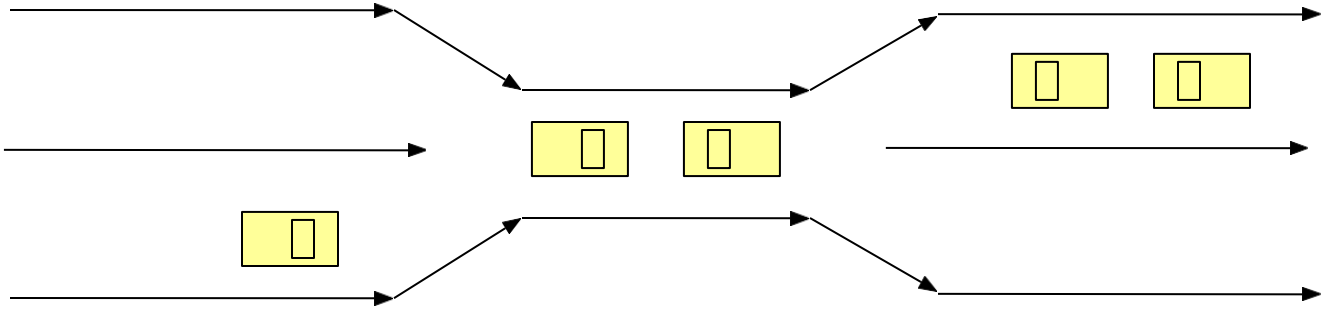
# Deadlocks

# The Deadlock Problem

- A deadlock consists of a set of blocked processes, each holding a resource and waiting to acquire a resource held by another process in the set
- Example #1
  - A system has 2 disk drives
  - $P_1$ and $P_2$ each hold one disk drive and each needs the other one
- Example #2
  - 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
- The resource is a one-lane bridge
- 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 $R_1$, $R_2$, . . ., $R_m$

  *CPU cycles, memory space, I/O devices*
- Each resource type $R_i$ has *1 or more* instances
- Each process utilizes a resource as follows:
  - request
  - use
  - release

# Deadlock Characterization

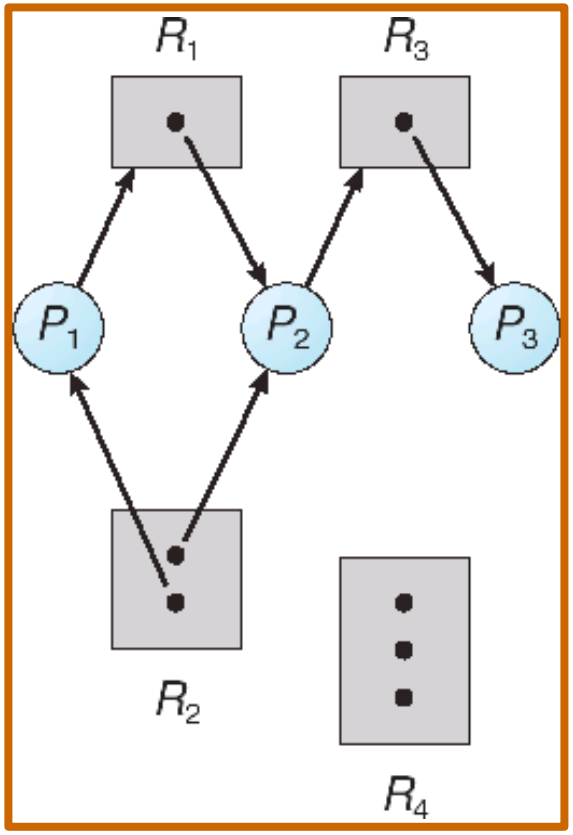
Deadlock can arise if four conditions hold simultaneously.

- **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 $P_n$ is waiting for a resource that is held by $P_0$

# Resource-Allocation Graph

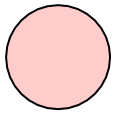
A set of vertices $V$ and a set of edges $E$.

