequential file. Additions to the file also present problems. Typically, a sequential file is stored in simple sequential ordering of the records within blocks. That is, the physical organization of the file on tape or disk directly matches the logical organization of the file. In this case, the usual procedure is to place new records in a separate pile file, called a log file or transaction file. Periodically, a batch update is performed that merges the log file with the master file to produce a new file in correct key sequence.

An alternative is to organize the sequential file physically as a linked list. One or more records are stored in each physical block. Each block on disk contains a pointer to the next block. The insertion of new records involves pointer manipulation but does not require that the new records occupy a particular physical block position. Thus, some added convenience is obtained at the cost of additional processing and overhead.

The Indexed Sequential File

A popular approach to overcoming the disadvantages of the sequential file is the indexed sequential file. The indexed sequential file maintains the key characteristic of the sequential file: Records are organized in sequence based on a key field. Two features are added: an index to the file to support random access, and an overflow file. The index provides a lookup capability to reach quickly the vicinity of a desired record. The overflow file is similar to the log file used with a sequential file but is integrated so that a record in the overflow file is located by following a pointer from its predecessor record.

In the simplest indexed sequential structure, a single level of indexing is used. The index in this case is a simple sequential file. Each record in the index file consists of two fields: a key field, which is the same as the key field in the main file, and a pointer into the main file. To find a specific field, the index is searched to find the highest key value that is equal to or precedes the desired key value. The search continues in the main file at the location indicated by the pointer.

To see the effectiveness of this approach, consider a sequential file with 1 million records. To search for a particular key value will require on average one-half million record accesses. Now suppose that an index containing 1,000 entries is constructed, with the keys in the index more or less evenly distributed over the main file. Now it will take on average 500 accesses to the index file followed by 500 accesses to the main file to find the record. The average search length is reduced from 500,000 to 1,000.

Additions to the file are handled in the following manner: Each record in the main file contains an additional field not visible to the application, which is a pointer to the overflow file. When a new record is to be inserted into the file, it is added to the overflow file. The record in the main file that immediately precedes the new record in logical sequence is updated to contain a pointer to the new record in the overflow file. If the immediately preceding record is itself in the overflow file, then the pointer in that record is updated. As with the sequential file, the indexed sequential file is occasionally merged with the overflow file in batch mode.

The indexed sequential file greatly reduces the time required to access a single record, without sacrificing the sequential nature of the file. To process the entire file sequentially, the records of the main file are processed in sequence until a pointer to the overflow file is found, then accessing continues in the overflow file until a null pointer is encountered, at which time accessing of the main file is resumed where it left off.

To provide even greater efficiency in access, multiple levels of indexing can be used. Thus the lowest level of index file is treated as a sequential file and a higher-level index file is created for that file. Consider again a file with 1 million records. A lower-level index with 10,000 entries is constructed. A higher-level index into the lower-level index of 100 entries can then be constructed. The search begins at the higher-level index (average length = 50 accesses) to find an entry point into the lower-level index. This index is then searched (average length = 50) to find an entry point into the main file, which is then searched (average length = 50). Thus the average length of search has been reduced from 500,000 to 1,000 to 150.

The Indexed File

The indexed sequential file retains one limitation of the sequential file: Effective processing is limited to that which is based on a single field of the file. For example, when it is necessary to search for a record on the basis of some other attribute than the key field, both forms of sequential file are inadequate. In some applications, the flexibility of efficiently searching by various attributes is desirable.

To achieve this flexibility, a structure is needed that employs multiple indexes, one for each type of field that may be the subject of a search. In the general indexed file, the concept of sequentiality and a single key are abandoned. Records are accessed only through their indexes. The result is that there is now no restriction on the placement of records as long as a pointer in at least one index refers to that record. Furthermore, variable-length records can be employed.

Two types of indexes are used. An exhaustive index contains one entry for every record in the main file. The index itself is organized as a sequential file for ease of searching. A partial index contains entries to records where the field of interest exists. With variable-length records, some records will not contain all fields. When a new record is added to the main file, all of the index files must be updated.

Indexed files are used mostly in applications where timeliness of information is critical and where data are rarely processed exhaustively. Examples are airline reservation systems and inventory control systems.

The Direct or Hashed File

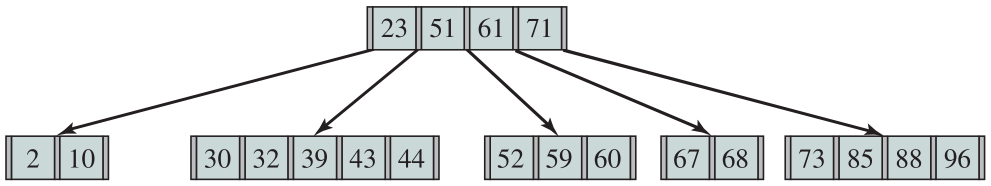
The direct, or hashed, file exploits the capability found on disks to access directly any block of a known address. As with sequential and indexed sequential files, a key field is required in each record. However, there is no concept of sequential ordering here.

The direct file makes use of hashing on the key value. This function is explained in Appendix F. Figure F.1b shows the type of hashing organization with an overflow file that is typically used in a hash file.

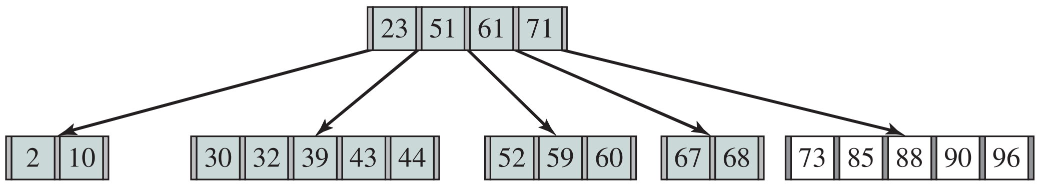
Direct files are often used where very rapid access is required, where fixed-length records are used, and where records are always accessed one at a time. Examples are directories, pricing tables, schedules, and name lists.

12.3 B-TREES

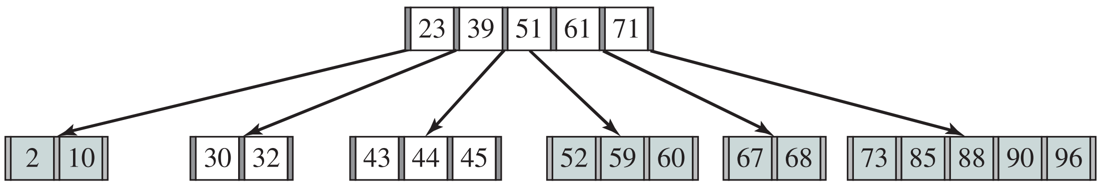
The preceding section referred to the use of an index file to access individual records in a file or database. For a large file or database, a single sequential file of indexes on the primary key does not provide for rapid access. To provide more efficient access, a structured index file is typically used. The simplest such structure is a two-level organization in which the original file is broken into sections and the upper level consists of a sequenced set of pointers to the lower-level sections. This structure can then be extended to more than two levels, resulting in a tree structure. Unless some discipline is imposed on the construction of the tree index, it is likely to end up with an uneven structure, with some short branches and some long branches, so that the time to search the index is uneven. Therefore, a balanced tree structure, with all branches of equal length, would appear to give the best average performance. Such a structure is the B-tree, which has become the standard method of organizing indexes for databases and is commonly used in OS file systems, including those supported by Mac OS X, Windows, and several Linux file systems. The B-tree structure provides for efficient searching, adding, and deleting of items.



