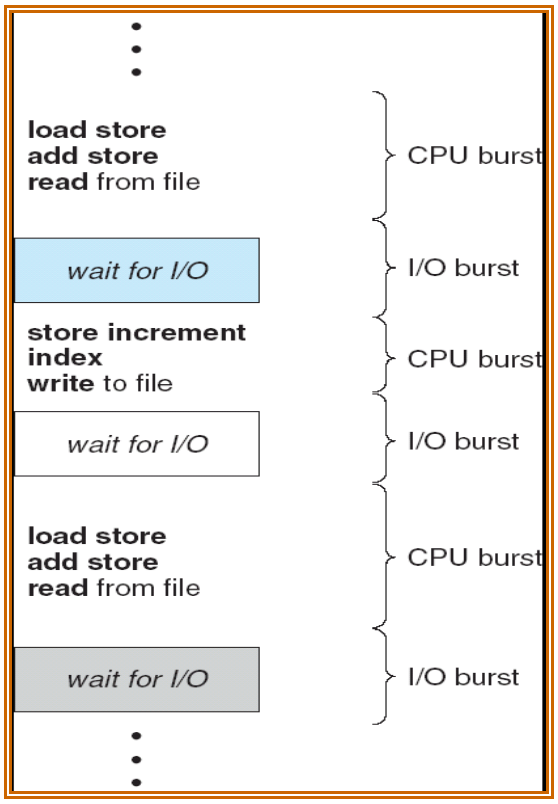
Unit II Process Scheduling and Synchronization

- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Multiple-Processor Scheduling
- Real-Time Scheduling
- Thread Scheduling
- Operating Systems Examples
- Java Thread Scheduling
- Algorithm Evaluation

CPU Scheduling

- 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

Alternating Sequence of CPU And I/O Bursts



CPU Scheduler

1) Selects from among the processes in memory that are ready to execute, and allocates the CPU to one of them
2) 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
3) Scheduling under 1 and 4 is *nonpreemptive*
4) All other scheduling is *preemptive*

Dispatcher

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

Scheduling Criteria

1) CPU utilization – keep the CPU as busy as possible
2) Throughput – # of processes that complete their execution per time unit
3) Turnaround time – amount of time to execute a particular process
4) Waiting time – amount of time a process has been waiting in the ready queue
5) 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)

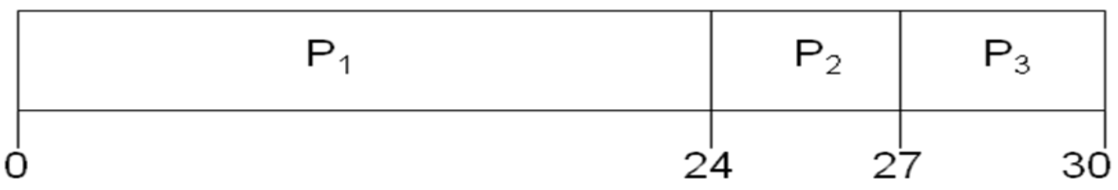
Optimization Criteria

1) Max CPU utilization
2) Max throughput
3) Min turnaround time
4) Min waiting time
5) 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:

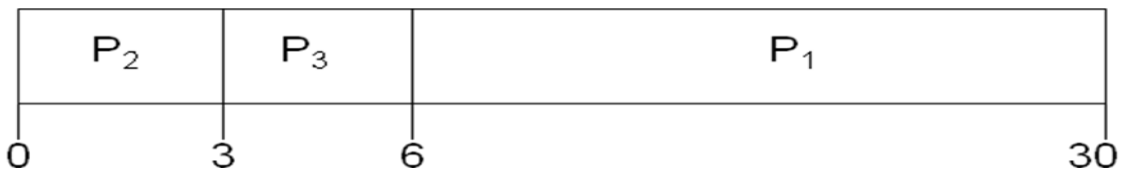


- Waiting time for P_1 = 0; P_2 = 24; P_3 = 27
- Average waiting time: (0 + 24 + 27)/3 = 17

Suppose that the processes arrive in the order

P_2 , P_3 , P_1

- The Gantt chart for the schedule is:



- Waiting time for $P_1 = 6; P_2 = 0; P_3 = 3$
- Average waiting time: (6 + 0 + 3)/3 = 3
- Much better than previous case
- *Convoy effect* short process behind long process

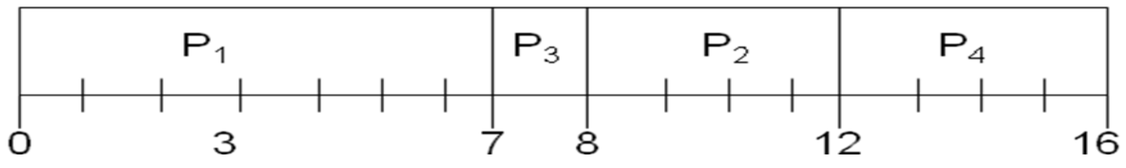
Shortest-Job-First (SJR) Scheduling

- Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time
- Two schemes:
  - nonpreemptive – once CPU given to the process it cannot be preempted until completes its CPU burst
  - preemptive – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt. This scheme is know as the Shortest-Remaining-Time-First (SRTF)
- SJF is optimal – gives minimum average waiting time for a given set of processes

Example of Non-Preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

- SJF (non-preemptive)

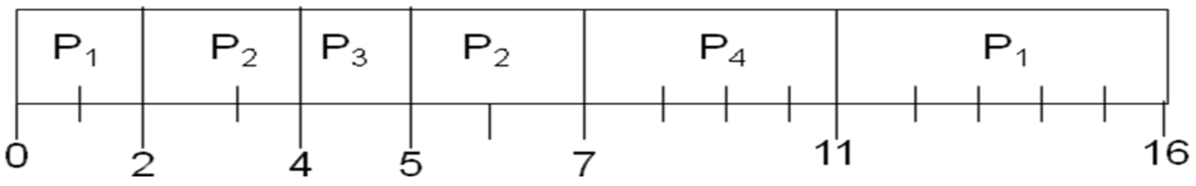


- Average waiting time = (0 + 6 + 3 + 7)/4 = 4

Example of Preemptive SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

- SJF (preemptive)



