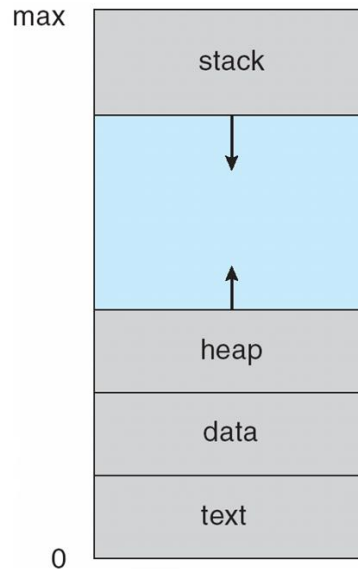# Process Concept

- An operating system executes a variety of programs:
- Batch system – jobs
- Time-shared systems – user programs or tasks
- Textbook uses the terms *job* and *process* almost interchangeably

Process – a program in execution; process execution must progress in sequential fashion

A process includes:

- program counter
- stack
- data section
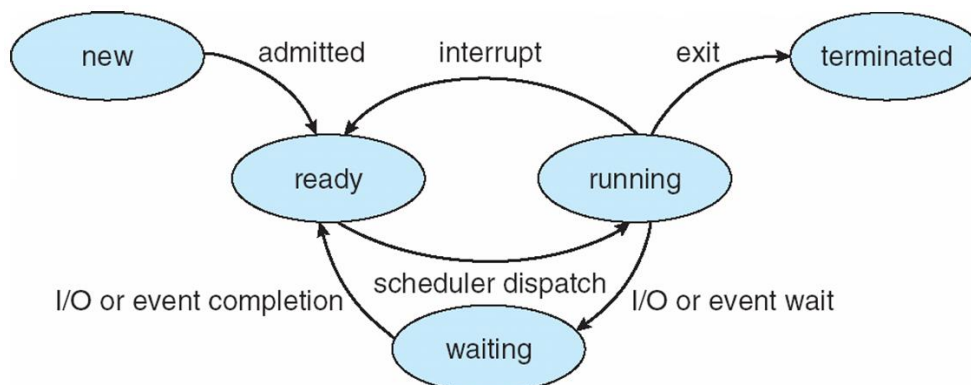
Process in Memory

Process State

As a process executes, it changes *state*

- **new**: The process is being created
- **running**: Instructions are being executed
- **waiting**: The process is waiting for some event to occur
- **ready**: The process is waiting to be assigned to a processor
- **terminated**: The process has finished execution
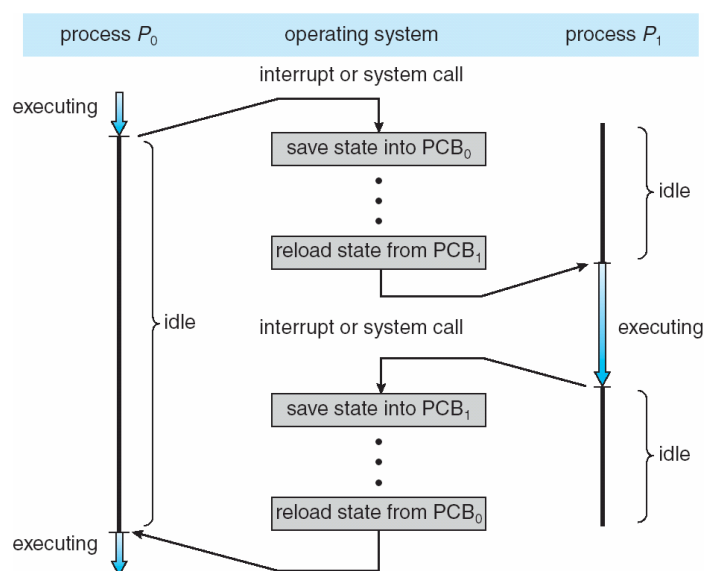
Diagram of Process State

Process Control Block (PCB)

Information associated with each process
- Process state
- Program counter
- CPU registers
- CPU scheduling information
- Memory-management information
- Accounting information
- I/O status information

process state
process number
program counter
registers
memory limits
list of open files
• • •

CPU Switch From Process to Process

process P_0	operating system	process P_1

executing

interrupt or system call

save state into PCB_0

• • •

reload state from PCB_1

idle

idle

executing

interrupt or system call

save state into PCB_1

• • •

reload state from PCB_0

idle

executing

Process Scheduling Queues

- **Job queue** – set of all processes in the system
- **Ready queue** – set of all processes residing in main memory, ready and waiting to execute
- **Device queues** – set of processes waiting for an I/O device
- Processes migrate among the various queues
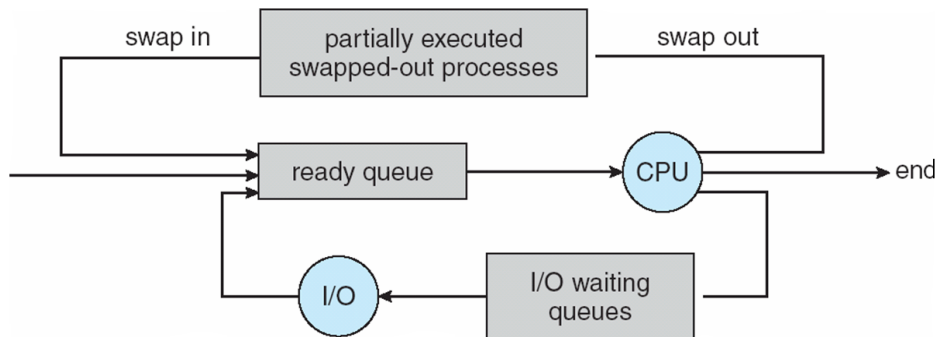
Ready Queue And Various I/O Device Queues
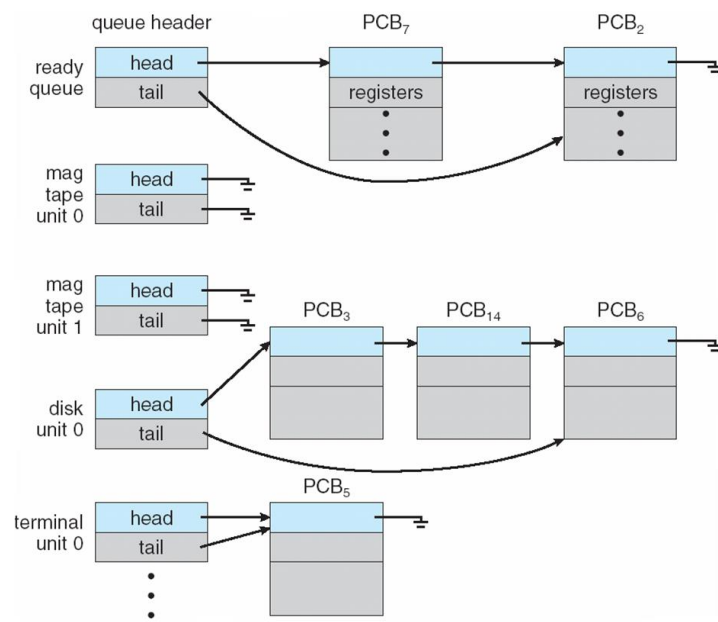
Representation of Process Scheduling
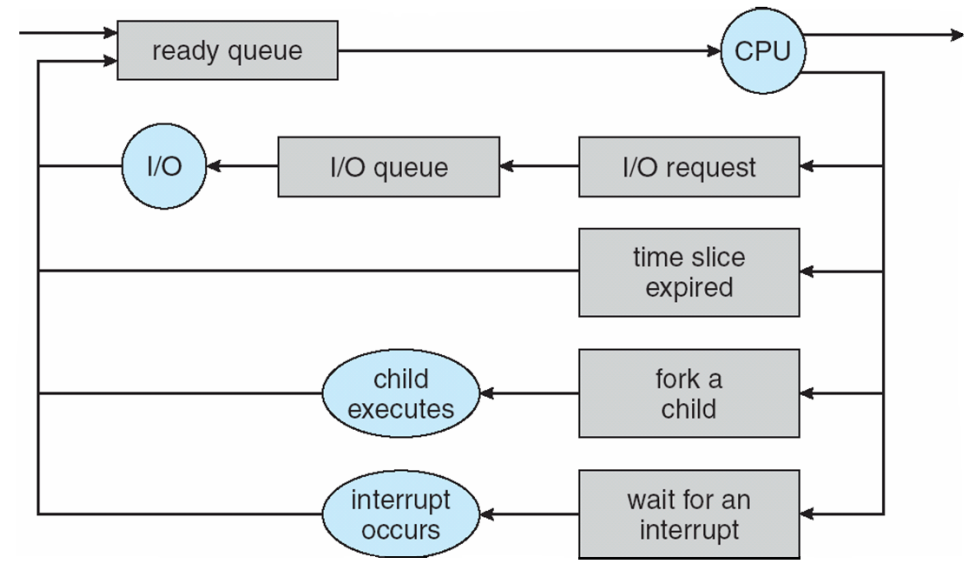
Schedulers

