MODULE 2
PROCESS MANAGEMENT

Process Management: *Process concept – Process state, PCB – Threads. Process scheduling Queue s- Schedulers – Context Switching - Process Creation and Termination.*

Interprocess communication *– Shared Memory, Message Passing, Pipes*

Early computers allowed only one program to be executed at a time. This program had complete control of the system and had access to all the system's resources. In contrast, contemporary computer systems allow multiple programs to be loaded into memory and executed concurrently. This evolution required firmer control and more compartmentalization of the various programs; and these needs resulted in the notion of a **process**, which is a program in execution. A process is the unit of work in a modern time-sharing system. The more complex the operating system is, the more it is expected to do on behalf of its users. Although its main concern is the execution of user programs, it also needs to take care of various system tasks that are better left outside the kernel itself. A system therefore consists of a collection of processes: operating system processes executing system code and user processes executing user code. Potentially, all these processes can execute concurrently, with the CPU (or CPUs) multiplexed among them. By switching the CPU between processes, the operating system can make the computer more productive.

PROCESS CONCEPT

A question that arises in discussing operating systems involves what to call all the CPU activities. A batch system executes **jobs**, whereas a time-shared system has **user programs**, or **tasks**. Even on a single-user system, a user may be able to run several programs at one time: a word processor, a Web browser, and an e-mail package. And even if a user can execute only one program at a time, such as on an embedded device that does not support multitasking, the operating system may need to support its own internal programmed activities, such as memory management. In many respects, all these activities are similar, so we call all of them **processes**.

The terms ***job*** and ***process*** are used almost interchangeably in this text. Although we personally prefer the term ***process***, much of operating-system theory and terminology was developed during a time when the major activity of operating systems was job processing. It would be misleading to avoid the use of commonly accepted terms that include the word ***job*** (such as ***job scheduling***) simply because ***process*** has superseded ***job.*** A process is more than the program code, which is sometimes known as the **text section**. It also includes the current activity, as represented by the value of the **program counter** and the contents of the processor's registers. A process generally also includes the process **stack**, which contains temporary data (such as function parameters, return addresses, and local variables), and a **data section**, which contains global variables. A process may also include

a **heap**, which is memory that is dynamically allocated during process run time. The structure of a process in memory is shown in Figure 3.1.

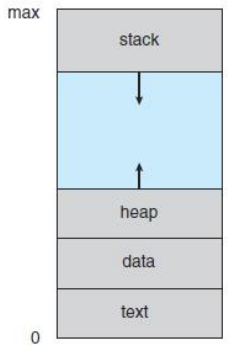


Figure 3.1 Process in memory.

We emphasize that a program by itself is not a process. A program is a ***passive*** entity, such as a file containing a list of instructions stored on disk (often called an **executable file**). In contrast, a process is an ***active*** entity, with a program counter specifying the next instruction to execute and a set of associated resources. A program becomes a process when an executable file is loaded into memory. Two common techniques for loading executable files are double-clicking an icon representing the executable file and entering the name of the executable file on the command line (as in prog.exe or a.out). Although two processes may be associated with the same program, they are nevertheless considered two separate execution sequences. For instance, several users may be running different copies of the mail program, or the same user may invoke many copies of the web browser program. Each of these is a separate process; and although the text sections are equivalent, the data, heap, and stack sections vary. It is also common to have a process that spawns many processes as it runs.

Process State

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

New. The process is being created.
Running. Instructions are being executed.
Waiting. The process is waiting for some event to occur (such as an I/0 completion or reception of a signal).
Ready. The process is waiting to be assigned to a processor.
Terminated. The process has finished execution.

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

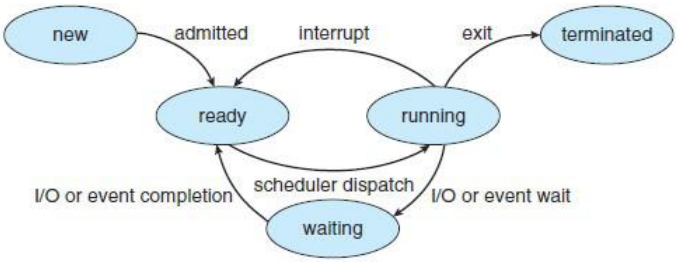


Figure 3.2 Diagram of process state.

Process Control Block

Each process is represented in the operating system by a **process control block (PCB)**—also called a **task control block.** A PCB is shown in Figure 3.3.

Figure 3.3 Process control block (PCB).

It contains many pieces of information associated with a specific process, including these:

• **Process state**. The state may be new, ready, running, waiting, halted, and so on.
• **Program counter**. The counter indicates the address of the next instruction to be executed for this process.
• **CPU registers**. The registers vary in number and type, depending on the computer architecture. They include accumulators, index registers, stack pointers, and general-purpose registers, plus any condition-code information. Along with the program counter, this state information must be saved when an interrupt occurs, to allow the process to be continued correctly afterward (Figure 3.4).

• **CPU-scheduling information**. This information includes a process priority, pointers to scheduling queues, and any other scheduling parameters.

- **Memory-management information**. This information may include such items as the value of the base and limit registers and the page tables, or the segment tables, depending on the memory system used by the operating system.
- **Accounting information**. This information includes the amount of CPU and real time used, time limits, account numbers, job or process numbers, and so on.
- **I/O status information**. This information includes the list of I/O devices allocated to the process, a list of open files, and so on.

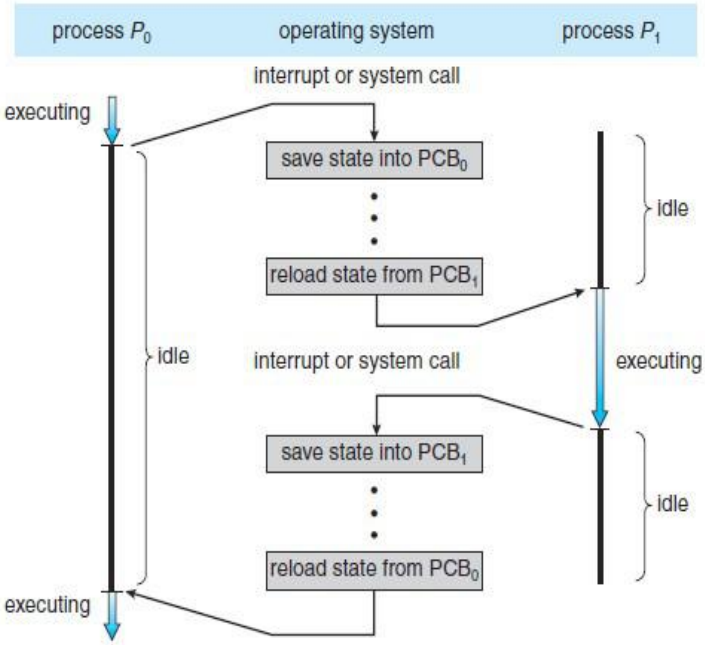


Figure 3.4 Diagram showing CPU switch from process to process.