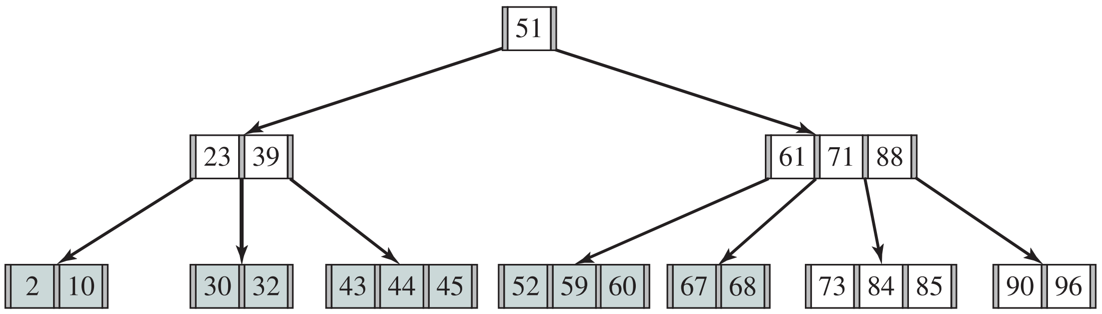
(a) B-tree of minimum degree $d = 3$.



(b) Key = 90 inserted. This is a simple insertion into a node.



(c) Key = 45 inserted. This requires splitting a node into two parts and promoting one key to the root node.



(d) Key = 84 inserted. This requires splitting a node into two parts and promoting one key to the root node. This then requires the root node to be split and a new root created.

Figure 12.5 Inserting Nodes into a B-tree

Figure 12.5 illustrates the insertion process on a B-tree of degree $d = 3$. In each part of the figure, the nodes affected by the insertion process are unshaded.

12.4 FILE DIRECTORIES

Contents

Associated with any file management system and collection of files is a file directory. The directory contains information about the files, including attributes, location, and ownership. Much of this information, especially that concerned with storage,

Table 12.2 Information Elements of a File Directory

	Basic Information
File Name	Name as chosen by creator (user or program). Must be unique within a specific directory
File Type	For example: text, binary, load module, etc.
File Organization	For systems that support different organizations
	Address Information
Volume	Indicates device on which file is stored
Starting Address	Starting physical address on secondary storage (e.g., cylinder, track, and block number on disk)
Size Used	Current size of the file in bytes, words, or blocks
Size Allocated	The maximum size of the file
	Access Control Information
Owner	User who is assigned control of this file. The owner may be able to grant/deny access to other users and to change these privileges.
Access Information	A simple version of this element would include the user's name and password for each authorized user.
Permitted Actions	Controls reading, writing, executing, and transmitting over a network
	Usage Information
Date Created	When file was first placed in directory
Identity of Creator	Usually but not necessarily the current owner
Date Last Read Access	Date of the last time a record was read
Identity of Last Reader	User who did the reading
Date Last Modified	Date of the last update, insertion, or deletion
Identity of Last Modifier	User who did the modifying
Date of Last Backup	Date of the last time the file was backed up on another storage medium
Current Usage	Information about current activity on the file, such as process or processes that have the file open, whether it is locked by a process, and whether the file has been updated in main memory but not yet on disk

is managed by the operating system. The directory is itself a file, accessible by various file management routines. Although some of the information in directories is available to users and applications, this is generally provided indirectly by system routines.

Table 12.2 suggests the information typically stored in the directory for each file in the system. From the user's point of view, the directory provides a mapping between file names, known to users and applications, and the files themselves. Thus, each file entry includes the name of the file. Virtually all systems deal with different types of files and different file organizations, and this information is also provided. An important category of information about each file concerns its storage, including its location and size. In shared systems, it is also important to provide information that is used to control access to the file. Typically, one user is the owner of the file and may grant certain access privileges to other users. Finally, usage information is needed to manage the current use of the file and to record the history of its usage.

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Structure

The way in which the information of Table 12.2 is stored differs widely among various systems. Some of the information may be stored in a header record associated with the file; this reduces the amount of storage required for the directory, making it easier to keep all or much of the directory in main memory to improve speed.

The simplest form of structure for a directory is that of a list of entries, one for each file. This structure could be represented by a simple sequential file, with the name of the file serving as the key. In some earlier single-user systems, this technique has been used. However, it is inadequate when multiple users share a system and even for single users with many files.

To understand the requirements for a file structure, it is helpful to consider the types of operations that may be performed on the directory:

- **Search:** When a user or application references a file, the directory must be searched to find the entry corresponding to that file.
- **Create file:** When a new file is created, an entry must be added to the directory.
- **Delete file:** When a file is deleted, an entry must be removed from the directory.
- **List directory:** All or a portion of the directory may be requested. Generally, this request is made by a user and results in a listing of all files owned by that user, plus some of the attributes of each file (e.g., type, access control information, usage information).
- **Update directory:** Because some file attributes are stored in the directory, a change in one of these attributes requires a change in the corresponding directory entry.

The simple list is not suited to supporting these operations. Consider the needs of a single user. The user may have many types of files, including word-processing text files, graphic files, spreadsheets, and so on. The user may like to have these organized by project, by type, or in some other convenient way. If the directory is a simple sequential list, it provides no help in organizing the files and forces the user to be careful not to use the same name for two different types of files. The problem is much worse in a shared system. Unique naming becomes a serious problem. Furthermore, it is difficult to conceal portions of the overall directory from users when there is no inherent structure in the directory.

A start in solving these problems would be to go to a two-level scheme. In this case, there is one directory for each user, and a master directory. The master directory has an entry for each user directory, providing address and access control information. Each user directory is a simple list of the files of that user. This arrangement means that names must be unique only within the collection of files of a single user and that the file system can easily enforce access restriction on directories. However, it still provides users with no help in structuring collections of files.

A more powerful and flexible approach, and one that is almost universally adopted, is the hierarchical, or tree-structure, approach (Figure 12.6). As before, there is a master directory, which has under it a number of user directories. Each of

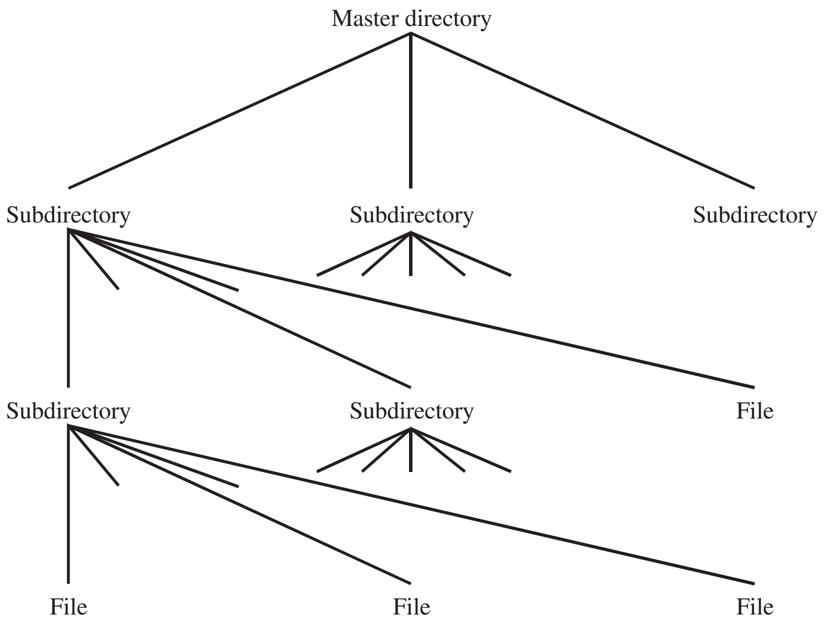

Figure 12.6 Tree-Structured Directory

these user directories, in turn, may have subdirectories and files as entries. This is true at any level: That is, at any level, a directory may consist of entries for subdirectories and/or entries for files.