- **Long-term scheduler** (or job scheduler) – selects which processes should be brought into the ready queue
- **Short-term scheduler** (or CPU scheduler) – selects which process should be executed next and allocates CPU

Addition of Medium Term Scheduling

- Short-term scheduler is invoked very frequently (milliseconds) Þ (must be fast)
- Long-term scheduler is invoked very infrequently (seconds, minutes) Þ (may be slow)
- The long-term scheduler controls the *degree of multiprogramming*
- Processes can be described as either:
- **I/O-bound process** – spends more time doing I/O than computations, many short CPU bursts
- **CPU-bound process** – spends more time doing computations; few very long CPU bursts

Context Switch

- When CPU switches to another process, the system must save the state of the old process and load the saved state for the new process via a context switch
- Context of a process represented in the PCB
- Context-switch time is overhead; the system does no useful work while switching
- Time dependent on hardware support

Process Creation

- **Parent** process create **children** processes, which, in turn create other processes, forming a tree of processes
- Generally, process identified and managed via **a process identifier** (**pid**)
- Resource sharing
- Parent and children share all resources
- Children share subset of parent's resources
- Parent and child share no resources
- Execution
- Parent and children execute concurrently
- Parent waits until children terminate

- Address space
- Child duplicate of parent
- Child has a program loaded into it
- UNIX examples
- **fork** system call creates new process
- **exec** system call used after a **fork** to replace the process' memory space with a new program

Process Creation
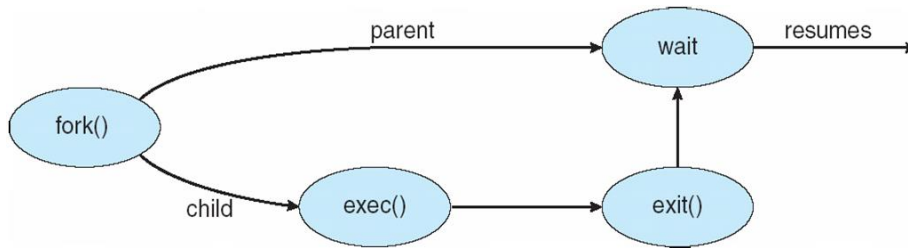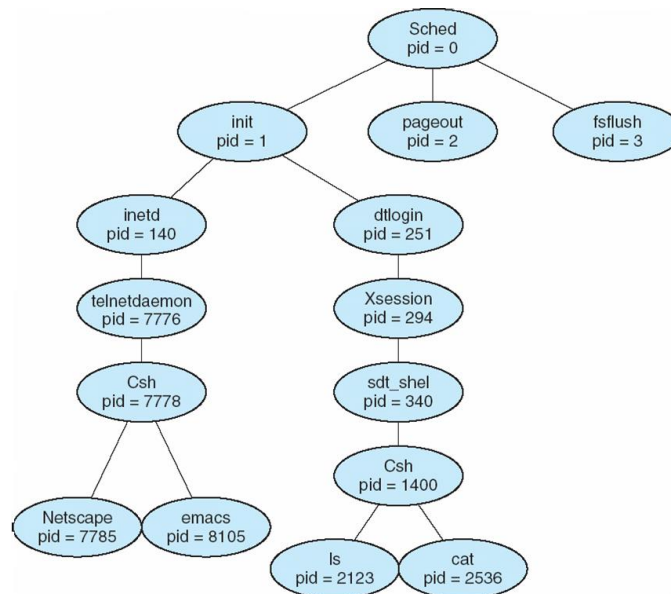

C Program Forking Separate Process

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

**A tree of processes on a typical Solaris**

Process Termination

- Process executes last statement and asks the operating system to delete it (**exit**)
- Output data from child to parent (via **wait**)
- Process' resources are deallocated by operating system
- Parent may terminate execution of children processes (**abort**)
- Child has exceeded allocated resources
- Task assigned to child is no longer required
- If parent is exiting
    - ‣ Some operating system do not allow child to continue if its parent terminates
      All children terminated - **cascading termination**

Interprocess Communication

- Processes within a system may be **independent** or **cooperating**
- Cooperating process can affect or be affected by other processes, including sharing data
- Reasons for cooperating processes:
- Information sharing
- Computation speedup
- Modularity
- Convenience
- Cooperating processes need **interprocess communication** (**IPC**)
- Two models of IPC
- Shared memory
- Message passing

Communications Models

(a)   (b)
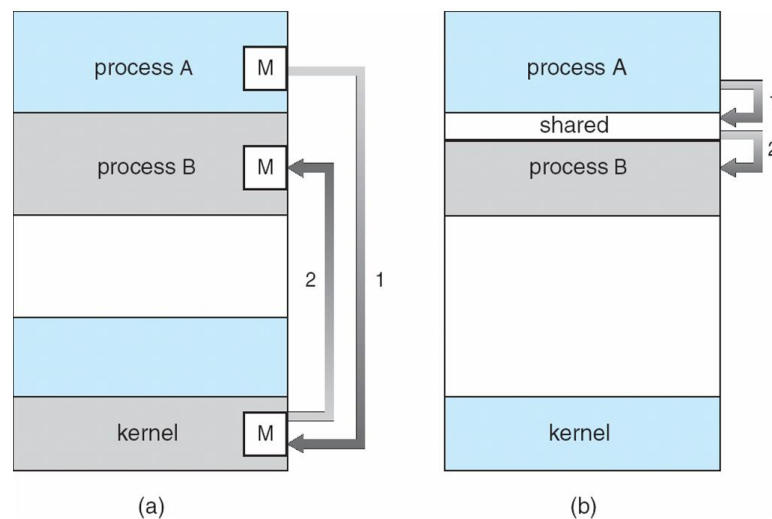
Cooperating Processes
- **Independent** process cannot affect or be affected by the execution of another process
- **Cooperating** process can affect or be affected by the execution of another process

Advantages of process cooperation
- Information sharing
- Computation speed-up
- Modularity
- Convenience

Producer-Consumer Problem
- Paradigm for cooperating processes, *producer* process produces information that is consumed by a *consumer* process
- *unbounded-buffer* places no practical limit on the size of the buffer
- *bounded-buffer* assumes that there is a fixed buffer size

Bounded-Buffer – Shared-Memory Solution

Shared data
```
#define BUFFER_SIZE 10
typedef struct {
        . . .
} item;
item buffer[BUFFER_SIZE];
int in = 0;
int out = 0;
```
Solution is correct, but can only use BUFFER_SIZE-1 elements

Bounded-Buffer – Producer

```
    while (true) {
  /* Produce an item */
      while (((in = (in + 1) % BUFFER SIZE count)  == out)
       ;   /* do nothing -- no free buffers */
      buffer[in] = item;
      in = (in + 1) % BUFFER SIZE;
   }
```

Bounded Buffer – Consumer

```
while (true) {
        while (in == out)
              ; // do nothing -- nothing to consume
        // remove an item from the buffer
        item = buffer[out];
        out = (out + 1) % BUFFER SIZE;
    return item;
    }
```

Interprocess Communication – Message Passing

- Mechanism for processes to communicate and to synchronize their actions
- Message system – processes communicate with each other without resorting to shared variables
- IPC facility provides two operations:
- **send**(*message*) – message size fixed or variable
- **receive**(*message*)
- If *P* and *Q* wish to communicate, they need to:
- establish a *communication link* between them
- exchange messages via send/receive
- Implementation of communication link
- physical (e.g., shared memory, hardware bus)
- logical (e.g., logical properties)

Direct Communication

- Processes must name each other explicitly:
- **send** (*P, message*) – send a message to process P
- **receive**(*Q, message*) – receive a message from process Q
- Properties of communication link
- Links are established automatically
- A link is associated with exactly one pair of communicating processes
- Between each pair there exists exactly one link
- The link may be unidirectional, but is usually bi-directional

Indirect Communication

- Messages are directed and received from mailboxes (also referred to as ports)
- Each mailbox has a unique id
- Processes can communicate only if they share a mailbox
- Properties of communication link
- Link established only if processes share a common mailbox
- A link may be associated with many processes
- Each pair of processes may share several communication links
- Link may be unidirectional or bi-directional
- Operations
- create a new mailbox
- send and receive messages through mailbox
- destroy a mailbox
- Primitives are defined as:
- **send**(*A, message*) – send a message to mailbox A
- **receive**(*A, message*) – receive a message from mailbox A
- Mailbox sharing
- P_1, P_2, and P_3 share mailbox A
- P_1, sends; P_2 and P_3 receive
- Who gets the message?
- Solutions
- Allow a link to be associated with at most two processes
- Allow only one process at a time to execute a receive operation
- Allow the system to select arbitrarily the receiver. Sender is notified who the receiver was.

