Module 2. PROCESS MANAGEMENT

2.1 PROCESS

A process can be defined in several ways:

- 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.

Two essential elements of a process are:

- **program code:** which may be shared with other processes that are executing the same program
- **Set of data:** associated with that code.

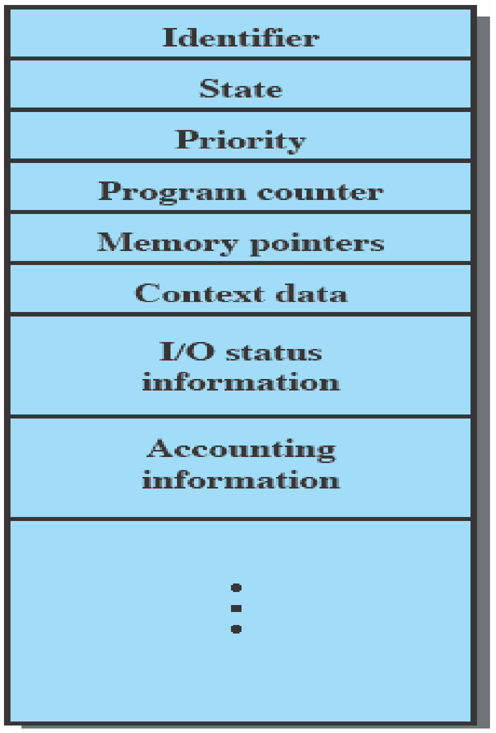

Figure 2.1 Process control block

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.

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- **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.

The above information is stored in a data structure known as ***process control block*** as shown in Figure 2.1. It is created and managed by OS.

2.2 PROCESS STATES

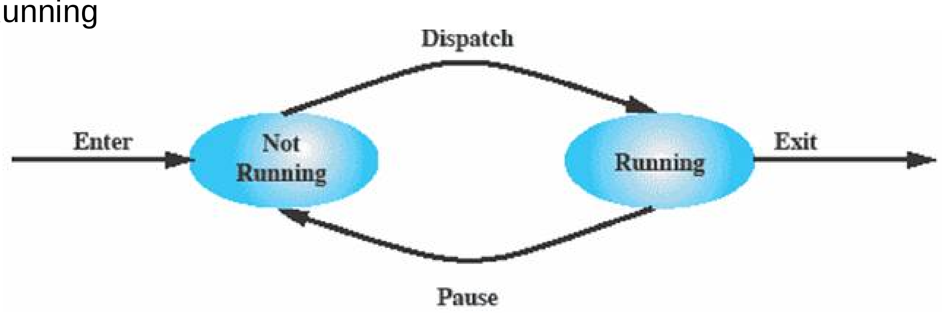
Execution of individual program involves a sequence of instructions within that program. This list of instructions is known as ***trace*** of the process. These instructions characterize the behavior of an individual process. ***Dispatcher*** is a small program which switches the processor from one process to another.

Major responsibility of an OS is to control the execution of processes. This task involves determining the inner pattern for execution and allocating resources to processes. Here we will consider two models of behavior of processes. These are known as process states.

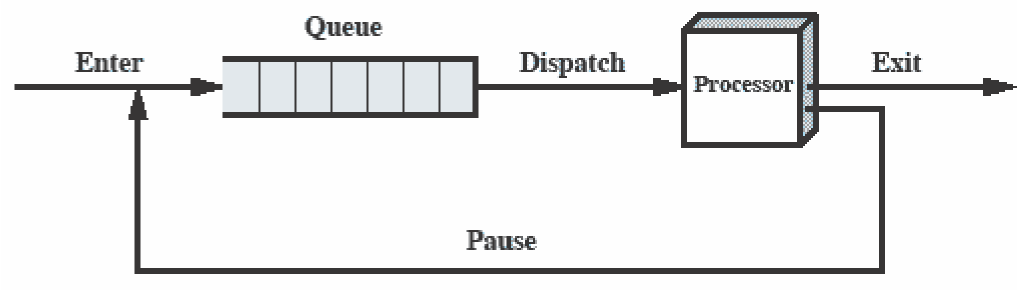
2.2.1 A Two – State Process Model

This is a simplest model and assumes that any process can be in any two states at any given point of time:

- Running
- Not Running



(a) State Transition Diagram



(b) Queuing Diagram

Figure 2.2 Two – State Process Model

When a job (or process) enters a job pool, it will be in a *not running* state. Once it is ready to execute and gets a processor, it will be into *running* state. When it has to wait for any resources or for I/O, it will be paused and sent into *not running* state again. During this time, another process may start *running.* Once the previous process is ready again, it will be switched from *not running* to *running.* This task is shown in Figure 2.2(a).

In this model, there must be some information relating to each process like current state, location in the memory etc. This will help OS to keep track of the process and is known as process control block. Processes that are not running must be kept in a queue, waiting for their turn to execute as shown in Figure 2.2(b). In this single queue, each entry is a pointer to the process control block of a particular process. In other words, each block represents one process here.

2.2.2 The Creation and Termination of Processes

The life of a process is bounded by its creation and termination. Hence, here we will discuss these aspects.

Process Creation: When a new process has to be added to the job pool, the OS builds the data structures for managing this process and allocates address space in main memory. These actions form the creation of a new process. The situations that will lead to the process creation are listed in Table 2.1.

Table 2.1 Reasons for Process Creation

Situation	Description
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 logon	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.

Table 2.2 Reasons for Process Termination

- Normal Completion
- Bounds violation
- Time overrun
- Privileged instruction
- Parent termination
- Time Limit exceeded
- Protection Error
- I/O failure
- Data misuse
- Parent request
- Memory unavailable
- Arithmetic error
- Invalid instruction
- Operator/OS intervention

Most of the times, the OS creates the processes depending on various situations. But, sometimes, it creates a process based on the explicit request of another process. This is called as ***process spawning***. When one process spawns another, the first process is called as ***parent process*** and the spawned process is called as ***child process***.

Process Termination: Every process that is created will be terminated at some moment of time. There are several reasons for a process to get terminated as listed in Table 2.2.

2.2.3 A Five-State Model

If all the processes are always ready to execute, then the queue system showed in Figure 2.2(b) will be effective. This queue may work on first-in-first-out basis or round-robin basis. But, we cannot say that all the processes in *not running* state are ready to run. Because some of them may be waiting for some I/O, blocked by other process etc. So, the dispatcher needs to look for a process which is really ready to execute.

To avoid this problem, it is better to split *not running* state into two parts viz. *ready* and *blocked.* This model, known as five-state model is shown in Figure 2.3. The five states of this model are explained below:

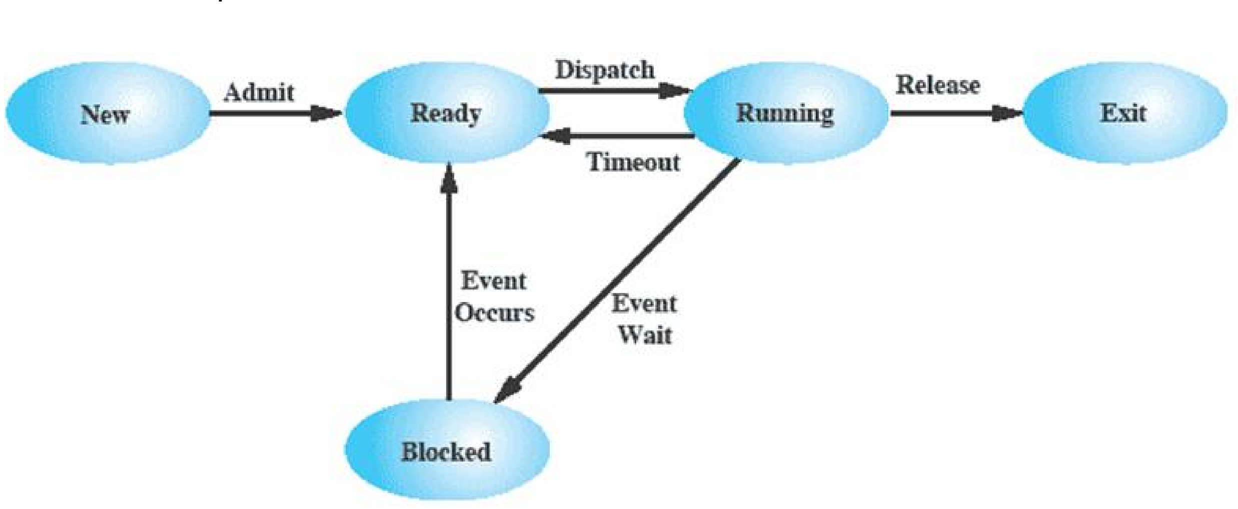
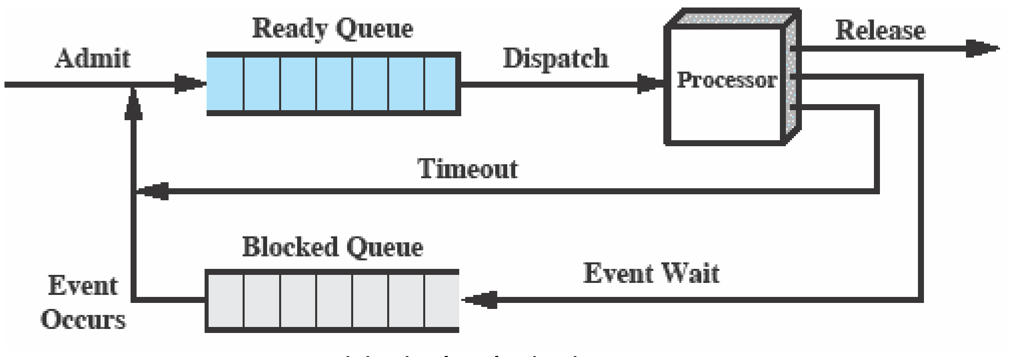
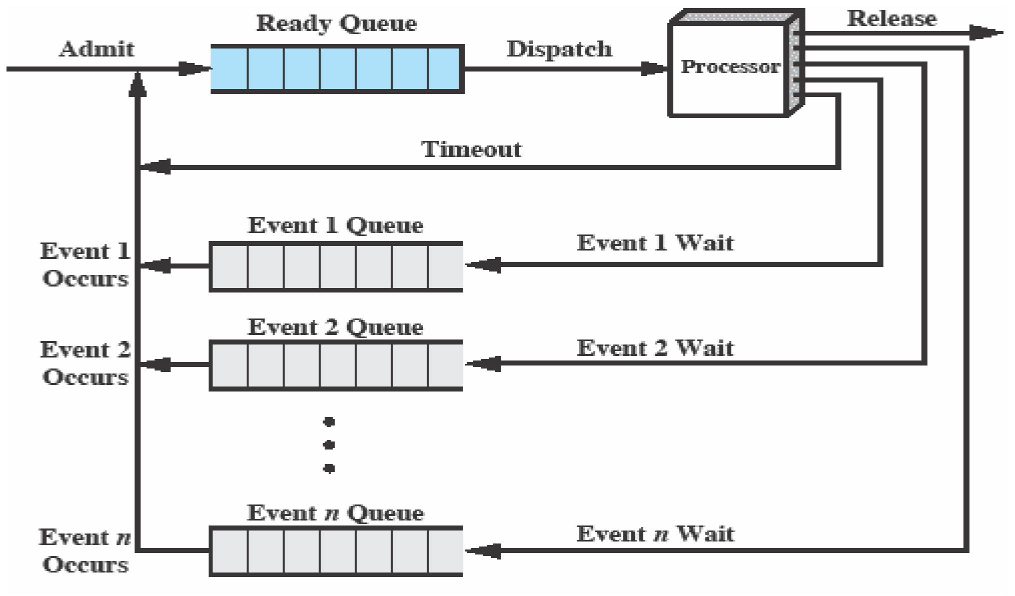


Figure 2.3 Five-state Process Model

- **Running:** The process that is currently being executed.
- **Ready:** A process that is ready to execute when given an opportunity.
- **Blocked/Waiting:** A process that cannot execute until some event occurs like I/O operation.
- **New:** A process that has been created just now and not yet been put into job pool by the OS. That is, the process which has not yet been loaded into main memory.
- **Exit:** A process that has been released from the job pool by OS, either because of successful termination or due to abnormal termination.



(a) Single Blocked Queue



(b) Multiple Blocked queues

Figure 2.4 Queuing model

Any process has to undergo transition between these states. The possible transitions are listed below:

- **Null to New:** A new process is created for execution. This event may occur due to any reasons listed in Table 2.1.
- **New to Ready:** The OS will move a process from New state to Ready when it is ready to take additional process. Generally, there will be a limit for a number of processes that can be kept on a queue so as to maintain the efficiency.
- **Ready to Running:** A scheduler or dispatcher selects one ready process for execution.
- **Running to Exit:** Currently running process is terminated by OS. (Refer Table 2.2 for reasons for termination).
- **Running to Ready:** Most of the OS have a limit for a time duration for which a process can run continuously. After that, even if it is not completed, it has to leave the processor for other waiting processes and has to enter a job queue.

- **Running to Blocked:** If a process requests for some resources, then it will be kept in a blocked state.
- **Blocked to Ready:** Once a process gets the requested resources and completes the task using those resources, it can enter into ready state.
- **Ready to Exit:** Though this state is not shown in the diagram, it may occur. Sometimes, a child process may be in ready state, and its parent may exit. Then, the child process also will be exited. Or, the parent itself may terminate the child.
- **Blocked to Exit:** A process may not get the resources that it requested or it exceeds the waiting time.

Figure 2.4 shows the queuing discipline maintained by processes with respect to the states mentioned in Figure 2.3.

2.2.4 Suspended Processes

In the whole course of process execution, OS may suspend a process sometimes. The reason is as explained below.

Assume an OS without virtual memory. Then all the processes to be executed must be loaded into main memory. Most of the processes will require I/O and hence may get blocked. As, I/O speed is much slower than that of processor, the processor would stay idle again. Hence, when none of the processes in the main memory is in Ready state, the OS can swap (move) one of the blocked processes into the disk. This will form a suspend queue. Now, any other process can be loaded into the main memory and start execution. As disk I/O is faster, the swapping will increase the performance. With the usage of swapping, one more state will be added to the process behavior model as shown in Figure 2.5 (a).

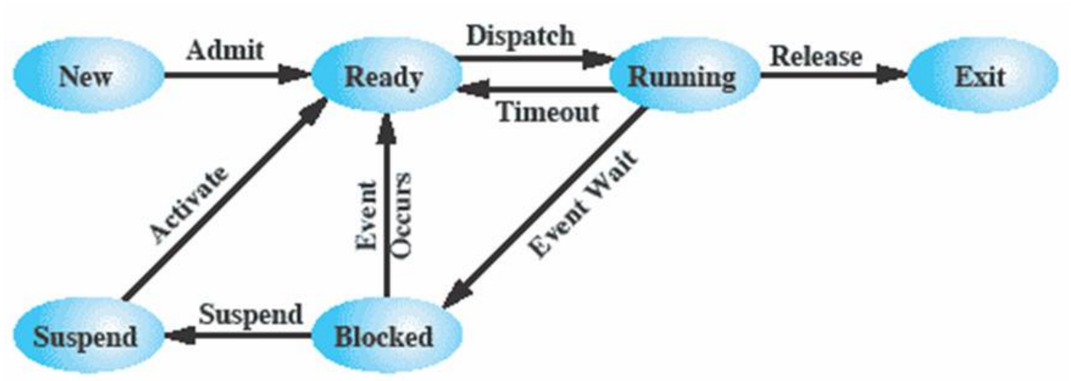
When OS performs a swapping-out operation, it can load either a newly created process into main memory or it can load a previously suspended process. But, a suspended process might have been actually a blocked process (waiting for I/O). Hence, the OS has to determine: Whether a process in suspended queue is

- a process waiting on an event – that is, blocked or not
- a process has been swapped out of main memory – that is suspended or not.

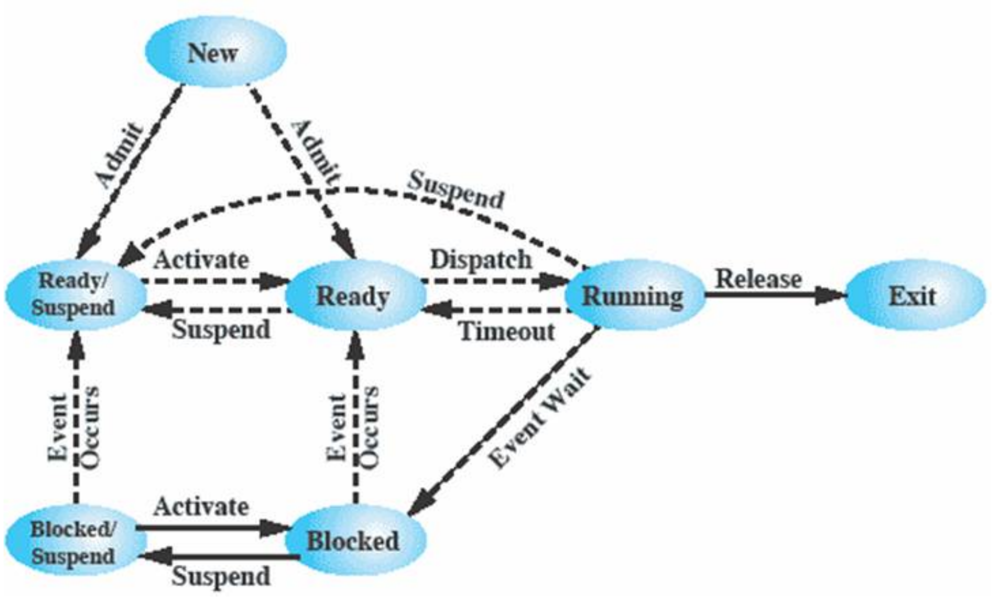
Keeping above two conditions, we will have four states:

- **Ready:** The process is in main memory and ready for execution
- **Blocked:** The process is in main memory and waiting for an event
- **Blocked/Suspend:** The process is on disk (secondary memory) and waiting for an event
- **Ready/Suspend:** The process is on disc, but ready for execution as soon as it gets loaded into main memory

These states can be included in the state diagram as shown in Figure 2.5(b).