It remains to say how each directory and subdirectory is organized. The simplest approach, of course, is to store each directory as a sequential file. When directories may contain a very large number of entries, such an organization may lead to unnecessarily long search times. In that case, a hashed structure is to be preferred.

Naming

Users need to be able to refer to a file by a symbolic name. Clearly, each file in the system must have a unique name in order that file references be unambiguous. On the other hand, it is an unacceptable burden on users to require that they provide unique names, especially in a shared system.

The use of a tree-structured directory minimizes the difficulty in assigning unique names. Any file in the system can be located by following a path from the root or master directory down various branches until the file is reached. The series of directory names, culminating in the file name itself, constitutes a **pathname** for the file. As an example, the file in the lower left-hand corner of Figure 12.7 has the pathname `User_B/Word/Unit_A/ABC`. The slash is used to delimit names in the sequence. The name of the master directory is implicit, because all paths start at that directory. Note that it is perfectly acceptable to have several files with the same file name, as long as they have unique pathnames, which is equivalent to saying that the same file name may be used in different directories. In our example, there is another file in the system with the file name ABC, but that has the pathname `/User_B/Draw/ABC`.

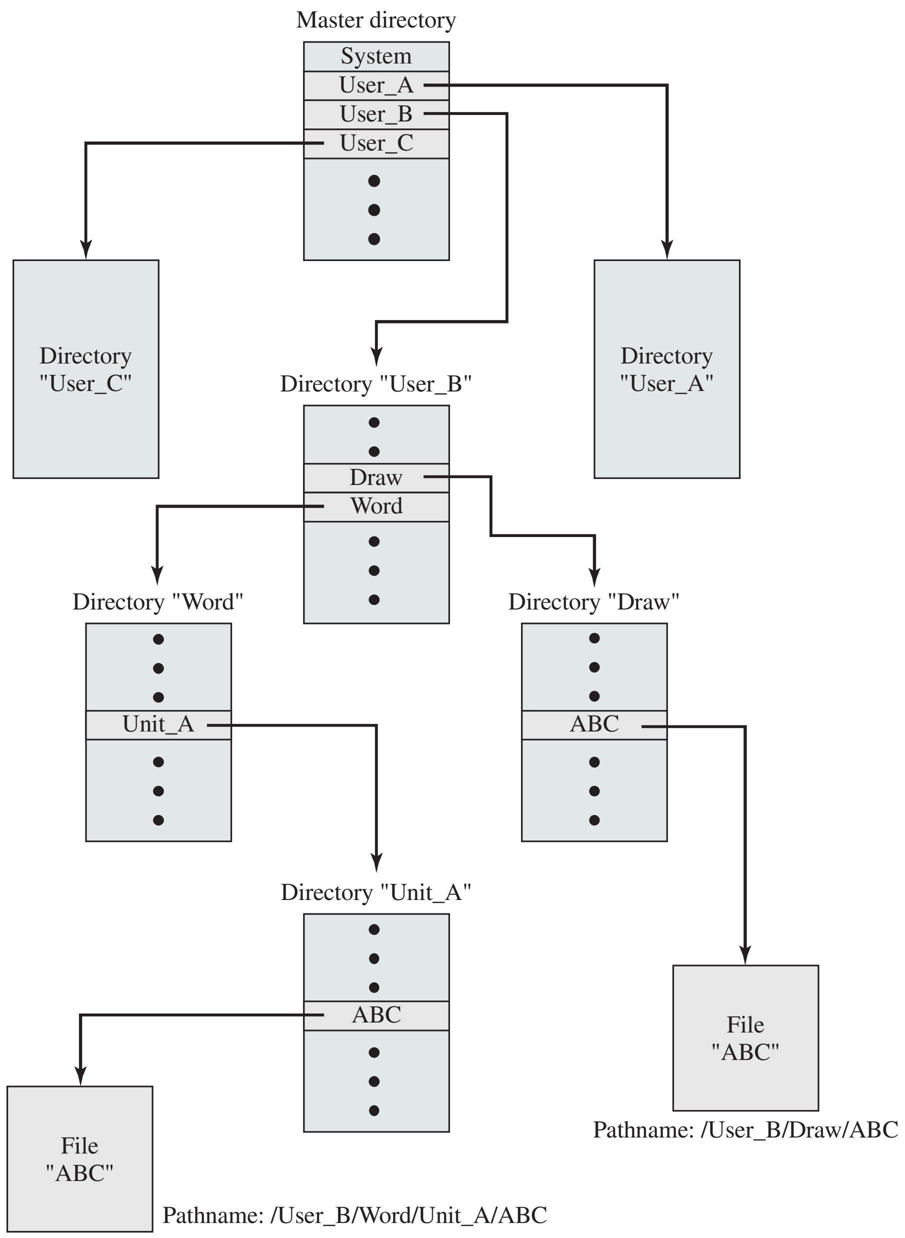

Figure 12.7 Example of Tree-Structured Directory

Although the pathname facilitates the selection of file names, it would be awkward for a user to have to spell out the entire pathname every time a reference is made to a file. Typically, an interactive user or a process has associated with it a current directory, often referred to as the **working directory**. Files are then referenced relative to the working directory. For example, if the working directory for user B is "Word," then the pathname `Unit_A/ABC` is sufficient to identify the file in the lower left-hand corner of Figure 12.7. When an interactive user logs on, or when a process is created, the default for the working directory is the user home directory. During execution, the user can navigate up or down in the tree to change to a different working directory.

12.5 FILE SHARING

In a multiuser system, there is almost always a requirement for allowing files to be shared among a number of users. Two issues arise: access rights and the management of simultaneous access.

Access Rights

The file system should provide a flexible tool for allowing extensive file sharing among users. The file system should provide a number of options so that the way in which a particular file is accessed can be controlled. Typically, users or groups of users are granted certain access rights to a file. A wide range of access rights has been used. The following list is representative of access rights that can be assigned to a particular user for a particular file:

- **None:** The user may not even learn of the existence of the file, much less access it. To enforce this restriction, the user would not be allowed to read the user directory that includes this file.
- **Knowledge:** The user can determine that the file exists and who its owner is. The user is then able to petition the owner for additional access rights.
- **Execution:** The user can load and execute a program but cannot copy it. Proprietary programs are often made accessible with this restriction.
- **Reading:** The user can read the file for any purpose, including copying and execution. Some systems are able to enforce a distinction between viewing and copying. In the former case, the contents of the file can be displayed to the user, but the user has no means for making a copy.
- **Appending:** The user can add data to the file, often only at the end, but cannot modify or delete any of the file's contents. This right is useful in collecting data from a number of sources.
- **Updating:** The user can modify, delete, and add to the file's data. This normally includes writing the file initially, rewriting it completely or in part, and removing all or a portion of the data. Some systems distinguish among different degrees of updating.
- **Changing protection:** The user can change the access rights granted to other users. Typically, this right is held only by the owner of the file. In some systems, the owner can extend this right to others. To prevent abuse of this mechanism, the file owner will typically be able to specify which rights can be changed by the holder of this right.
- **Deletion:** The user can delete the file from the file system.