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

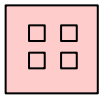


# Resource-Allocation Graph (Cont.)

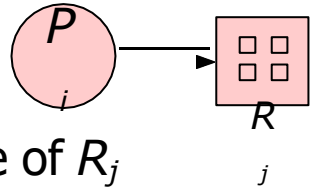
- Process



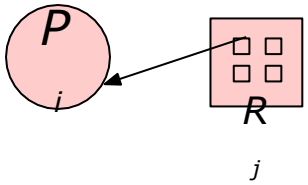
- Resource Type with 4 instances



- $P_i$ requests instance of $R_j$

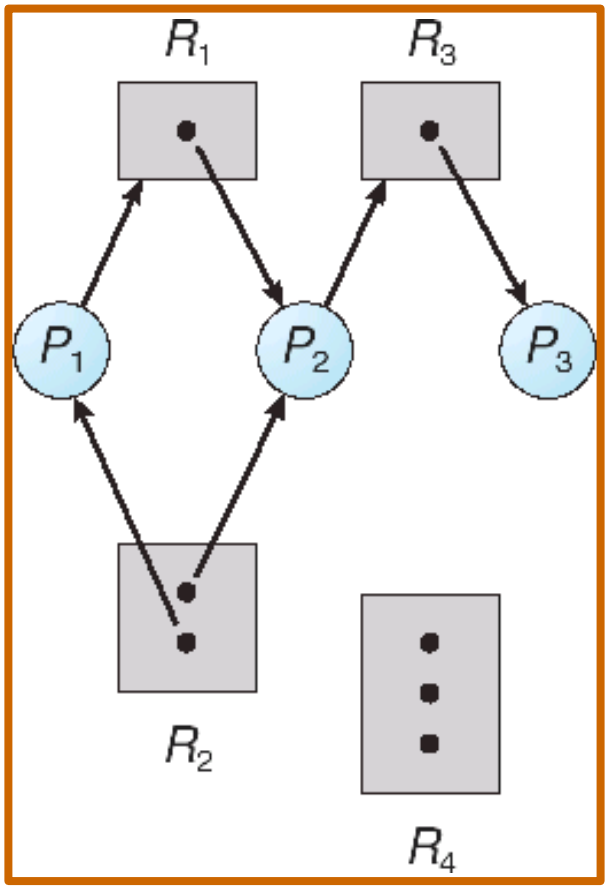



- $P_i$ is holding an instance of $R_j$

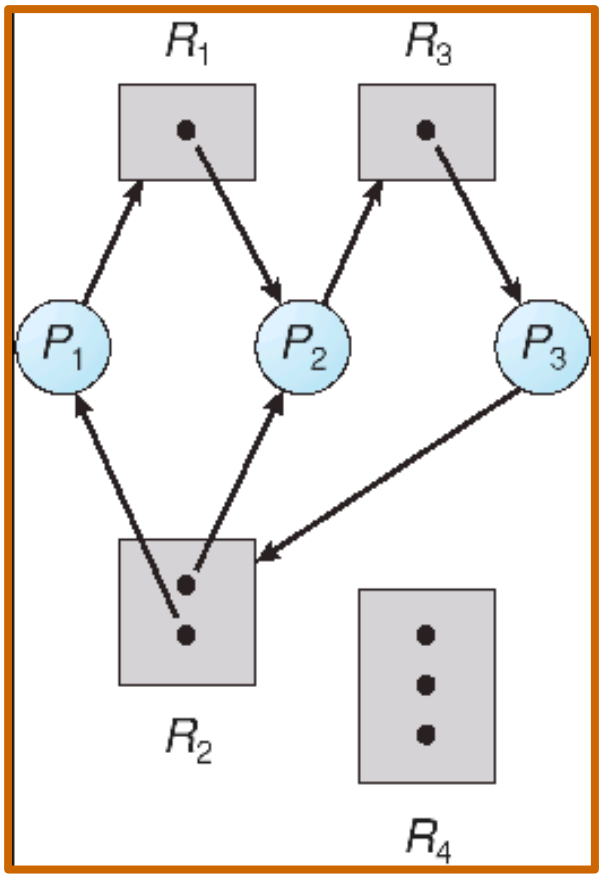


# Resource Allocation Graph With A Deadlock

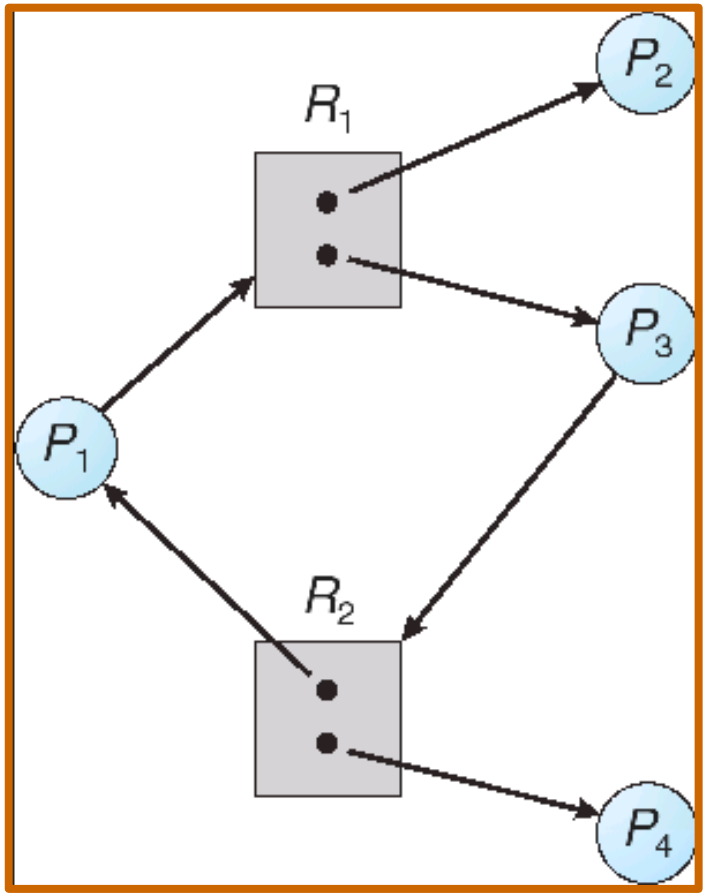
Before $P_3$ requested an instance of $R_2$




After $P_3$ requested an instance of $R_2$



# Graph With A Cycle But No Deadlock




Process $P_4$ may release its instance of resource type $R_2$. That resource can then be allocated to P3, thereby breaking the cycle.

# Relationship of cycles to deadlocks

- If a resource allocation graph contains no cycles ⇒ no deadlock
- If a resource allocation graph contains a cycle and if only one instance exists per resource type ⇒ deadlock
- If a resource allocation graph contains a cycle and and if several instances exists per resource type ⇒ possibility of deadlock

# Methods for Handling Deadlocks

- **Prevention**
  - Ensure that the system will *never* enter a deadlock state
- **Avoidance**
  - Ensure that the system will *never* enter an unsafe state
- **Detection**
  - Allow the system to enter a deadlock state and then recover
- **Do Nothing**
  - Ignore the problem and let the user or system administrator respond to the problem; used by most operating systems, including Windows and UNIX

# Deadlock Prevention

To prevent deadlock, we can restrain the ways that a request can be made

- **Mutual Exclusion** – The mutual-exclusion condition must hold for non-sharable resources

- **Hold and Wait** – we must guarantee that whenever a process requests a resource, it does not hold any other resources
  - Require a process to request and be allocated all its resources before it begins execution, or allow a process to request resources only when the process has none
  - Result: Low resource utilization; starvation possible

# Deadlock Prevention (Cont.)

- **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
  - A 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. For example:

  F(tape drive) = 1
  F(disk drive) = 5
  F(printer) = 12

# 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
- A resource-allocation *state* is defined by the number of available and allocated resources, and the maximum demands of the processes

a priori: formed or conceived beforehand

# Safe State

- When a process requests an available resource, the system must decide if immediate allocation leaves the system in a safe state
- A system is in a safe state only if there exists a safe sequence
- A sequence of processes $<P_1, P_2, \ldots, P_n>$ is a safe sequence for the current allocation state if, for each $P_i$, the resource requests that $P_i$ can still make, can be satisfied by currently available resources plus resources held by all $P_j$, with $j < i$.
- That is:
  - If the $P_i$ 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