(a) With one suspend state



(b) With two suspend states

Figure 2.5 Process State Transition Diagram with Suspend States

2.2.5 Other Uses of Suspension

A suspended process has following characteristics:

- The process is not immediately available for execution
- The process may or may not be waiting for an event
- The process was kept in suspended queue by an agent –the process itself, or parent or OS.
- The process may not be removed from this state until the agent explicitly orders to remove.

Some of the reason for process suspension is listed in Table 2.3. It also describes the usages by suspending the process.

Table 2.3 Reasons for Process Suspension

Reason	Description
Swapping	The OS needs to release sufficient main memory to bring in a process that is ready to execute.
Other OS Reason	OS suspects process of causing a problem.
Interactive User Request	User may wish to suspend a process to debug or in connection with the use of a resource
Timing	A process may be executed periodically and may be suspended while waiting for the next time slot.
Parent Process Request	A parent process may wish to suspend execution of a child to examine or modify the suspended process, or to coordinate the activity of various children.

2.3 PROCESS DESCRIPTION

OS is an entity which manages the usage of system resources by the processes as shown in Figure 2. 6.

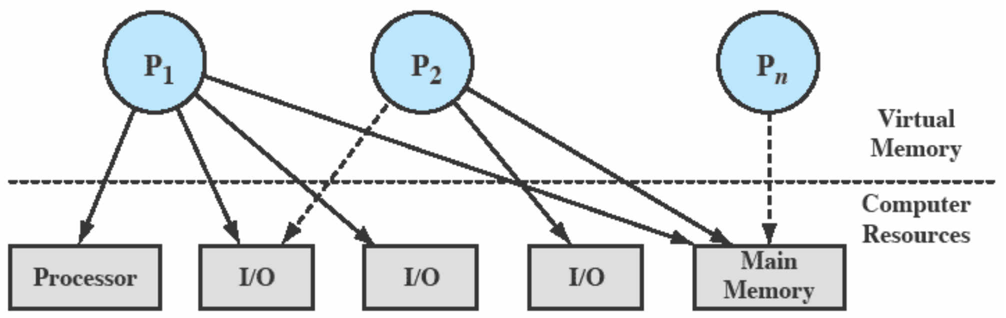


Figure 2.6 Processes and Resources (Resource allocation at one moment of time)

In a multiprogramming environment, there are a number of processes (P1,…, Pn) that have been created and exist in virtual memory. Each process needs to access system resources during its execution. In Figure 2.6, process P1 is running; at least part of the process is in main memory, and it has control of two I/O devices. Process P2 is also in main memory but is blocked waiting for an I/O device allocated to P1. Process Pn has been swapped out and is therefore suspended.

2.3.1 OS Control Structures

To manage the processes, the OS should have the information about the current status of each process and resource. For this purpose OS constructs and maintains tables for each entity as shown in Figure 2.7. The four types of tables maintained by OS are explained here.

- **Memory Table:** Used to keep track of both main and secondary memory. They must include the following information:
    - Allocation of main memory to processes
    - Allocation of secondary memory to processes
    - Protection attributes for access to shared memory regions
    - Information needed to manage virtual memory

- **I/O Table:** Used by OS to manage the I/O devices and the channels. At any given moment of time, the OS needs to know
  - Whether the I/O device is available or assigned
  - The status of I/O operation
  - The location in main memory being used as the source or destination of the I/O transfer
- **File Table:** Most of the times, these tables are maintained by file management system. These tables provide information about:
  - Existence of files
  - Location on secondary memory
  - Current Status
  - Any other relevant attributes
- **Process Table:** To manage processes the OS needs to know following details of the processes
  - Current state
  - Process ID
  - Location in memory

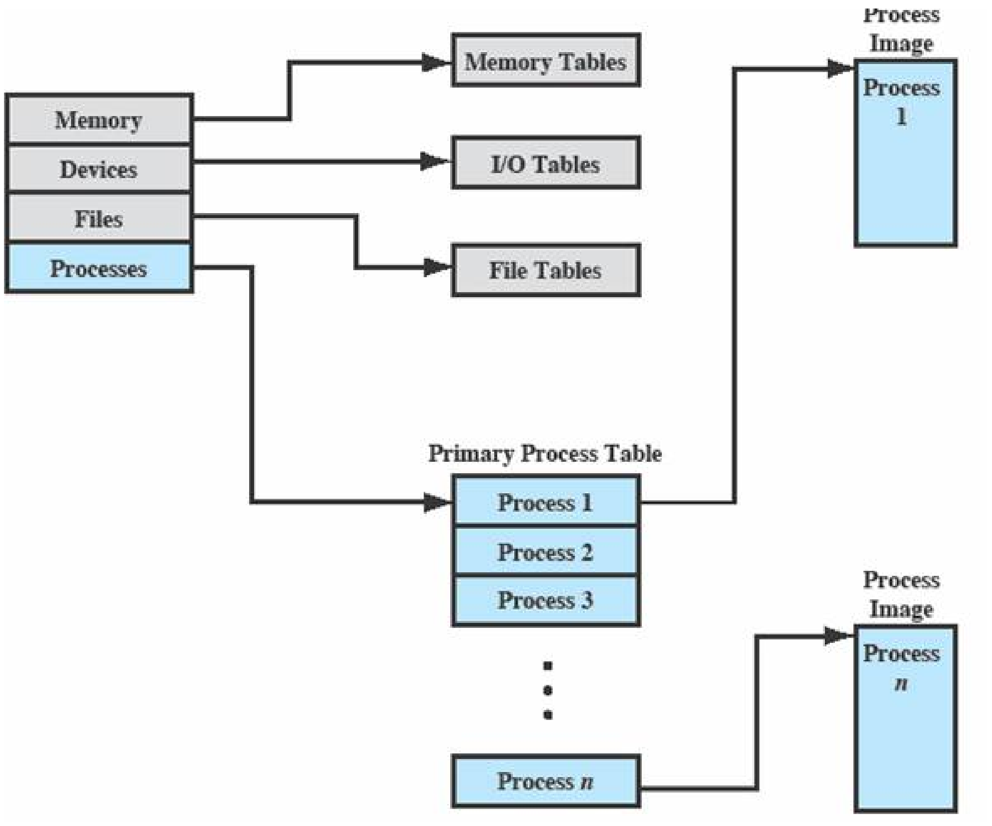


Figure 2.7 General Structure of OS Control Tables

2.3.2 Process Control Structures

To control and manage a process, OS must know where the process is located and the process attributes.

Process Location: Before checking where the process is located, we should understand the process image. ***Process image*** is a collection of user program, data, stack and process control block as shown in Table 2.4.

Table 2.4 Elements of Process Image

Elements	Description
User Data	A modifiable user program, user stack area, and relevant data
User program	The program to be executed
Stack	Each process has a stack associated with it. It is used for storing parameters and calling addresses
Process control block	Collection of attributes needed by OS to control the process

The process image is usually maintained as a contiguous block of memory and is stored on the disk. As the entire process image has to be loaded into main memory for process execution, the OS must know the exact location of process image on the disk.

The structure of location information can be understood using Figure 2.7. Here, the primary process table has one entry for each process. Each entry has one pointer to a process image.

Process Attributes: The information required by OS about a process can be categorized as follows:

- **Process Identification**: It is a unique number assigned every process. It includes
  - Identifier of this process
  - Identifier of parent process
  - User identifier
- **Processor state information:** Consists of processor registers like –
  - User visible registers
  - Control and status registers
  - Stack pointers
- **Process control information:** Includes the information like –
  - Scheduling and state information
  - Data structuring
  - Interprocess communication
  - Process privileges
  - Memory management
  - Resource ownership and utilization

Figure 2.8 shows the structure of process images in virtual memory.

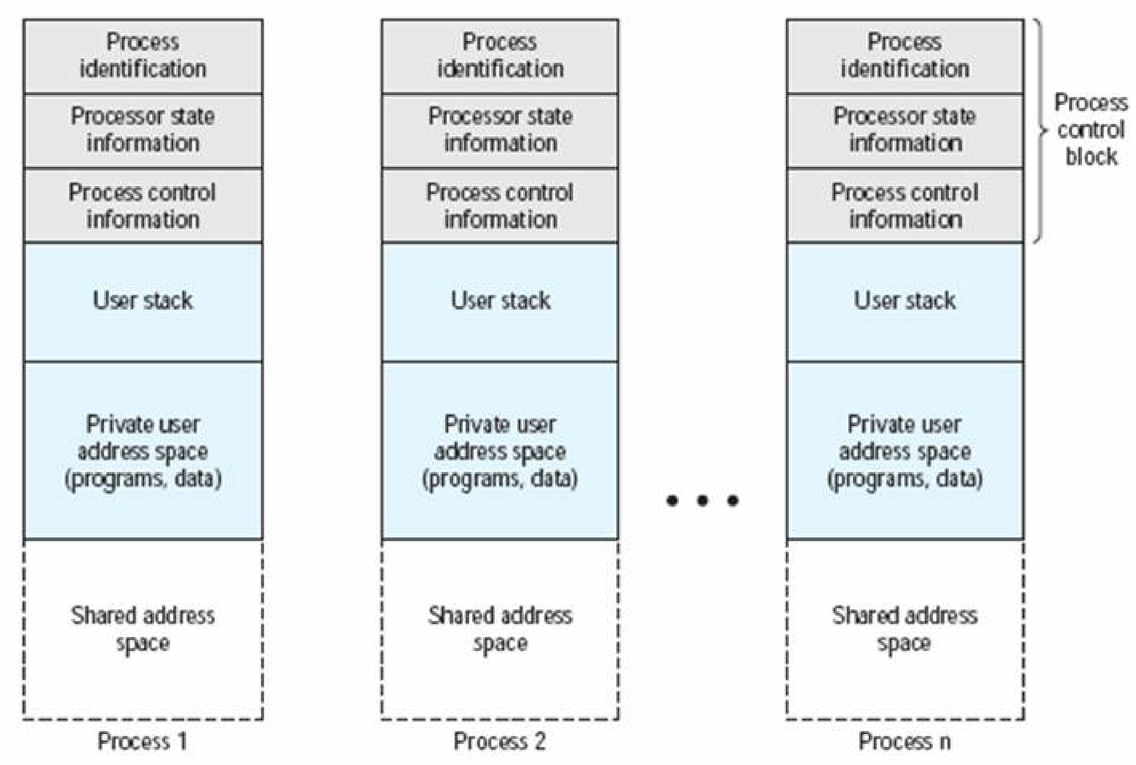


Figure 2.8 User Processes in virtual memory

2.4 PROCESS CONTROL

In the following sections, we will discuss how OS controls the processes.

2.4.1 Modes of Execution

Most of the processors support two modes of execution:

- **User Mode:** user programs are executed in this mode and it is a less-privileged mode.
- **System Mode:** It is also known as ***control mode*** or ***kernel mode***. It is a more privileged mode.

The OS and the important tables, process control blocks etc. must be protected from interference of user program. Hence, two modes must be provided separately. Typical functions of OS kernel are:

- Process management
- Memory management
- I/O management
- Support functions (like interrupt handling, accounting etc)

2.4.2 Process Creation

When OS decides to create a new process, it does the following:

- Assign a unique process identifier to the new process
- Allocate space for the process

- Initialize the process control block
- Set the appropriate linkages
- Create or expand other data structures

2.4.3 Process Switching
Sometimes, the OS will interrupt a running process and assigns another process to running state. That is, OS switches the process. Table 2.5 indicates few situations when process switch occurs.

Table 2.5 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

2.4.4 Change of Process State
The steps involved in the change of process state are as below:
- Save context of processor including program counter and other registers
- Update the process control block of the process that is currently in the Running state
- Move process control block to appropriate queue – ready; blocked; ready/suspend
- Select another process for execution
- Update the process control block of the process selected
- Update memory-management data structures
- Restore context of the selected process

2.5 EXECUTION OF THE OPERATING SYSTEM
We normally say that OS is also software. Hence the question is: 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? Who (what) controls it? These aspects are discussed here.

2.5.1 Nonprocess Kernel
The traditional approach of OS execution is to execute the kernel of the OS outside any process. Here, the OS has its own memory region and own system stack. Hence, the concept of process is applied only to user programs and OS code is executed as a separate entity that operates in privileged mode. This procedure is shown in Figure 2.9 (a).

2.5.2 Execution within User Processes
Another approach of OS execution is to execute the OS within the user process as shown in Figure 2.9(b). Here, there is no need of process switch to run an OS routine. This approach is common in small computers like PC and workstations.

2.5.3 Process-based OS

OS can be treated as collection of system processes as shown in Figure 2.9(c). As in the other options, the software that is part of the kernel executes in a kernel mode. But, major kernel functions are organized as separate processes.

This approach has several advantages:

- It imposes a modular OS with minimal, clean interfaces between the modules.
- Some noncritical OS functions are conveniently implemented as separate processes.
- Implementing the OS as a set of processes is useful in a multiprocessor or multicomputer environment, in which some of the OS services can be shipped out to dedicated processors, improving performance.

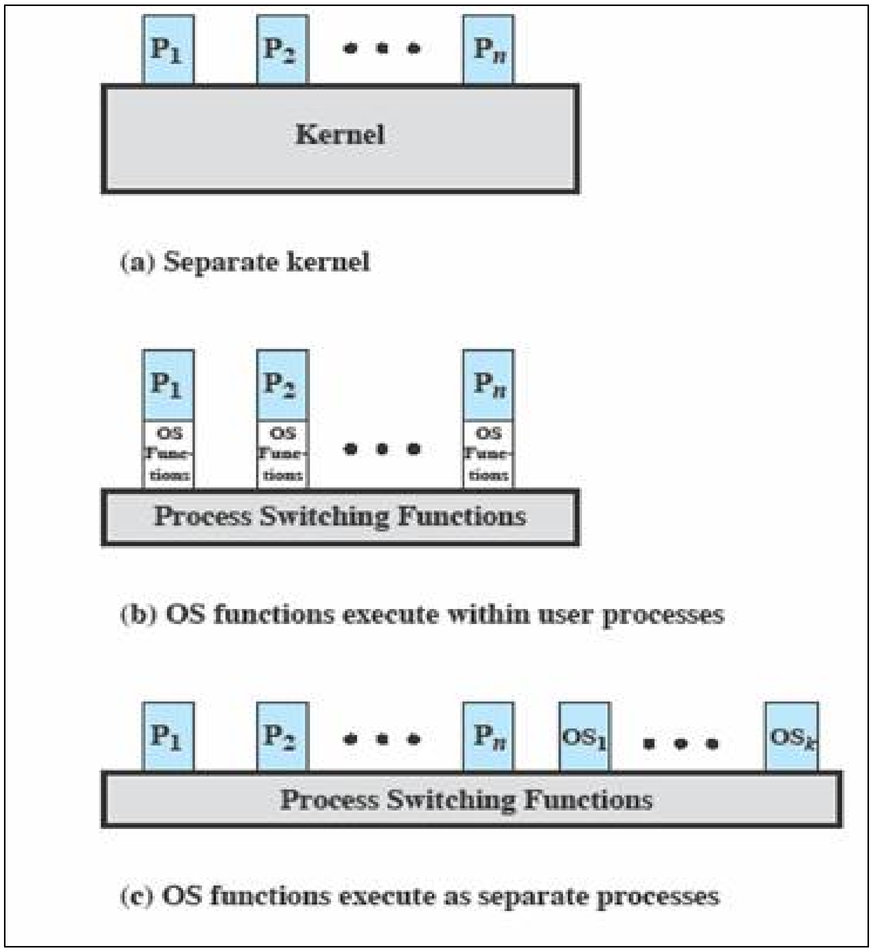

P1
P2
Pn
Kernel
(a) Separate kernel
OS Func-tions
Process Switching Functions
(b) OS functions execute within user processes
OS1
OSk
Process Switching Functions
(c) OS functions execute as separate processes

Figure 2.9 Relationship between OS and User Processes

2.6 SECURITY ISSUES

An OS associates a set of privileges with each process. These privileges indicate what resources the process may access, including regions of memory, files, privileged system instructions, and so on.

Typically the highest level of privilege is referred to as administrator, supervisor, or root, access. Root access provides access to all the functions and services of the operating system.

A key security issue in the design of any OS is to prevent anything (user or process) from gaining unauthorized privileges on the system – especially from gaining root access. Different types of threats to the OS and the respective countermeasures are discussed below.

2.6.1 System Access Threats

System access threats fall into two categories:

- **Intruders:** It is also called as hacker or cracker. There are 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

- **Malicious Software:** These are very sophisticated types of threats that are presented by programs and exploit vulnerabilities in the computing system.