These rights can be considered to constitute a hierarchy, with each right implying those that precede it. Thus, if a particular user is granted the updating right for a particular file, then that user is also granted the following rights: knowledge, execution, reading, and appending.

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One user is designated as owner of a given file, usually the person who initially created a file. The owner has all of the access rights listed previously and may grant rights to others. Access can be provided to different classes of users:

- **Specific user:** Individual users who are designated by user ID
- **User groups:** A set of users who are not individually defined. The system must have some way of keeping track of the membership of user groups.
- **All:** All users who have access to this system. These are public files.

Simultaneous Access

When access is granted to append or update a file to more than one user, the operating system or file management system must enforce discipline. A brute-force approach is to allow a user to lock the entire file when it is to be updated. A finer grain of control is to lock individual records during update. Essentially, this is the readers/writers problem discussed in Chapter 5. Issues of mutual exclusion and deadlock must be addressed in designing the shared access capability.

12.6 RECORD BLOCKING

As indicated in Figure 12.2, records are the logical unit of access of a structured file,[3] whereas blocks are the unit of I/O with secondary storage. For I/O to be performed, records must be organized as blocks.

There are several issues to consider. First, should blocks be of fixed or variable length? On most systems, blocks are of fixed length. This simplifies I/O, buffer allocation in main memory, and the organization of blocks on secondary storage. Second, what should the relative size of a block be compared to the average record size? The trade-off is this: The larger the block, the more records that are passed in one I/O operation. If a file is being processed or searched sequentially, this is an advantage, because the number of I/O operations is reduced by using larger blocks, thus speeding up processing. On the other hand, if records are being accessed randomly and no particular locality of reference is observed, then larger blocks result in the unnecessary transfer of unused records. However, combining the frequency of sequential operations with the potential for locality of reference, we can say that the I/O transfer time is reduced by using larger blocks. The competing concern is that larger blocks require larger I/O buffers, making buffer management more difficult.

Given the size of a block, there are three methods of blocking that can be used:

- **Fixed blocking:** Fixed-length records are used, and an integral number of records are stored in a block. There may be unused space at the end of each block. This is referred to as internal fragmentation.
- **Variable-length spanned blocking:** Variable-length records are used and are packed into blocks with no unused space. Thus, some records must span two blocks, with the continuation indicated by a pointer to the successor block.

[3] As opposed to a file that is treated only as a stream of bytes, such as in the UNIX file system.

- **Variable-length unspanned blocking:** Variable-length records are used, but spanning is not employed. There is wasted space in most blocks because of the inability to use the remainder of a block if the next record is larger than the remaining unused space.

Figure 12.8 illustrates these methods assuming that a file is stored in sequential blocks on a disk. The figure assumes that the file is large enough to span two tracks.[4] The effect would not be changed if some other file allocation scheme were used (see Section 12.6).

Fixed blocking is the common mode for sequential files with fixed-length records. Variable-length spanned blocking is efficient of storage and does not limit

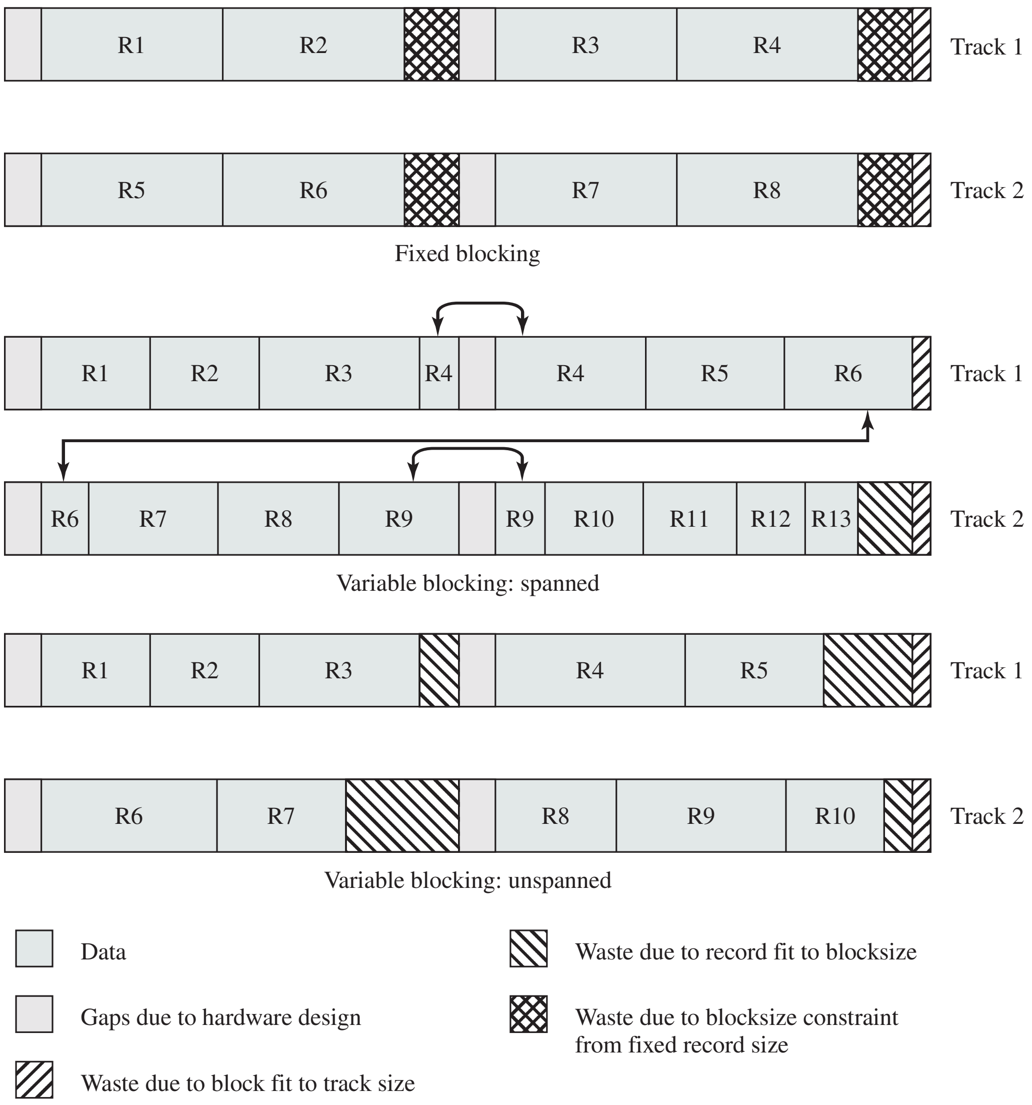

R1
R2
R3
R4
Track 1
R5
R6
R7
R8
Track 2
Fixed blocking
R1
R2
R3
R4
R4
R5
R6
Track 1
R6
R7
R8
R9
R9
R10
R11
R12
R13
Track 2
Variable blocking: spanned
R1
R2
R3
R4
R5
Track 1
R6
R7
R8
R9
R10
Track 2
Variable blocking: unspanned
Data
Gaps due to hardware design
Waste due to block fit to track size
Waste due to record fit to blocksize
Waste due to blocksize constraint from fixed record size

Figure 12.8 Record Blocking Methods [WIED87]

[4]Recall from Appendix J that the organization of data on a disk is in a concentric set of rings, called *tracks*. Each track is the same width as the read/write head.

the size of records. However, this technique is difficult to implement. Records that span two blocks require two I/O operations, and files are difficult to update, regardless of the organization. Variable-length unspanned blocking results in wasted space and limits record size to the size of a block.