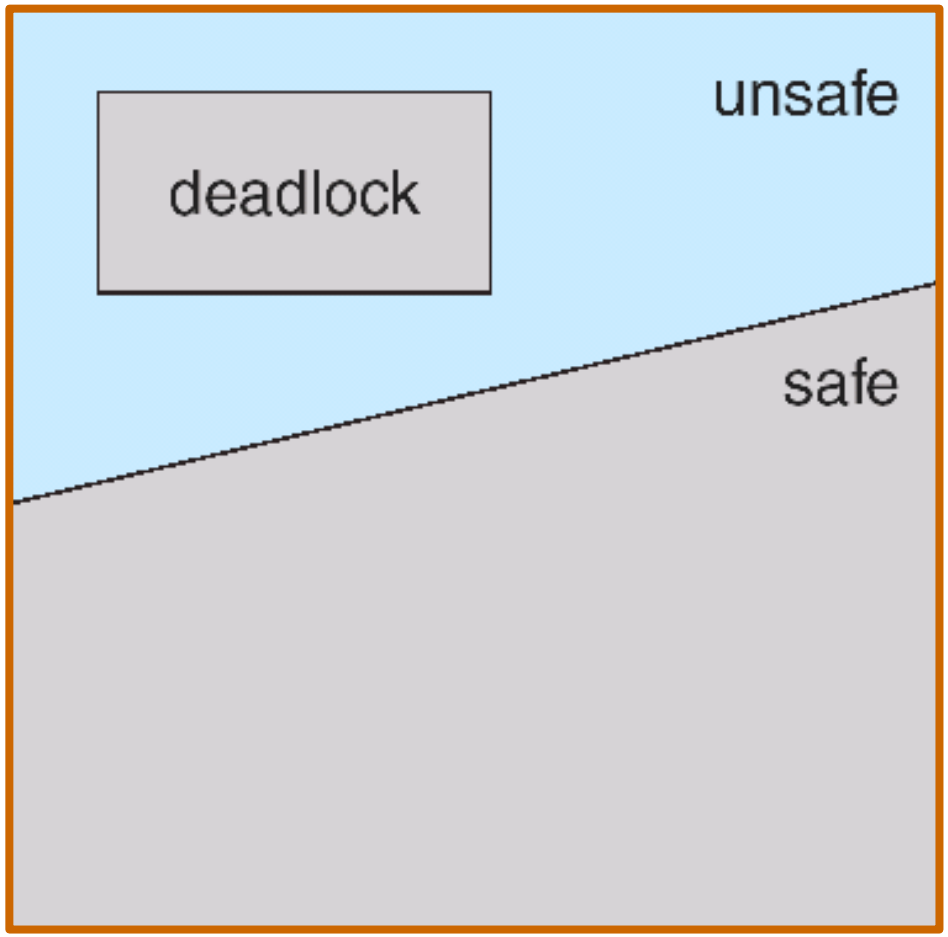
# Safe State (continued)



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

# Safe, Unsafe , Deadlock State





# Avoidance algorithms



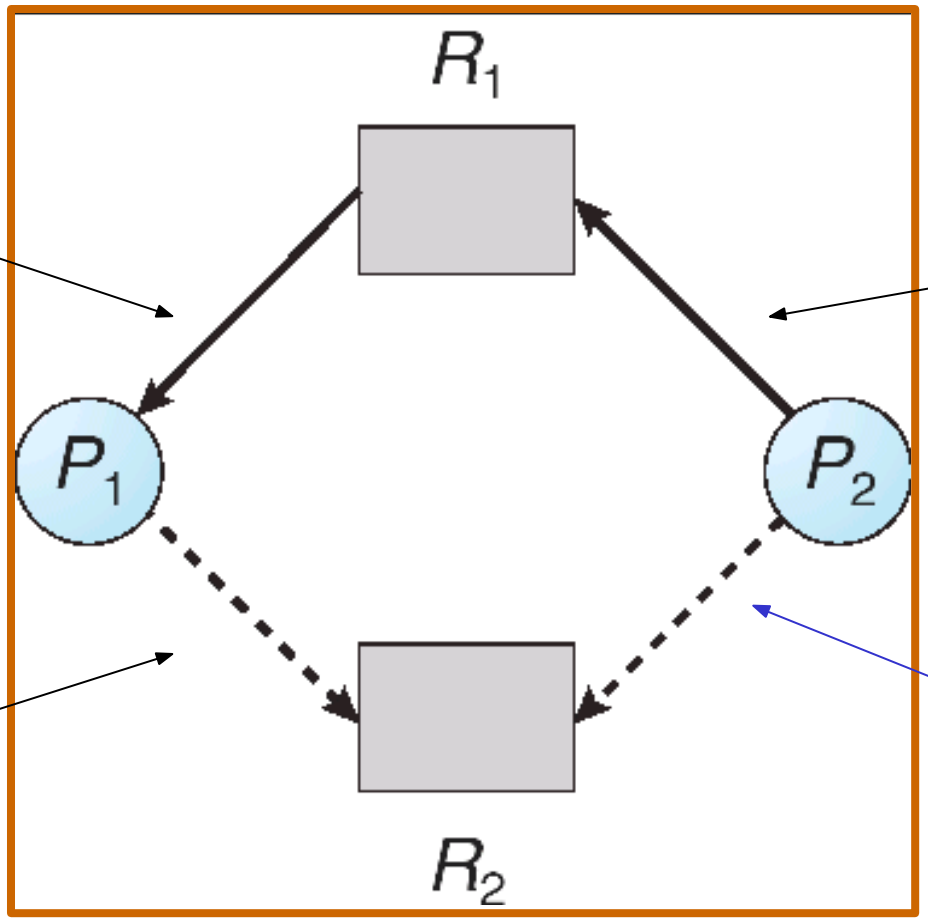
- For a single instance of a resource type, use a resource-allocation graph