2.6.2 Countermeasures

Following are the different ways of facing the security threats:

- **Intrusion Detection:** Intrusion detection systems (IDS) are typically designed to detect human intruder and malicious software behaviour. They may be host or network based. Intrusion detection systems (IDS) typically comprise
  - Sensors
  - Analyzers
  - User Interface
- **Authentication:** User authentication is a basic building block for defense consisting of two steps:
  - Identification
  - Verification

  There are four ways of authenticating a user's identity:
  - Something the individual ***knows*** (like password)
  - Something the individual ***possesses*** (like ID Card)
  - Something the individual ***is*** (static biometrics like finger print, iris etc.)
  - Something the individual ***does*** (dynamic biometrics like voice, gait etc.)

- **Access Control:** It implements a security policy to indicate who/what can access each resource. A security administrator maintains an authorization database. The access control function consults this to determine whether to grant access. An auditing function monitors and keeps a record of user accesses to system resources.

- **Firewalls:** Traditionally, a firewall is a dedicated computer that:
    - o interfaces with computers outside a network
    - o has special security precautions built into it to protect sensitive files on computers within the network.

2.7 PROCESSES AND THREADS

Processes have two characteristics:

- **Resource Ownership:** On regular intervals, a process will be allocated the control or ownership of resources like main memory, I/O devices, files etc. 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 through one or more programs. Then, OS will dispatch the process after completion.

To distinguish the two characteristics, the unit of dispatching is usually referred to as a ***thread*** or ***lightweight process***. The unit of resource ownership is referred as *process* or *task.*

2.7.1 Multithreading

The ability of OS to support multiple, concurrent paths of execution within a single process is called as ***multithreading.*** 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. MS-DOS is an example of OS which supports single process and single thread. Some versions of UNIX support multiple processes, but single thread per process. Java runtime environment supports multiple threads per single process. These are depicted in Figure 2.10.

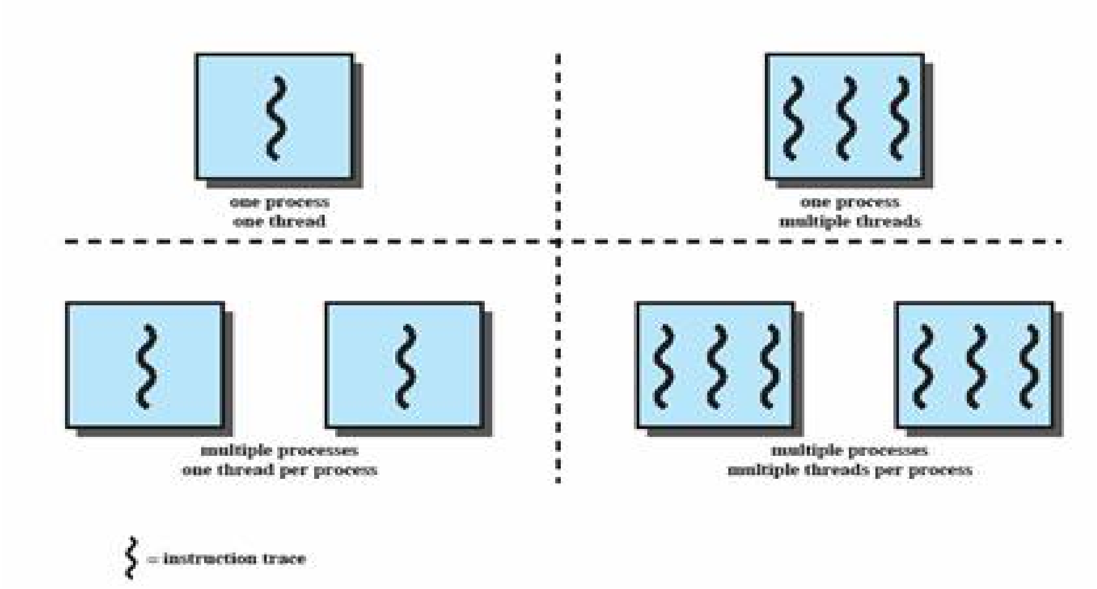


Figure 2.10 Threads and Processes

In a multithreaded environment, a process is defined as the unit of resource allocation and a unit of protection. Every process is associated with –

- A virtual address space that holds the process image
- Protected access to processors, other processes, files and I/O resources

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

- An execution state (running, ready, etc.)
- Saved thread context when not running
- An execution stack
- Some per-thread static storage for local variables
- Access to the memory and resources of its process (all threads of a process share this)

The difference between threads and processes from the view of process management is shown in Figure 2.11. A single threaded process means there is no thread. In this model, the process includes its control block, user address space and user/kernel stacks. In multithreaded model, there will be a separate control block for each thread. And, all threads of one process share the state and resources of that process.

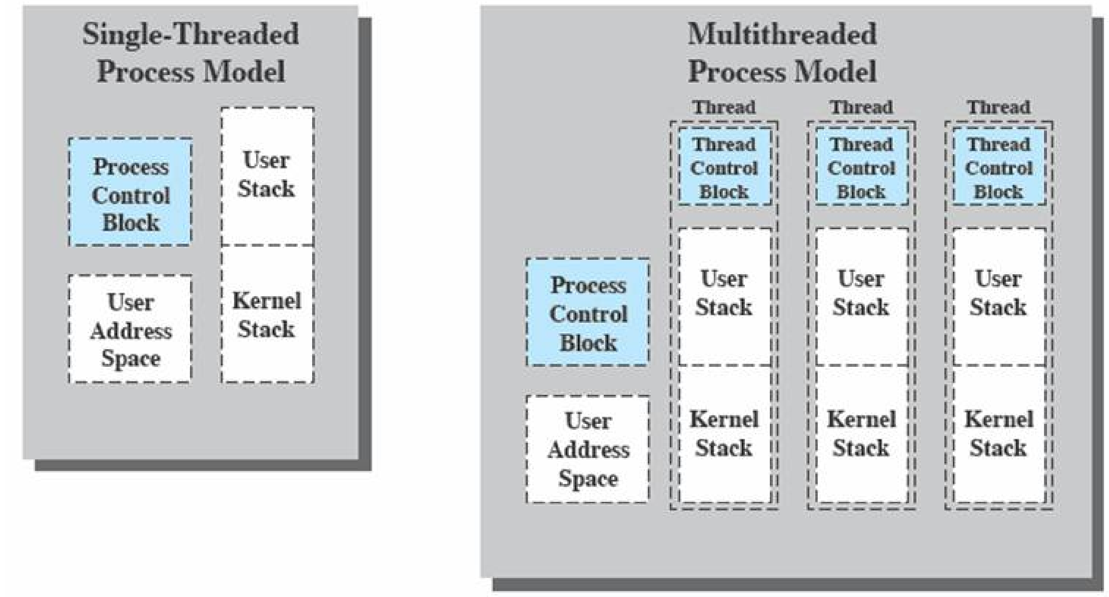


Figure 2.11 Single threaded and multithreaded process models

The benefits of threads are:

- Thread takes less time to create compared to a process
- It takes less time to terminate compared to a process
- Switching between two threads takes less time than switching processes
- Threads can communicate with each other without invoking the kernel

Thus, if any application has to be implemented as a set of related units of execution, it is better to have them as a collection of threads rather than collection of processes. The usage of threads in a single-user multiprocessing system are listed below –

- **Foreground and background work:** For example, in a spread sheet program, one thread may display menus and read user input; whereas another thread may enter user commands and update the spreadsheet.
- **Asynchronous Processing:** A thread may be created to save the word document in a periodic interval where as other thread may be writing the data into the document.
- **Speed of Execution:** A multithreaded process can compute one batch of data while reading the next batch from a device.
- **Modular program structure:** Programs that involve a variety of activities like input and output will be easier to design and implement using threads.

2.7.2 Thread Functionality

Similar to processes, threads also can have execution states and they may synchronize with one another.

Thread States: The key states of threads are Running, Ready and Blocked. But, since all the threads share the same address space of the process, they will be swapped out when a process is swapped out. Hence, suspending a single thread makes no sense.

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

- **Spawn:** When a new process is spawned, a thread for that process is also spawned. Also, a thread within a process may spawn another thread within the same process.
- **Block:** When thread needs to wait for an event, it will be blocked.
- **Unblock:** When an event for which a thread was blocked occurs, the thread is unblocked and moved into ready queue.
- **Finish:** When a thread completes, its registers and stacks are deallocated.

Thread Synchronization: All the threads of a process share the same address space and other resources like files. So, any alteration of a resource by one thread affects the behavior of other threads in the same process. Hence, it is necessary to synchronize the activities of the various threads so that they do not interfere with each other.

2.7.3 User – level and Kernel – level Threads

A thread can be implemented as either a user – level thread (ULT) or kernel – level thread (KLT). The KLT is also known as *kernel – supported threads* or *lightweight processes.*

User – level Threads: In ULT, all work of thread management is done by the application and the kernel is not aware of the existence of threads. It is shown in Figure 2.12 (a). Any application can be programmed to be multithreaded by using a threads library, which a package of routines for ULT management.

Usually, 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. The application may spawn a new thread within the same process during its execution. But, kernel is not aware of this activity.

The advantages of ULT compared to KLT are given below:

- Thread switching doesn't require kernel mode privileges. Hence, the overhead of two switches (user to kernel and kernel back to user) is saved.
- Scheduling can be application specific. So, OS scheduling need not be disturbed.
- ULTs can run on any OS. So, no change in kernel design is required to support ULTs.

There are certain disadvantages of ULTs compared to KLTs:

- Usually, in OS many system calls are blocking. So, when a ULT executes a system call, all the threads within the process are blocked.
- In a pure ULT, a multithreaded application cannot take advantage of multiprocessing.

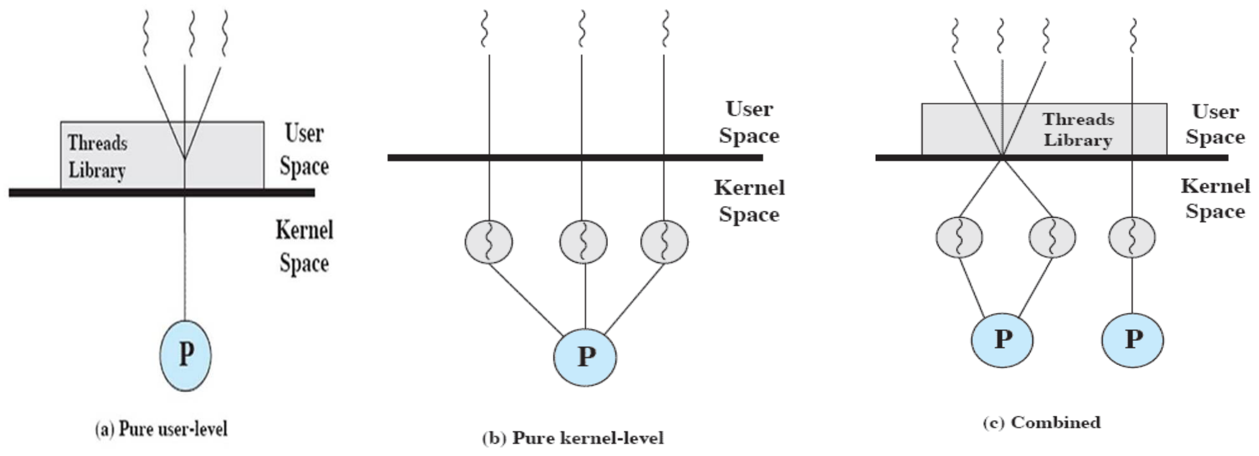


Figure 2.12 ULT and KLT

Kernel – level Threads: In pure KLT model, all work of thread management is done by the kernel. Thread management code will not be in the application level. This model is shown in Figure 2.12(b). The kernel maintains context information for the process as a whole and for individual threads within the process. So, there are certain advantages of KLT :

- The kernel can simultaneously schedule multiple threads from the same process on multiple processors.
- If one thread in a process is blocked, the kernel can schedule another thread of the same process.
- Kernel routines themselves can be multithreaded.

But, there is a disadvantage as well: The transfer of control from one thread to another within the same process requires a mode switch to the kernel.

Combined Approach: Some OS provide a combination of ULT and KLT as shown in Figure 2.12 (c). In this model, thread creation is done completely in user space. The multiple ULTs from a single application are mapped onto number of KLTs. The programmer may adjust the number of KLTs for a particular application and processor to achieve the best results.

2.7.4 Relationship between Threads and Processes

The interrelationship between threads and processes has been listed here:

Threads : Processes	Description
1:1	Each thread of execution is a unique process with its own address space and resources
M:1	A process defines an address space and dynamic resource ownership. Multiple threads may be created and executed within that process.
1:M	A thread may migrate from one process environment to another. This allows a thread to be easily moved among distinct systems
M:N	Combines attributes of M:1 and 1:M cases

2.8 SYMMETRIC MULTIPROCESSING (SMP)

Traditionally, the computer has been viewed as a sequential machine. That is, a processor executes instructions one at a time in a sequence and each instruction is a sequence of operations. But, as computer technology has evolved, parallel processing got importance. One of the popular approaches for providing parallelism is symmetric multiprocessors (SMPs), where processors are replicated.

2.8.1 SMP Architecture

Before understanding how SMP works, it is better to observe all parallel processors which are depicted in Figure 2.13.

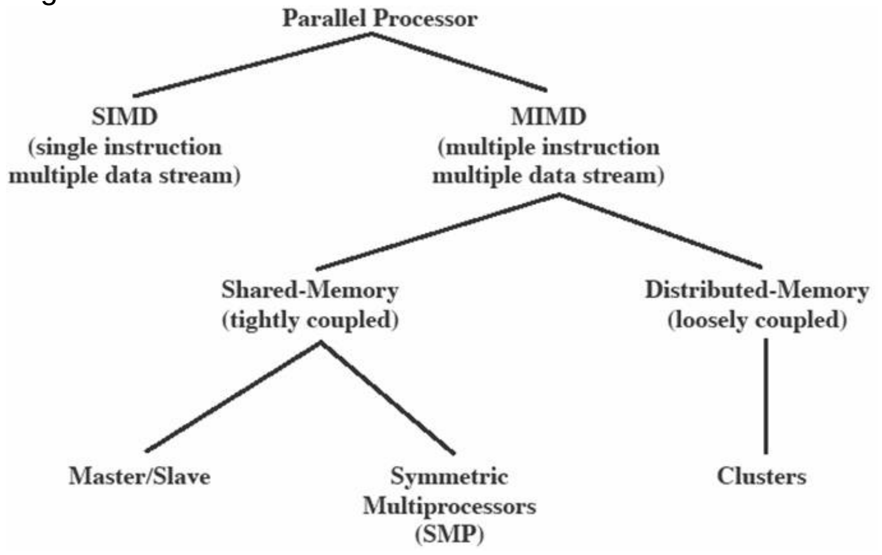

Parallel Processor
SIMD (single instruction multiple data stream)
MIMD (multiple instruction multiple data stream)
Shared-Memory (tightly coupled)
Distributed-Memory (loosely coupled)
Master/Slave
Symmetric Multiprocessors (SMP)
Clusters

Figure 2.13 Parallel Processor Architectures

- **Single instruction single data (SISD) stream:** A single processor executes a single instruction stream to operate on data stored in a single memory.
- **Single instruction multiple data (SIMD) stream:** Each instruction is executed on a different set of data by the different processors.
- **Multiple instruction single data (MISD) stream:** A sequence of data is transmitted to a set of processors, each of execute a different instruction sequence.
- **Multiple instruction multiple data (MIMD) stream**: A set of processors simultaneously execute different instruction sequences on different data sets.

Based on the communication among processors, MIMD can be further divided. If every processor has a dedicated memory, then each processing element is a self-contained computer. Communication among the computers is either via fixed path or via some network. Such a system is known as a ***cluster***. If the processors share a common memory, it is known as ***shared-memory multiprocessor.*** This again can be further divided into ***master/slave*** architecture and ***SMP.*** The master/slave architecture has disadvantages:

- A failure of the master brings down the whole system
- As master has to do all scheduling and process management, the performance may slow down.

But, in SMP, the kernel can execute on any processor and it allows portions of kernel to execute in parallel. Here, each processor does self-scheduling from the pool of available process or threads.

2.8.2 SMP Organization

In SMP, there are multiple processors, each of which contains its own control unit, arithmetic-logic unit and registers as shown in Figure 2.14. Each processor has access to a shared main memory and the I/O devices through a shared bus.