The record-blocking technique may interact with the virtual memory hardware, if such is employed. In a virtual memory environment, it is desirable to make the page the basic unit of transfer. Pages are generally quite small, so that it is impractical to treat a page as a block for unspanned blocking. Accordingly, some systems combine multiple pages to create a larger block for file I/O purposes. This approach is used for VSAM files on IBM mainframes.

12.7 SECONDARY STORAGE MANAGEMENT

On secondary storage, a file consists of a collection of blocks. The operating system or file management system is responsible for allocating blocks to files. This raises two management issues. First, space on secondary storage must be allocated to files, and second, it is necessary to keep track of the space available for allocation. We will see that these two tasks are related; that is, the approach taken for file allocation may influence the approach taken for free space management. Further, we will see that there is an interaction between file structure and allocation policy.

We begin this section by looking at alternatives for file allocation on a single disk. Then we look at the issue of free space management, and finally we discuss reliability.

File Allocation

Several issues are involved in file allocation:

1. When a new file is created, is the maximum space required for the file allocated at once?
2. Space is allocated to a file as one or more contiguous units, which we shall refer to as portions. That is, a **portion** is a contiguous set of allocated blocks. The size of a portion can range from a single block to the entire file. What size of portion should be used for file allocation?
3. What sort of data structure or table is used to keep track of the portions assigned to a file? An example of such a structure is a **file allocation table (FAT),** found on DOS and some other systems.

Let us examine these issues in turn.

Preallocation versus Dynamic Allocation A preallocation policy requires that the maximum size of a file be declared at the time of the file creation request. In a number of cases, such as program compilations, the production of summary data files, or the transfer of a file from another system over a communications network, this value can be reliably estimated. However, for many applications, it is difficult if not impossible to estimate reliably the maximum potential size of the file. In those cases, users and application programmers would tend to overestimate file size so as not to run out of space. This clearly is wasteful from the point of view of secondary storage allocation. Thus, there are advantages to the use of dynamic allocation, which allocates space to a file in portions as needed.

Portion Size The second issue listed is that of the size of the portion allocated to a file. At one extreme, a portion large enough to hold the entire file is allocated. At the other extreme, space on the disk is allocated one block at a time. In choosing a portion size, there is a trade-off between efficiency from the point of view of a single file versus overall system efficiency. [WIED87] lists four items to be considered in the trade-off:

1. Contiguity of space increases performance, especially for `Retrieve_Next` operations, and greatly for transactions running in a transaction-oriented operating system.
2. Having a large number of small portions increases the size of tables needed to manage the allocation information.
3. Having fixed-size portions (e.g., blocks) simplifies the reallocation of space.
4. Having variable-size or small fixed-size portions minimizes waste of unused storage due to overallocation.

Of course, these items interact and must be considered together. The result is that there are two major alternatives:

- **Variable, large contiguous portions:** This will provide better performance. The variable size avoids waste, and the file allocation tables are small. However, space is hard to reuse.
- **Blocks:** Small fixed portions provide greater flexibility. They may require large tables or complex structures for their allocation. Contiguity has been abandoned as a primary goal; blocks are allocated as needed.

Either option is compatible with preallocation or dynamic allocation. In the case of variable, large contiguous portions, a file is preallocated one contiguous group of blocks. This eliminates the need for a file allocation table; all that is required is a pointer to the first block and the number of blocks allocated. In the case of blocks, all of the portions required are allocated at one time. This means that the file allocation table for the file will remain of fixed size, because the number of blocks allocated is fixed.

With variable-size portions, we need to be concerned with the fragmentation of free space. This issue was faced when we considered partitioned main memory in Chapter 7. The following are possible alternative strategies:

- **First fit:** Choose the first unused contiguous group of blocks of sufficient size from a free block list.
- **Best fit:** Choose the smallest unused group that is of sufficient size.
- **Nearest fit:** Choose the unused group of sufficient size that is closest to the previous allocation for the file to increase locality.

It is not clear which strategy is best. The difficulty in modeling alternative strategies is that so many factors interact, including types of files, pattern of file

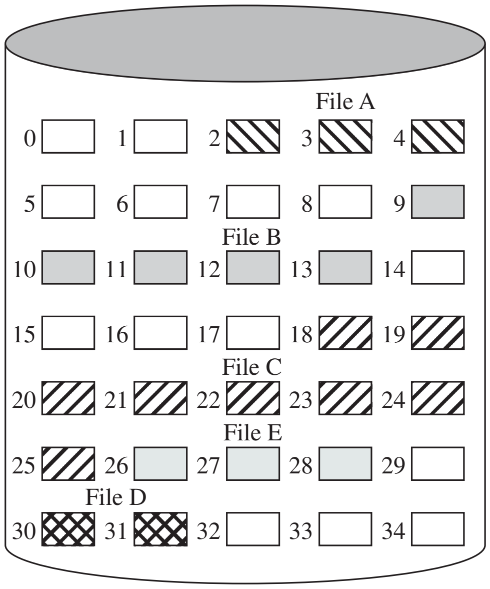
Table 12.3 File Allocation Methods

	Contiguous	**Chained**	**Indexed**	
Preallocation?	Necessary	Possible	Possible	
Fixed or Variable Size Portions?	Variable	Fixed blocks	Fixed blocks	Variable
Portion Size	Large	Small	Small	Medium
Allocation Frequency	Once	Low to high	High	Low
Time to Allocate	Medium	Long	Short	Medium
File Allocation Table Size	One entry	One entry	Large	Medium

access, degree of multiprogramming, other performance factors in the system, disk caching, disk scheduling, and so on.

File Allocation Methods Having looked at the issues of preallocation versus dynamic allocation and portion size, we are in a position to consider specific file allocation methods. Three methods are in common use: contiguous, chained, and indexed. summarizes some of the characteristics of each method.

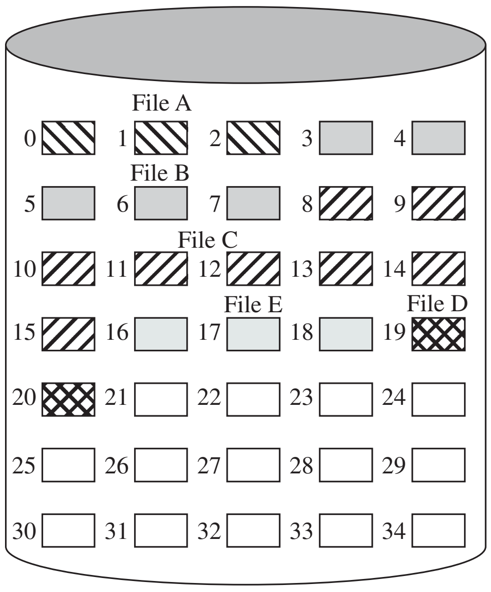
With **contiguous allocation**, a single contiguous set of blocks is allocated to a file at the time of file creation (Figure 12.9). Thus, this is a preallocation strategy, using variable-size portions. The file allocation table needs just a single entry for each file, showing the starting block and the length of the file. Contiguous allocation is the best from the point of view of the individual sequential file. Multiple blocks can be read in at a time to improve I/O performance for sequential processing. It is also easy to retrieve a single block. For example, if a file starts at block b, and the ith block of the file is wanted, its location on secondary storage is simply $b + i - 1$. Contiguous allocation presents some problems. External fragmentation will occur, making it difficult to find contiguous blocks of space of sufficient length. From time