PROCESS SCHEDULING

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

Scheduling Queues

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

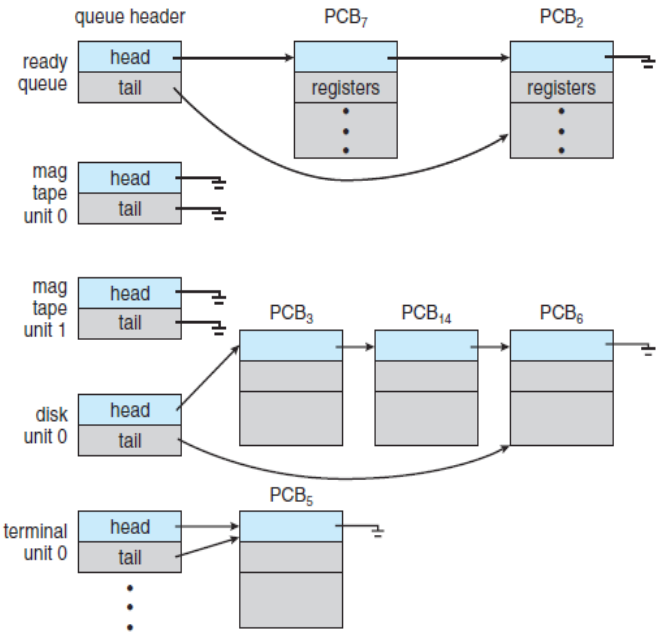


Figure 3.5 The ready queue and various I/O device queues.

The system also includes other queues. When a process is allocated the CPU, it executes for a while and eventually quits, is interrupted, or waits for the occurrence of a particular event, such as the completion of an I/O request. Suppose the process makes an I/O request to a shared device, such as a disk. Since there are many processes in the system, the disk may be busy with the I/O request of some other process. The process therefore may have to wait for the disk. The list of processes waiting for a particular I/O device is called a **device queue**. Each device has its own device queue (Figure 3.5).

A common representation of process scheduling is a **queuing diagram**, such as that in Figure 3.6.

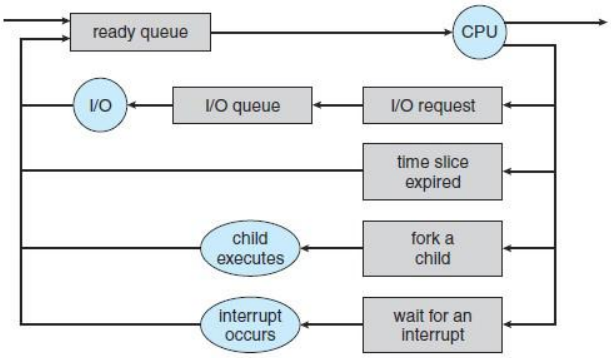


Figure 3.6 Queueing-diagram representation of process scheduling.

Each rectangular box represents a queue. Two types of queues are present: the ready queue and a set of device queues. The circles represent the resources that serve the queues, and the arrows indicate the flow of processes in the system.

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

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

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

Schedulers

A process migrates among the various scheduling queues throughout its lifetime. The operating system must select, for scheduling purposes, processes from these queues in some fashion. The selection process is carried out by the appropriate **scheduler**.

Often, in a batch system, more processes are submitted than can be executed immediately. These processes are spooled to a mass-storage device (typically a disk), where they are kept for later execution. The **long-term scheduler**, or **job scheduler**, selects processes from this pool and loads them into memory for execution. The **short-term scheduler**, or **CPU scheduler**, selects from among the processes that are ready to execute and allocates the CPU to one of them. The primary distinction between these two schedulers lies in frequency of execution. The short-term scheduler must select a new process for the CPU frequently. A process may execute for only a few milliseconds before waiting for an I/O request. Often, the short-term scheduler executes at least once every 100 milliseconds. Because of the short time between executions, the short-term scheduler must be fast.

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

It is important that the long-term scheduler make a careful selection. In general, most processes can be described as either I/O bound or CPU bound. An **I/O-bound process** is one that spends more of its time doing I/O than it spends doing computations. A **CPU-bound process**, in contrast, generates I/O requests infrequently, using more of its time doing computations. It is important that the long-term scheduler select a good ***process mix*** of I/O-bound and CPU-bound processes. If all processes are I/O bound, the ready queue will almost always be empty, and the short-term scheduler will have little to do. If all processes are CPU bound, the I/O waiting queue will almost always be empty, devices will go unused, and again the system will be unbalanced. The system with the best performance will thus have a combination of CPU-bound and I/O-bound processes.

Some operating systems, such as time-sharing systems, may introduce an additional, intermediate level of scheduling. This **medium-term scheduler** is diagrammed in Figure 3.7.

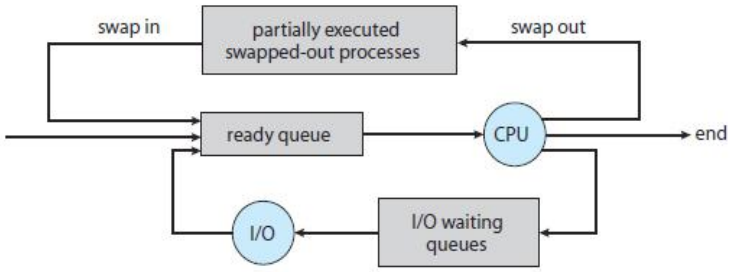


Figure 3.7 Addition of medium-term scheduling to the queueing diagram.

The key idea behind a medium-term scheduler is that sometimes it can be advantageous to remove a process from memory (and from active contention for the CPU) and thus reduce the degree of multiprogramming. Later, the process can be reintroduced into memory, and its execution can be continued where it left off. This scheme is called **swapping**. The process is swapped out, and is later swapped in, by the medium-term scheduler. Swapping may be necessary to improve the process mix or because a change in memory requirements has overcommitted available memory, requiring memory to be freed up.