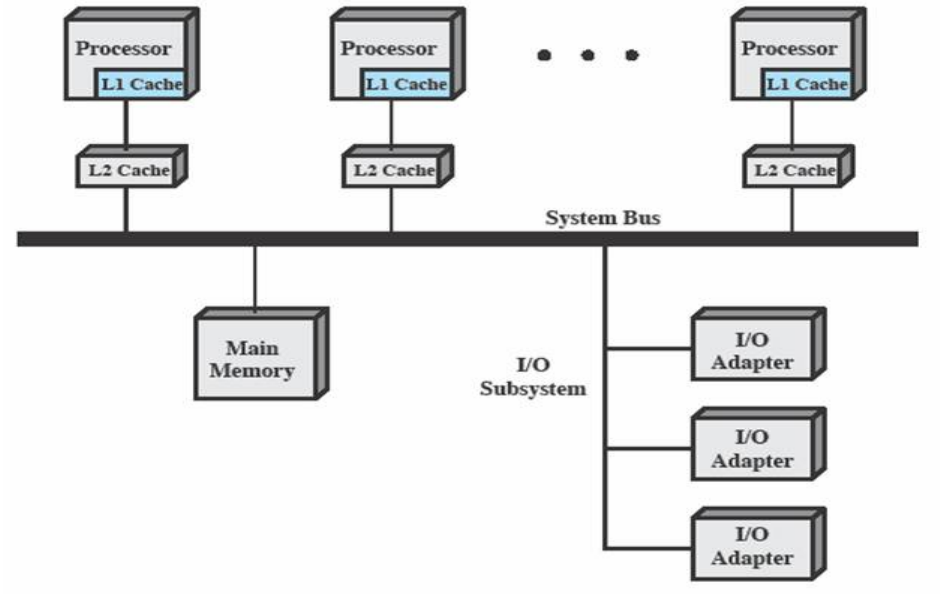


Figure 2.14 SMP Organization

2.8.3 Multiprocessor OS Design Considerations

An SMP OS manages processor and other computer resources so that the user may view the system as if it is a multiprogramming uni-processor system. Hence, the design issues of SMP OS are as below:

- **Simultaneous concurrent processes or threads:** Kernel routines should allow several processors to execute the same kernel code simultaneously.
- **Scheduling:** Scheduling may be performed by any processor to avoid conflicts.
- **Synchronization:** As multiple active processes can access shared address spaces and shared I/O resources, proper synchronization between the processes must be achieved.
- **Memory Management:** All the issues of memory management found in a uni-processor system have to be addressed here as well.
- **Reliability and Fault Tolerance:** OS should provide graceful degradation in case of processor failure.

2.9 MICRO KERNELS

A microkernel is a small OS core that provides the foundation for modular extensions. The question is how small must a kernel be to qualify as a microkernel? *Must* drivers be in user space? In theory, this approach provides a high degree of flexibility and modularity.

2.9.1 Microkernel Architecture

In the early days, OS were designed without a proper structure. Problems caused by mutual dependence and interaction were underestimated. This kind of ***monolithic operating systems***, one procedure couldn't call another procedure. To solve these problems, ***layered operating systems*** got evolved as shown in Figure 2.15(a). Here, functions are organized hierarchically and interaction takes between only adjacent layers.

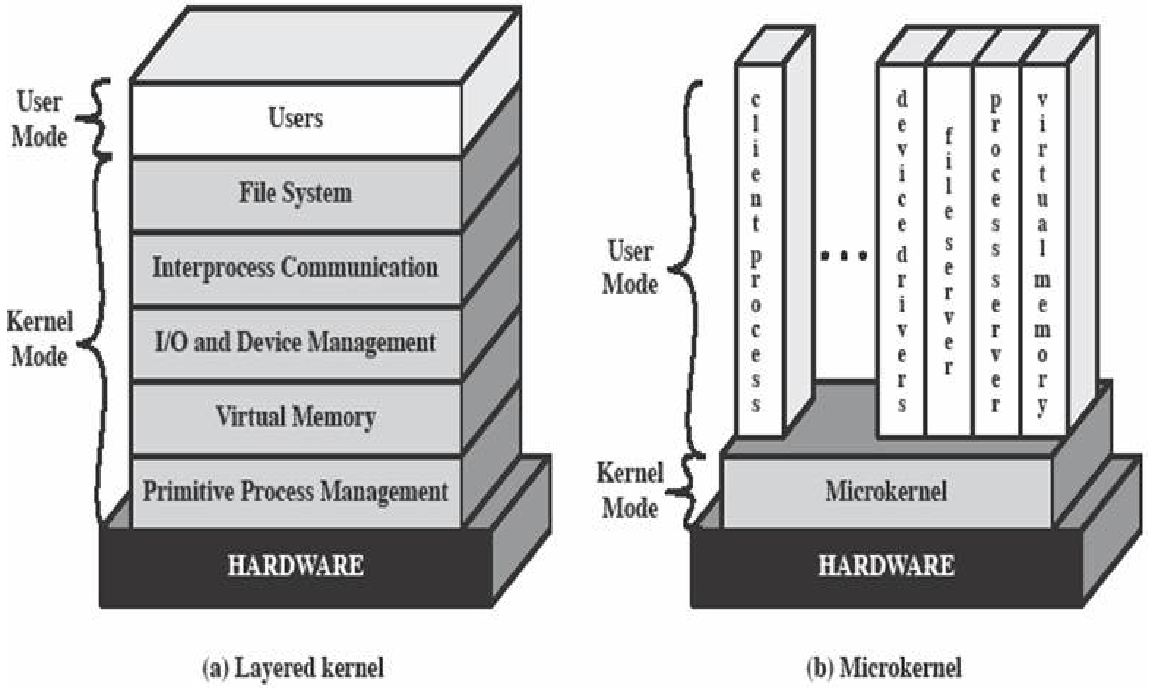


Figure 2.15 Kernel Architecture

But, the layered approach had problems: Change in one layer could affect the working of adjacent layers. To solve such problems, the concept of ***microkernels*** has been proposed. Here, only essential core OS functions will be in kernel as shown in Figure 2.15(b). And, the less important functions/services/applications are built on the microkernel and execute in user mode.

2.9.2 Benefits of Microkernel Organization

Advantages of using microkernels have been listed here:

- Uniform Interfaces
- Extensibility
- Flexibility
- Portability
- Reliability
- Distributed System Support
- Support for Object Oriented Operating Systems

2.9.3 Microkernel Performance

There are certain disadvantages of microkernels with respect to their performance:

- It takes longer to build and send a message
- Longer time to accept and decode the reply
- Performance depends on size and functionality of the microkernel.

2.9.4 Microkernel Design

There is no set of rules to indicate what functions must be provided by the microkernel and what structure has to be implemented. But, in general, it should include following functions:

- **Low – level Memory management:** The microkernel has to control the hardware concept of address space to make it possible to implement protection at the process level. Also, it should map each virtual page to a physical page frame as shown in Figure 2.16.

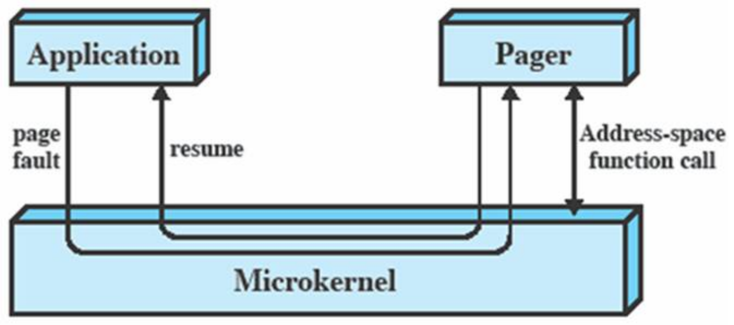


Figure 2.16 Page Fault Processing

- **Inter-process Communication:** Communication between processes or threads in a microkernel OS is via messages. A message includes:
    - o A header that identifies the sending and receiving process and
    - o A body that contains direct data, a pointer to a block of data, or some control information about the process.

- **I/O and Interrupt Management:** Within a microkernel it is possible to handle hardware interrupts as messages and to include I/O ports in address spaces. A particular user-level process is assigned to the interrupt and the kernel maintains the mapping.

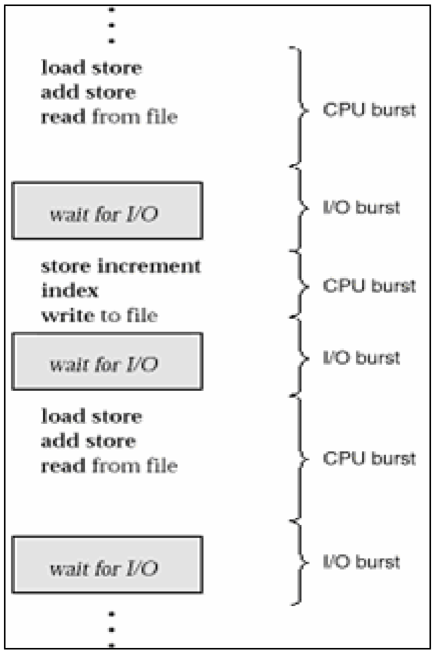
2.10 CPU SCHEDULER

CPU scheduling is a basis of multiprogrammed OS. By switching CPU among processes, the OS makes the computer more productive. In multiprogrammed OS, some process has to keep running all the time in CPU without keeping it idle. This will lead to maximum CPU utilization.

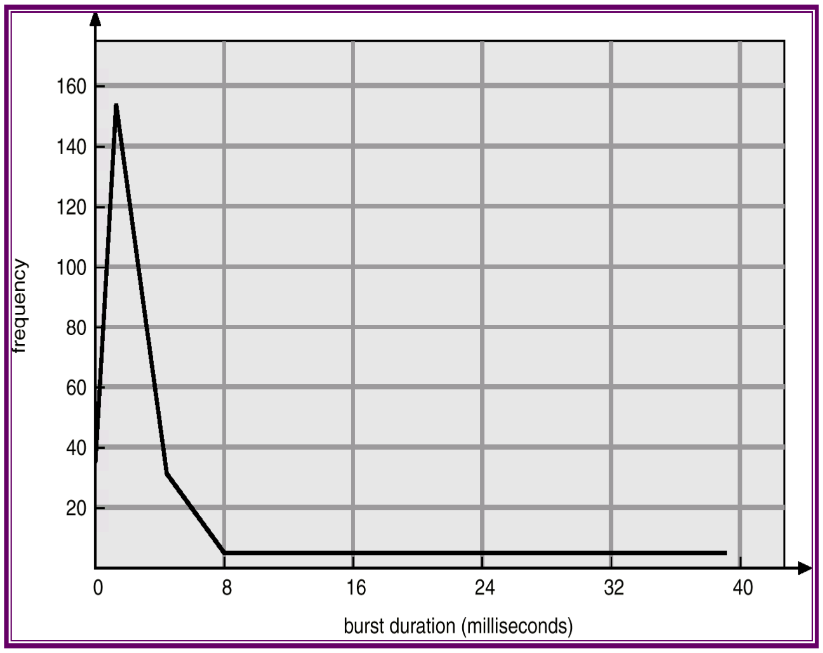
Whenever the CPU becomes idle, the OS must select one of the processes in the ready queue to be executed. The selection process is carried out by the ***short-term scheduler*** (or ***CPU scheduler***). The processed picked from ready queue need not be first-come-first-out queue. There are various types like shortest job first, round robin etc.

2.10.1 CPU – I/O Burst Cycle

The success of CPU scheduling depends on the following property of processes: Process execution consists of a cycle of CPU execution and I/O wait. Processes alternate between these two states. Process execution begins with a CPU burst. That is followed by an I/O burst, then another CPU burst, then another I/O burst, and so on. Eventually, the last CPU burst will end with a system request to terminate execution, rather than with another I/O burst. This is illustrated in Figure 2.17(a). The duration of CPU bursts vary by the process and by the computer. Still, they have exponential/hyper exponential frequency curve with many short CPU bursts and few long CPU bursts as shown in Figure 2.17(b).



(a)



(b)

Figure 2.17(a) Alternating sequence of CPU & I/O bursts (b) Histogram of CPU burst times

2.10.2 Preemptive Scheduling

CPU scheduling decisions may take place under the following four circumstances:

1. When a process switches from the running state to the waiting state
2. When a process switches from the running state to the ready state
3. When a process switches from the waiting state to the ready state
4. When a process terminates

In the situations (1) and (4) above, there is no choice for scheduling. A new process has to be taken from ready queue. This is called as ***non-preemptive*** scheduling. But, in the situations (2) and (3), there will be ***preemptive*** scheduling.

Under non-preemptive scheduling, once the CPU has been allocated to a process, the process keeps the CPU until it releases the CPU either by terminating or by switching to the waiting state. Preemptive scheduling incurs a cost. Consider the case of two processes sharing data. One may be in the midst of updating the data when it is preempted and the second process is run. The second process may try to read the data, which are currently in an inconsistent state.

2.10.3 Dispatcher

The dispatcher is the module that gives control of the CPU to the process selected by the short-term scheduler. This function involves:

- Switching context
- Switching to user mode
- Jumping to the proper location in the user program to resume that program

The dispatcher should be as fast as possible, because it will be invoked during every process switch.

2.10.4 Scheduling Criteria

Different scheduling algorithms have different properties to support different types of processes. There are many criteria to compare CPU scheduling algorithms as given below:

- **CPU Utilization:** CPU must be as busy as possible. CPU utilization may range from 0% to 100%. The real time systems have CPU utilization as 40% to 90%.
- **Throughput:** The number of processes completed per time unit is called as throughput.
- **Turnaround time**: The interval from the time of submission of a process to the time of completion is the turnaround time. Turnaround time is the sum of the duration spent waiting to get into memory, waiting in the ready queue, executing on the CPU, and doing I/O.
- **Waiting Time:** The CPU-scheduling algorithm does not affect the amount of time during which a process executes or does I/O; it affects only the amount of time that a process spends waiting in the ready queue. Waiting time is the sum of the durations spent waiting in the ready queue.
- **Response Time:** The time duration from the submission of a request till the first response received is known as response time.

The optimization criteria for CPU scheduling will be –

- Maximum CPU utilization
- Maximum throughput
- Minimum turnaround time
- Minimum waiting time
- Minimum response time

2.11 SCHEDULING ALGORITHMS

CPU scheduling deals with the problem of deciding which of the processes in the ready queue is to be allocated the CPU. We will discuss various algorithms used for CPU scheduling.

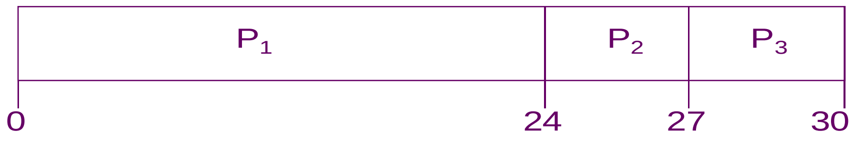
2.11.1 First Come, First Serve Scheduling

FCFS is the simplest algorithm which is managed by a simple FIFO queue. When a process enters the ready queue, its PCB is linked onto the tail of the queue. When the CPU is free, it is allocated to the process at the head of the queue. The running process is then removed from the queue. Usually, the average waiting time for FCFS will be more.

Example 1: The three processes P_1 , P_2 , and P_3 arrive at a time 0 with the CPU burst time given as below. Calculate average waiting time and average turnaround time.

Process	Burst Time
P_1	24
P_2	3
P_3	3

Solution: Suppose, the processes arrive in the order P_1, P_2 , P_3, then the Gantt Chart for the schedule is –



We can observe that,

Waiting time for P_1 = 0
Waiting time for P_2 = 24
Waiting time for P_3 = 27

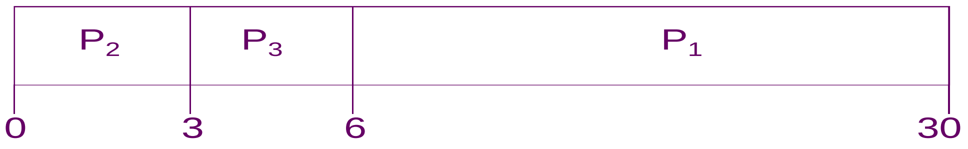
Thus, **Average waiting time = (0 + 24 + 27)/3 = 17 milliseconds**

Turnaround time is the duration from submission of the process till its completion. Hence, turnaround time for P1= 24
Turnaround time for P2 = 27
Turnaround time for P3 = 30
Average turnaround time = (24+27+30)/3 = 27 milliseconds

Throughput is total number of processes completed per one unit of time. Here, 30 time units were for completing 3 processes. So, for 1 time unit, the number of processes that can be completed is 3/30. That is,

Throughput = 3/30 = 0.1

Example 2:
Assume, in the above example, the processes arrive in the order P_2 , P_3 , P_1 then the Gantt Chart for the schedule is –



Now,

Waiting time for P_1 = 6
Waiting time for P_2 = 0
Waiting time for P_3 = 3

Thus, **Average waiting time = (6 + 0 + 3)/3 = 3 milliseconds**
Average turnaround time = (30 + 3 + 6)/3 = 13 milliseconds
Here also, **throughput = 3/30=0.1**

NOTE: We can observe that average waiting time in FCFS vary substantially if there is a much variation in CPU burst time of the processes.

Disadvantages:

- FCFS is non-preemptive, hence the average waiting time can be more.
- Troublesome in time-sharing systems, where each user needs to get a share of CPU. But, FCFS scheme will keep CPU for a longer duration.

2.11.2 Shortest-Job-First Scheduling

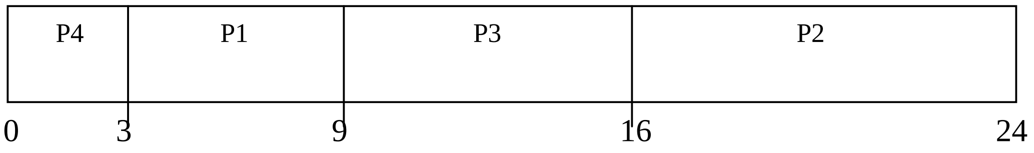
As the name suggests, in SJF scheduling, the process with a shortest CPU-burst is allocated the CPU first. If two processes have equal CPU-burst value, then FCFS is used to break a tie. There are two schemes in SJF viz. non-preemptive and preemptive.

- **Non-preemptive SJF Scheduling:** Here, once the CPU is given to the process, it cannot be preempted until completes its CPU burst.