- Average waiting time = (9 + 1 + 0 +2)/4 = 3

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

1. t_n = actual lenght of n^{th} CPU burst
2. τ_{n+1} = predicted value for the next CPU burst
3. $\alpha, 0 \leq \alpha \leq 1$
4. Define :

$$\tau_{n=1} = \alpha\, t_n + (1-\alpha)\tau_n .$$

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

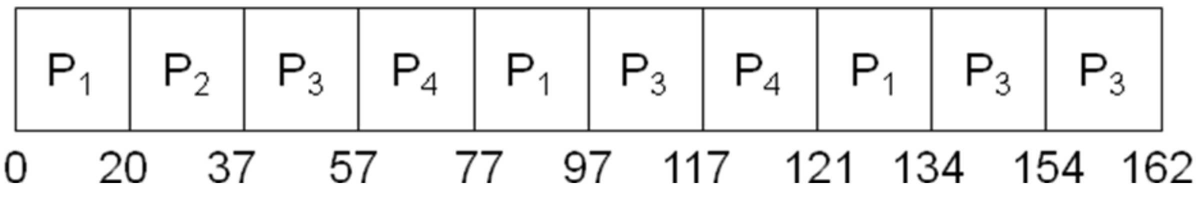
Round Robin (RR)

- 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 $(n-1)q$ time units.
- Performance
  - q large $\Rightarrow$ FIFO
  - q small $\Rightarrow$ q must be large with respect to context switch, otherwise overhead is too high

Example of RR with Time Quantum = 20

Process	Burst Time
P_1	53
P_2	17
P_3	68
P_4	24

- The Gantt chart is:



Typically, higher average turnaround than SJF, but better *response*

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 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.

Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available
- *Homogeneous processors* within a multiprocessor
- *Load sharing*
- *Asymmetric multiprocessing* – only one processor accesses the system data structures, alleviating the need for data sharing

Real-Time Scheduling

- *Hard real-time* systems – required to complete a critical task within a guaranteed amount of time
- *Soft real-time* computing – requires that critical processes receive priority over less fortunate ones

Algorithm Evaluation

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

Process Synchronization

- ✓ Concurrent access to shared data may result in data inconsistency
- ✓ Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes
- ✓ Suppose that we wanted to provide a solution to the consumer-producer problem that fills all the buffers. We can do so by having an integer count that keeps track of the number of full buffers. Initially, count is set to 0. It is incremented by the producer after it produces a new buffer and is decremented by the consumer after it consumes a buffer.

Producer

```
while (true){
                /* produce an item and put in nextProduced
                while (count == BUFFER_SIZE)
                        ; // do nothing
                buffer [in] = nextProduced;
                in = (in + 1) % BUFFER_SIZE;
                count++;
    }
```

Consumer

```
  while (1)
```

```
{
            while (count == 0)
                  ; // do nothing
            nextConsumed =  buffer[out];
            out = (out + 1) % BUFFER_SIZE;
            count--;
            /*  consume the item in nextConsumed
  }
```

Race Condition

- count++ could be implemented as

  register1 = count
  register1 = register1 + 1
  count = register1

- count-- could be implemented as

  register2 = count
  register2 = register2 - 1
  count = register2

- Consider this execution interleaving with "count = 5" initially:
  - ✓ S0: producer execute register1 = count   {register1 = 5}
  - ✓ S1: producer execute register1 = register1 + 1   {register1 = 6}
  - ✓ S2: consumer execute register2 = count   {register2 = 5}
  - ✓ S3: consumer execute register2 = register2 - 1   {register2 = 4}
  - ✓ S4: producer execute count = register1   {count = 6 }

- ✓ S5: consumer execute count = register2 {count = 4}

Solution to Critical-Section Problem

1) Mutual Exclusion - If process P_i is executing in its critical section, then no other processes can be executing in their critical sections
2) Progress - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely
3) Bounded Waiting - A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted
    - Assume that each process executes at a nonzero speed
    - No assumption concerning relative speed of the N processes

Peterson's Solution

- ➢ Two process solution
- ➢ Assume that the LOAD and STORE instructions are atomic; that is, cannot be interrupted.
- ➢ The two processes share two variables:
    - int turn;
    - Boolean flag[2]
- ➢ The variable turn indicates whose turn it is to enter the critical section.
- ➢ The flag array is used to indicate if a process is ready to enter the critical section. flag[i] = true implies that process P_i is ready!

Algorithm for Process P_i

do {

```
        flag[i] = TRUE;

        turn = j;

        while ( flag[j] && turn == j);

            CRITICAL SECTION

        flag[i] = FALSE;

             REMAINDER SECTION

    } while (TRUE);
```

Synchronization Hardware

❖ Many systems provide hardware support for critical section code

❖ Uniprocessors – could disable interrupts

- ➢ Currently running code would execute without preemption
- ➢ Generally too inefficient on multiprocessor systems
    - ▪ Operating systems using this not broadly scalable

❖ Modern machines provide special atomic hardware instructions

- ▪ Atomic = non-interruptable
- ➢ Either test memory word and set value

❖ Or swap contents of two memory words

TestAndndSet Instruction

- ➢ Definition:

```
    boolean TestAndSet (boolean *target)

    {

        boolean rv = *target;
        *target = TRUE;

        return rv:

    }
```

Solution using TestAndSet

- Shared boolean variable lock., initialized to false.
- Solution:

```
    do {

      while ( TestAndSet (&lock ))

                ;   /* do nothing

         //    critical section

      lock = FALSE;

         //      remainder section

     } while ( TRUE);
```

Swap Instruction

- Definition:

```
   void Swap (boolean *a, boolean *b)

    {

        boolean temp = *a;

        *a = *b;

        *b = temp:

    }
```

Solution using Swap

- Shared Boolean variable lock initialized to FALSE; Each process has a local Boolean variable key.
- Solution:

```
do {
     key = TRUE;
      while ( key == TRUE)
           Swap (&lock, &key );

             //    critical section
       lock = FALSE;
           //      remainder section
     } while ( TRUE);
```

Semaphore

- Synchronization tool that does not require busy waiting
- Semaphore *S* – integer variable
- Two standard operations modify S: wait() and signal()
    - Originally called P() and V()
- Less complicated
- Can only be accessed via two indivisible (atomic) operations
    - wait (S) {

```
     while S <= 0
                    ; // no-op
        S--;
```

```
}
```

- signal (S) {

```
  S++;
}
```

Semaphore as General Synchronization Tool

- Counting semaphore – integer value can range over an unrestricted domain
- Binary semaphore – integer value can range only between 0 and 1; can be simpler to implement
  - Also known as mutex locks
- Can implement a counting semaphore S as a binary semaphore
- Provides mutual exclusion
  - Semaphore S;   // initialized to 1
  - wait (S);
    - Critical Section
  - signal (S);

Semaphore Implementation

- Must guarantee that no two processes can execute wait () and signal () on the same semaphore at the same time
- Thus, implementation becomes the critical section problem where the wait and signal code are placed in the crtical section.
  - Could now have busy waiting in critical section implementation
    - But implementation code is short
    - Little busy waiting if critical section rarely occupied

- Note that applications may spend lots of time in critical sections and therefore this is not a good solution.