Synchronization

- Message passing may be either blocking or non-blocking
- **Blocking** is considered **synchronous**
- **Blocking send** has the sender block until the message is received
- **Blocking receive** has the receiver block until a message is available
- **Non-blocking** is considered **asynchronous**
- **Non-blocking** send has the sender send the message and continue
- **Non-blocking** receive has the receiver receive a valid message or null

Buffering

Queue of messages attached to the link; implemented in one of three ways
1.   Zero capacity – 0 messages
Sender must wait for receiver (rendezvous)
2.   Bounded capacity – finite length of *n* messages
Sender must wait if link full
3.   Unbounded capacity – infinite length
Sender never waits

Examples of IPC Systems - POSIX

- POSIX Shared Memory
- Process first creates shared memory segment
- `segment id = shmget(IPC PRIVATE, size, S IRUSR | S IWUSR);`
- Process wanting access to that shared memory must attach to it
- `shared memory = (char *) shmat(id, NULL, 0);`
- Now the process could write to the shared memory
- `printf(shared memory, "Writing to shared memory");`
- When done a process can detach the shared memory from its address space
- `shmdt(shared memory);`

Examples of IPC Systems ˉ Mach

- Mach communication is message based
- Even system calls are messages
- Each task gets two mailboxes at creation- Kernel and Notify
- Only three system calls needed for message transfer
- `msg_send(), msg_receive(), msg_rpc()`
- Mailboxes needed for commuication, created via
- `port_allocate()`

Examples of IPC Systems – Windows XP

- Message-passing centric via local procedure call (LPC) facility
- Only works between processes on the same system
- Uses ports (like mailboxes) to establish and maintain communication channels
- Communication works as follows:
  - ‣ The client opens a handle to the subsystem's connection port object
  - ‣ The client sends a connection request
  - ‣ The server creates two private communication ports and returns the handle to one of them to the client
  - ‣ The client and server use the corresponding port handle to send messages or callbacks and to listen for replies

Local Procedure Calls in Windows XP
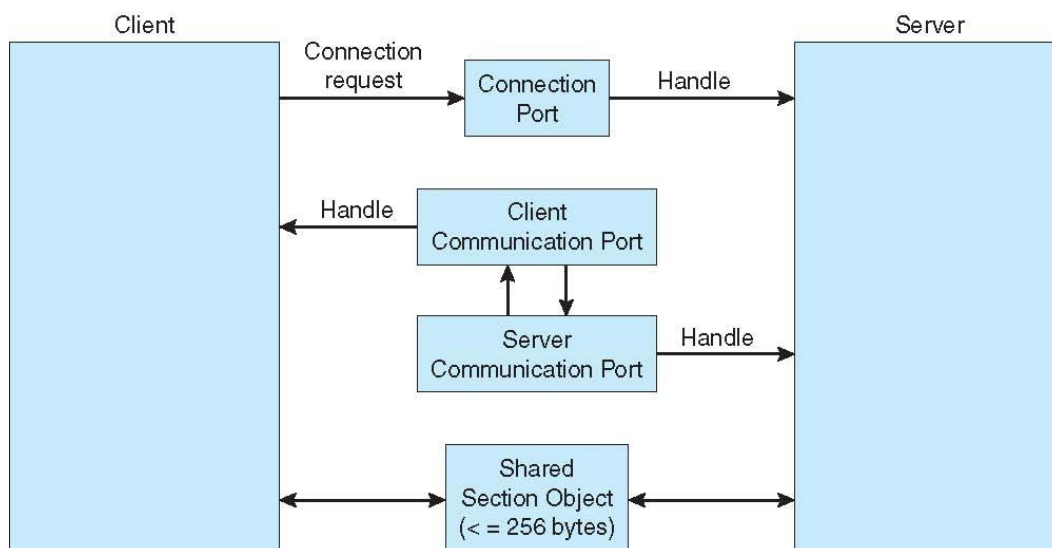
Communications in Client-Server Systems
- Sockets
- Remote Procedure Calls
- Remote Method Invocation (Java)

Sockets
- A socket is defined as an *endpoint for communication*
- Concatenation of IP address and port
- The socket **161.25.19.8:1625** refers to port **1625** on host **161.25.19.8**
- Communication consists between a pair of sockets

Socket Communication
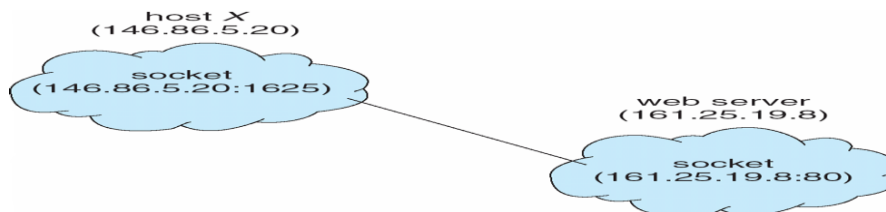
Remote Procedure Calls
- Remote procedure call (RPC) abstracts procedure calls between processes on networked systems
- **Stubs** – client-side proxy for the actual procedure on the server
- The client-side stub locates the server and *marshalls* the parameters
- The server-side stub receives this message, unpacks the marshalled parameters, and peforms the procedure on the server
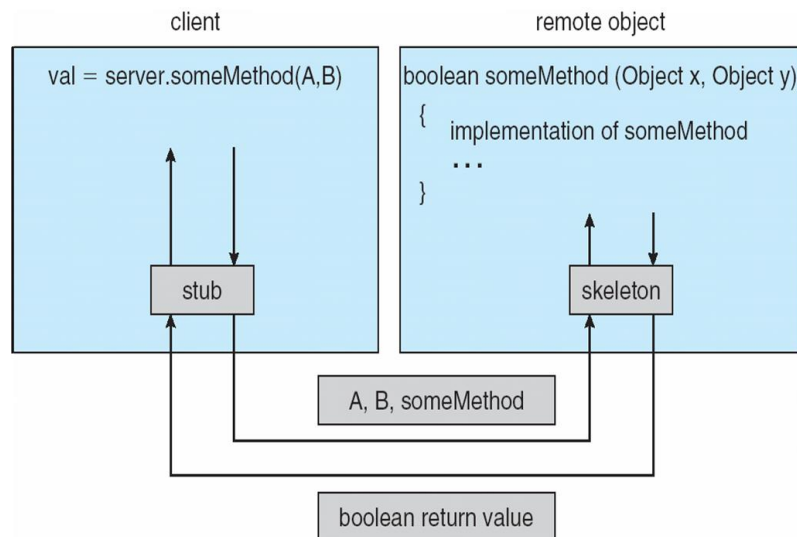
Execution of RPC
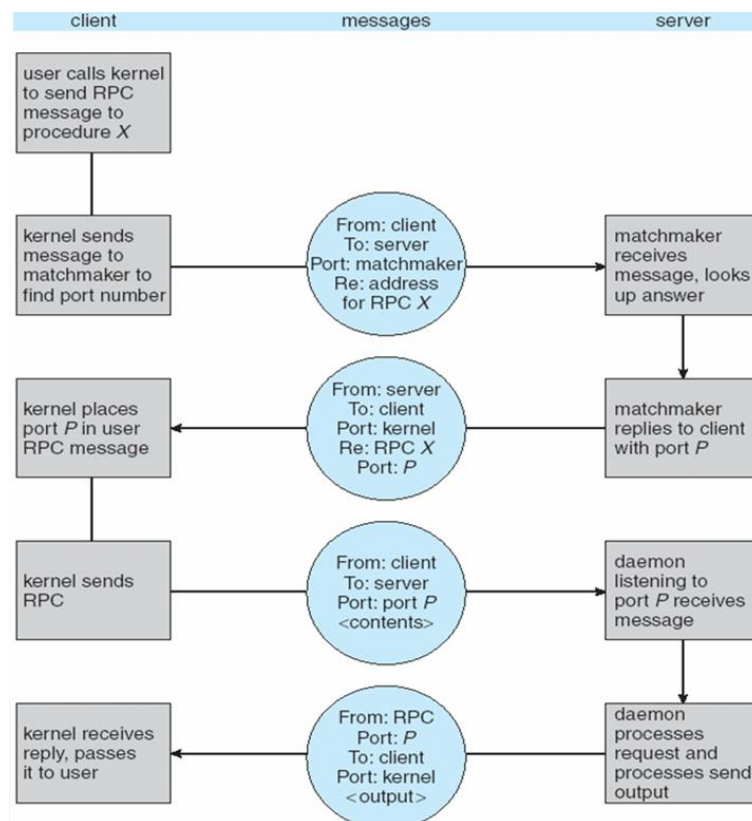
Remote Method Invocation