  Example 1: There are four processes P1 to P4 all arrived at the time 0 and burst time is as given below. Compute average waiting time and average turnaround time.

Process	Burst Time
P1	6
P2	8
P3	7
P4	3

  The Gantt chart would be –



Waiting time for P1 = 3
Waiting time for P2 = 16
Waiting time for P3 = 9
Waiting time for P4 = 0
Average waiting time = (3+16+9+0)/4 = 7 milliseconds

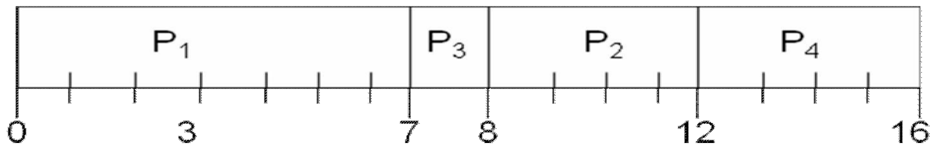
Turnaround time for P1 = 9
Turnaround time for P2 =24
Turnaround time for P3 = 16
Turnaround time for P4 = 3
Average turnaround time = (9 + 24 + 16 + 3)/4 = 13 milliseconds
Throughput = 4/24 = 0.1667

Note that, if we would have used FCFS here, the average waiting time would have been 10.25 milliseconds.

Example 2: There are four processes P1 to P4 which arrived at different times as given below. Compute average waiting time and average turnaround time.

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4

Solution:
In SJF – non-preemptive algorithm when arrival time of processes is different, one should be careful while drawing Gantt chart. Here, at the time 0, only one process P1 is in a ready queue. Hence, it will take a CPU. At the time 2, the process P2 arrives, whose burst time is smaller than P1. But, as it is non-preemptive, P1 will continue to execute. When P1 completes the execution and leaves the CPU at the time 7, observe that all three processes P2, P3 and P4 are arrived. Now, take the shorter one, that is P3. After completion of P3, there is a tie between P2 and P4 as both have same burst time. Now, resolve the tie using FCFS. Hence, the Gantt chart would be –



Waiting time for P1 = 0
Waiting time for P2 = 8 – 2 (arrival time) = 6

Waiting time for P3 = 7 – 4 (arrival time) = 3
Waiting time for P4 = 12 – 5 (arrival time) = 7
Average waiting time = (0+6+3+7)/4 = 4ms

Turnaround time for P1 = 7 (completion time) – 0 (arrival time) = 7
Turnaround time for P2 = 12 (completion time) –2 (arrival time) = 10
Turnaround time for P3 = 8 (completion time) – 4 (arrival time) = 4
Turnaround time for P4 = 16 (completion time) –5 (arrival time) = 11
Average turnaround time = (7+10+4+11)/4 = 8ms
Throughput = 4/16 = 0.25

SJF algorithms usually give minimum average-waiting time and hence an optimal algorithm. But, the problem is – in a dynamic situation, knowing the length of next CPU burst will be difficult.

- **Preemptive SJF Scheduling:** When a new process enters a ready queue while another process is still executing, there will be a choice. If a new process arrives with CPU burst length less than remaining time of current executing process, preempt. This scheme is also known as the ***Shortest-Remaining-Time-First (SRTF)***. In this scheme, the arrival time of every process plays a key role.

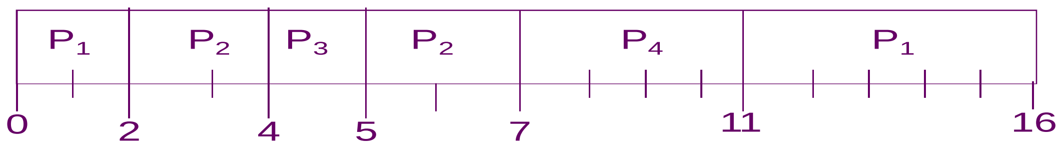
Example: There are four processes P1 to P4 arrived at different time as given below. Compute average waiting time and average turnaround time.

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	1
P4	5	4

Solution: Here, at the time 0, only process P1 is in a ready queue and hence will start executing. But, after 2 milliseconds, the process P2 arrives with a burst time as 4. The remaining time for P1 is 5, which is greater than time required for P2. Hence, P1 is preempted and P2 gets CPU. After 2 more milliseconds (that is, at the time 4), P3 arrives. The burst time of P3 (1) is lesser than the remaining time of P2(2). Hence, P2 is preempted and P3 is given a CPU. When P3 completes, the remaining time of other three processes are –

P1 -- 5
P2 – 2
P4 – 4

Now, the shortest job will be getting the CPU. Hence, the Gantt chart would be –



Now, the waiting time for each process is calculated as below:
Waiting time for P1: P1 arrived at the time 0 and had been given CPU. After 2ms, it has been preempted. Later, at the time 11, it was given a CPU again. Note that, it has finished the task of 2ms already, hence, the waiting time would be

11 – 2 (completed portion) = 9

Waiting time for P2: P2 arrived at the time 2, and given CPU immediately. Then after 2 ms, it has been preempted. Again, CPU was given at the time 5. So, waiting time will be

5 – 2 (arrival time) – 2 (completed time) = 1

Waiting time for P3: P3 arrived at the time 4 and was given CPU immediately. It was not preempted during its execution. And hence, the waiting time is 0.
Waiting time for P4: P4 arrived at the time 5 and was given CPU at the time 7. Hence, its waiting time is 2.

The average waiting time = (9+1+0+2)/4 = 3 ms.

Turnaround time is calculated as below –

Turnaround time for P1 = 16 (completion time) – 0 (arrival time) = 16
Turnaround time for P2 = 7 (completion time) – 2 (arrival time) = 5
Turnaround time for P3 = 5 (completion time) – 4 (arrival time) = 1
Turnaround time for P4 = 11 (completion time) – 5 (arrival time) = 6
Average turnaround time = (16+5+1+6)/4 = 7 ms

Throughput = 4/16 = 0.25

2.11.3 Priority Scheduling

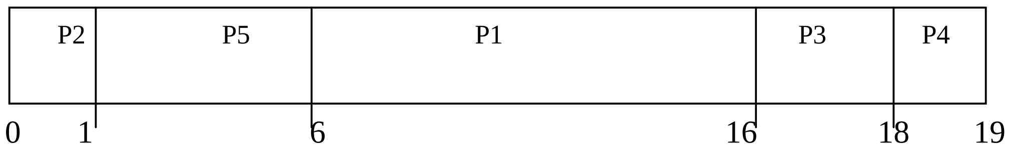
Priority scheduling is a special case of general priority scheduling algorithm. A priority is associated with each process, and the CPU is allocated to the process with the highest priority. Equal-priority processes are scheduled in FCFS order. SJF is a priority algorithm where priority is nothing but, its burst time – smaller the burst time, higher the priority. Priority status is normally treated as – lower the number, higher the priority.

The priority scheduling also can be preemptive and non-preemptive. In non-preemptive, normally, the priorities of all the processes are known before. That is, here, we assume that all the processes have arrived at the same time and CPU is assigned based on their priorities. But, sometimes, all the processes may not enter the ready queue at the same time. While one process is running, another process with higher priority than the currently executing process may enter the ready queue. Then currently executing process has to be preempted. So, here, preemption will be based on the arrival of new job with higher priority. This is somewhat similar to preemptive SJF, where new job with lesser burst time will be given a CPU.

Example 1: There are five processes P1, P2, P3, P4 and P5 and have arrived at the time 0 in that order. The priority and burst time are as given below –

Process	Burst Time	Priority
P1	10	3
P2	1	1
P3	2	4
P4	1	5
P5	5	2

Now, the Gantt chart would be –

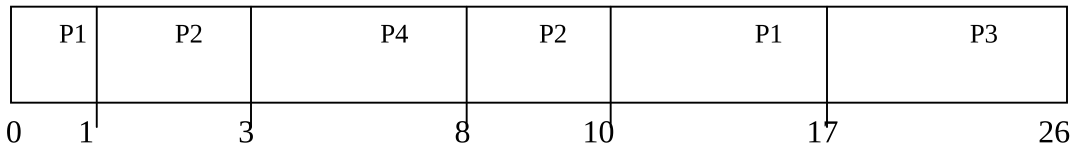


The average waiting time = (6+0+16+18+1)/5 = 8.2 milliseconds
The average turnaround time = (16+1+18+19+6)/5 = 12 ms
Throughput = 5/19 = 0.2632

Example 2: Assume there are four processes whose arrival time, burst time and priority have been given as below. Compute average waiting time and turnaround time.

Process	Arrival Time	Burst Time	Priority
P1	0	8	3
P2	1	4	2
P3	2	9	4
P4	3	5	1

Solution:
Note that, the process P1 with priority 3 arrived at the time 0 and no other process is there in a ready queue. Hence, it will be given a CPU. But, just after 1 millisecond, the process P2 with higher priority than P1 arrives and so, P1 has to be preempted and P2 will get CPU. When P2 is under execution, P3 arrives at the time 2. But, its priority is lower than P2. Hence, P2 will continue to execute. Later, P4 arrives at the time 3, which has higher priority than the currently executing P2. So, P2 will be preempted at P4 gets the CPU. Thus, P4 will finish execution before all other processes. Now, the remaining processes will be executed as per their priorities. Thus, the Gantt chart would be –



Waiting time for P1 = 10 – 1 (completed duration) – 0 (arrival time) = 9
Waiting time for P2 = 8 – 2 (completed duration) – 1 (arrival time) = 5
Waiting time for P3 = 17 – 2 (arrival time) = 15
Waiting time for P4 = 0
Average waiting time = (9+5+15+0)/4 = 7.25ms

Turnaround time for P1 = 17 – 0 (arrival time) = 17
Turnaround time for P2 = 10 – 1 (arrival time) = 9
Turnaround time for P3 = 26 – 2 (arrival time) = 24
Turnaround time for P4 = 8 – 3 (arrival time) = 5
Average Turnaround time = (17+9+24+5)/4 = 13.75ms
Throughput = 4/26 = 0.1538

NOTE: The priority scheduling has one drawback: the lower priority processes may never gets executed. This problem is known as ***starvation.*** As higher priority processes keeps getting added to ready queue, the lower priority processes will find indefinite delay in getting the CPU. In such a situation, either the process will run only when the system becomes free, or eventually, it may crash with all un-finished processes. To solve this problem, there is a remedy called – ***aging.*** Here, the priority of the process will be increased as the time passes by. Hence, an initially lower priority process will eventually becomes higher priority process and gets the CPU.

2.11.4 Round-Robin Scheduling

This algorithm is designed for time-sharing systems. It is similar to FCFS, but a time quantum is introduced. CPU will be given to the process for one unit of time quantum. After that, the process will be preempted and added back to ready queue. The ready queue will behave as a circular queue. The scheduler will go around the ready queue and allocates CPU for each process for a time interval of one time quantum. The value of time quantum here can be 10ms to 100ms.

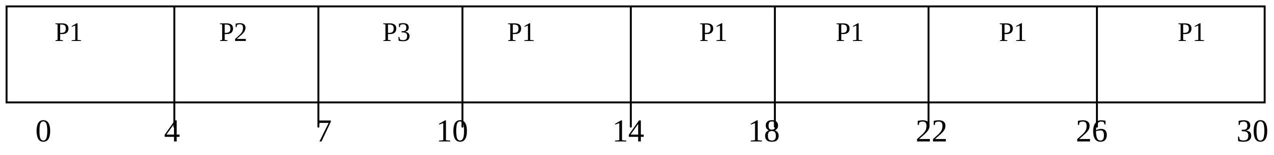
There are two possibilities:

- o The process will not be completed in a one time quantum. Then, the context switch will happen and the current process is kept back at the tail of the ready queue. And, the next process in a ready queue is picked and allotted a CPU.
- o The process will be completed within the duration of one time quantum. Then the process will give up the CPU voluntarily. Then, next process in a ready queue will be picked for execution.

Example 1: Consider the processes P1, P2 and P3 which are arrived at the time 0. Let the time quantum be 4 milliseconds. The burst time is given as below:

Process	Burst Time
P1	24
P2	3
P3	3

The Gantt chart would be –



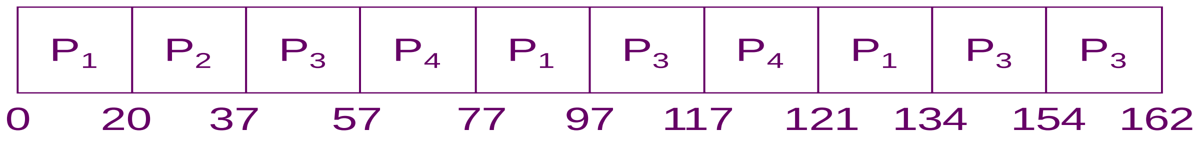
Note that, the burst time of processes P2 and P3 are lesser than the actual time quantum and hence, they will give up the CPU immediately after their completion.

Waiting time for P1 = 0 (first pickup) + {10 (next pickup) – 4 (previous CPU release)} = 6
Waiting time for P2 = 4
Waiting time for P3 = 7
Average waiting time = (6+4+7)/3 = 5. 67ms
Average turnaround time = (30 +7+10)/3 = 15.67ms
Throughput = 3/30 = 0.1

Example 2: Consider the processes P1, P2, P3 and P4 which are arrived at the time 0. Let the time quantum be 20 milliseconds. The burst time is given as below:

Process	Burst Time
P1	53
P2	17
P3	68
P4	24

The Gantt chart would be –



Waiting time for P1 = 0 (first pickup) + {77 (next pickup) – 20 (previous release)}
+ {121(next pick up) – 97 (previous release)}
= 81

Waiting time for P2 = 20 (first pickup)

Waiting time for P3 = 37 (first pickup) + {97 (next pickup) – 57 (previous release)} +
{134 (next pickup) – 117 (previous release)} +
{154 (next pickup) - 154 (previous release)}
= 94

Waiting time for P4 = 57 (first pickup) + {117 (next pickup) – 77 (previous release)}
= 97
Average waiting time = (81+20+94+97))/4 = 73 ms
Average turnaround time = (134+37+162+121)/4 =113.5 ms
Throughput = 4/162 = 0.0247

2.11.5 Multilevel Queue Scheduling

Sometimes, the processes can be easily classified into different groups like –
- o Foreground (or interactive) processes
- o Background (or batch) processes

These two types have different response – time requirements and different scheduling needs. And, foreground processes may have higher priority over background processes.

A multilevel queue scheduling algorithm partitions the ready queue into several separate queues as shown in Figure 2.18 . Each queue has its own scheduling algorithm. Normally, foreground queue will have Round Robin algorithm whereas, the background queue has FCFS algorithm.

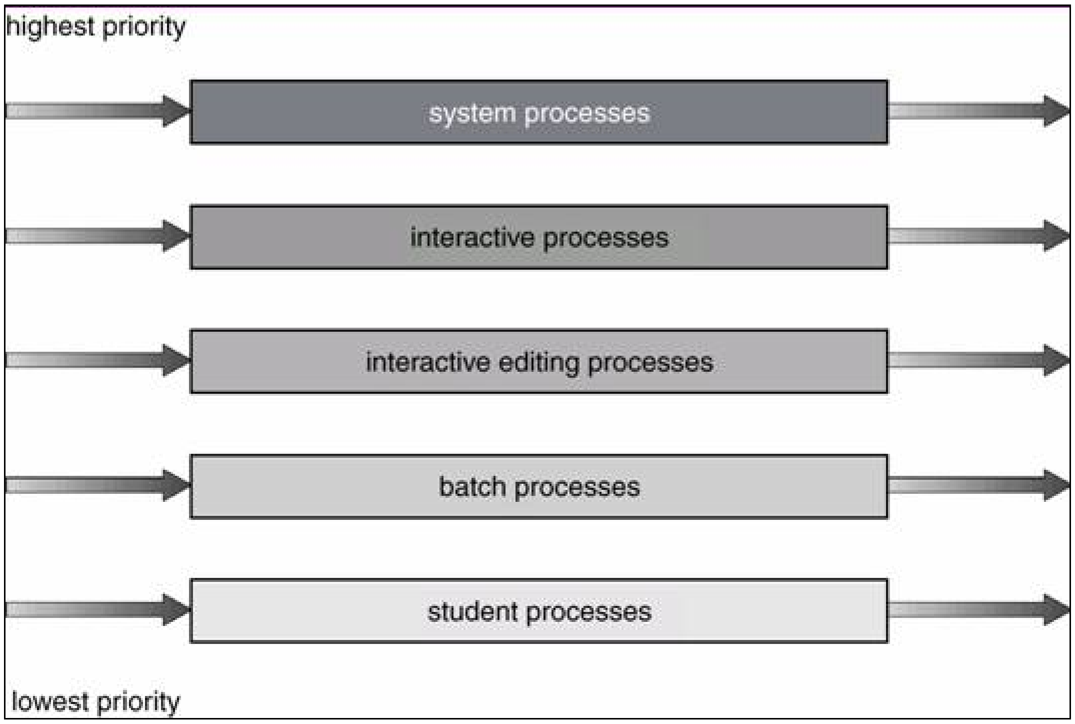


Figure 2.18 Multilevel queue scheduling

2.11.6 Multilevel Feedback Queue Scheduling

In, multilevel queue scheduling algorithm, processes are permanently assigned to a queue as soon as they enter a system. They do not move between the queues. This inflexibility is solved using multilevel feedback queue scheduling algorithm, where each process can move to any other queue. The idea is to separate processes with different CPU – burst characteristics. If a process uses too much CPU time, it will be moved to a lower priority queue. Similarly, if a process waits too long in a lower priority queue, it may be moved to a higher-priority queue.