File allocation table

File name	Start block	Length
File A	2	3
File B	9	5
File C	18	8
File D	30	2
File E	26	3

Figure 12.9 **Contiguous File Allocation**



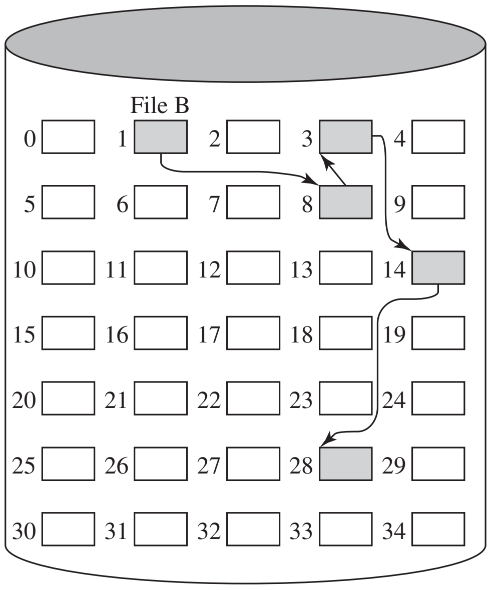
File allocation table

File name	Start block	Length
File A	0	3
File B	3	5
File C	8	8
File D	19	2
File E	16	3

Figure 12.10 Contiguous File Allocation (After Compaction)

to time, it will be necessary to perform a compaction algorithm to free up additional space on the disk (Figure 12.10). Also, with preallocation, it is necessary to declare the size of the file at the time of creation, with the problems mentioned earlier.

At the opposite extreme from contiguous allocation is **chained allocation** (Figure 12.11). Typically, allocation is on an individual block basis. Each block contains a pointer to the next block in the chain. Again, the file allocation table needs just a single entry for each file, showing the starting block and the length of the file. Although preallocation is possible, it is more common simply to allocate blocks as needed. The selection of blocks is now a simple matter: Any free block can be added to a chain. There is no external fragmentation to worry about because only



File allocation table

File name	Start block	Length
•••	•••	•••
File B	1	5
•••	•••	•••

Figure 12.11 Chained Allocation

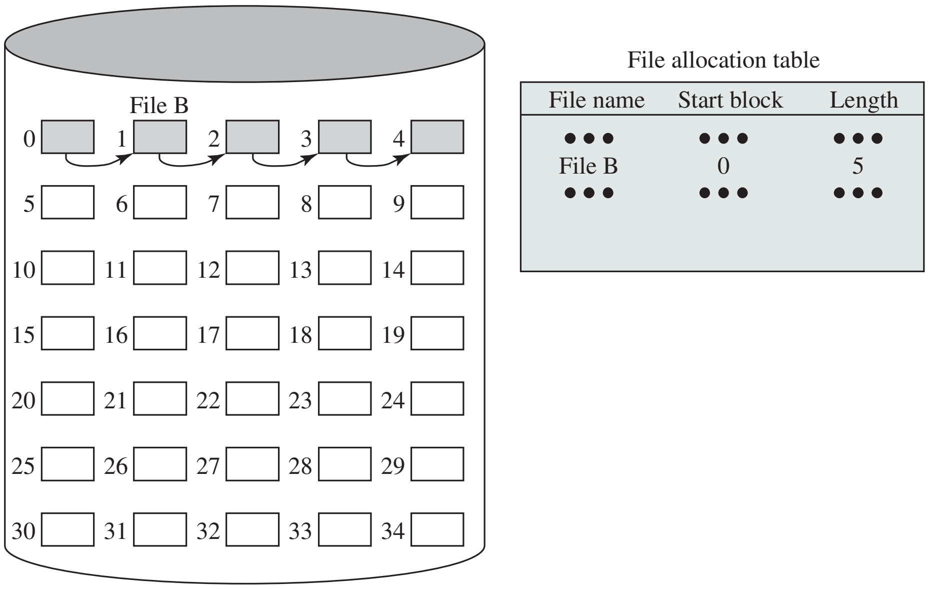


Figure 12.12 **Chained Allocation (After Consolidation)**

one block at a time is needed. This type of physical organization is best suited to sequential files that are to be processed sequentially. To select an individual block of a file requires tracing through the chain to the desired block.

One consequence of chaining, as described so far, is that there is no accommodation of the principle of locality. Thus, if it is necessary to bring in several blocks of a file at a time, as in sequential processing, then a series of accesses to different parts of the disk are required. This is perhaps a more significant effect on a single-user system but may also be of concern on a shared system. To overcome this problem, some systems periodically consolidate files (Figure 12.12).

Indexed allocation addresses many of the problems of contiguous and chained allocation. In this case, the file allocation table contains a separate one-level index for each file; the index has one entry for each portion allocated to the file. Typically, the file indexes are not physically stored as part of the file allocation table. Rather, the file index for a file is kept in a separate block, and the entry for the file in the file allocation table points to that block. Allocation may be on the basis of either fixed-size blocks (Figure 12.13) or variable-size portions (Figure 12.14). Allocation by blocks eliminates external fragmentation, whereas allocation by variable-size portions improves locality. In either case, file consolidation may be done from time to time. File consolidation reduces the size of the index in the case of variable-size portions, but not in the case of block allocation. Indexed allocation supports both sequential and direct access to the file and thus is the most popular form of file allocation.

Free Space Management

Just as the space that is allocated to files must be managed, so the space that is not currently allocated to any file must be managed. To perform any of the file allocation techniques described previously, it is necessary to know what blocks on the disk are available. Thus we need a **disk allocation table** in addition to a file allocation table. We discuss here a number of techniques that have been implemented.

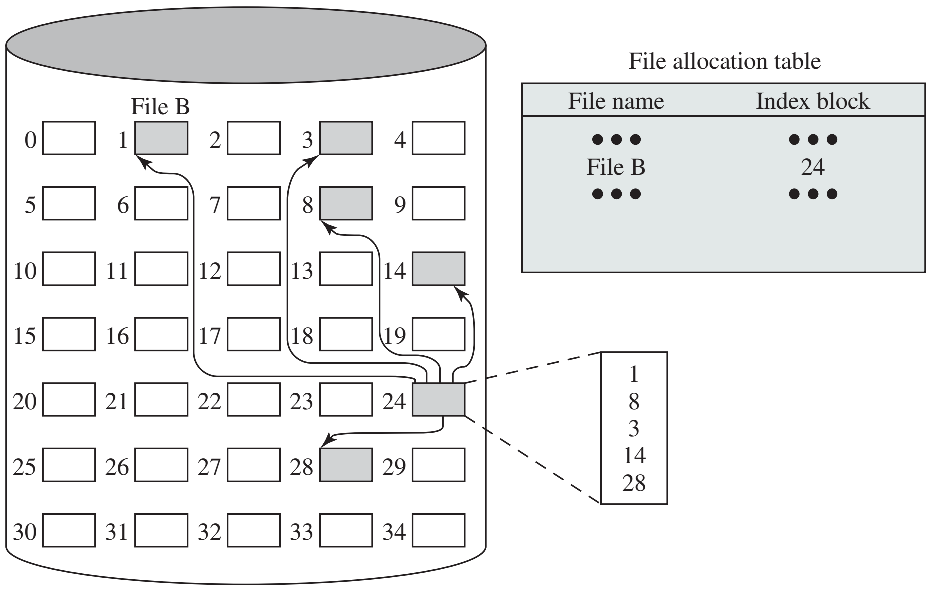


Figure 12.13 **Indexed Allocation with Block Portions**

Bit Tables This method uses a vector containing one bit for each block on the disk. Each entry of a 0 corresponds to a free block, and each 1 corresponds to a block in use. For example, for the disk layout of Figure 12.9, a vector of length 35 is needed and would have the following value:

00111000011111000011111111111011000

A bit table has the advantage that it is relatively easy to find one or a contiguous group of free blocks. Thus, a bit table works well with any of the file allocation methods outlined. Another advantage is that it is as small as possible.