- Remote Method Invocation (RMI) is a Java mechanism similar to RPCs
- RMI allows a Java program on one machine to invoke a method on a remote object
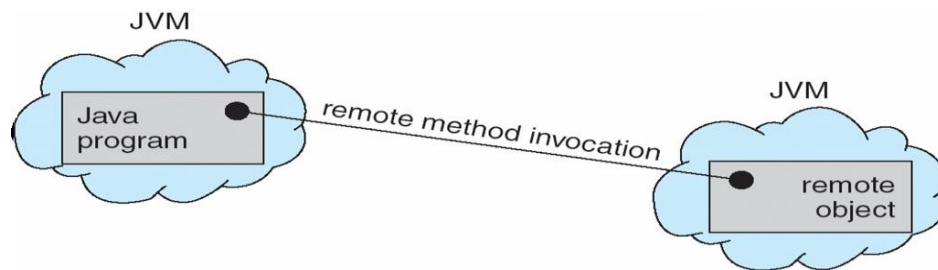

Marshalling Parameters

Threads

- To introduce the notion of a thread — a fundamental unit of CPU utilization that forms the basis of multithreaded computer systems
- To discuss the APIs for the Pthreads, Win32, and Java thread libraries
- To examine issues related to multithreaded programming

Single and Multithreaded Processes

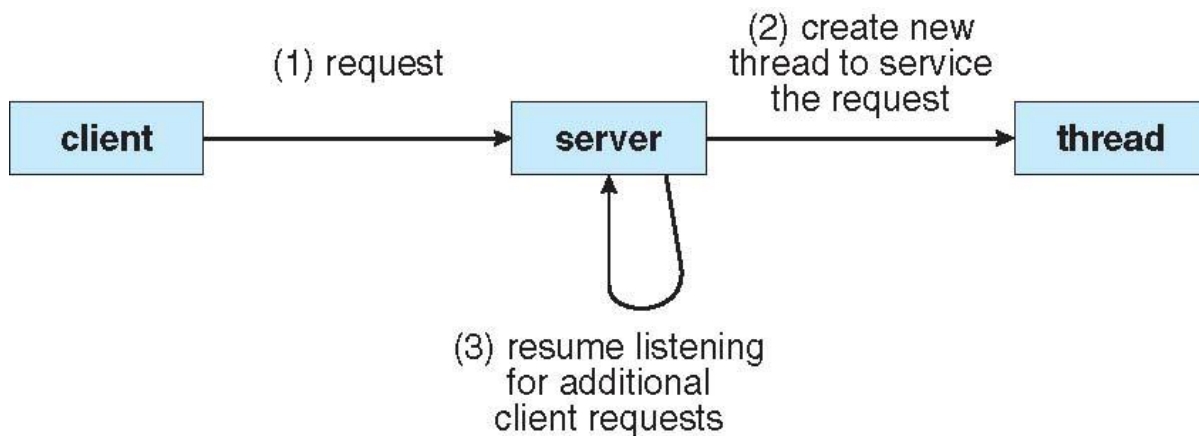single-threaded process   multithreaded process
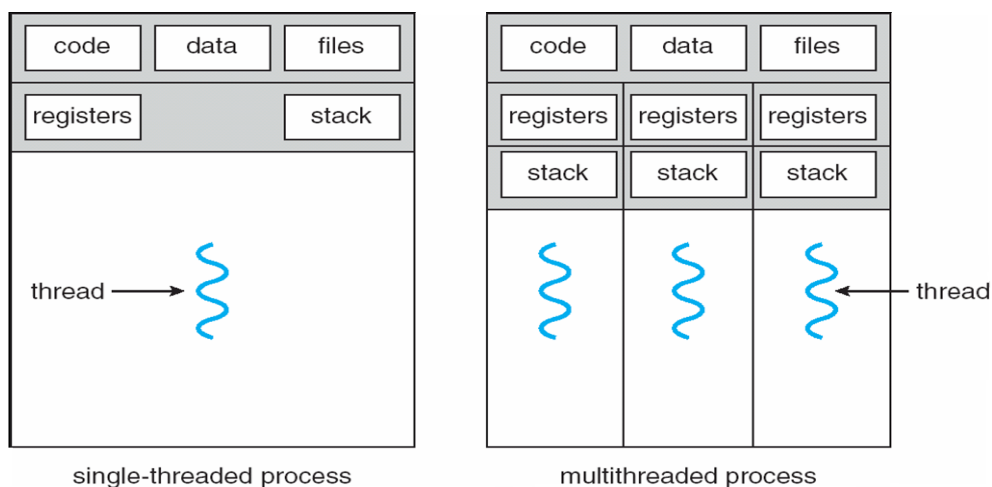
Benefits
- Responsiveness
- Resource Sharing
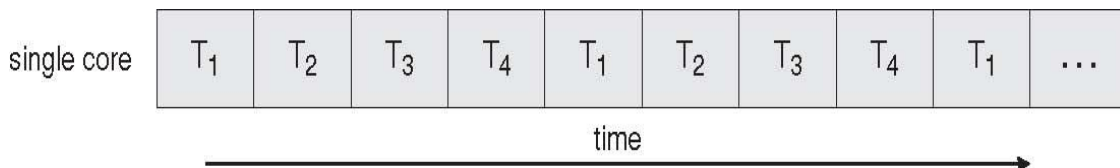- Economy
- Scalability

Multicore Programming
Multicore systems putting pressure on programmers, challenges include
- **Dividing activities**
- **Balance**
- **Data splitting**
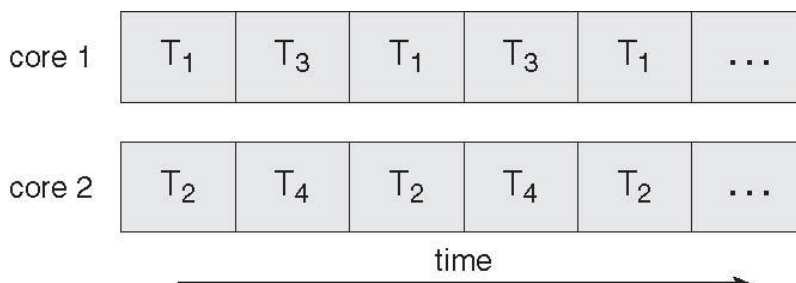- **Data dependency**
- **Testing and debugging**

Multithreaded Server Architecture

Concurrent Execution on a Single-core System

Parallel Execution on a Multicore System

User Threads
- Thread management done by user-level threads library. Three primary thread libraries:
- POSIX Pthreads. Win32 threads
- Java threads

Kernel Threads
Supported by the Kernel
Examples
- Windows XP/2000
- Solaris
- Linux
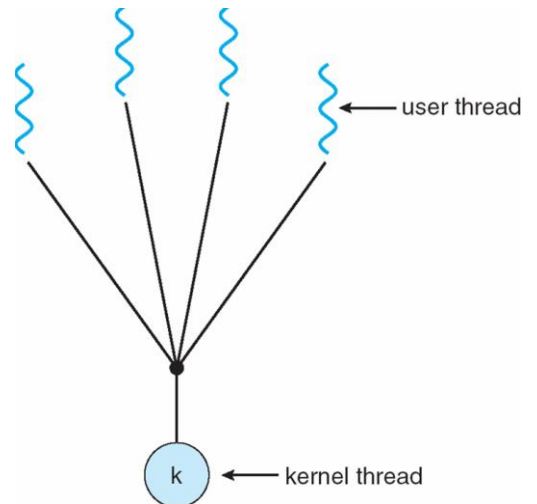- Tru64 UNIX
- Mac OS X

Multithreading Models
- Many-to-One
- One-to-One
- Many-to-Many

Many-to-One
Many user-level threads mapped to single kernel thread
Examples:
- Solaris Green Threads
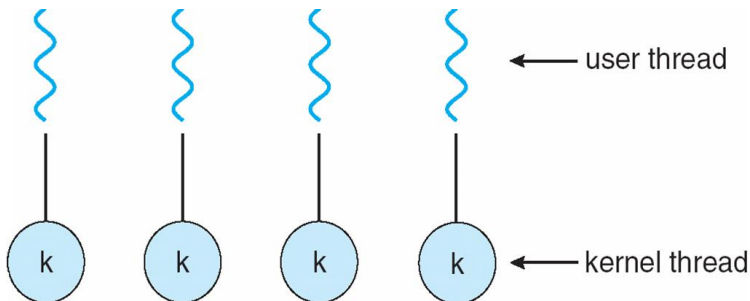- GNU Portable Threads

One-to-One
Each user-level thread maps to kernel thread
Examples
Windows NT/XP/2000
Linux
Solaris 9 and later

Many-to-Many Model
- Allows many user level threads to be mapped to many kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Solaris prior to version 9