Semaphore Implementation with no Busy waiting

- With each semaphore there is an associated waiting queue. Each entry in a waiting queue has two data items:
  - value (of type integer)
  - pointer to next record in the list
- Two operations:
  - block – place the process invoking the operation on the appropriate waiting queue.
  - wakeup – remove one of processes in the waiting queue and place it in the ready queue.
- Implementation of wait:

```
wait (S){
    • value--;
    • if (value < 0) {
        ♦ add this process to waiting queue
        ♦ block();  }
}
```

- Implementation of signal:

```
Signal (S){
        ♦ value++;
        ♦ if (value <= 0) {
        ♦ remove a process P from the waiting queue
        ♦ wakeup(P);  }
}
```

Deadlock and Starvation

- Deadlock – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Let S and Q be two semaphores initialized to 1

```
        P0              P1
      wait (S);                     wait (Q);
       wait (Q);                    wait (S);
         .                            .
         .                            .
         .                            .
       signal  (S);                signal (Q);
       signal (Q);                signal (S);
```

- Starvation – indefinite blocking. A process may never be removed from the semaphore queue in which it is suspended.

Classical Problems of Synchronization

✓ Bounded-Buffer Problem

- ✓ Readers and Writers Problem
- ✓ Dining-Philosophers Problem

Bounded-Buffer Problem

- ➢ *N* buffers, each can hold one item
- ➢ Semaphore mutex initialized to the value 1
- ➢ Semaphore full initialized to the value 0
- ➢ Semaphore empty initialized to the value N.
- ➢ The structure of the producer process

```
do {
        //   produce an item
    wait (empty);
    wait (mutex);
       //  add the item to the  buffer
     signal (mutex);
     signal (full);
  } while (true);
```

- ➢ The structure of the consumer process

```
do {
    wait (full);
    wait (mutex);
       //  remove an item from  buffer
     signal (mutex);
```

```
        signal (empty);


            //  consume the removed item

    } while (true);
```

Readers-Writers Problem

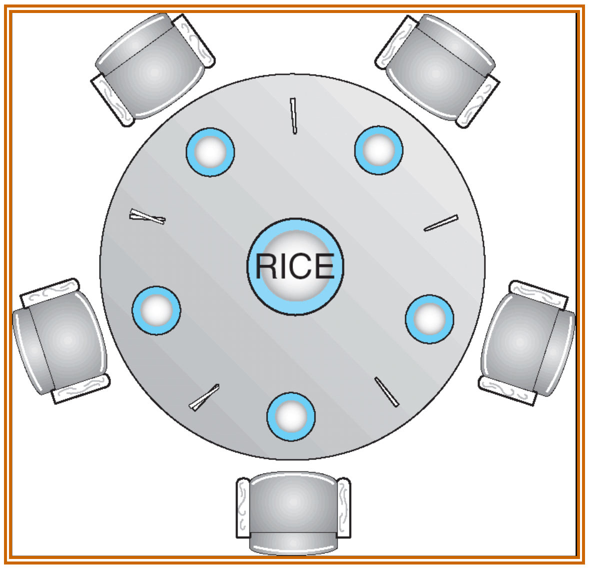
- A data set is shared among a number of concurrent processes
  - Readers – only read the data set; they do not perform any updates
  - Writers – can both read and write.
- Problem – allow multiple readers to read at the same time. Only one single writer can access the shared data at the same time.
- Shared Data
  - Data set
  - Semaphore mutex initialized to 1.
  - Semaphore wrt initialized to 1.
  - Integer readcount initialized to 0.
  - The structure of a writer process

```
     do  {
            wait (wrt) ;


              //    writing is performed
            signal (wrt) ;
       } while (true)
```

- The structure of a reader process

```
          do  {
         wait (mutex) ;
         readcount ++ ;
         if (readercount == 1)  wait (wrt) ;
         signal (mutex)


               // reading is performed
         wait (mutex) ;
         readcount  - - ;
         if redacount  == 0)  signal (wrt) ;
         signal (mutex) ;
     } while (true)
```

Dining-Philosophers Problem



- Shared data
  - Bowl of rice (data set)
  - Semaphore chopstick [5] initialized to 1
- The structure of Philosopher *i*:

```
Do  {
     wait ( chopstick[i] );
         wait ( chopStick[ (i + 1) % 5] );


              //  eat
         signal ( chopstick[i] );
         signal (chopstick[ (i + 1) % 5] );


         //  think
} while (true) ;
```

Critical Region

- Correct use of semaphore operations:
  - signal (mutex) …. wait (mutex)
  - wait (mutex) … wait (mutex)
  - Omitting of wait (mutex) or signal (mutex) (or both)