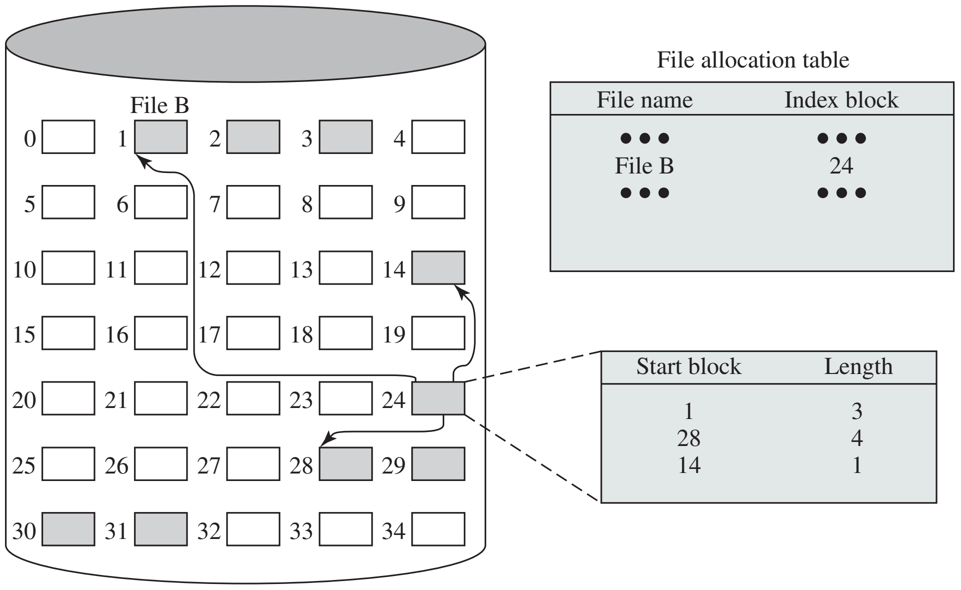


Figure 12.14 **Indexed Allocation with Variable-Length Portions**

However, it can still be sizable. The amount of memory (in bytes) required for a block bitmap is

$$\frac{\text{disk size in bytes}}{8 \times \text{file system block size}}$$

Thus, for a 16-Gbyte disk with 512-byte blocks, the bit table occupies about 4 Mbytes. Can we spare 4 Mbytes of main memory for the bit table? If so, then the bit table can be searched without the need for disk access. But even with today's memory sizes, 4 Mbytes is a hefty chunk of main memory to devote to a single function. The alternative is to put the bit table on disk. But a 4-Mbyte bit table would require about 8,000 disk blocks. We can't afford to search that amount of disk space every time a block is needed, so a bit table resident in memory is indicated.

Even when the bit table is in main memory, an exhaustive search of the table can slow file system performance to an unacceptable degree. This is especially true when the disk is nearly full and there are few free blocks remaining. Accordingly, most file systems that use bit tables maintain auxiliary data structures that summarize the contents of subranges of the bit table. For example, the table could be divided logically into a number of equal-size subranges. A summary table could include, for each subrange, the number of free blocks and the maximum-sized contiguous number of free blocks. When the file system needs a number of contiguous blocks, it can scan the summary table to find an appropriate subrange and then search that subrange.

Chained Free Portions The free portions may be chained together by using a pointer and length value in each free portion. This method has negligible space overhead because there is no need for a disk allocation table, merely for a pointer to the beginning of the chain and the length of the first portion. This method is suited to all of the file allocation methods. If allocation is a block at a time, simply choose the free block at the head of the chain and adjust the first pointer or length value. If allocation is by variable-length portion, a first-fit algorithm may be used: The headers from the portions are fetched one at a time to determine the next suitable free portion in the chain. Again, pointer and length values are adjusted.

This method has its own problems. After some use, the disk will become quite fragmented and many portions will be a single block long. Also note that every time you allocate a block, you need to read the block first to recover the pointer to the new first free block before writing data to that block. If many individual blocks need to be allocated at one time for a file operation, this greatly slows file creation. Similarly, deleting highly fragmented files is very time consuming.

Indexing The indexing approach treats free space as a file and uses an index table as described under file allocation. For efficiency, the index should be on the basis of variable-size portions rather than blocks. Thus, there is one entry in the table for every free portion on the disk. This approach provides efficient support for all of the file allocation methods.

Free Block List In this method, each block is assigned a number sequentially and the list of the numbers of all free blocks is maintained in a reserved portion of the disk. Depending on the size of the disk, either 24 or 32 bits will be needed to store a single block number, so the size of the free block list is 24 or 32 times the size of the corresponding bit table and thus must be stored on disk rather than in main memory. However, this is a satisfactory method. Consider the following points:

1. The space on disk devoted to the free block list is less than 1% of the total disk space. If a 32-bit block number is used, then the space penalty is 4 bytes for every 512-byte block.
2. Although the free block list is too large to store in main memory, there are two effective techniques for storing a small part of the list in main memory.
    a. The list can be treated as a push-down stack (Appendix P) with the first few thousand elements of the stack kept in main memory. When a new block is allocated, it is popped from the top of the stack, which is in main memory. Similarly, when a block is deallocated, it is pushed onto the stack. There only has to be a transfer between disk and main memory when the in-memory portion of the stack becomes either full or empty. Thus, this technique gives almost zero-time access most of the time.
    b. The list can be treated as a FIFO queue, with a few thousand entries from both the head and the tail of the queue in main memory. A block is allocated by taking the first entry from the head of the queue and deallocated by adding it to the end of the tail of the queue. There only has to be a transfer between disk and main memory when either the in-memory portion of the head of the queue becomes empty or the in-memory portion of the tail of the queue becomes full.

In either of the strategies listed in the preceding point (stack or FIFO queue), a background thread can slowly sort the in-memory list or lists to facilitate contiguous allocation.

Volumes

The term *volume* is used somewhat differently by different operating systems and file management systems, but in essence a volume is a logical disk. [CARR05] defines a volume as follows:

Volume: A collection of addressable sectors in secondary memory that an OS or application can use for data storage. The sectors in a volume need not be consecutive on a physical storage device; instead, they need only appear that way to the OS or application. A volume may be the result of assembling and merging smaller volumes.

In the simplest case, a single disk equals one volume. Frequently, a disk is divided into partitions, with each partition functioning as a separate volume. It is also common to treat multiple disks as a single volume or partitions on multiple disks as a single volume.