Windows NT/2000 with the *ThreadFiber* package
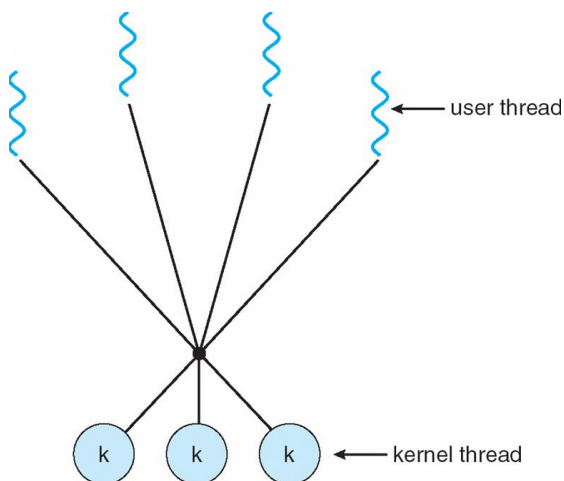
Two-level Model
Similar to M:M, except that it allows a user thread to be **bound** to kernel thread
Examples
- IRIX
- HP-UX
- Tru64 UNIX
- Solaris 8 and earlier
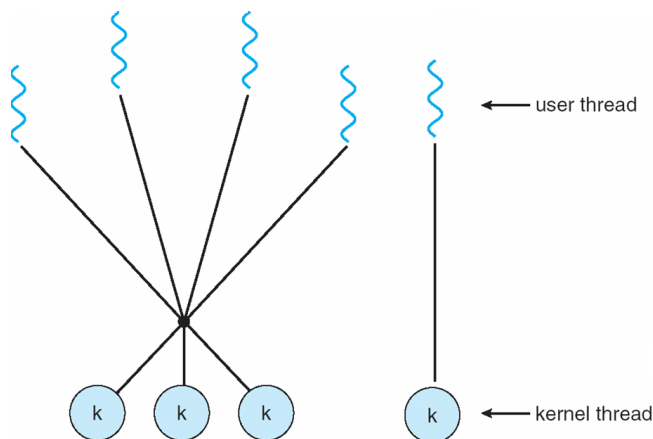
Thread Libraries
- Thread library provides programmer with API for creating and managing threads
- Two primary ways of implementing
- Library entirely in user space
- Kernel-level library supported by the OS

Pthreads
- May be provided either as user-level or kernel-level
- A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization

- API specifies behavior of the thread library, implementation is up to development of the library
- Common in UNIX operating systems (Solaris, Linux, Mac OS X)

Java Threads

- Java threads are managed by the JVM
- Typically implemented using the threads model provided by underlying OS
- Java threads may be created by:1Extending Thread class
- Implementing the Runnable interface

Threading Issues

- Semantics of **fork()** and **exec()** system calls
- Thread cancellation of target thread
- Asynchronous or deferred
- Signal handling
- Thread pools
- Thread-specific data
- Scheduler activations

Thread Cancellation

- Terminating a thread before it has finished
- Two general approaches:
- **Asynchronous cancellation** terminates the target thread immediately
- **Deferred cancellation** allows the target thread to periodically check if it should be cancelled

Signal Handling

- Signals are used in UNIX systems to notify a process that a particular event has occurred
- A signal handler is used to process signals
- 1.Signal is generated by particular event
- 2.Signal is delivered to a process
- 3.Signal is handled
- Options:
- Deliver the signal to the thread to which the signal applies
- Deliver the signal to every thread in the process
- Deliver the signal to certain threads in the process

- Assign a specific threa to receive all signals for the process

Thread Pools

- Create a number of threads in a pool where they await work
- Advantages:
- Usually slightly faster to service a request with an existing thread than create a new thread
- Allows the number of threads in the application(s) to be bound to the size of the pool

Thread Specific Data
- Allows each thread to have its own copy of data
- Useful when you do not have control over the thread creation process (i.e., when using a thread pool)

Scheduler Activations
- Both M:M and Two-level models require communication to maintain the appropriate number of kernel threads allocated to the application
- Scheduler activations provide upcalls - a communication mechanism from the kernel to the thread library
- This communication allows an application to maintain the correct number kernel threads

Windows XP Threads
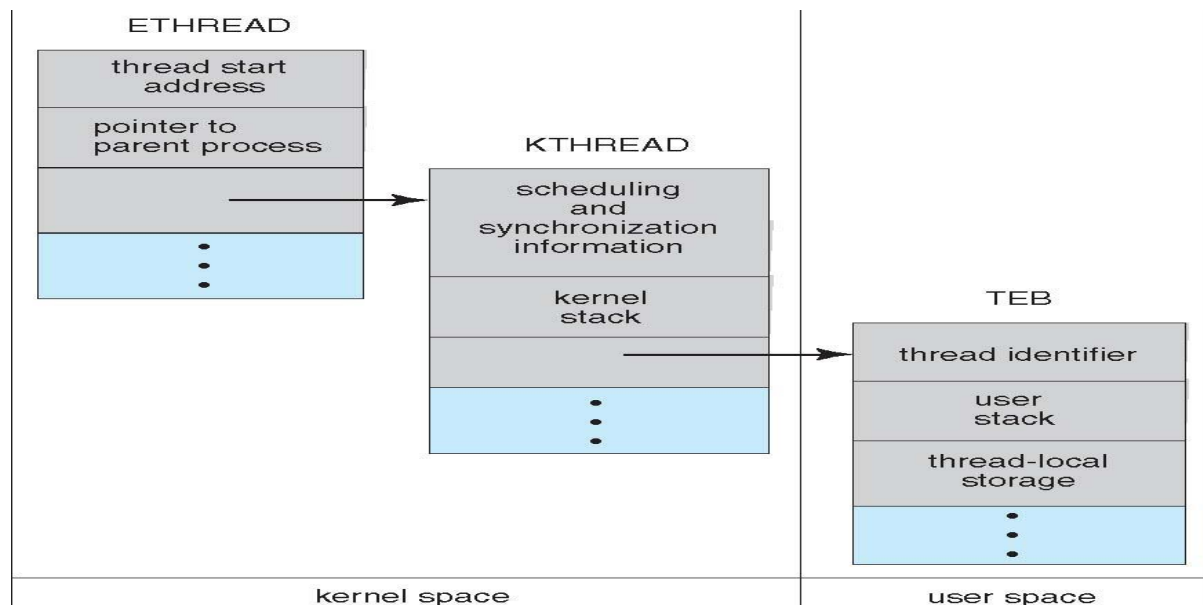
Implements the one-to-one mapping, kernel-level
- Each thread contains
- A thread id
- Register set
- Separate user and kernel stacks
- Private data storage area
- The register set, stacks, and private storage area are known as the context of the threads
- The primary data structures of a thread include:
- ETHREAD (executive thread block)
- KTHREAD (kernel thread block)

- TEB (thread environment block)

Linux Threads

flag	meaning
CLONE_FS	File-system information is shared.
CLONE_VM	The same memory space is shared.
CLONE_SIGHAND	Signal handlers are shared.
CLONE_FILES	The set of open files is shared.

- Linux refers to them as *tasks* rather than *threads*
- Thread creation is done through **clone()** system call
- **clone()** allows a child task to share the address space of the parent task (process)

CPU Scheduling

- To introduce CPU scheduling, which is the basis for multiprogrammed operating systems
- To describe various CPU-scheduling algorithms
- To discuss evaluation criteria for selecting a CPU-scheduling algorithm for a particular system
- Maximum CPU utilization obtained with multiprogramming
- CPU–I/O Burst Cycle – Process execution consists of a *cycle* of CPU execution and I/O wait
- **CPU burst** distribution