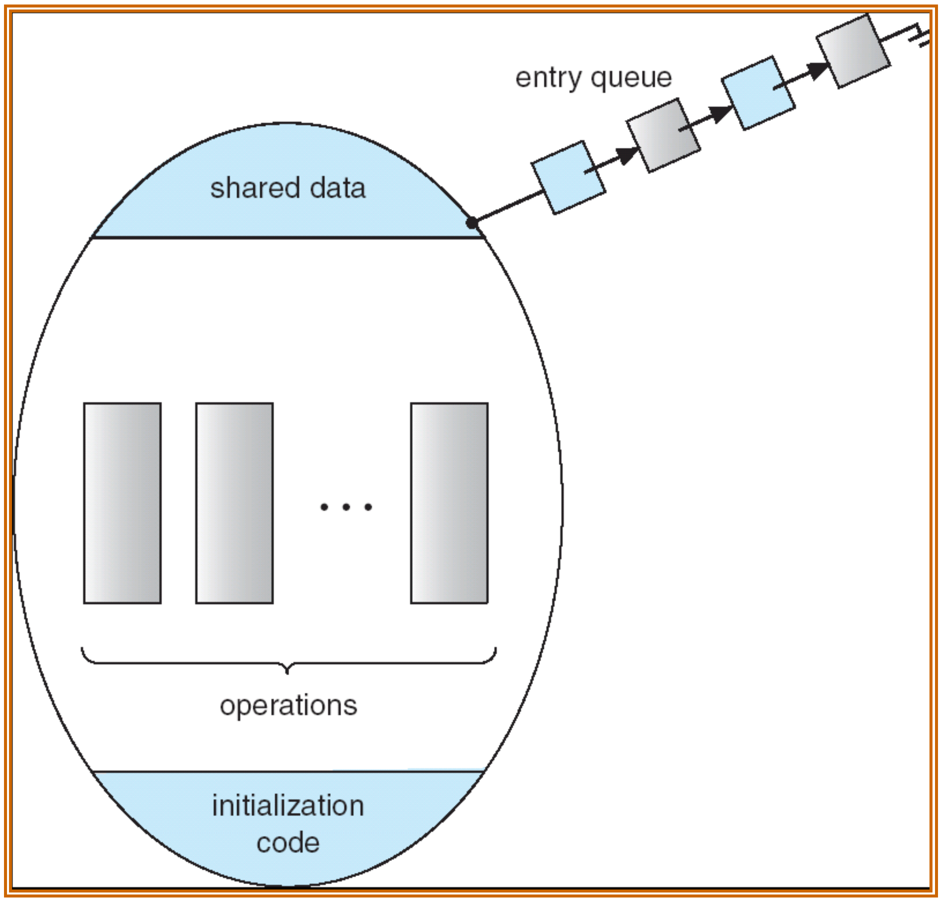
Monitors

- A high-level abstraction that provides a convenient and effective mechanism for process synchronization

- Only one process may be active within the monitor at a time monitor monitor-name

```
{
        // shared variable declarations
        procedure P1 (…) { …. }
                …
        procedure Pn (…) {……}
    Initialization code ( ….) { … }
                …
        }
}
```

Schematic view of a Monitor



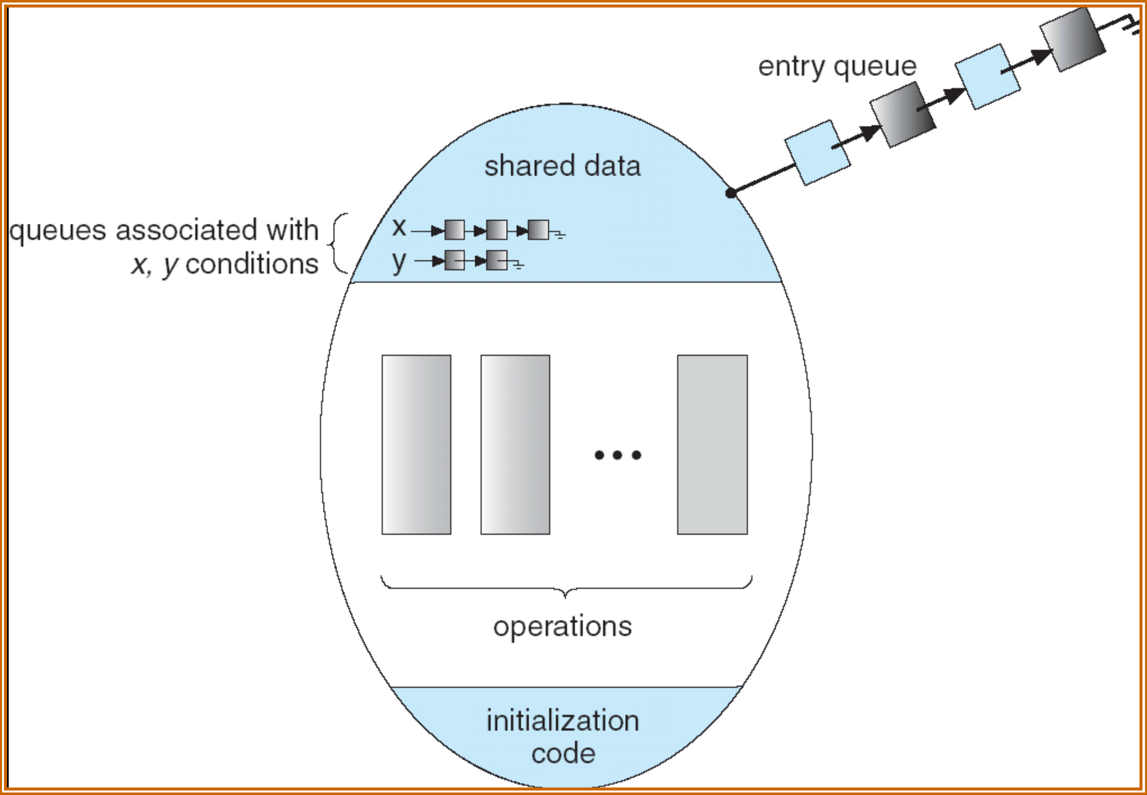
Condition Variables

❖ condition x, y;

❖ Two operations on a condition variable:

- ➢ x.wait () – a process that invokes the operation is suspended.
- ➢ x.signal () – resumes one of processes (if any) than invoked x.wait ()

Monitor with Condition Variables



Deadlocks

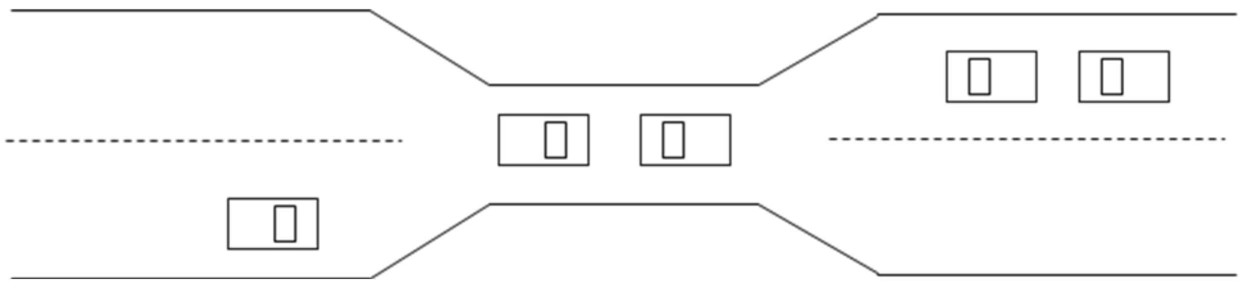
The Deadlock Problem

- A set of blocked processes each holding a resource and waiting to acquire a resource held by another process in the set.
- Example
  - ✓ System has 2 tape drives.
  - ✓ P_1 and P_2 each hold one tape drive and each needs another one.
- Example
- semaphores A and B, initialized to 1

P_0 P_1

wait (A);	*wait(B)*
wait (B);	*wait(A)*

Bridge Crossing Example



- Traffic only in one direction.
- Each section of a bridge can be viewed as a resource.
- If a deadlock occurs, it can be resolved if one car backs up (preempt resources and rollback).
- Several cars may have to be backed up if a deadlock occurs.
- Starvation is possible.