Multilevel-feedback-queue scheduler defined by the following parameters:

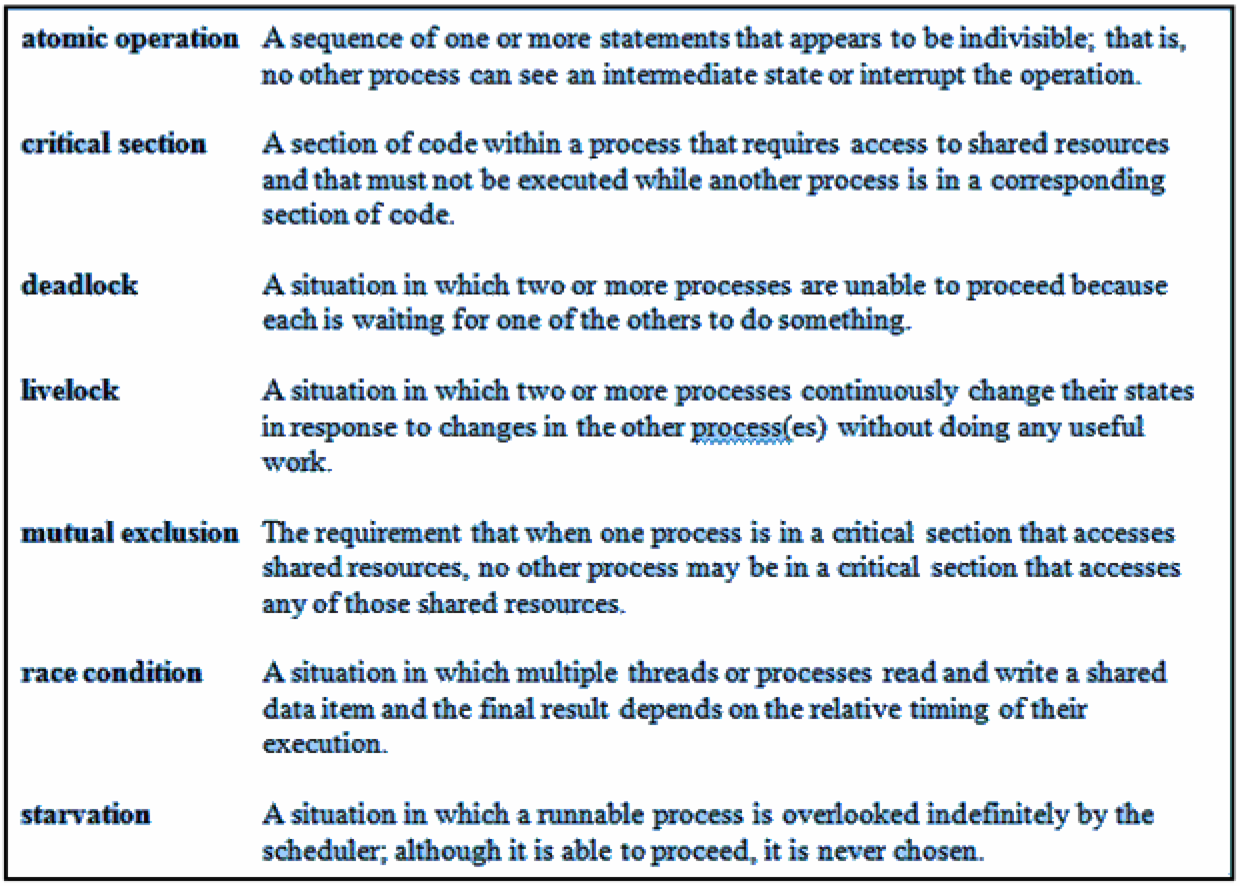
- number of queues
- scheduling algorithms for each queue
- method used to determine when to upgrade a process
- method used to determine when to demote a process
- method used to determine which queue a process will enter when that process needs service

2.12 INTRODUCTION TO MUTUAL EXCLUSION AND SYNCHRONIZATION

The OS design is concerned more about management of processes and threads with respect to multiprogramming, multiprocessing and distributed processing. Concurrency is a fundamental issue for all these areas. Concurrency includes design issues like communication among processes, sharing of and competing for resources, synchronization of the activities of multiple processes, and allocation of processor time to processes. 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.
- **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.

In this chapter, the importance of concurrency is discussed in detail. Some of the important key words in the study of concurrency are listed below.



atomic operation	A sequence of one or more statements that appears to be indivisible; that is, no other process can see an intermediate state or interrupt the operation.
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.

One can understand the meaning of concurrency with the definition: ***concurrency is the property of program, algorithm, or problem decomposability into order-independent or partially-ordered components or units.***

2.13 PRINCIPLES OF CONCURRENCY

In a single – processor systems, the processes are switched (interleaved) among themselves (Figure 2.19) and appear to be executed simultaneously. In multiprocessing systems, the processes may be switched as well as overlapped (Figure 2.20).

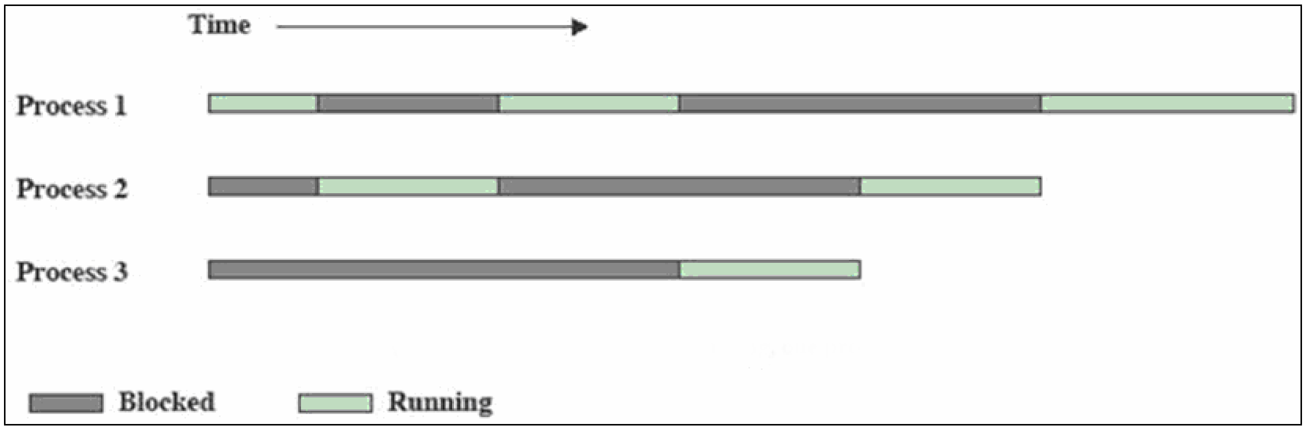


Figure 2.19 Single – processing system: Interleaving of processes

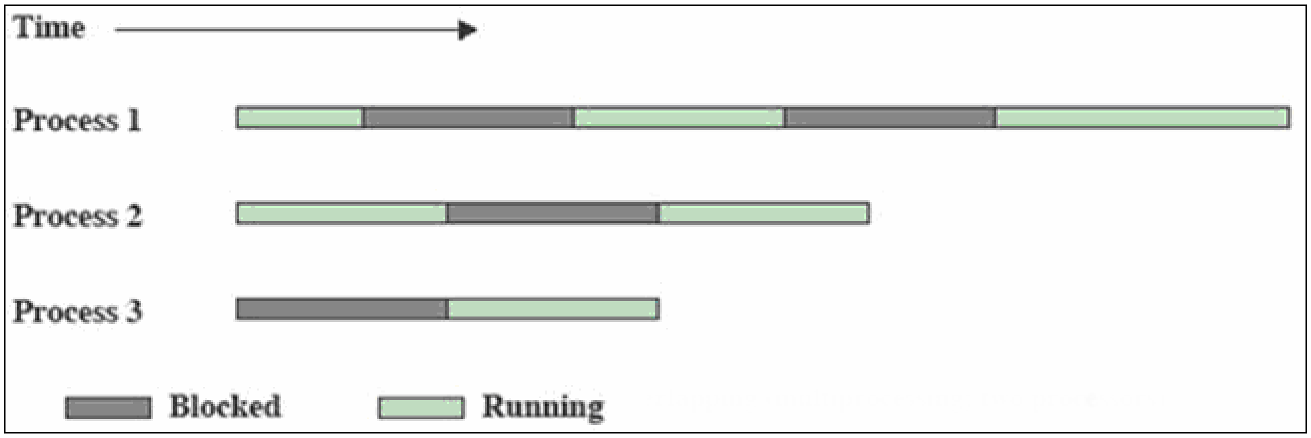


Figure 2.20 Multi – processing system: Interleaving and overlapping of processes

Interleaving and overlapping cause certain problems as listed below:

- Sharing of global resources may be dangerous
- Optimal allocation of resources may be difficult for OS
- Difficult to locating programming errors

To understand these problems, an example is considered in the following section.

2.13.1 A Simple Example

Consider the following function:

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

It is easily observed that `chin` and `chout` are global variables. The function `echo()` reads one character from the keyboard and stores into `chin`. It is then assigned to `chout`. And then it is displayed. The `echo()` function is global and available to all applications. Hence, only a single copy of `echo()` is loaded into main memory. Sharing of such global variables will cause certain problems in both single-processor and multi-processor systems.

In a single-processor multiprogramming system, assume there is only one I/O devices (keyboard and monitor). Assume, a process P1 invokes `echo()` function and it is interrupted immediately (due to some reason) after reading a character, say, `x` from the keyboard. Now, the global variable `chin` contains `x`. At this moment of time, the process P2 invokes the function `echo()`and executes. Let the character read now be `y`. Assume, the process P2 completes its execution and displays `y`. Now, the process P1 is resumed and displays the character as `y`, because, the recent content of `chin` is being `y`.

To solve this problem, only one process should be allowed to invoke `echo()` function for a given moment of time. That is, when P1 has invoked the function and got interrupted, P2 may try to invoke the same function. But, P2 must be suspended and should be made to wait. Only after P1 comes out of the `echo()` function, P2 must be resumed.

Thus, it is necessary to control the code for protecting shared global variable (or any other global resources).

In a multiprocessor system, similar problem occurs. Consider there are two processes P1 and P2 executing on two different processors. The execution of instructions of `echo()` function for both P1 and P2 are as shown below. Note that, the instructions on same line executes in parallel.

	Process P1	**Process P2**
1	------------------------	-----------------------
2	chin = getchar();	-----------------------
3	------------------------	chin = getchar();
4	chout=chin;	chout=chin;
5	putchar(chout);	----------------------
6	------------------------	putchar(chout);
7	-----------------------	----------------------

One can observe that, the global variable `chin,` initially read through P1, is overwritten by P2. Here also, to avoid the problem, control the access of shared resources.

2.13.2 Race Condition

A race condition occurs when multiple threads/processes read/write data items so that the final result depends on order of execution of instructions. Consider two examples to understand this concept.

Example 1: Assume that two processes P1 and P2 are sharing a global variable *a.* The process P1 has an instruction to update the value of *a* as –

a= 1;

The process P2 also has an instruction –

a= 2;

Both P1 and P2 will be executing their own set of instructions. Now, the value of *a* depends on the order of execution of above statements. In other words, the loser of the race (the process which executes last) will decide the value of *a*.

Example 2: Let there are two processes P3 and P4 sharing two global variables *b* and *c.* Initially,

b=1 and c = 2

The process P3 has a statement –

b=b+c;

whereas, the process P4 has a statement –

c=b+c;

One can easily make out that, the final value of *b* and *c* depends on order of execution of both of these statements. If P3 executes first,

b =3 and
c = 5

On the other hand, if P4 executes first,

b= 4 and
c = 3

2.13.3 Operating System Concerns

With respect to concurrency, following design issues OS have to be considered. The OS must

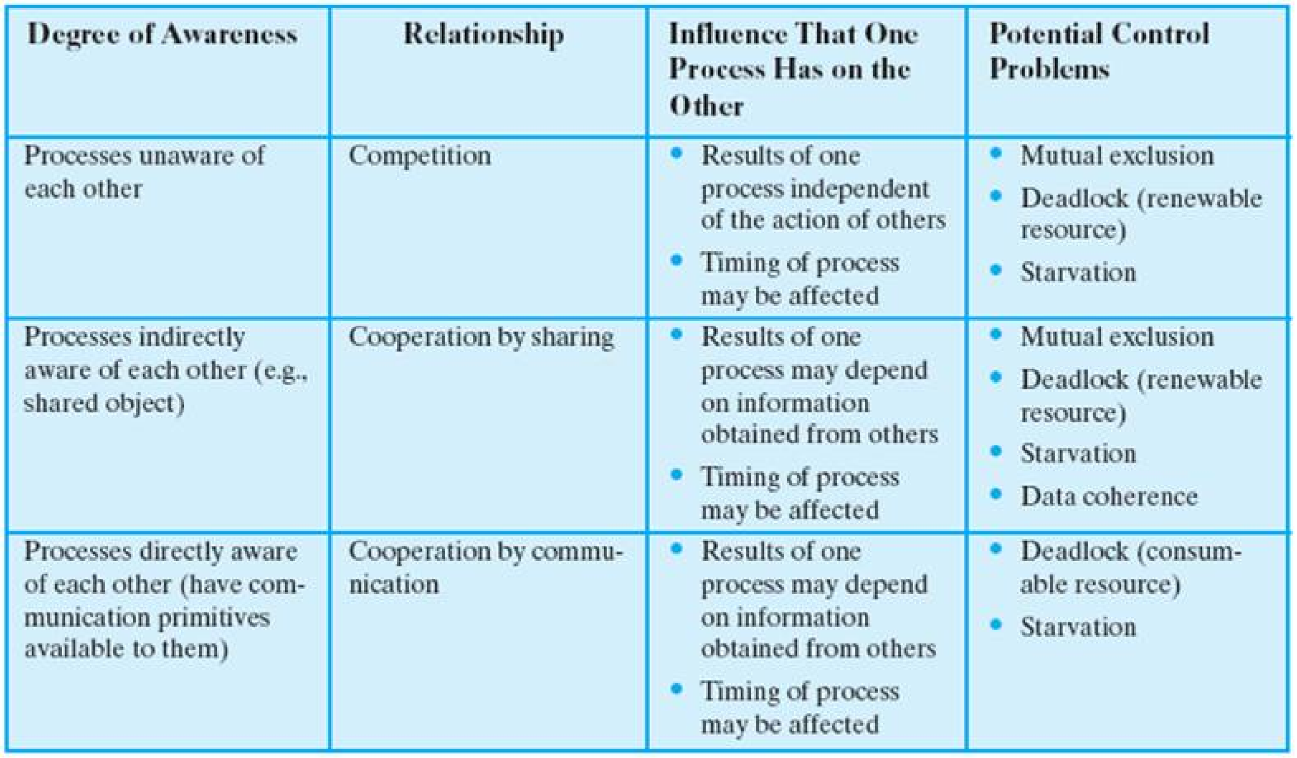
- keep track of processes
- allocate and de-allocate resources to active processes
- Protect the data and resources against interference by other processes.
- Ensure that the processes and outputs are independent of the processing speed

To understand the speed independence, the various ways of process interaction has to be considered.

2.13.4 Process Interaction

The ways in which processes are interacted is depending on how/whether they are aware of each other's existence. There are three ways as listed in Table 2.6. Now, let us discuss pros and cons of various types of relationships among processes.

Table 2.6 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 conflict with each other when they are competing for a same resource. In such a situation, three control problems will arise. The first one is need for ***mutual exclusion***. Suppose two processes require an access to single non-sharable resource like 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 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. For example, in case of the printer, we want only one process to have control of the printer till it finishes printing the entire document. Otherwise, lines from competing processes will be interleaved.

  The enforcement of mutual exclusion will lead to two other control problems: ***deadlock*** and ***starvation***. Assume, process P1 is holding the resource R1 and P2 is holding the resource R2. Now, P1 is waiting for R2 for its completion, whereas P2 is waiting for R1 for its completion. None of P1 and P2 releases the respective resources and hence it is a deadlock. Consider another situation: The processes P1, P2 and P3 require periodic

access to a resource R. If OS allocates R to only P1 and P2 periodically one after the other (in a round-robin manner), then the P2 will never get resource R and it will be a starvation.
OS should provide some solution to such problems by say, locking the resource before its use.

- **Cooperation among processes by sharing:** Here, the processes are aware of existence of other processes. Hence, processes may cooperate while updating the shared data. But, as data are held on resources, the problems of mutual exclusion, deadlock and starvation are still present. On top of these, a new problem – data coherence is introduced. Data coherence means the requirement of consistency in the shared data. For example, if two global variables *a* and *b* are equal at the beginning, they should remain equal even after execution of multiple processes. If the relationship among them is *a less than b*, it should remain as it is. To maintain such data integrity, the entire sequence of instructions in the processes must be made as critical region.
- **Cooperation among processes by Communication:** Here, the processes communicate with each other by sending messages. Hence, there won't be any requirement for mutual exclusion. But, the problem of deadlock and starvation still persist.