Histogram of CPU-burst Times
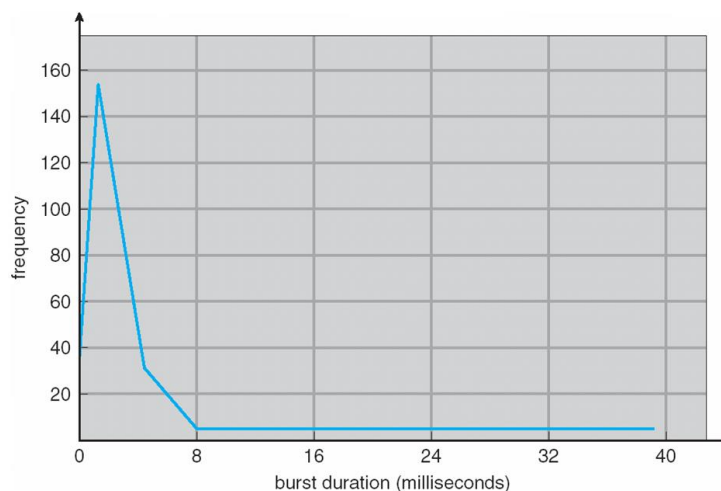
Alternating Sequence of CPU And I/O Bursts
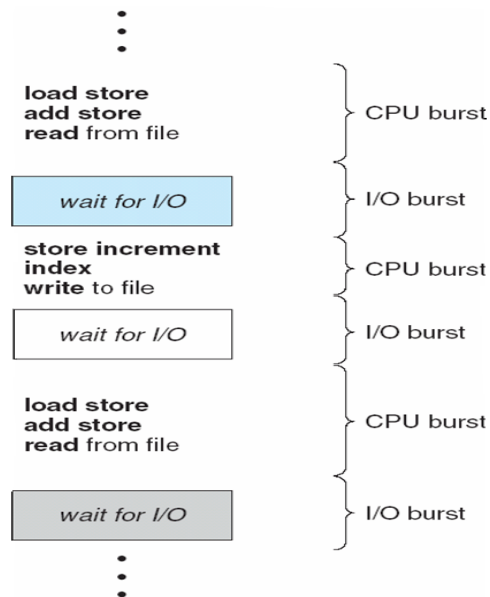
CPU Scheduler
Selects from among the processes in memory that are ready to execute, and allocates the CPU to one of them
CPU scheduling decisions may take place when a process:
1.   Switches from running to waiting state
2.   Switches from running to ready state
3.   Switches from waiting to ready
4.   Terminates
Scheduling under 1 and 4 is **nonpreemptive**
All other scheduling is **preemptive**

Dispatcher
- Dispatcher module gives control of the CPU to the process selected by the short-term scheduler; this involves:
- switching context
- switching to user mode
- jumping to the proper location in the user program to restart that program
- **Dispatch latency** – time it takes for the dispatcher to stop one process and start another running

Scheduling Criteria
- **CPU utilization** – keep the CPU as busy as possible
- **Throughput** – # of processes that complete their execution per time unit
- **Turnaround time** – amount of time to execute a particular process
- **Waiting time** – amount of time a process has been waiting in the ready queue

- **Response time** – amount of time it takes from when a request was submitted until the first response is produced, not output (for time-sharing environment)
- Max CPU utilization
- Max throughput
- Min turnaround time
- Min waiting time
- Min response time

First-Come, First-Served (FCFS) Scheduling

Process	Burst Time
P_1	24
P_2	3
P_3	3

Suppose that the processes arrive in the order: P_1 , P_2 , P_3
The Gantt Chart for the schedule is:

Waiting time for P_1 = 0; P_2 = 24; P_3 = 27
Average waiting time: (0 + 24 + 27)/3 = 17
Suppose that the processes arrive in the order

$$P_2 , P_3 , P_1$$

The Gantt chart for the schedule is:nnnnWaiting time for P_1 = 6; P_2 = 0; P_3 = 3nAverage waiting time: (6 + 0 + 3)/3 = 3
Much better than previous case
Convoy effect short process behind long process

Shortest-Job-First (SJF) Scheduling

- Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time
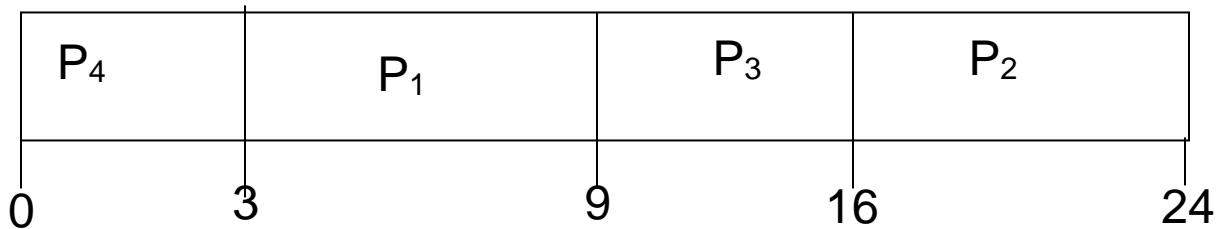- SJF is optimal – gives minimum average waiting time for a given set of processes

The difficulty is knowing

Process	Arrival Time	Burst Time
P_1	0.0	6
P_2	2.0	8
P_3	4.0	7
P_4	5.0	3

SJF scheduling chart

average waiting time = (3 + 16 + 9 + 0) / 4 = 7the length of the next CPU request

P_4	P_1	P_3	P_2

0   3   9   16   24

1. $t_n =$ actual length of nth CPU burst

2. $\tau_{n+1} =$ predicted value for the next CPU burst

3. $\alpha, 0 \leq \alpha \leq 1$

4. Define :

Determining Length of Next CPU Burst
- Can only estimate the length
- Can be done by using the length of previous CPU bursts, using exponential averaging

Prediction of the Length of the Next CPU Burst

CPU burst (t_i)		6	4	6	4	13	13	13	. . .
"guess" (τ_i)	10	8	6	6	5	9	11	12	. . .
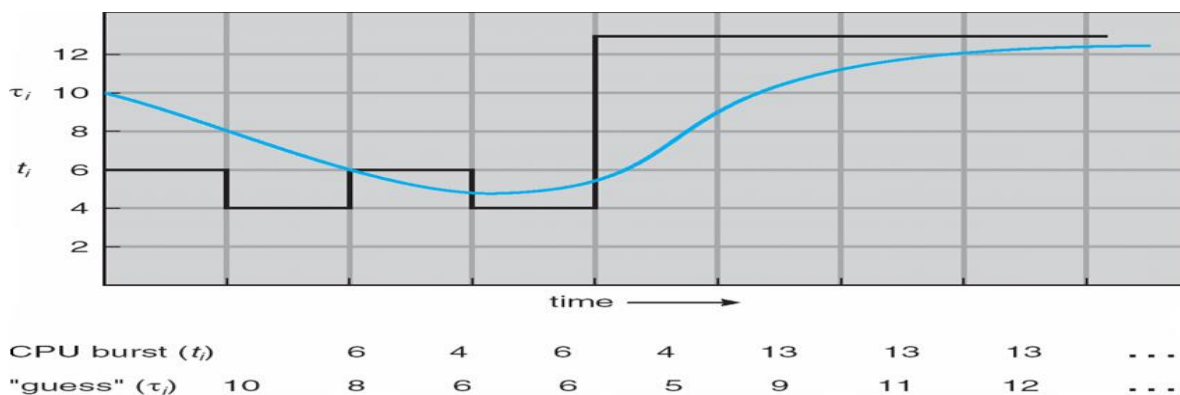
Examples of Exponential Averaging

$a = 0$

$t_{n+1} = t_n$

Recent history does not count

$a = 1$

$t_{n+1} = a\ t_n$

Only the actual last CPU burst counts

If we expand the formula, we get:

$t_{n+1} = a\ t_n + (1 - a)a\ t_n - 1 + \dots$

$\qquad + (1 - a)^j a\ t_{n-j} + \dots$

$\qquad + (1 - a)^{n+1} t_0$

Since both a and $(1 - a)$ are less than or equal to 1, each successive term has less weight than its predecessor

Priority Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority (smallest integer ° highest priority)
- Preemptive
- nonpreemptive
- SJF is a priority scheduling where priority is the predicted next CPU burst time
- Problem ° **Starvation** – low priority processes may never execute
- Solution ° **Aging** – as time progresses increase the priority of the process

Round Robin (RR)

- Each process gets a small unit of CPU time (*time quantum*), usually 10-100 milliseconds. After this time has elapsed, the process is preempted and added to the end of the ready queue.
- If there are *n* processes in the ready queue and the time quantum is *q*, then each process gets $1/n$ of the CPU time in chunks of at most *q* time units at once. No process waits more than $(n\text{-}1)q$ time units.
- Performance
- *q* large Þ FIFO
- *q* small Þ *q* must be large with respect to context switch, otherwise overhead is too high

Example of RR with Time Quantum = 4

Process	Burst Time
P_1	24
P_2	3
P_3	3

The Gantt chart is:

P_1	P_2	P_3	P_1	P_1	P_1	P_1	P_1

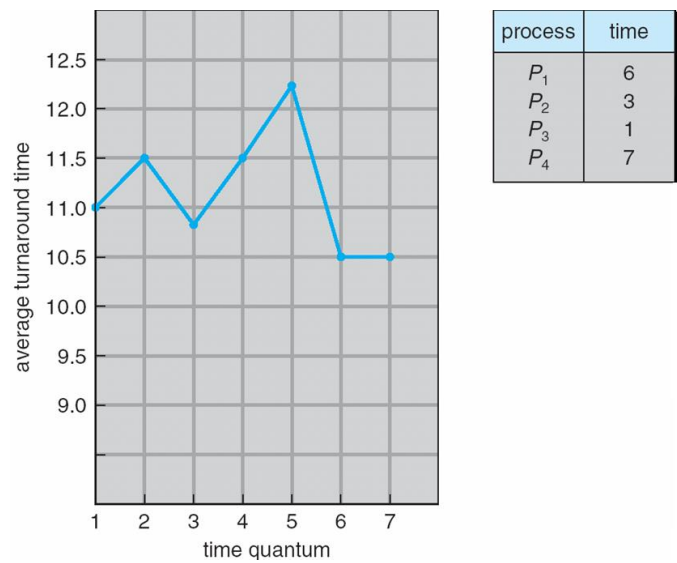0   4   7   10   14   18   22   26   30
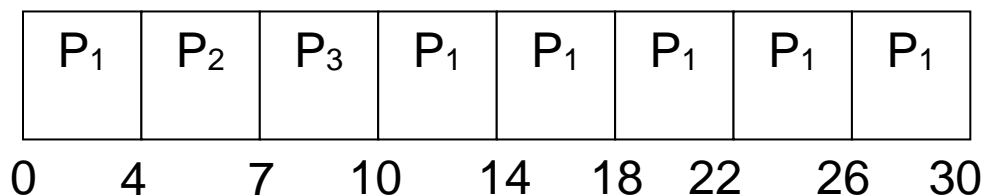
Typically, higher average turnaround than SJF, but better *response*

Time Quantum and Context Switch Time

process time = 10		quantum	context switches
0 ——————————— 10		12	0
0 ————— 6 ————— 10		6	1
0 1 2 3 4 5 6 7 8 9 10		1	9
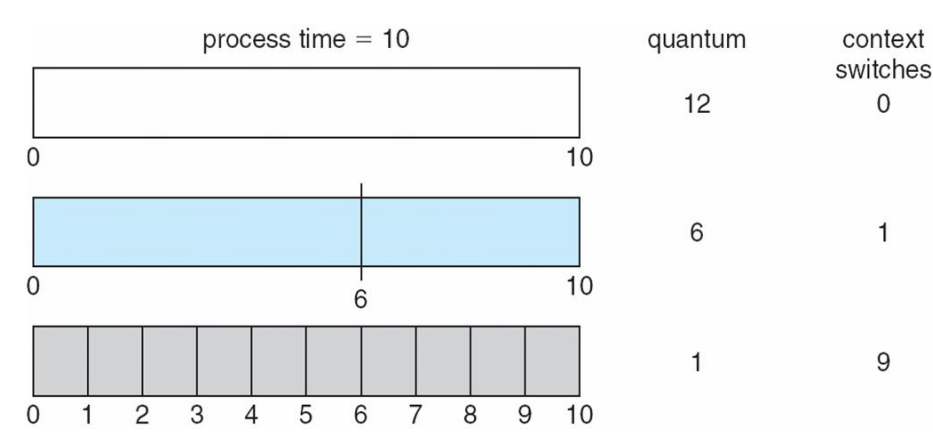
Turnaround Time Varies With The Time Quantum

| process	time
P_1	6
P_2	3
P_3	1
P_4	7

Multilevel Queue

- Ready queue is partitioned into separate queues:
  foreground (interactive)
  background (batch)
- Each queue has its own scheduling algorithm
- foreground – RR
- background – FCFS
- Scheduling must be done between the queues
- Fixed priority scheduling; (i.e., serve all from foreground then from background). Possibility of starvation.
- Time slice – each queue gets a certain amount of CPU time which it can schedule amongst its processes; i.e., 80% to foreground in RR

20% to background in FCFS

Multilevel Queue Scheduling
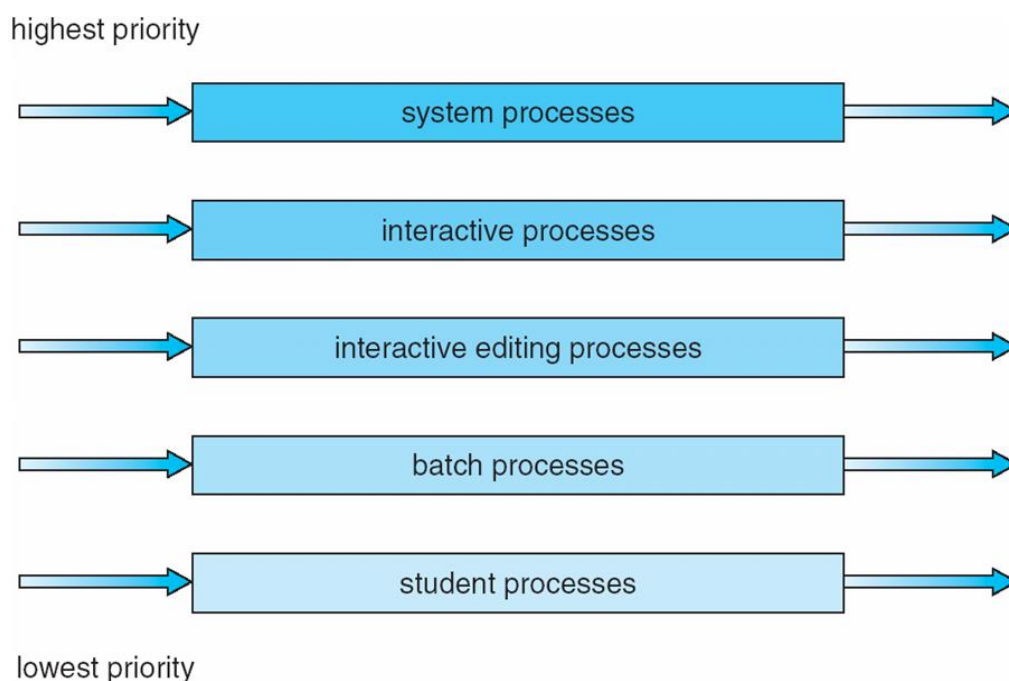
Multilevel Feedback Queue

- A process can move between the various queues; aging can be implemented this way
- 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

Example of Multilevel Feedback Queue

Three queues:
- Q_0 – RR with time quantum 8 milliseconds
- Q_1 – RR time quantum 16 milliseconds
- Q_2 – FCFS
- Scheduling
- A new job enters queue Q_0 which is served FCFS. When it gains CPU, job receives 8 milliseconds. If it does not finish in 8 milliseconds, job is moved to queue Q_1.
- At Q_1 job is again served FCFS and receives 16 additional milliseconds. If it still does not complete, it is preempted and moved to queue Q_2.

Multilevel Feedback Queues
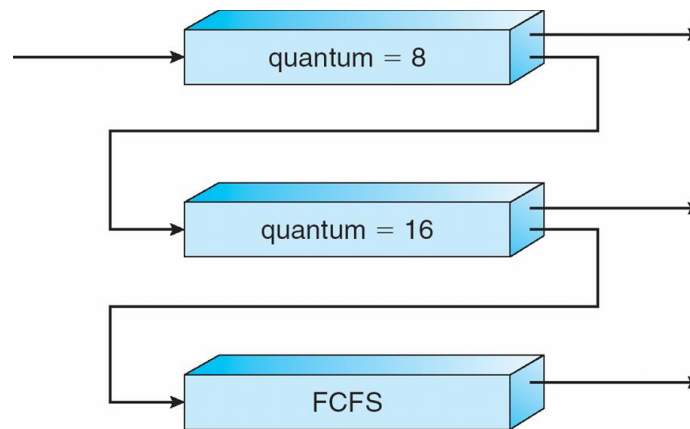
Thread Scheduling
- Distinction between user-level and kernel-level threads
- Many-to-one and many-to-many models, thread library schedules user-level threads to run on LWP
- Known as **process-contention scope (PCS)** since scheduling competition is within the process
- Kernel thread scheduled onto available CPU is **system-contention scope (SCS)** – competition among all threads in system

Pthread Scheduling
- API allows specifying either PCS or SCS during thread creation
- PTHREAD SCOPE PROCESS schedules threads using PCS scheduling
- PTHREAD SCOPE SYSTEM schedules threads using SCS scheduling.