System Model

- Resource types $R_1, R_2, \ldots, R_m$

  CPU cycles, memory space, I/O devices

- Each resource type R_i has W_i instances.
- Each process utilizes a resource as follows:
  - request
  - use
  - release

Deadlock Characterization

Deadlock can arise if four conditions hold simultaneously

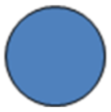
- **Mutual exclusion:** only one process at a time can use a resource.
- **Hold and wait:** a process holding at least one resource is waiting to acquire additional resources held by other processes.
- **No preemption:** a resource can be released only voluntarily by the process holding it, after that process has completed its task.
- **Circular wait:** there exists a set $\{P_0, P_1, \ldots, P_0\}$ of waiting processes such that P_0 is waiting for a resource that is held by P_1, P_1 is waiting for a resource that is held by

$P_2, \ldots, P_{n-1}$ is waiting for a resource that is held by
P_n, and P_0 is waiting for a resource that is held by P_0.

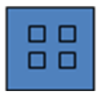
Resource-Allocation Graph

A set of vertices V and a set of edges E.

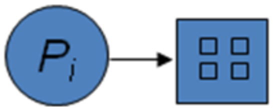
- V is partitioned into two types:
  - l $P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system.
  - l $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system.
- request edge – directed edge $P_1 \rightarrow R_j$
- assignment edge – directed edge $R_j \rightarrow P_i$
- Process