Context Switch

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

Context-switch times are highly dependent on hardware support. For instance, some processors (such as the Sun Ultra SPARC) provide multiple sets of registers. A context switch here simply requires changing the pointer to the current register set. Of course, if there are more active processes than there are register sets, the system resorts to copying register data to and from memory, as before. Also, the more complex the operating system, the greater the amount of work that must be done during a context switch.

Operations on Processes

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

Process Creation

During the course of execution, a process may create several new processes. As mentioned earlier, the creating process is called a parent process, and the new processes are called the children of that process. Each of these new processes may in turn create other processes, forming a **tree** of processes.
Most operating systems (including UNIX, Linux, and Windows) identify processes according to a unique **process identifier** (or **pid**), which is typically an integer number. The pid provides a unique value for each process in the system, and it can be used as an index to access various attributes of a process within the kernel.

Figure 3.8 illustrates a typical process tree for the Linux operating system, showing the name of each process and its pid. (We use the term ***process*** rather loosely, as Linux prefers the term ***task*** instead.) The init process (which always has a **pid** of 1) serves as the root parent process for all user processes. Once the system has booted, the **init** process can also create various user processes, such as a web or print server, an **ssh** server, and the like.

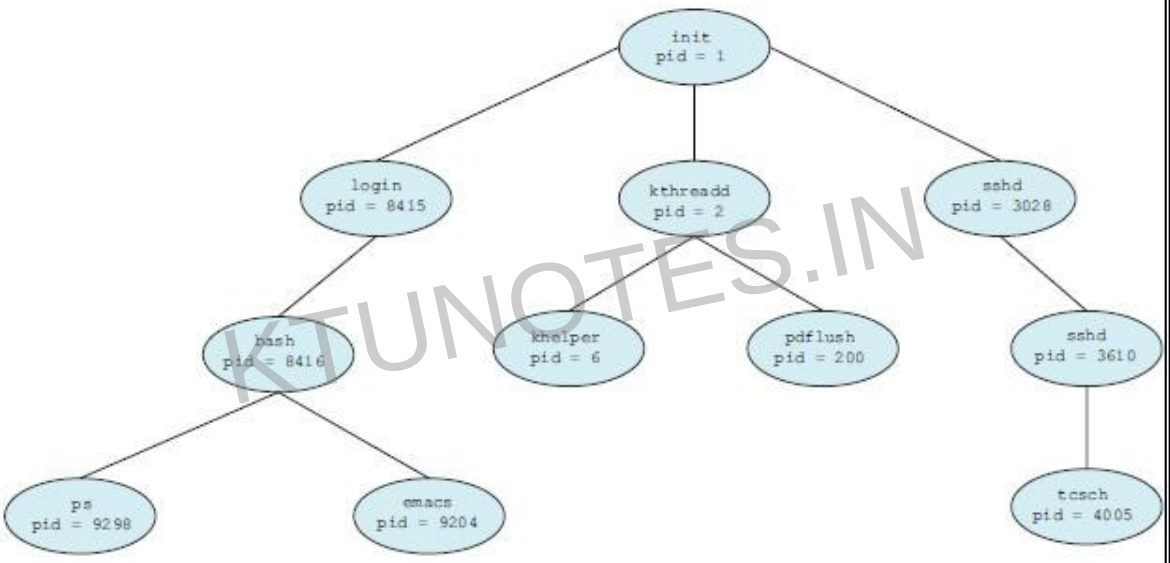


Figure 3.8 A tree of processes on a typical Linux system.

In Figure 3.8, we see two children of **init—kthreadd** and **sshd**. The **kthreadd** process is responsible for creating additional processes that perform tasks on behalf of the kernel (in this situation, **khelper** and **pdflush**). The **sshd** process is responsible for managing clients that connect to the system by using **ssh** (which is short for ***secure shell***). The login process is responsible for managing clients that directly log onto the system. In this example, a client has logged on and is using the bash shell, which has been assigned **pid** 8416. Using the bash command-line interface, this user has created the process **ps** as well as the **emacs** editor.

On UNIX and Linux systems, we can obtain a listing of processes by using the **ps** command. For example, the command **ps –el** will list complete information for all processes currently active in the system. It is easy to construct a process tree similar to the

one shown in Figure 3.8 by recursively tracing parent processes all the way to the **init** process.

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

In addition to supplying various physical and logical resources, the parent process may pass along initialization data (input) to the child process. For example, consider a process whose function is to display the contents of a file —say, image.jpg—on the screen of a terminal. When the process is created, it will get, as an input from its parent process, the name of the file ***image.jpg***. Using that file name, it will open the file and write the contents out. It may also get the name of the output device. Alternatively, some operating systems pass resources to child processes. On such a system, the new process may get two open files, image.jpg and the terminal device, and may simply transfer the datum between the two.

When a process creates a new process, two possibilities for execution exist:
1. The parent continues to execute concurrently with its children.
2. The parent waits until some or all of its children have terminated.
There are also two address-space possibilities for the new process:
1. The child process is a duplicate of the parent process (it has the same program and data as the parent).
2. The child process has a new program loaded into it.

To illustrate these differences, let's first consider the UNIX operating system. In UNIX, as we've seen, each process is identified by its process identifier, which is a unique integer. A new process is created by the fork() system call. The new process consists of a copy of the address space of the original process. This mechanism allows the parent process to communicate easily with its child process. Both processes (the parent and the child) continue execution at the instruction after the fork(), with one difference: the return code for the fork() is zero for the new (child) process, whereas the (nonzero) process identifier of the child is returned to the parent.

After a fork() system call, one of the two processes typically uses the exec() system call to replace the process's memory space with a new program. The exec() system call loads a binary file into memory (destroying the memory image of the program containing the exec() system call) and starts its execution. In this manner, the two processes are able to

communicate and then go their separate ways. The parent can then create more children; or, if it has nothing else to do while the child runs, it can issue a wait() system call to move itself off the ready queue until the termination of the child. Because the call to exec() overlays the process's address space with a new program, the call to exec() does not return control unless an error occurs.