Pthread Scheduling API

```
#include <pthread.h>
#include <stdio.h>
#define NUM THREADS 5
int main(int argc, char *argv[])
{
     int i;  pthread t tid[NUM THREADS];
    pthread attr t attr;
    /* get the default attributes */
    pthread attr init(&attr);
    /* set the scheduling algorithm to PROCESS or SYSTEM */
    pthread attr setscope(&attr, PTHREAD SCOPE SYSTEM);
    /* set the scheduling policy - FIFO, RT, or OTHER */
    pthread attr setschedpolicy(&attr, SCHED OTHER);
    /* create the threads */
    for (i = 0; i < NUM THREADS; i++)
        pthread create(&tid[i],&attr,runner,NULL);
/* now join on each thread */
    for (i = 0; i < NUM THREADS; i++)
        pthread join(tid[i], NULL);
}
 /* Each thread will begin control in this function */
void *runner(void *param)
{
    printf("I am a thread\n");
    pthread exit(0);
}
```

Multiple-Processor Scheduling
- CPU scheduling more complex when multiple CPUs are available
- **Homogeneous processors** within a multiprocessor
- **Asymmetric multiprocessing** – only one processor accesses the system data structures, alleviating the need for data sharing
- **Symmetric multiprocessing (SMP)** – each processor is self-scheduling, all processes in common ready queue, or each has its own private queue of ready processes
- **Processor affinity** – process has affinity for processor on which it is currently running
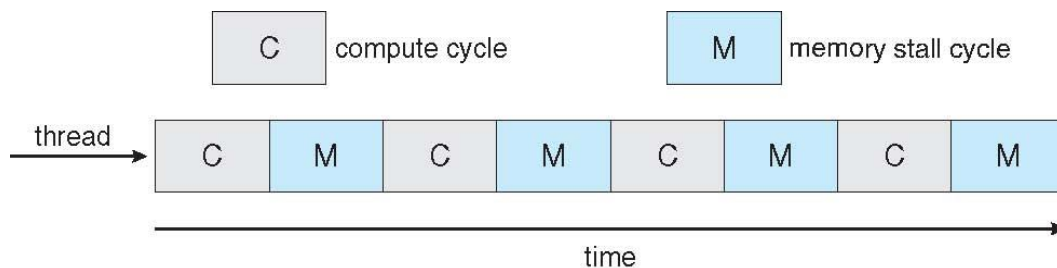- **soft affinity**
- **hard affinity**

NUMA and CPU Scheduling
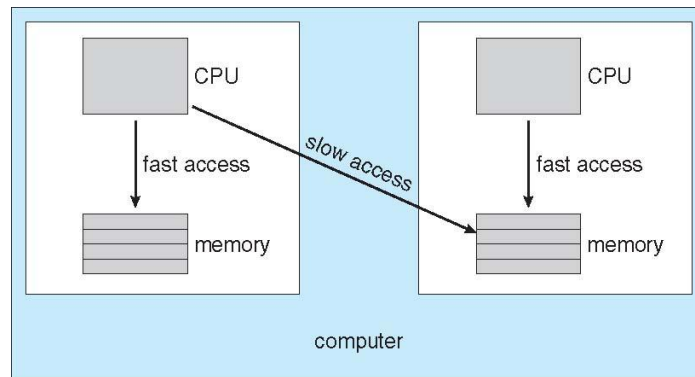
Multicore Processors
- Recent trend to place multiple processor cores on same physical chip
- Faster and consume less power
- Multiple threads per core also growing
- Takes advantage of memory stall to make progress on another thread while memory retrieve happens
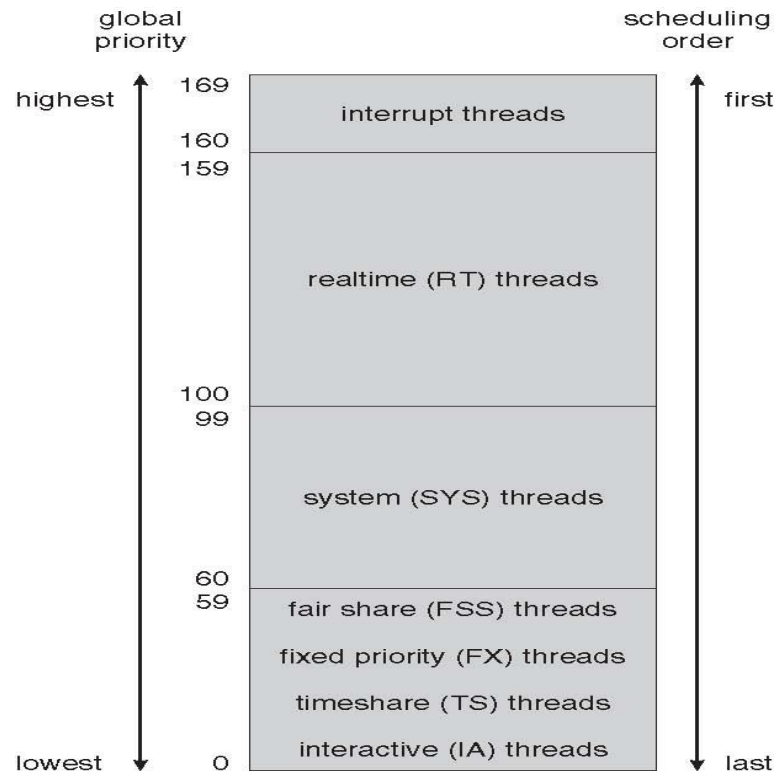
Multithreaded Multicore System

Operating System Examples
- Solaris scheduling
- Windows XP scheduling
- Linux scheduling

Solaris Dispatch Table

priority	time quantum	time quantum expired	return from sleep
0	200	0	50
5	200	0	50
10	160	0	51
15	160	5	51
20	120	10	52
25	120	15	52
30	80	20	53
35	80	25	54
40	40	30	55
45	40	35	56
50	40	40	58
55	40	45	58
59	20	49	59

Solaris Scheduling

Windows XP Priorities

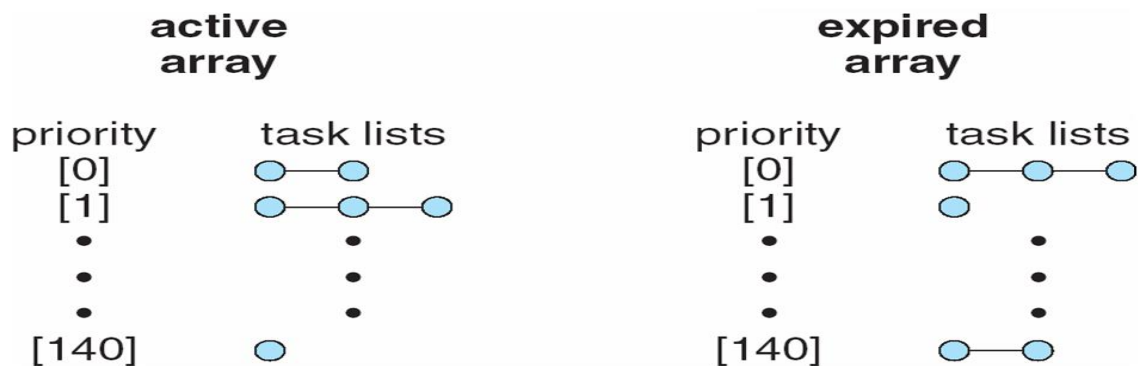|	real-time	high	above normal	normal	below normal	idle priority
time-critical	31	15	15	15	15	15
highest	26	15	12	10	8	6
above normal	25	14	11	9	7	5
normal	24	13	10	8	6	4
below normal	23	12	9	7	5	3
lowest	22	11	8	6	4	2
idle	16	1	1	1	1	1

Linux Scheduling

- Constant order $O(1)$ scheduling time
- Two priority ranges: time-sharing and real-time
- **Real-time** range from 0 to 99 and **nice** value from 100 to 140

Priorities and Time-slice length

numeric priority	relative priority		time quantum
0	highest	real-time tasks	200 ms
•			
•			
•			
99			
100			
•		other tasks	
•			
•			
140	lowest		10 ms
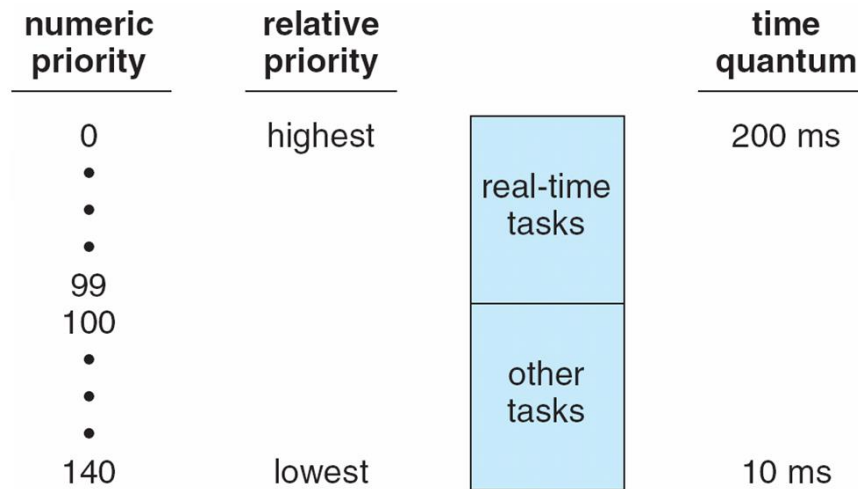
List of Tasks Indexed According to Priorities

Algorithm Evaluation
- Deterministic modeling – takes a particular predetermined workload and defines the performance of each algorithm for that workload
- Queueing models
- Implementation

Evaluation of CPU schedulers k