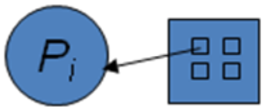
- Resource Type with 4 instances



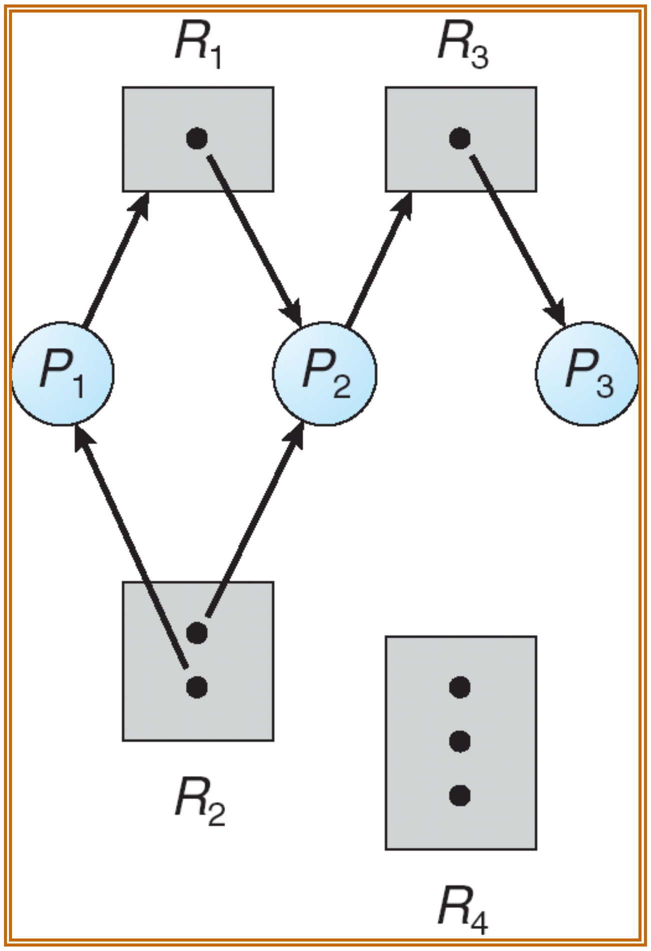
- P_i requests instance of R_j



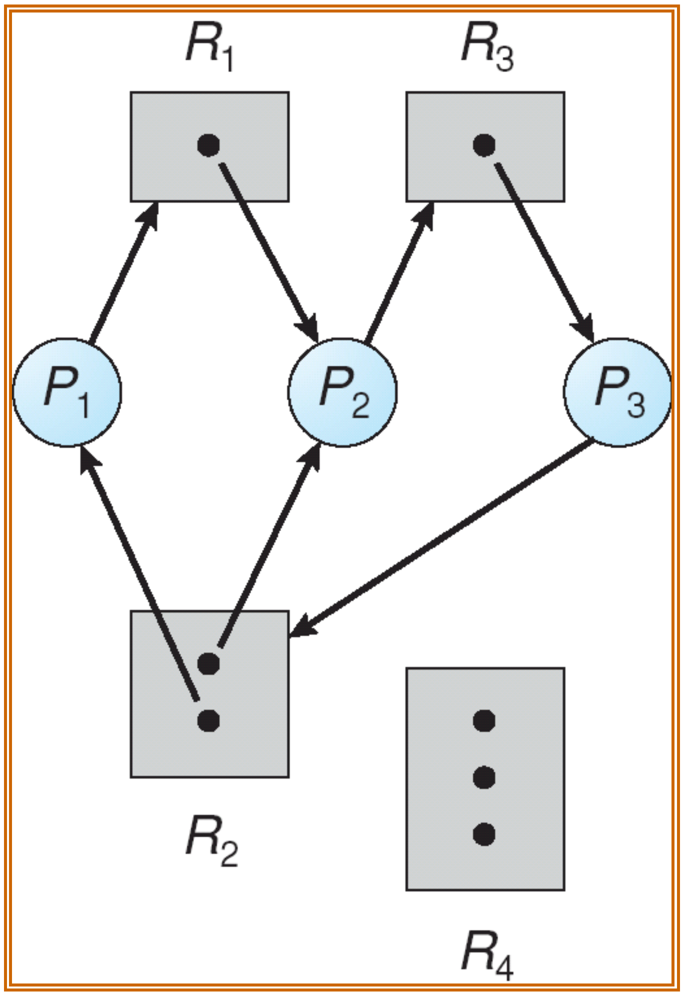
- P_i is holding an instance of R_j



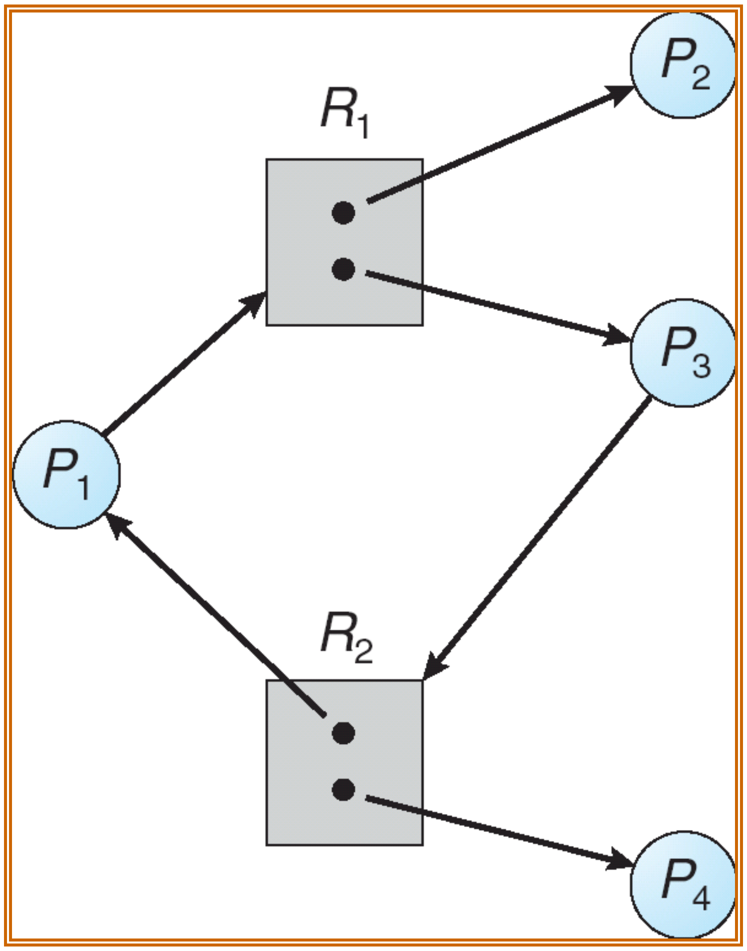
Example of a Resource Allocation Graph



Resource Allocation Graph With A Deadlock



Resource Allocation Graph With A Cycle But No Deadlock



- If graph contains no cycles ⇒ no deadlock.
- If graph contains a cycle ⇒
  - if only one instance per resource type, then deadlock.
  - if several instances per resource type, possibility of deadlock.

Methods for Handling Deadlocks

- Ensure that the system will *never* enter a deadlock state.
- Allow the system to enter a deadlock state and then recover.
- Ignore the problem and pretend that deadlocks never occur in the system; used by most operating systems, including UNIX.

Deadlock Prevention

Restrain the ways request can be made.

- **Mutual Exclusion** – not required for sharable resources; must hold for nonsharable resources.
- **Hold and Wait** – must guarantee that whenever a process requests a resource, it does not hold any other resources.
    - Require process to request and be allocated all its resources before it begins execution, or allow process to request resources only when the process has none.
    - Low resource utilization; starvation possible.
- **No Preemption** –
    - If a process that is holding some resources requests another resource that cannot be immediately allocated to it, then all resources currently being held are released.
    - Preempted resources are added to the list of resources for which the process is waiting.
    - Process will be restarted only when it can regain its old resources, as well as the new ones that it is requesting.
- **Circular Wait** – impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration.

Deadlock Avoidance

Requires that the system has some additional *a priori* information available.

- Simplest and most useful model requires that each process declare the *maximum number* of resources of each type that it may need.

- The deadlock-avoidance algorithm dynamically examines the resource-allocation state to ensure that there can never be a circular-wait condition.
- Resource-allocation *state* is defined by the number of available and allocated resources, and the maximum demands of the processes.

Safe State

- When a process requests an available resource, system must decide if immediate allocation leaves the system in a safe state.
- System is in safe state if there exists a safe sequence of all processes.
- Sequence <P_1, P_2, …, P_n> is safe if for each P_i, the resources that P_i can still request can be satisfied by currently available resources + resources held by all the P_j, with j<I.
  - ✓ If P_i resource needs are not immediately available, then P_i can wait until all P_j have finished.
  - ✓ When P_j is finished, P_i can obtain needed resources, execute, return allocated resources, and terminate.
  - ✓ When P_i terminates, P_{i+1} can obtain its needed resources, and so on.

Basic Facts

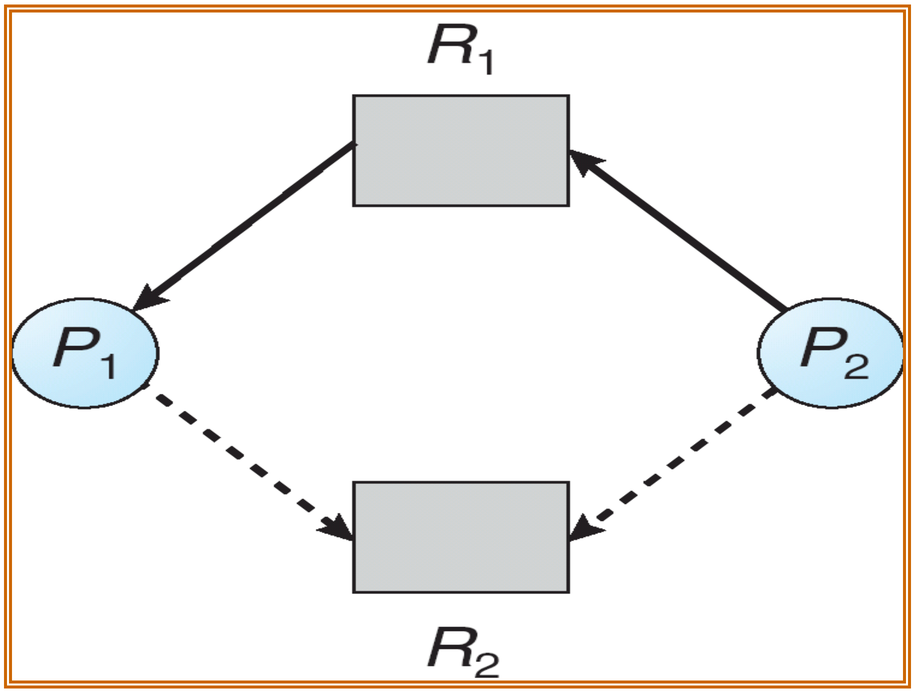
- If a system is in safe state $\Rightarrow$ no deadlocks.
- If a system is in unsafe state $\Rightarrow$ possibility of deadlock.
- Avoidance $\Rightarrow$ ensure that a system will never enter an unsafe state.