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

int main()
{
pid_t pid;

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

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

    return 0;
}
```


Figure 3.9 Creating a separate process using the UNIX `fork()` system call.

The C program shown in **Figure 3.9** illustrates the UNIX system calls previously described. We now have two different processes running copies of the same program. The only difference is that the value of pid (the process identifier) for the child process is zero, while that for the parent is an integer value greater than zero (in fact, it is the actual pid of the child process). The child process inherits privileges and scheduling attributes from the parent, as well certain resources, such as open files. The child process then overlays its address space with the UNIX command /bin/ls (used to get a directory listing) using the **execlp**() system call (**execlp**() is a version of the exec() system call). The parent waits for the child process to complete with the wait() system call. When the child process completes (by either implicitly or explicitly invoking exit()), the parent process resumes from the call to wait(), where it completes using the exit() system call. This is also illustrated in **Figure 3.10.** Of course, there is nothing to prevent the child from ***not*** invoking exec() and instead continuing to execute as a copy of the parent process. In this scenario, the parent and child are concurrent processes running the same code instructions. Because the child is a copy of the parent, each process has its own copy of any data.

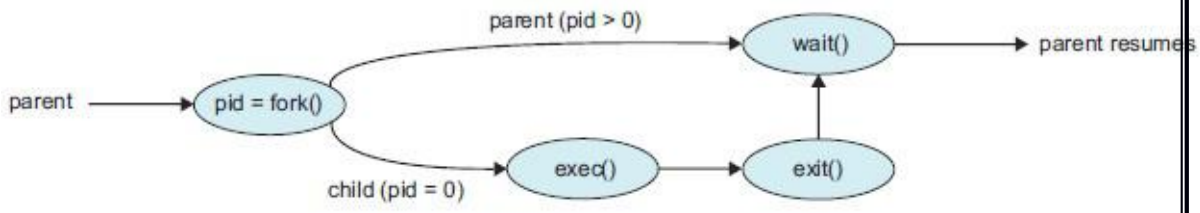


Figure 3.10 Process creation using the `fork()` system call.

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

In Figure 3.9, the parent process waits for the child to complete by invoking the wait() system call. The equivalent of this in Windows is WaitForSingleObject(), which is passed a handle of the child process—pi.hProcess—and waits for this process to complete. Once the child process exits, control returns from the WaitForSingleObject() function in the parent process.

Process Termination

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

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

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

• The child has exceeded its usage of some of the resources that it has been allocated. (To determine whether this has occurred, the parent must have a mechanism to inspect the state of its children.)

• The task assigned to the child is no longer required.

• The parent is exiting, and the operating system does not allow a child to continue if its parent terminates.

Some systems do not allow a child to exist if its parent has terminated. In such systems, if a process terminates (either normally or abnormally), then all its children must also be terminated. This phenomenon, referred to as **cascading termination**, is normally initiated by the operating system. To illustrate process execution and termination, consider that, in Linux and UNIX systems, we can terminate a process by using the exit() system call, providing an exit status as a parameter:

```
/* exit with status 1 */
exit(1);
```

In fact, under normal termination, exit() may be called either directly (as shown above) or indirectly (by a return statement in main()). A parent process may wait for the termination of a child process by using the wait() system call. The wait() system call is passed a parameter that allows the parent to obtain the exit status of the child. This system call also returns the process identifier of the terminated child so that the parent can tell which of its children has terminated:

```
pid t pid;
int status;
pid = wait(&status);
```


When a process terminates, its resources are deallocated by the operating system. However, its entry in the process table must remain there until the parent calls wait(), because the process table contains the process's exit status. A process that has terminated, but whose parent has not yet called wait(), is known as a **zombie** process. All processes transition to this state when they terminate, but generally they exist as zombies only briefly. Once the parent calls wait(), the process identifier of the zombie process and its entry in the process table are released.

Now consider what would happen if a parent did not invoke wait() and instead terminated, thereby leaving its child processes as **orphans**. Linux and UNIX address this scenario by assigning the init process as the new parent to orphan processes. (Recall from Figure 3.8 that the init process is the root of the process hierarchy in UNIX and Linux systems.) The init process periodically invokes wait(), thereby allowing the exit status of any orphaned process to be collected and releasing the orphan's process identifier and process-table entry.

INTERPROCESS COMMUNICATION

Processes executing concurrently in the operating system may be either independent processes or cooperating processes. A process is ***independent*** if it cannot affect or be affected by the other processes executing in the system. Any process that does not share

data with any other process is independent. A process is ***cooperating*** if it can affect or be affected by the other processes executing in the system. Clearly, any process that shares data with other processes is a cooperating process.

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

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

Cooperating processes require an **interprocess communication (IPC)** mechanism that will allow them to exchange data and information. There are two fundamental models of interprocess communication: **shared memory** and **message passing**. In the shared-memory model, a region of memory that is shared by cooperating processes is established. Processes can then exchange information by reading and writing data to the shared region. In the message-passing model, communication takes place by means of messages exchanged between the cooperating processes. The two communications models are contrasted in **Figure 3.12.**

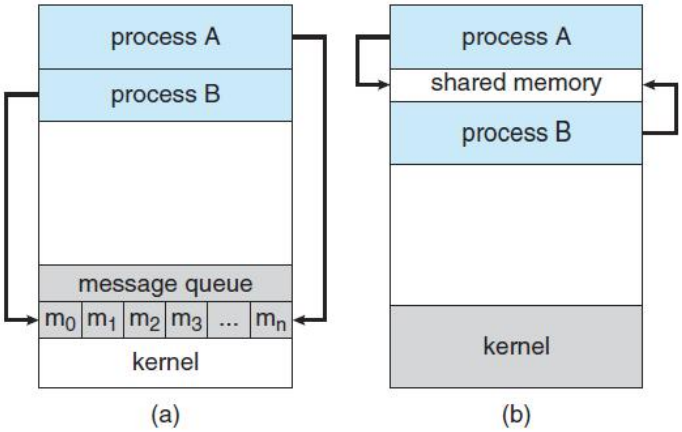


Figure 3.12 Communications models. (a) Message passing. (b) Shared memory.

Both of the models just mentioned are common in operating systems, and many systems implement both. Message passing is useful for exchanging smaller amounts of data, because no conflicts need be avoided. Message passing is also easier to implement in a distributed system than shared memory. (Although there are systems that provide distributed shared memory, we do not consider them in this text.) Shared memory can be

faster than message passing, since message-passing systems are typically implemented using system calls and thus require the more time-consuming task of kernel intervention. In shared-memory systems, system calls are required only to establish shared memory regions. Once shared memory is established, all accesses are treated as routine memory accesses, and no assistance from the kernel is required. Recent research on systems with several processing cores indicates that message passing provides better performance than shared memory on such systems. Shared memory suffers from cache coherency issues, which arise because shared data migrate among the several caches. As the number of processing cores on systems increases, it is possible that we will see message passing as the preferred mechanism for IPC.

- **Shared-Memory Systems**

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

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

For example, a web server produces (that is, provides) HTML files and images, which are consumed (that is, read) by the client web browser requesting the resource. One solution to the producer–consumer problem uses shared memory. To allow producer and consumer processes to run concurrently, we must have available a buffer of items that can be filled by the producer and emptied by the consumer. This buffer will reside in a region of memory that is shared by the producer and consumer processes. A producer can produce one item while the consumer is consuming another item. The producer and consumer must be synchronized, so that the consumer does not try to consume an item that has not yet been produced.

Two types of buffers can be used. The **unbounded buffer** places no practical limit on the size of the buffer. The consumer may have to wait for new items, but the producer can

always produce new items. The **bounded buffer** assumes a fixed buffer size. In this case, the consumer must wait if the buffer is empty, and the producer must wait if the buffer is full.

Let's look more closely at how the bounded buffer illustrates interprocess communication using shared memory. The following variables reside in a region of memory shared by the producer and consumer processes:

```
#define BUFFER SIZE 10
typedef struct {
. . .
}item;
item buffer[BUFFER SIZE];
int in = 0;
int out = 0;
```

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

The code for the producer process is shown in **Figure 3.13**, and the code for the consumer process is shown in **Figure 3.14**. The producer process has a local variable next produced in which the new item to be produced is stored. The consumer process has a local variable next consumed in which the item to be consumed is stored.

```
item next_produced;

while (true) {
    /* produce an item in next_produced */

    while (((in + 1) % BUFFER_SIZE) == out)
       ; /* do nothing */

    buffer[in] = next_produced;
    in = (in + 1) % BUFFER_SIZE;
}
```

Figure 3.13 The producer process using shared memory.

This scheme allows at most BUFFER SIZE − 1 items in the buffer at the same time. We leave it as an exercise for you to provide a solution in which BUFFER SIZE items can be in the buffer at the same time.

```
item next_consumed;

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

      next_consumed = buffer[out];
      out = (out + 1) % BUFFER_SIZE;

      /* consume the item in next_consumed */
}
```

Figure 3.14 The consumer process using shared memory.

- **Message-Passing Systems**

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

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

A message-passing facility provides at least two operations: **send(message)** **receive(message)**

Messages sent by a process can be either fixed or variable in size. If only fixed-sized messages can be sent, the system-level implementation is straightforward. This restriction, however, makes the task of programming more difficult. Conversely, variable-sized messages require a more complex system level implementation, but the programming task becomes simpler. This is a common kind of tradeoff seen throughout operating-system design. If processes *P* and *Q* want to communicate, they must send messages to and receive messages from each other: a ***communication link*** must exist between them. This link can be implemented in a variety of ways.

We are concerned here not with the link's physical implementation (such as shared memory, hardware bus, or network) but rather with its logical implementation. Here are several methods for logically implementing a link and the send()/receive() operations:
• Direct or indirect communication
• Synchronous or asynchronous communication
• Automatic or explicit buffering
We look at issues related to each of these features next.

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

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

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

A communication link in this scheme has the following properties:
• A link is established automatically between every pair of processes that want to communicate. The processes need to know only each other's identity to communicate.
• A link is associated with exactly two processes.
• Between each pair of processes, there exists exactly one link.

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

• send(P, message)—Send a message to process P.
• receive(id, message)—Receive a message from any process.

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

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

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

In this scheme, a communication link has the following properties:
• A link is established between a pair of processes only if both members of the pair have a shared mailbox.
• A link may be associated with more than two processes.
• Between each pair of communicating processes, a number of different links may exist, with each link corresponding to one mailbox.

Now suppose that processes *P*1, *P*2, and *P*3 all share mailbox *A*. Process *P*1 sends a message to *A*, while both *P*2 and *P*3 execute a receive() from *A*. Which process will receive the message sent by *P*1?

The answer depends on which of the following methods we choose:
• Allow a link to be associated with two processes at most.
• Allow at most one process at a time to execute a receive() operation.
• Allow the system to select arbitrarily which process will receive the message (that is, either *P*2 or *P*3, but not both, will receive the message).

The system may define an algorithm for selecting which process will receive the message (for example, ***round robin,*** where processes take turns receiving messages). The system may identify the receiver to the sender.

A mailbox may be owned either by a process or by the operating system. If the mailbox is owned by a process (that is, the mailbox is part of the address space of the process), then we distinguish between the owner (which can only receive messages through this mailbox) and the user (which can only send messages to the mailbox). Since each mailbox has a unique owner, there can be no confusion about which process should receive a message sent to this mailbox. When a process that owns a mailbox terminates, the mailbox disappears. Any process that subsequently sends a message to this mailbox must be notified that the mailbox no longer exists. In contrast, a mailbox that is owned by the operating system has an existence of its own. It is independent and is not attached to any particular process. The operating system then must provide a mechanism that allows a process to do the following:

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

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

Synchronization

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

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

Different combinations of send() and receive() are possible. When both send() and receive() are blocking, we have a **rendezvous** between the sender and the receiver. The solution to the producer–consumer problem becomes trivial when we use blocking send() and receive() statements. The producer merely invokes the blocking send() call and waits until the message is delivered to either the receiver or the mailbox. Likewise, when the consumer invokes receive(), it blocks until a message is available. This is illustrated in **Figures 3.15 and 3.16**.

```
message next_produced;

while (true) {
     /* produce an item in next_produced */

     send(next_produced);
}
```

Figure 3.15 The producer process using message passing.

```
message next_consumed;

while (true) {
     receive(next_consumed);