Reliability

Consider the following scenario:

1. User A requests a file allocation to add to an existing file.
2. The request is granted and the disk and file allocation tables are updated in main memory but not yet on disk.
3. The system crashes and subsequently restarts.
4. User B requests a file allocation and is allocated space on disk that overlaps the last allocation to user A.
5. User A accesses the overlapped portion via a reference that is stored inside A’s file.

This difficulty arose because the system maintained a copy of the disk allocation table and file allocation table in main memory for efficiency. To prevent this type of error, the following steps could be performed when a file allocation is requested:

1. Lock the disk allocation table on disk. This prevents another user from causing alterations to the table until this allocation is completed.
2. Search the disk allocation table for available space. This assumes that a copy of the disk allocation table is always kept in main memory. If not, it must first be read in.
3. Allocate space, update the disk allocation table, and update the disk. Updating the disk involves writing the disk allocation table back onto disk. For chained disk allocation, it also involves updating some pointers on disk.
4. Update the file allocation table and update the disk.
5. Unlock the disk allocation table.

This technique will prevent errors. However, when small portions are allocated frequently, the impact on performance will be substantial. To reduce this overhead, a batch storage allocation scheme could be used. In this case, a batch of free portions on the disk is obtained for allocation. The corresponding portions on disk are marked “in use.” Allocation using this batch may proceed in main memory. When the batch is exhausted, the disk allocation table is updated on disk and a new batch may be acquired. If a system crash occurs, portions on the disk marked “in use” must be cleaned up in some fashion before they can be reallocated. The technique for cleanup will depend on the file system’s particular characteristics.

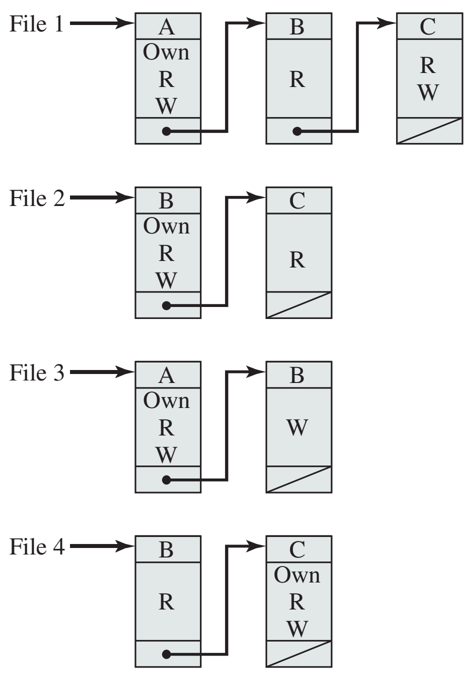
12.8 FILE SYSTEM SECURITY

Following successful log-on, the user has been granted access to one or a set of hosts and applications. This is generally not sufficient for a system that includes sensitive data in its database. Through the user–access control procedure, a user can be identified to the system. Associated with each user, there can be a profile that specifies permissible operations and file accesses. The operating system can then enforce rules based on the user profile. The database management system, however, must control access to specific records or even portions of records. For example, it may be permissible for anyone in administration to obtain a list of company personnel, but only selected individuals may have access to salary information. The issue is more than just a matter of level of detail. Whereas the operating system may grant a user permission to access a file or use an application, following which there are no further security checks, the database management system must make a decision on each individual access attempt. That decision will depend not only on the user's identity but also on the specific parts of the data being accessed and even on the information already divulged to the user.

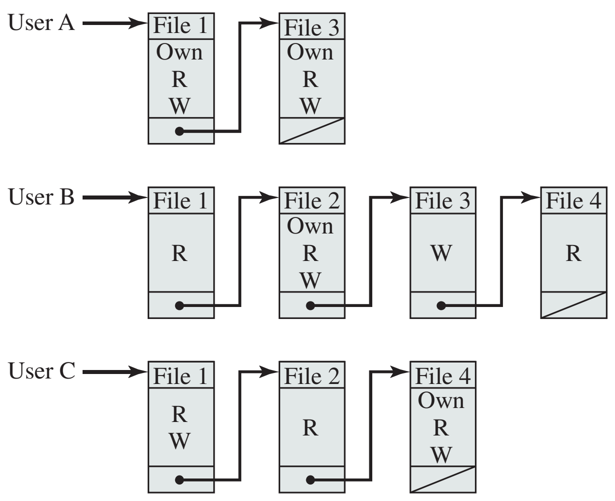
A general model of access control as exercised by a file or database management system is that of an **access matrix** (Figure 12.15a, based on a figure in [SAND94]). The basic elements of the model are as follows:

	File 1	File 2	File 3	File 4	Account 1	Account 2
User A	Own R W		Own R W		Inquiry credit	
User B	R	Own R W	W	R	Inquiry debit	Inquiry credit
User C	R W	R		Own R W		Inquiry debit

(a) Access matrix



(b) Access control lists for files of part (a)



(c) Capability lists for files of part (a)

Figure 12.15 Example of Access Control Structures

- **Subject:** An entity capable of accessing objects. Generally, the concept of subject equates with that of process. Any user or application actually gains access to an object by means of a process that represents that user or application.
- **Object:** Anything to which access is controlled. Examples include files, portions of files, programs, segments of memory, and software objects (e.g., Java objects).
- **Access right:** The way in which an object is accessed by a subject. Examples are read, write, execute, and functions in software objects.

One dimension of the matrix consists of identified subjects that may attempt data access. Typically, this list will consist of individual users or user groups, although access could be controlled for terminals, hosts, or applications instead of or in addition to users. The other dimension lists the objects that may be accessed. At the greatest level of detail, objects may be individual data fields. More aggregate groupings, such as records, files, or even the entire database, may also be objects in the matrix. Each entry in the matrix indicates the access rights of that subject for that object.

In practice, an access matrix is usually sparse and is implemented by decomposition in one of two ways. The matrix may be decomposed by columns, yielding **access control lists** (Figure 12.15b). Thus for each object, an access control list lists users and their permitted access rights. The access control list may contain a default, or public, entry. This allows users that are not explicitly listed as having special rights to have a default set of rights. Elements of the list may include individual users as well as groups of users.

Decomposition by rows yields **capability tickets** (Figure 12.15c). A capability ticket specifies authorized objects and operations for a user. Each user has a number of tickets and may be authorized to loan or give them to others. Because tickets may be dispersed around the system, they present a greater security problem than access control lists. In particular, the ticket must be unforgeable. One way to accomplish this is to have the operating system hold all tickets on behalf of users. These tickets would have to be held in a region of memory inaccessible to users.

Network considerations for data–oriented access control parallel those for user–oriented access control. If only certain users are permitted to access certain items of data, then encryption may be needed to protect those items during transmission to authorized users. Typically, data access control is decentralized, that is, controlled by host–based database management systems. If a network database server exists on a network, then data access control becomes a network function.

12.9 UNIX FILE MANAGEMENT

In the UNIX file system, six types of files are distinguished:

- **Regular, or ordinary:** Contains arbitrary data in zero or more data blocks. Regular files contain information entered in them by a user, an application program, or a system utility program. The file system does not impose any internal structure to a regular file but treats it as a stream of bytes.
- **Directory:** Contains a list of file names plus pointers to associated inodes (index nodes), described later. Directories are hierarchically organized (Figure 12.6).