Resource-Allocation Graph Algorithm

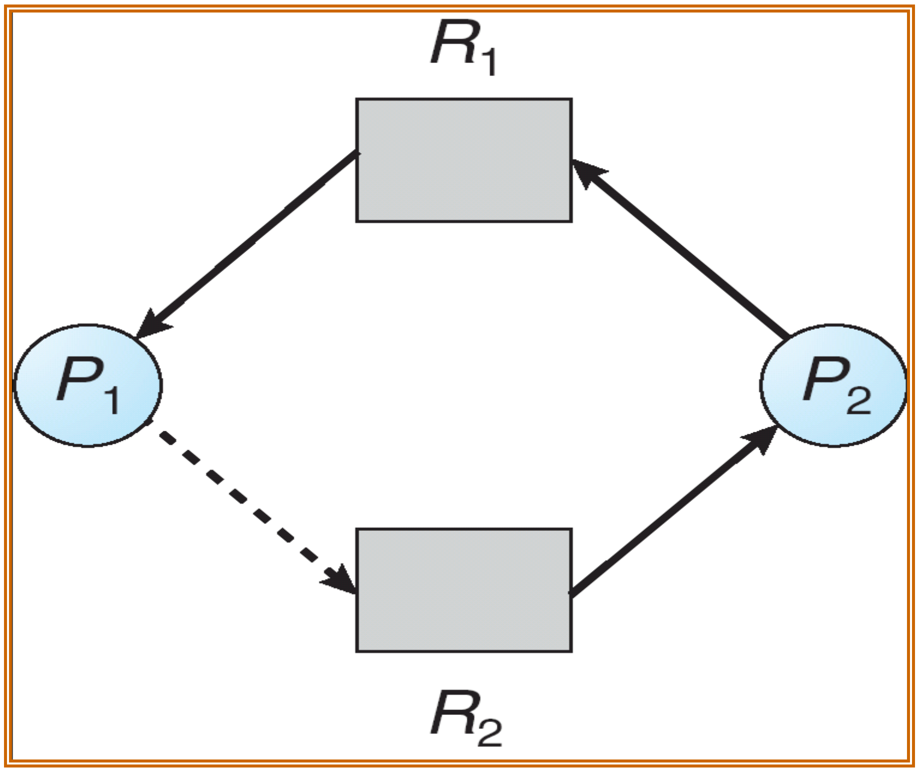
- *Claim edge* $P_i \rightarrow R_j$ indicated that process P_j may request resource R_j; represented by a dashed line.
- Claim edge converts to request edge when a process requests a resource.

- When a resource is released by a process, assignment edge reconverts to a claim edge.
- Resources must be claimed *a priori* in the system.

Resource-Allocation Graph For Deadlock Avoidance



Unsafe State In Resource-Allocation Graph



Banker's Algorithm

- Multiple instances.
- Each process must a priori claim maximum use.
- When a process requests a resource it may have to wait.
- When a process gets all its resources it must return them in a finite amount of time.

Data Structures for the Banker's Algorithm

Let *n* = number of processes, and *m* = number of resources types.

- *Available:* Vector of length *m*. If available [*j*] = *k*, there are *k* instances of resource type R_j available.
- *Max: n x m* matrix. If *Max* [*i*,*j*] = *k*, then process P_i may request at most *k* instances of resource type R_j.

- *Allocation:* n x m matrix. If Allocation[i,j] = k then P_i is currently allocated k instances of R_j.
- *Need:* n x m matrix. If *Need*[i,j] = k, then P_i may need k more instances of R_j to complete its task.

Need [i,j] = *Max*[i,j] – *Allocation* [i,j].

Safety Algorithm

1.Let *Work* and *Finish* be vectors of length m and n, respectively. Initialize:

Work = *Available*

Finish [i] = *false* for i - 1,3, …, n.

2. Find and i such that both:

(a) *Finish* [i] = *false*

(b) $Need_i \leq Work$

If no such i exists, go to step 4.

3. $Work = Work + Allocation_i$
Finish[i] = *true*
go to step 2.

4. If *Finish* [i] == true for all i, then the system is in a safe state.

Resource-Request Algorithm for Process P_i

Request = request vector for process P_i. If $Request_i$ [j] = k then process P_i wants k instances of resource type R_j.

1. If $Request_i \leq Need_i$ go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim.

2. If $Request_i \leq Available$, go to step 3. Otherwise P_i must wait, since resources are not available.

3. Pretend to allocate requested resources to P_i by modifying the state as follows:

$Available = Available = Request_i;$

$Allocation_i = Allocation_i + Request_i;$

$Need_i = Need_i – Request_i;$

- ✓ *If safe* $\Rightarrow$ *the resources are allocated to Pi.*
- ✓ *If unsafe* $\Rightarrow$ *Pi must wait, and the old resource-allocation state is restored*

Example of Banker's Algorithm

- 5 processes P_0 through P_4; 3 resource types *A* (10 instances), *B* (5instances, and *C* (7 instances).
- Snapshot at time T_0:

	Allocation	Max	Available
	A B C	A B C	A B C
P_0	0 1 0	7 5 3	3 3 2
P_1	2 0 0	3 2 2	
P_2	3 0 2	9 0 2	
P_3	2 1 1	2 2 2	
P_4	0 0 2	4 3 3	

- The content of the matrix. Need is defined to be Max – Allocation.

	Need
	A B C
P_0	7 4 3

P_1	1 2 2
P_2	6 0 0
P_3	0 1 1
P_4	4 3 1

- The system is in a safe state since the sequence $< P_1, P_3, P_4, P_2, P_0>$ satisfies safety criteria.

Example P_1 Request (1,0,2)

- Check that Request ≤ Available (that is, $(1,0,2) \le (3,3,2) \Rightarrow$ true.

	Allocation	*Need*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 1 0	7 4 3	2 3 0
P_1	3 0 2	0 2 0	
P_2	3 0 1	6 0 0	
P_3	2 1 1	0 1 1	
P_4	0 0 2	4 3 1	

- Executing safety algorithm shows that sequence <P1, P3, P4, P0, P2> satisfies safety requirement.
- Can request for (3,3,0) by P4 be granted?
- Can request for (0,2,0) by P0 be granted?