2.13.5 Requirements for Mutual Exclusion

The facility of mutual exclusion should meet the following requirements:

- Only one process at a time is allowed in the critical section for a resource
- A process that halts in its non-critical section must do so without interfering with other processes
- No deadlock or starvation
- A process must not be delayed access to a critical section when there is no other process using it
- No assumptions are made about relative process speeds or number of processes
- A process remains inside its critical section for a finite time only

These requirements of mutual exclusion can be satisfied by number of ways:

- Leaving the responsibility of concurrent execution to processes themselves
- Usage of special-purpose machine instructions
- Providing the support within the OS or programming language

2.14 MUTUAL EXCLUSION: HARDWARE SUPPORT

There are many software algorithms for enforcing mutual exclusion. But they have high processing overhead and the risk of logical errors. Hence, we will here consider few hardware approaches.

2.14.1 Interrupt Disabling

In a single-processor system, concurrent processes cannot be overlapped, but can be interleaved. Moreover, a process will continue to execute until it is interrupted. Hence, to guarantee mutual exclusion, a process has to be prevented from being interrupted. This capability can be provided in the form of primitives defined by OS kernel for disabling and enabling interrupts. So, a process should not be interrupted till it completes its critical section. But, by doing so, the efficiency of OS will slow-down, as OS cannot switch between the processes. Moreover, this approach does not guarantee mutual exclusion in case of multi-processor systems.

2.14.2 Special Machine Instructions

Normally, access to a memory location excludes any other access to that same location. Hence, processor designers have proposed several machine instructions that carry out two actions atomically (that is, an instruction is a single step and not interrupted), such as reading and writing or reading and testing, of a single memory location with one instruction fetch cycle. During execution of the instruction, access to the memory location is blocked for any other instruction referencing that location. Two most commonly implemented instructions are explained below:

- **Compare and Swap Instruction:** It compares the contents of a memory location to a given value. If they are same, it modifies the contents of that memory location to a given new value. This is done as a single atomic operation. The atomicity guarantees that the new value is calculated based on up-to-date information; if the value had been updated by another process in the meantime, the write would fail. The result of the operation must indicate whether it performed the substitution; this can be done either with a simple boolean response, or by returning the value read from the memory location.
- **Exchange Instruction:** The instruction exchanges the contents of a register with that of a memory location.

The use of a special machine instruction to enforce mutual exclusion has a number of advantages:

- It is applicable to any number of processes on either a single processor or multiple processors sharing main memory.
- It is simple and therefore easy to verify.
- It can be used to support multiple critical sections; each critical section can be defined by its own variable.

There are some serious disadvantages as well:

- **Busy waiting is employed:** Thus, while a process is waiting for access to a critical section, it continues to consume processor time.
- **Starvation is possible:** When a process leaves a critical section and more than one process is waiting, the selection of a waiting process is arbitrary. Thus, some process could indefinitely be denied access.
- **Deadlock is possible:** Consider the following scenario on a single-processor system. Process P1 executes the special instruction and enters its critical section. P1 is then interrupted to give the processor to P2, which has higher priority. If P2 now attempts to use the same resource as P1, it will be denied access because of the mutual exclusion mechanism. Thus, it will go into a busy waiting loop. However, P1 will never be dispatched because it is of lower priority than another ready process, P2.

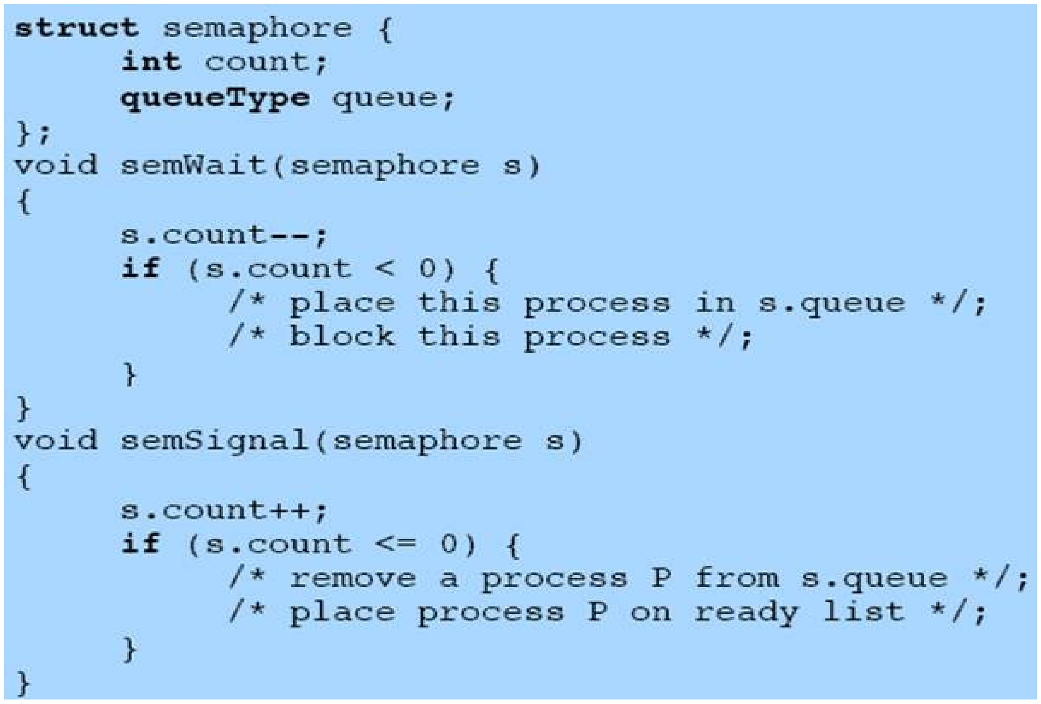
2.15 SEMAPHORES

As discussed earlier, apart from hardware-enabled mechanism for concurrency, there are OS and programming language mechanisms as well. Semaphore is one such mechanism for providing concurrency. ***Semaphore is an integer value used for signaling among processes.*** Only three operations may be performed on a semaphore, all of which are atomic: ***initialize, decrement,*** and ***increment.*** The decrement operation is for blocking of a process, and the increment operation is for unblocking of a process.

The fundamental principle is: Two or more processes can cooperate by means of simple signals, such that a process can be forced to stop at a specified place until it has received a specific signal. For signaling, special variables called semaphores are used. To transmit a signal via semaphore *s*, a process executes the primitive *semSignal(s)*. To receive a signal via semaphore *s*, a process executes the primitive *semWait(s)*. If the corresponding signal has not yet been transmitted, the process is suspended until the transmission takes place.

To achieve the desired effect, we can view the semaphore as a variable that has an integer value upon which only three operations are defined:

1. A semaphore may be initialized to a nonnegative integer value.
2. The *semWait* operation decrements the semaphore value. If the value becomes negative, then the process executing the *semWait* is blocked. Otherwise, the process continues execution.
3. The *semSignal* operation increments the semaphore value. If the resulting value is less than or equal to zero, then a process blocked by a *semWait* operation, if any, is unblocked.



```
struct semaphore {
     int count;
     queueType queue;
};
void semWait(semaphore s)
{
     s.count--;
     if (s.count < 0) {
          /* place this process in s.queue */;
          /* block this process */;
     }
}
void semSignal(semaphore s)
{
     s.count++;
     if (s.count <= 0) {
          /* remove a process P from s.queue */;
          /* place process P on ready list */;
     }
}
```

Figure 2.21 Definition of semaphore primitives

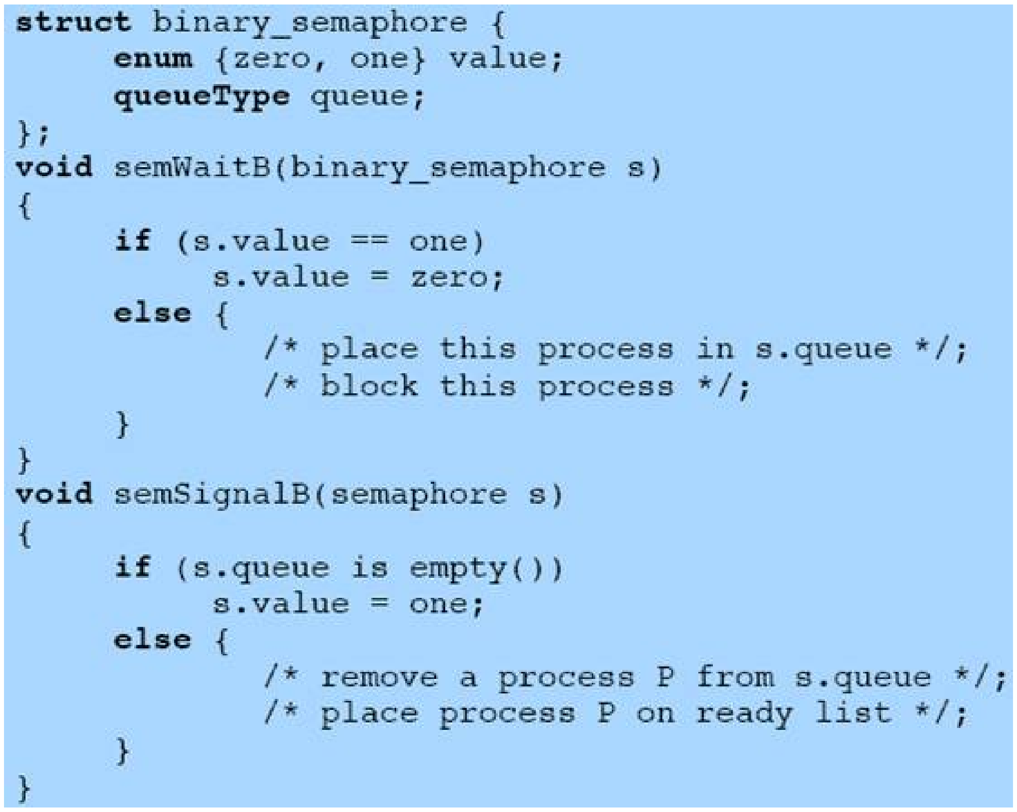
From the definition of semaphores, it can be observed that:

- Before process decrements a semaphore, it is not possible to know whether the process will get blocked or not.
- After a process increments a semaphore and another process gets woken up, both processes continue running concurrently. There is no way to know which process will continue immediately on a uniprocessor system.
- When you signal a semaphore, you don't necessarily know whether another process is waiting, so the number of unblocked processes may be zero or one.

The formal definition of semaphores can be understood using the code segment given in Figure 2.21.

There a stricter version of semaphore, viz. ***binary semaphore.*** It is defined by three operations as below and explained using code segment given in Figure 2.22.

1. A binary semaphore may be initialized to 0 or 1.
2. The *semWaitB* operation checks the semaphore value. If the value is zero, then the process executing the *semWaitB* is blocked. If the value is one, then the value is changed to zero and the process continues execution.
3. The *semSignalB* operation checks to see if any processes are blocked on this semaphore (semaphore value equals 0). If so, then a process blocked by a *semWaitB* operation is unblocked. If no processes are blocked, then the value of the semaphore is set to one.



```
struct binary_semaphore {
     enum {zero, one} value;
     queueType queue;
};
void semWaitB(binary_semaphore s)
{
     if (s.value == one)
          s.value = zero;
     else {
               /* place this process in s.queue */;
               /* block this process */;
     }
}
void semSignalB(semaphore s)
{
     if (s.queue is empty())
          s.value = one;
     else {
               /* remove a process P from s.queue */;
               /* place process P on ready list */;
     }
}
```

Figure 2.22 Definition of Binary Semaphore primitives

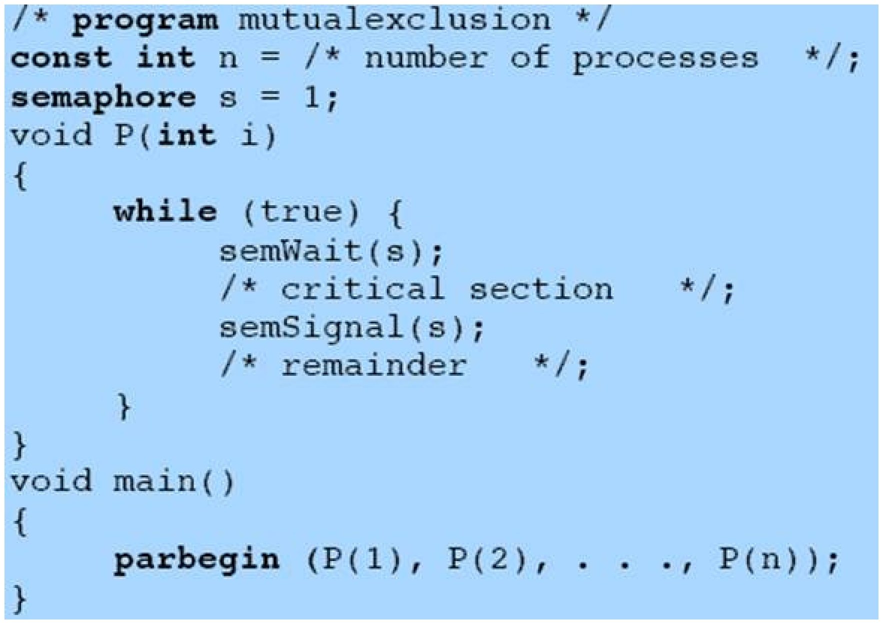
The non-binary semaphore is also known as ***counting semaphore*** or ***general semaphore.***

A concept related to the binary semaphore is the ***mutex***. The process that locks the mutex (sets the value to zero) must be the one to unlock it (sets the value to 1). In contrast, it is possible for one process to lock a binary semaphore and for another to unlock it.

For both counting semaphores and binary semaphores, a queue is used to hold processes waiting on the semaphore. Normally, the process that has been blocked the longest is released from the queue first – that is, in a FIFO manner. A semaphore whose definition includes this policy is called a ***strong semaphore***. A semaphore that does not specify the order in which processes are removed from the queue is a ***weak semaphore***.

2.15.1 Mutual Exclusion

The code segment given in Figure 2.23 gives a straight forward solution to the problem of mutual exclusion using a semaphore *s*. The construct **parbegin (P1, P2, …, Pn)** in this code means the following: suspend the execution of the main program; initiate concurrent execution of procedures P1, P2, …, Pn ; when all of P1, P2, …, Pn have terminated, resume the main program.



```
/* program mutualexclusion */
const int n = /* number of processes  */;
semaphore s = 1;
void P(int i)
{
     while (true) {
          semWait(s);
          /* critical section   */;
          semSignal(s);
          /* remainder   */;
     }
}
void main()
{
     parbegin (P(1), P(2), . . ., P(n));
}
```

Figure 2.23 Mutual exclusion using semaphores

Consider *n* processes, P(i), all of which need access the same resource. Each process has a critical section used to access the resource. In each process, a *semWait(s)* is executed just before its critical section. If the value of *s* becomes negative, the process is blocked. If the value is 1, then it is decremented to 0 and the process immediately enters its critical section; because *s* is no longer positive, no other process will be able to enter its critical section.

The semaphore is initialized to 1. Thus, the first process that executes a *semWait* will be able to enter the critical section immediately, setting the value of s to 0. Any other process attempting to enter the critical section will find it busy and will be blocked, setting the value of s to –1.