     /* consume the item in next_consumed */
}
```

Figure 3.16 The consumer process using message passing.

Buffering

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

Zero capacity. The queue has a maximum length of zero; thus, the link cannot have any messages waiting in it. In this case, the sender must block until the recipient receives the message.

• **Bounded capacity**. The queue has finite length *n;* thus, at most *n* messages can reside in it. If the queue is not full when a new message is sent, the message is placed in the queue (either the message is copied or a pointer to the message is kept), and the sender can continue execution without waiting. The link's capacity is finite, however. If the link is full, the sender must block until space is available in the queue.

• **Unbounded capacity**. The queue's length is potentially infinite; thus, any number of messages can wait in it. The sender never blocks. The zero-capacity case is sometimes referred to as a message system with no buffering. The other cases are referred to as systems with automatic buffering.

- **PIPES**

Regular files are not a satisfactory communication medium for processes running in parallel. Take for example a reader/writer situation in which one process writes data and the other reads them. If a file is used as the communication medium, the reader can detect that the file does not grow any more (read returns zero), but it does not know whether the writer is finished or simply busy computing more data. Moreover, the file keeps track of all the data transmitted, requiring needless disk space.

Pipes provide a mechanism suitable for this kind of communication. A pipe is made of two file descriptors. The first one represents the pipe's output. The second one represents the pipe's input. Pipes are created by the system call pipe:

val pipe : unit -> file_descr * file_descr

The call returns a pair (fd_in, fd_out) where fd_in is a file descriptor open in *read mode* on the pipe's output and fd_out is file descriptor open in *write mode*on the pipe's input. The pipe itself is an internal object of the kernel that can only be accessed via these two descriptors. In particular, it has no name in the file system.

A pipe behaves like a queue (*first-in, first-out*). The first thing written to the pipe is the first thing read from the pipe. Writes (calls to write on the pipe's input descriptor) fill the pipe and block when the pipe is full. They block until another process reads enough data at the other end of the pipe and return when all the data given to write have been transmitted. Reads (calls to read on the pipe's output descriptor) drain the pipe. If the pipe is empty, a call to read blocks until at least a byte is written at the other end. It then returns immediately without waiting for the number of bytes requested by read to be available.

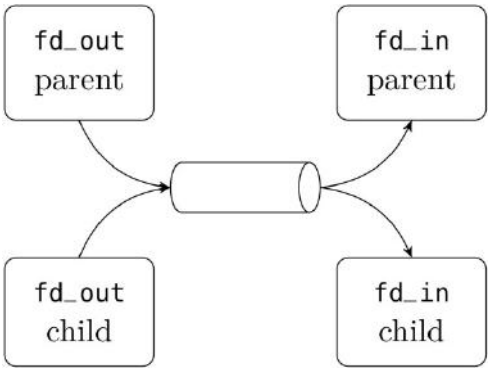
Pipes are useless if they are written and read by the same process (such a process will likely block forever on a substantial write or on a read on the empty pipe). Hence they are usually read and written by different processes. Since a pipe has no name, one of these processes must be created by forking the process that created the pipe. Indeed, the two file descriptors of the pipe, like any other file descriptors, are duplicated by the call to fork and thus refer to the same pipe in the parent and the child process.

Example

The following snippet of code is typical.

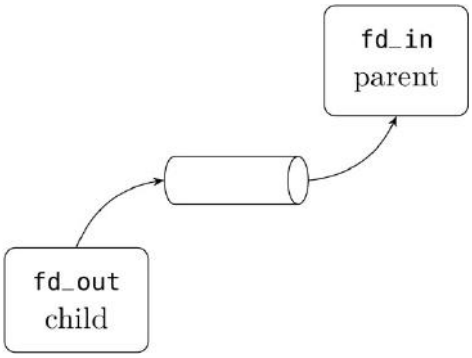
let (fd_in, fd_out) = pipe () **in**
match fork () **with**
| 0 -> close fd_in; ... write fd_out buffer1 offset1 count1 ...
| pid -> close fd_out; ... read fd_in buffer2 offset2 count2 ...

After the fork there are two descriptors open on the pipe's input, one in the parent and the other in the child. The same holds for the pipe's output.



In this example the child becomes the writer and the parent the reader. Consequently the child closes its descriptor fd_in on the pipe's output (to save descriptors and to avoid programming errors). This leaves the descriptor fd_in of the parent unchanged as

descriptors are allocated in process memory and after the fork the parent's and child's memory are disjoint. The pipe, allocated in system memory, still lives as there's still the descriptor fd_in of the parent open in read mode on the pipe's output. Following the same reasoning the parent closes its descriptor on the pipe's input. The result is as follows:



Data written by the child on fd_out is transmitted to fd_in in the parent.

When all the descriptors on a pipe's input are closed and the pipe is empty, a call to read on its output returns zero: end of file. And when all the descriptors on a pipe's output are closed, a call to write on its input kills the writing process. More precisely the kernel sends the signal sigpipe to the process calling write and the default handler of this signal terminates the process. If the signal handler of sigpipe is changed, the call to write fails with an EPIPE error.

THREADS

The process model introduced earlier assumed that a process was an executing program with a single thread of control. Virtually all modern operating systems, however, provide features enabling a process to contain multiple threads of control. Here, we introduce many concepts associated with multithreaded computer systems, including a discussion of the APIs for the Pthreads, Windows, and Java thread libraries.

Overview

A thread is a basic unit of CPU utilization; it comprises a thread ID, a program counter, a register set, and a stack. It shares with other threads belonging to the same process its code section, data section, and other operating-system resources, such as open files and signals. A traditional (or ***heavyweight***) process has a single thread of control. If a process has multiple threads of control, it can perform more than one task at a time. **Figure 4.1**

illustrates the difference between a traditional **single-threaded** process and a **multithreaded** process.

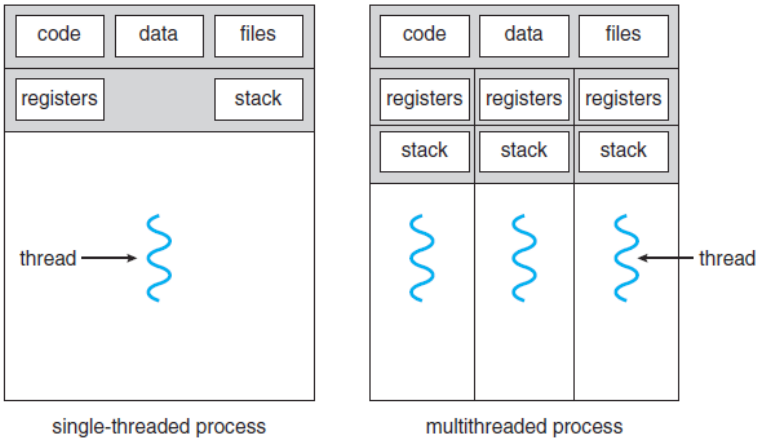


Figure 4.1 Single-threaded and multithreaded processes.

Motivation

Most software applications that run on modern computers are multithreaded. An application typically is implemented as a separate process with several threads of control. A web browser might have one thread display images or text while another thread retrieves data from the network, for example. A word processor may have a thread for displaying graphics, another thread for responding to keystrokes from the user, and a third thread for performing spelling and grammar checking in the background. Applications can also be designed to leverage processing capabilities on multicore systems. Such applications can perform several CPU-intensive tasks in parallel across the multiple computing cores.