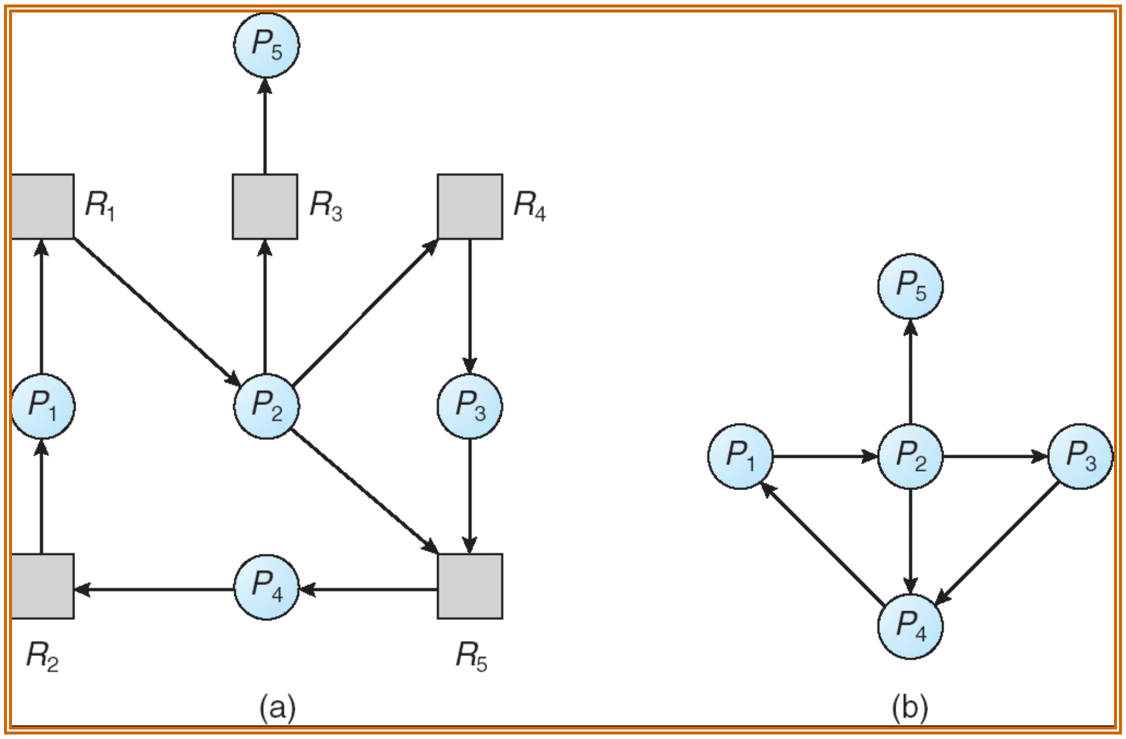
Deadlock Detection

- Allow system to enter deadlock state
- Detection algorithm
- Recovery scheme

Single Instance of Each Resource Type

- Maintain *wait-for* graph
  - ✓ Nodes are processes.
  - ✓ $P_i \rightarrow P_j$ if P_i is waiting for P_j.
- Periodically invoke an algorithm that searches for a cycle in the graph.
- An algorithm to detect a cycle in a graph requires an order of n^2 operations, where n is the number of vertices in the graph.

Resource-Allocation Graph and Wait-for Graph



Resource-Allocation Graph Corresponding wait-for graph

Several Instances of a Resource Type

- *Available:* A vector of length *m* indicates the number of available resources of each type.

- *Allocation:* An n x m matrix defines the number of resources of each type currently allocated to each process.
- *Request:* An n x m matrix indicates the current request of each process. If *Request* $[i_j] = k$, then process P_i is requesting k more instances of resource type. R_j.

Detection Algorithm

Let *Work* and *Finish* be vectors of length m and n, respectively Initialize:

(a) *Work* = *Available*

(b) For $i = 1,2, \ldots, n$, if $Allocation_i \neq 0$, then
Finish[i] = false;otherwise, *Finish*[i] = *true*.

2. Find an index i such that both:

(a) *Finish*[i] == *false*

(b) $Request_i \leq Work$

If no such i exists, go to step 4.

$Work = Work + Allocation_i$
Finish[i] = *true*
go to step 2.

4. If *Finish*[i] == false, for some i, $1 \leq i \leq n$, then the system is in deadlock state. Moreover, if *Finish*[i] == *false*, then P_i is deadlocked.

Algorithm requires an order of O(m x $n^{2)}$ operations to detect whether the system is in deadlocked state.

Example of Detection Algorithm

- Five processes P_0 through P_4; three resource types
  A (7 instances), *B* (2 instances), and *C* (6 instances).

- Snapshot at time T_0:

	Allocation	*Request*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 1 0	0 0 0	0 0 0
P_1	2 0 0	2 0 2	
P_2	3 0 3	0 0 0	
P_3	2 1 1	1 0 0	
P_4	0 0 2	0 0 2	

- Sequence <P_0, P_2, P_3, P_1, P_4> will result in *Finish*[*i*] = true for all *i*.
- P_2 requests an additional instance of type *C*.

	Request
	A B C
P_0	0 0 0
P_1	2 0 1
P_2	0 0 1
P_3	1 0 0
P_4	0 0 2

- State of system?
  - ✓ Can reclaim resources held by process P_0, but insufficient resources to fulfill other processes; requests.
  - ✓ Deadlock exists, consisting of processes P_1, P_2, P_3, and P_4.

Detection-Algorithm Usage

- When, and how often, to invoke depends on:
    - How often a deadlock is likely to occur?
    - How many processes will need to be rolled back?
        - one for each disjoint cycle
- If detection algorithm is invoked arbitrarily, there may be many cycles in the resource graph and so we would not be able to tell which of the many deadlocked processes "caused" the deadlock.

Recovery from Deadlock: Process Termination

- Abort all deadlocked processes.
- Abort one process at a time until the deadlock cycle is eliminated.
- In which order should we choose to abort?
    - ✓ Priority of the process.
    - ✓ How long process has computed, and how much longer to completion.
    - ✓ Resources the process has used.
    - ✓ Resources process needs to complete.
    - ✓ How many processes will need to be terminated.
    - ✓ Is process interactive or batch?

Recovery from Deadlock: Resource Preemption

- Selecting a victim – minimize cost.
- Rollback – return to some safe state, restart process for that state.

- Starvation – same process may always be picked as victim, include number of rollback in cost factor.