2.15.2 The Producer/Consumer Problem

The producer/consumer problem is one of the most commonly faced problems in concurrent processing. The general statement is this: There are one or more producers generating some type of data (records, characters) and placing these in a buffer. There is a single consumer that is taking items out of the buffer one at a time. The system is to be constrained to prevent the overlap of buffer operations. That is, only one agent (producer or consumer) may access the buffer at any one time. **The problem is to make sure that the producer won't try to add data into the buffer if it's full and that the consumer won't try to remove data from an empty buffer.**

Let us assume that the buffer is of infinite size. Consider the code segments for producer and consumer as given below:

Producer

```
while (true)
{
      /* produce item v */;
      b[in] = v;
      in++;
}
```

Consumer

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

      w = b[out];
      out++;
      /* consume item w */;
}
```

The Figure 2.24 illustrates the structure of buffer *b*. The producer can generate items and store them in the buffer at its own speed. Each time, an index *in* is incremented. The consumer proceeds in a similar fashion but must make sure that it does not attempt to read from an empty buffer. Hence, the consumer makes sure that the producer is ahead of consumer (*in* > *out*).

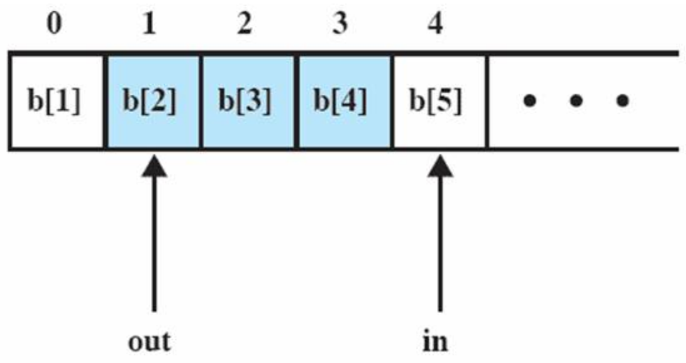


Figure 2.24 Infinite buffer for producer/consumer problem

If we add a realistic restriction on this problem, it can be solved easily using semaphore. The restriction is: instead of taking infinite buffer, consider a finite buffer of size *n* having a circular storage as shown in Figure 2.25.

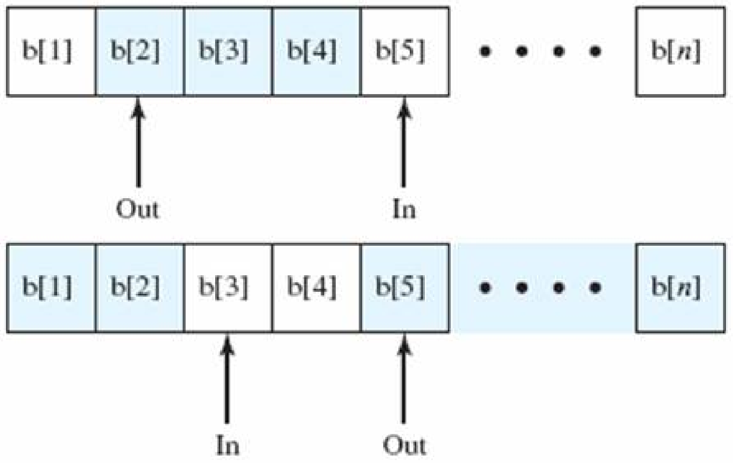


Figure 2.25 Finite circular buffer for producer/consumer problem

Since, it will work in circular manner, the pointers *in* and *out* will be considered with modulo *n*. Now, the situations would be –

Block on	**Unblock on**
Producer: insert in full buffer	Consumer: item inserted
Consumer: remove from empty buffer	Producer: item removed

Now, the producer and consumer functions can be given as –

Producer	**Consumer**

```
while (true)
{
      /*produce item v */
      while((in+1)%n==out)
            //do nothing
      b[in]=v;
      in=(in+1)%n;
}
```
	```
	while (true)
	{
	      while(in==out)
	            //do nothing
	      w=b[out];
	      out=(out+1)%n;
	      /*consume item w */
	}
	```

2.16 MONITORS

The monitor is a programming-language construct that provides equivalent functionality to that of semaphores and that is easier to control. The monitor construct has been implemented many programming languages like Concurrent Pascal, Pascal-Plus, Java etc. It has also been implemented as a program library. This allows programmers to put a monitor lock on any object. For example, we can lock all linked list with one lock, or one lock for each list or one lock for each element of every list.

2.16.1 Monitor with Signal

A monitor is a software module consisting of one or more procedures, an initialization sequence, and local data. The chief characteristics of a monitor are the following:

1. The local variables are accessible only by the monitor's procedures and not by any external procedure.
2. A process enters the monitor by invoking one of its procedures.
3. Only one process may be executing in the monitor at a time; any other processes that have invoked the monitor are blocked, waiting for the monitor to become available.

Monitor must include synchronization tools for helping concurrency. For example, suppose a process invokes the monitor and, while in the monitor, it must be blocked until some condition is satisfied. A facility is needed by which the process is not only blocked but releases the monitor so that some other process may enter it. Later, when the condition is satisfied and the monitor is again available, the process needs to be resumed and allowed to reenter the monitor at the point of its suspension.

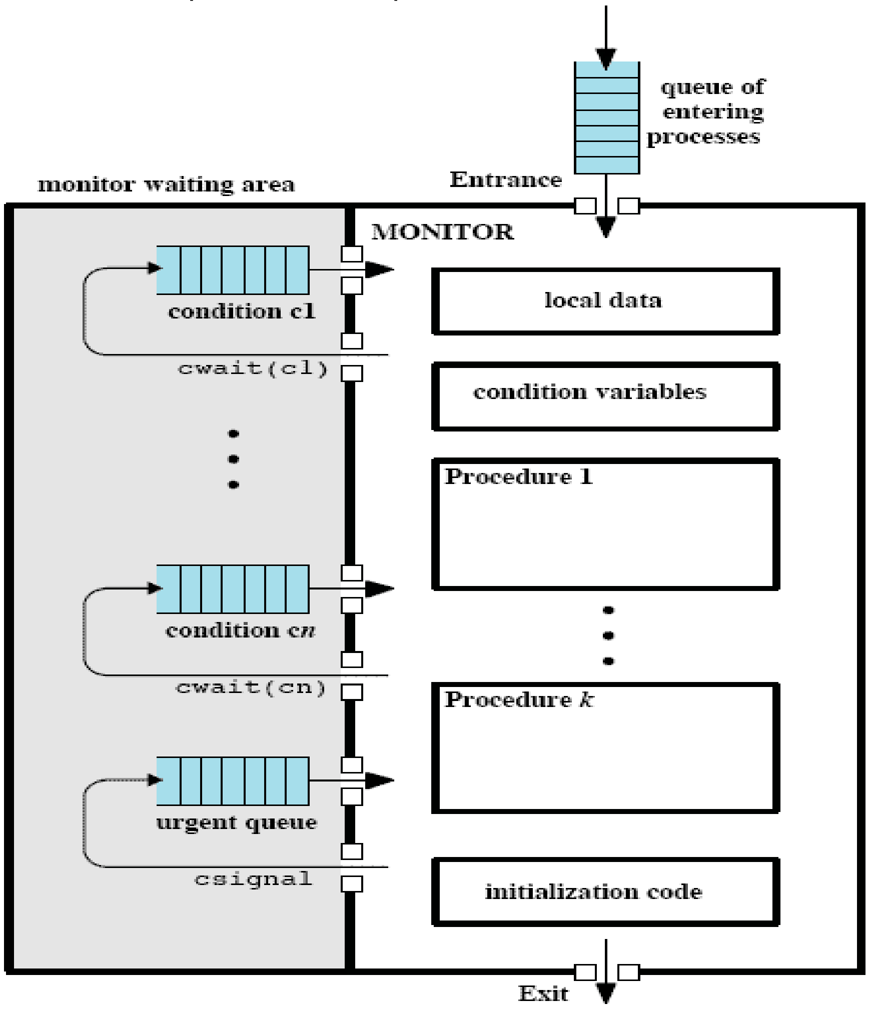


Figure 2.26 Structure of Monitor

A monitor supports synchronization by the use of condition variables that are contained within the monitor and accessible only within the monitor. Condition variables are a special data type in monitors, which are operated on by two functions:

- cwait(c) : Suspend execution of the calling process on condition c . The monitor is now available for use by another process.
- csignal(c) : Resume execution of some process blocked after a *cwait* on the same condition. If there are several such processes, choose one of them; if there is no such process, do nothing.

Figure 2.26 shows the structure of monitor.

2.17 MESSAGE PASSING

When processes interact with one another, two fundamental requirements must be satisfied:

- synchronization
- communication.

Message Passing is one solution to the second requirement. It also works with shared memory *and* with distributed systems. The actual function of message passing is normally provided in the form of a pair of primitives:

```
o send (destination, message)
o receive (source, message)
```

Various design issues related to message passing are:

- Synchronization
- Addressing
- Message Passing
- Queuing Discipline

They are discussed in the following sections.

2.17.1 Synchronization

When a message is being passed from one process to the other, there must be some level of synchronization. That is, wee need to specify what happens to a process after it issues a `send` or `receive` primitive. Three situations may arise now:

- **Blocking send, blocking receive:** Both the sender and receiver are blocked until the message is delivered; this is sometimes referred to as a ***rendezvous***. This combination allows for tight synchronization between processes.
- **Nonblocking send, blocking receive:** The sender may continue, but the receiver is blocked until the requested message arrives. This is probably the most useful combination. It allows a process to send one or more messages to a variety of destinations as quickly as possible. A process that must receive a message before it can do useful work needs to be blocked until such a message arrives.
- **Nonblocking send, nonblocking receive**: Neither party is required to wait.

The non-blocking send is most generic and useful in many situations. Still, it has a problem: an error could lead to a situation in which a process repeatedly generates messages. Because there is no blocking to discipline the process, these messages could consume system resources, including processor time and buffer space. Also, the nonblocking send places the burden on the programmer to determine that a message has been received: Processes must employ reply messages to acknowledge receipt of a message.

For `receive` primitive, blocking seems to be good idea. But, if the message is lost (say, in a distributed system setup) before it is being received, then the process may remain blocked for indefinite time.

2.17.2 Addressing

It is necessary to specify in the `send` primitive that to which process the message is being sent. Similarly, a `receive` primitive may get to know from where it is receiving the message. To maintain this information, two types of addressing are used.

- **Direct Addressing:** Here, the `send` primitive includes the identifier (or address) of the destination process. The `receive` primitive may include the information about the source process. That is, the receiving process has prior knowledge about the sending process. But, in some cases, it is impossible to know the sender. For example, a printer connected to a networked system will not know from where it is receiving the print command before receiving the actual command. Hence, after receiving the message, the receiver can acknowledge the sender.
- **Indirect Addressing:** Here, messages are not sent directly from sender to receiver but rather are sent to a shared data structure consisting of queues that can temporarily hold messages. Such queues are generally referred to as *mailboxes*. Thus, for two processes to communicate, one process sends a message to the appropriate mailbox and the other process picks up the message from the mailbox.

The indirect addressing facilitates decoupling of sender and receiver and hence allows greater flexibility. The relationship between sender and receiver may be (Figure 2.27):

- **one-to-one:** allows a private communications link to be set up between two processes. There won't be any interference.
- **one-to-many:** allows for one sender and multiple receivers; it is useful for applications where a message or some information is to be broadcast to a set of processes.
- **many-to-one:** is useful for client/server interaction; one process provides service to a number of other processes. In this case, the mailbox is often referred to as a port.
- **many-to-many:** A many-to-many relationship allows multiple server processes to provide concurrent service to multiple clients.

The association of mailboxes to processes may be static or dynamic. Usually, one-to-one relationship is static. Ports are statically associated and owned by the receivers. In other two cases, the association will by dynamic and managed by OS.

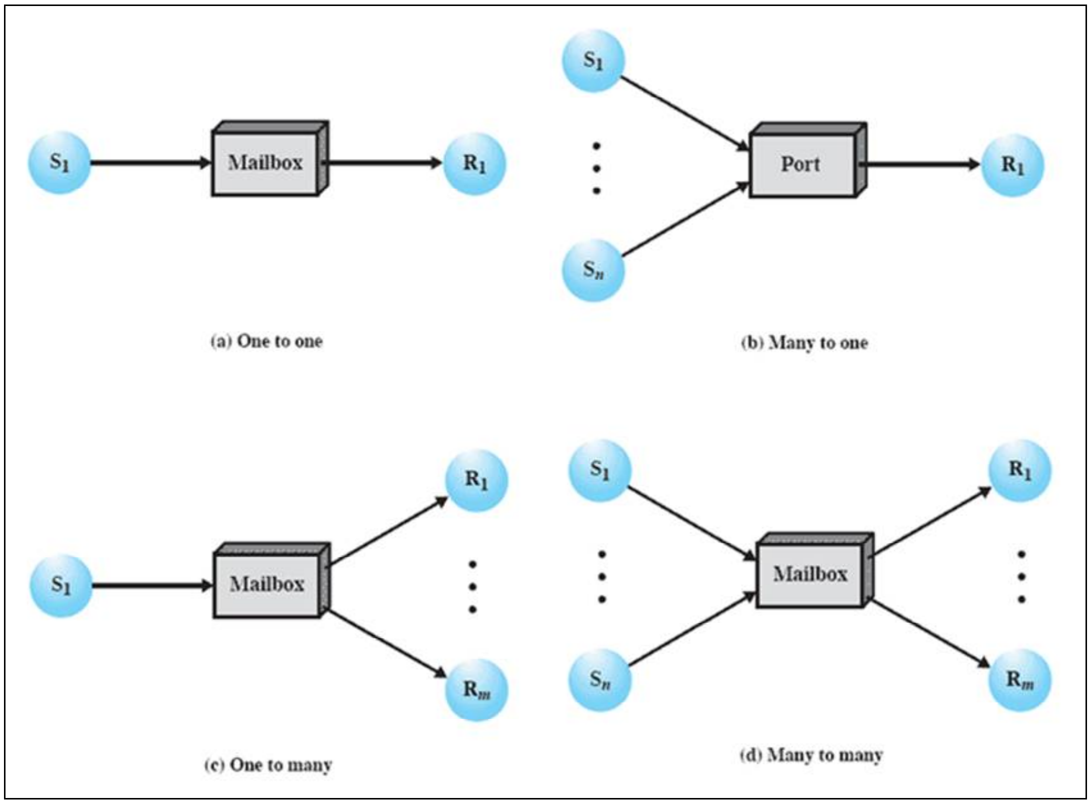


Figure 2.27 Indirect process communication

2.17.3 Message Format

The format of the message depends on the objectives of the messaging facility and whether the facility runs on a single computer or on a distributed system. Figure 2.28 shows a typical message format for operating systems that support variable-length messages.

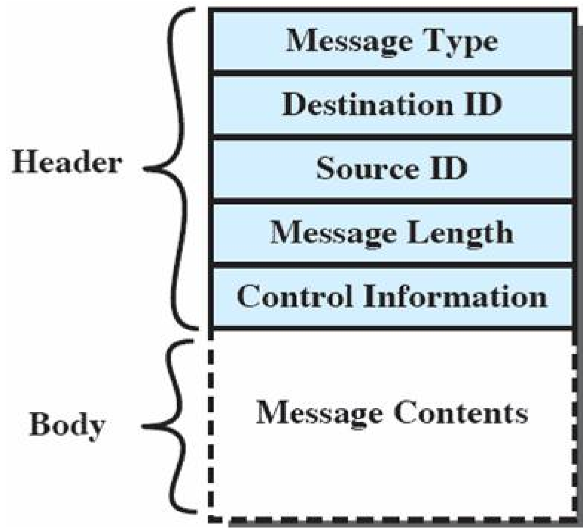


Figure 2.28 General Message format

The message is divided into two parts:

- **header**, which contains information about the message.
    - The header may contain an identification of the source and intended destination of the message, a length field, and a type field to discriminate among various types of messages.
    - additional control information, e.g. pointer field so a linked list of messages can be created; a sequence number, to keep track of the number and order of messages passed between source and destination; and a priority field.
- **body**, which contains the actual contents of the message.

2.17.4 Queuing Discipline

The simplest queuing discipline is first-in-first-out, but this may not be sufficient if some messages are more urgent than others. An alternative is to allow the specifying of message priority, on the basis of message type or by designation by the sender. Another alternative is to allow the receiver to inspect the message queue and select which message to receive next.

2.18 READERS/WRITERS PROBLEM

The readers/writers problem is defined as follows:

There is a data area shared among a number of processes. The data area could be a file, a block of main memory, or a set of processor registers. There are a number of processes that only read the data area (readers) and a number that only write to the data area (writers). The conditions that must be satisfied are as follows:

1. Any number of readers may simultaneously read the file.
2. Only one writer at a time may write to the file.
3. If a writer is writing to the file, no reader may read it.

Thus, we can make out that, a writer wants every other process to be blocked for its execution; whereas, a reader need not block other processes.

The problem can be solved with the help of semaphores. Here, there are two ways: readers having the priority and writers having priority.

2.18.1 Readers Have Priority

Here, once a single reader has begun to access the data area, it is possible for readers to retain control of the data area as long as there is at least one reader in the act of reading. The procedure is explained here –

- The first reader blocks if there is a writer; any other readers who try to enter block on mutex.
- While exiting, the last reader gives signal to a waiting writer.
- When a writer exits, if there is both a reader and writer waiting, which goes next depends on the scheduler.
- If a writer exits and a reader goes next, then all other waiting readers will get a chance to access.

But, in this methodology, writers are subject to starvation.

2.18.2 Writers have Priority

Unlike the previous case, here writers are decision makers. No new readers are allowed access to the data area once at least one writer has declared a desire to write. This is accomplished by forcing every reader to lock and release the semaphore individually. The writers on the other hand don't need to lock it individually. Only the first writer will lock the semaphore and then all subsequent writers can simply use the resource as it gets freed by the previous writer. The very last writer must release the semaphore, thus opening the gate for readers to try reading.

In this methodology, the readers may starve.

As both solutions using semaphore will lead to starvation, another solution using message passing can be adopted. In this case, there is a controller process that has access to the shared data area. Other processes wishing to access the data area send a request message to the controller, are granted access with an "OK" reply message, and indicate completion of access with a "finished" message. The controller is equipped with three mailboxes, one for each type of message (i.e. – a request, an OK, a finished) that it may receive. The controller process services write request messages before read request messages to give writers priority. In addition, mutual exclusion must be enforced.

Few Exercise Problems on CPU Scheduling:

1. Draw the Gantt Chart and compute average waiting time, average turnaround time and throughput using the following algorithms:
(i) FCFS (ii) SJF (preemptive and non-preemptive)

Process	Arrival Time	Burst Time
P1	0	8
P2	1	4
P3	2	9
P4	3	5

2. Draw the Gantt Chart and compute average waiting time, average turnaround time and throughput using the following algorithms:
(i) FCFS (ii) SJF (ii) RR (Quantum= 10ms)

Process	Burst Time
P1	10
P2	29
P3	3
P4	7
P5	12

3. Draw the Gantt Chart and compute average waiting time, average turnaround time and throughput using the following algorithms:
(i) FCFS (ii) SJF (preemptive) (ii) Priority(preemptive) (iv) RR (Q=4)

Process	Arrival Time	Burst Time	Priority
P1	0	8	3
P2	1	4	2
P3	2	9	4
P4	3	5	1

4. Draw the Gantt Chart and compute average waiting time, average turnaround time and throughput using the following algorithms:
(i) FCFS (ii) SJF (ii) Priority (iv) RR (Q=1)

Process	Burst Time	Priority
P1	8	4
P2	2	1
P3	2	3
P4	3	3
P5	5	2