In certain situations, a single application may be required to perform several similar tasks. For example, a web server accepts client requests for web pages, images, sound, and so forth. A busy web server may have several (perhaps thousands of) clients concurrently accessing it. If the web server ran as a traditional single-threaded process, it would be able to service only one client at a time, and a client might have to wait a very long time for its request to be serviced.

One solution is to have the server run as a single process that accepts requests. When the server receives a request, it creates a separate process to service that request. In fact, this process-creation method was in common use before threads became popular. Process creation is time consuming and resource intensive, however. If the new process will perform the same tasks as the existing process, why incur all that overhead? It is generally more efficient to use one process that contains multiple threads. If the web-server process is multithreaded, the server will create a separate thread that listens for client requests. When a request is made, rather than creating another process, the server creates a new thread to service the request and resume listening for additional requests. This is illustrated in **Figure 4.2**.

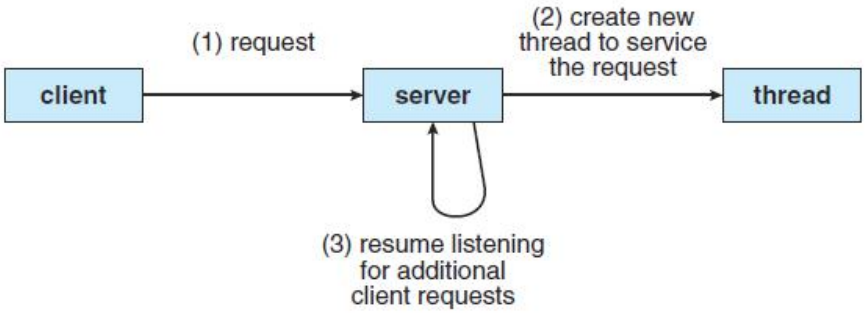


Figure 4.2 Multithreaded server architecture.

Threads also play a vital role in remote procedure call (RPC) systems. RPCs allow interprocess communication by providing a communication mechanism similar to ordinary function or procedure calls.

Typically, RPC servers are multithreaded. When a server receives a message, it services the message using a separate thread. This allows the server to service several concurrent requests.

Finally, most operating-system kernels are now multithreaded. Several threads operate in the kernel, and each thread performs a specific task, such as managing devices, managing memory, or interrupt handling. For example, Solaris has a set of threads in the kernel specifically for interrupt handling; Linux uses a kernel thread for managing the amount of free memory in the system.

Benefits

The benefits of multithreaded programming can be broken down into four major categories:

1. Responsiveness. Multithreading an interactive application may allow a program to continue running even if part of it is blocked or is performing a lengthy operation, thereby increasing responsiveness to the user. This quality is especially useful in designing user interfaces. For instance, consider what happens when a user clicks a button that results in the performance of a time-consuming operation. A single-threaded application would be unresponsive to the user until the operation had completed. In contrast, if the time-consuming operation is performed in a separate thread, the application remains responsive to the user.

2. Resource sharing. Processes can only share resources through techniques such as shared memory and message passing. Such techniques must be explicitly arranged by the programmer. However, threads share the memory and the resources of the process to which they belong by default. The benefit of sharing code and data is that it allows an application to have several different threads of activity within the same address space.

3. Economy. Allocating memory and resources for process creation is costly. Because threads share the resources of the process to which they belong, it is more economical to create and context-switch threads. Empirically gauging the difference in overhead can be difficult, but in general it is significantly more time consuming to create and manage

processes than threads. In Solaris, for example, creating a process is about thirty times slower than is creating a thread, and context switching is about five times slower.

4. Scalability. The benefits of multithreading can be even greater in a multiprocessor architecture, where threads may be running in parallel on different processing cores. A single-threaded process can run on only one processor, regardless how many are available.

Multicore Programming

Earlier in the history of computer design, in response to the need for more computing performance, single-CPU systems evolved into multi-CPU systems. A more recent, similar trend in system design is to place multiple computing cores on a single chip. Each core appears as a separate processor to the operating system. Whether the cores appear across CPU chips or within CPU chips, we call these systems **multicore** or **multiprocessor** systems.

Multithreaded programming provides a mechanism for more efficient use of these multiple computing cores and improved concurrency. Consider an application with four threads. On a system with a single computing core, concurrency merely means that the execution of the threads will be interleaved over time **(Figure 4.3),** because the processing core is capable of executing only one thread at a time. On a system with multiple cores, however, concurrency means that the threads can run in parallel, because the system can assign a separate thread to each core **(Figure 4.4).**

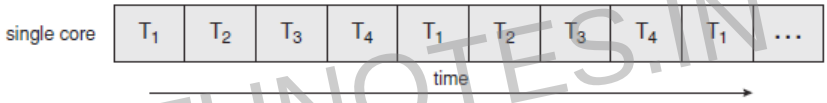


Figure 4.3 Concurrent execution on a single-core system.

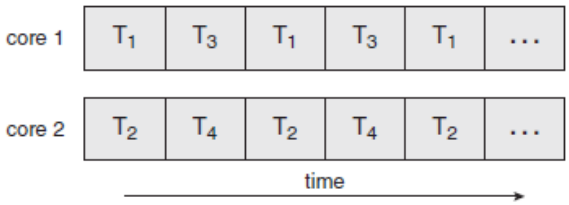


Figure 4.4 Parallel execution on a multicore system.

Notice the distinction between ***parallelism*** and ***concurrency*** in this discussion. A system is parallel if it can perform more than one task simultaneously. In contrast, a concurrent system supports more than one task by allowing all the tasks to make progress. Thus, it is possible to have concurrency without parallelism. Before the advent of SMP and multicore architectures, most computer systems had only a single processor. CPU schedulers were designed to provide the illusion of parallelism by rapidly switching between processes in the system, thereby allowing each process to make progress. Such processes were running concurrently, but not in parallel.

As systems have grown from tens of threads to thousands of threads, CPU designers have improved system performance by adding hardware to improve thread performance.

Modern Intel CPUs frequently support two threads per core, while the Oracle T4 CPU supports eight threads per core. This support means that multiple threads can be loaded into the core for fast switching. Multicore computers will no doubt continue to increase in core counts and hardware thread support.

Programming Challenges

The trend towards multicore systems continues to place pressure on system designers and application programmers to make better use of the multiple computing cores. Designers of operating systems must write scheduling algorithms that use multiple processing cores to allow the parallel execution shown in Figure 4.4. For application programmers, the challenge is to modify existing programs as well as design new programs that are multithreaded.

In general, five areas present challenges in programming for multicore systems:

1. Identifying tasks. This involves examining applications to find areas that can be divided into separate, concurrent tasks. Ideally, tasks are independent of one another and thus can run in parallel on individual cores.

2. Balance. While identifying tasks that can run in parallel, programmers must also ensure that the tasks perform equal work of equal value. In some instances, a certain task may not contribute as much value to the overall process as other tasks. Using a separate execution core to run that task may not be worth the cost.

3. Data splitting. Just as applications are divided into separate tasks, the data accessed and manipulated by the tasks must be divided to run on separate cores.

4. Data dependency. The data accessed by the tasks must be examined for dependencies between two or more tasks. When one task depends on data from another, programmers must ensure that the execution of the tasks is synchronized to accommodate the data dependency.

5. Testing and debugging. When a program is running in parallel on multiple cores, many different execution paths are possible. Testing and debugging such concurrent programs is inherently more difficult than testing and debugging single-threaded applications.

Because of these challenges, many software developers argue that the advent of multicore systems will require an entirely new approach to designing software systems in the future. (Similarly, many computer science educators believe that software development must be taught with increased emphasis on parallel programming.)

Types of Parallelism

In general, there are two types of parallelism: data parallelism and task parallelism.

Data parallelism focuses on distributing subsets of the same data across multiple computing cores and performing the same operation on each core. Consider, for example, summing the contents of an array of size N. On a single-core system, one thread would simply sum the elements [0] . . . [N − 1]. On a dual-core system, however, thread A,

running on core 0, could sum the elements [0] . . . [*N*/2 − 1] while thread *B*, running on core 1, could sum the elements [*N*/2] . . . [*N* − 1]. The two threads would be running in parallel on separate computing cores.

Task parallelism involves distributing not data but tasks (threads) across multiple computing cores. Each thread is performing a unique operation. Different threads may be operating on the same data, or they may be operating on different data. Consider again our example above. In contrast to that situation, an example of task parallelism might involve two threads, each performing a unique statistical operation on the array of elements. The threads again are operating in parallel on separate computing cores, but each is performing a unique operation.

Fundamentally, then, data parallelism involves the distribution of data across multiple cores and task parallelism on the distribution of tasks across multiple cores. In practice, however, few applications strictly follow either data or task parallelism. In most instances, applications use a hybrid of these two strategies.

Multithreading Models

So far has treated threads in a generic sense. However, support for threads may be provided either at the user level, for **user threads**, or by the kernel, for **kernel threads**. User threads are supported above the kernel and are managed without kernel support, whereas kernel threads are supported and managed directly by the operating system. Virtually all contemporary operating systems—including Windows, Linux, Mac OS X, and Solaris— support kernel threads. Ultimately, a relationship must exist between user threads and kernel threads. In this section, we look at three common ways of establishing such a relationship: the many-to-one model, the one-to-one model, and the many-to many model.

Many-to-One Model

The many-to-one model **(Figure 4.5)** maps many user-level threads to one kernel thread. Thread management is done by the thread library in user space, so it is efficient. However, the entire process will block if a thread makes a blocking system call. Also, because only one thread can access the kernel at a time, multiple threads are unable to run in parallel on multicore systems. **Green threads**—a thread library available for Solaris systems and adopted in early versions of Java—used the many-to-one model. However, very few systems continue to use the model because of its inability to take advantage of multiple processing cores.

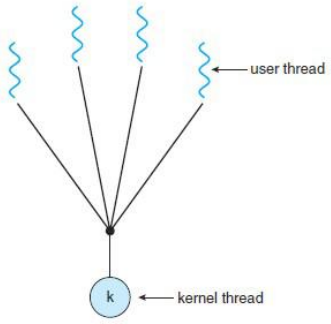


Figure 4.5 Many-to-one model.

One-to-One Model

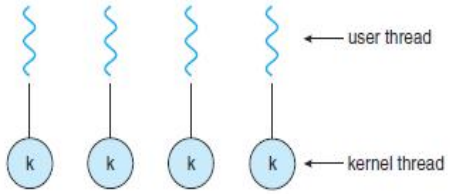


Figure 4.6 One-to-one model.

The one-to-one model (Figure 4.6) maps each user thread to a kernel thread. It provides more concurrency than the many-to-one model by allowing another thread to run when a thread makes a blocking system call. It also allows multiple threads to run in parallel on multiprocessors. The only drawback to this model is that creating a user thread requires creating the corresponding kernel thread. Because the overhead of creating kernel threads can burden the performance of an application, most implementations of this model restrict the number of threads supported by the system. Linux, along with the family of Windows operating systems, implement the one-to-one model.

Many-to-Many Model

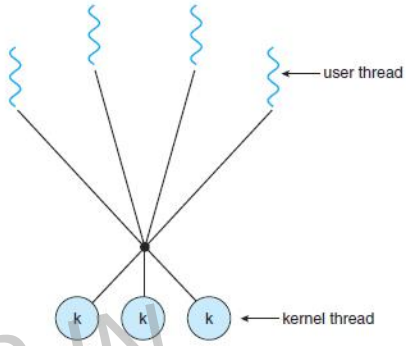


Figure 4.7 Many-to-many model.

The many-to-many model (Figure 4.7) multiplexes many user-level threads to a smaller or equal number of kernel threads. The number of kernel threads may be specific to either a particular application or a particular machine (an application may be allocated more kernel threads on a multiprocessor than on a single processor).

Let's consider the effect of this design on concurrency. Whereas the many to- one model allows the developer to create as many user threads as she wishes, it does not result in true concurrency, because the kernel can schedule only one thread at a time. The one-to-one model allows greater concurrency, but the developer has to be careful not to create too many threads within an application (and in some instances may be limited in the number of threads she can create). The many-to many model suffers from neither of these shortcomings: developers can create as many user threads as necessary, and the corresponding kernel threads can run in parallel on a multiprocessor. Also, when a thread performs a blocking system call, the kernel can schedule another thread for execution.

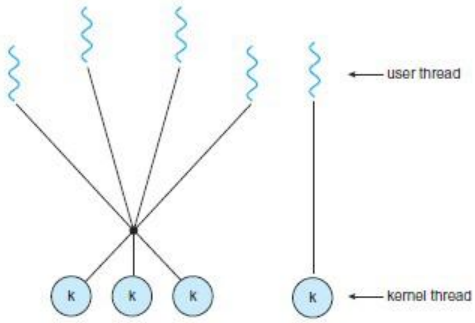


Figure 4.8 Two-level model.

One variation on the many-to-many model still multiplexes many user level threads to a smaller or equal number of kernel threads but also allows a user-level thread to be bound to a kernel thread. This variation is sometimes referred to as the **two-level model (Figure 4.8).** The Solaris operating system supported the two-level model in versions older than Solaris 9. However, beginning with Solaris 9, this system uses the one-to-one model.