- For multiple instances of a resource type, use the banker's algorithm

# Resource-Allocation Graph Scheme

- Introduce a new kind of edge called a claim edge
- *Claim edge* $P_i \longrightarrow R_j$ indicates that process $P_j$ may request resource $R_j$; which is represented by a dashed line
- A claim edge converts to a request edge when a process **requests** a resource
- A request edge converts to an assignment edge when the resource is **allocated** to the process
- When a resource is **released** by a process, an assignment edge reconverts to a claim edge
- Resources must be **claimed *a priori*** in the system

# Resource-Allocation Graph with Claim Edges



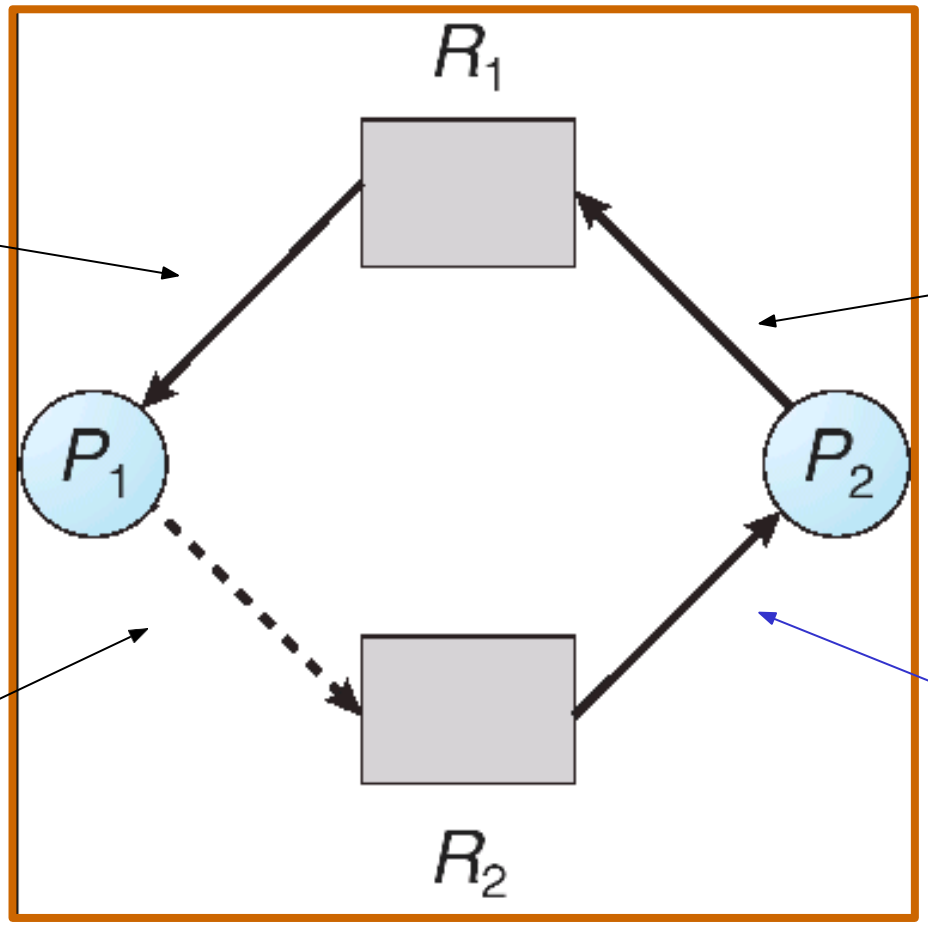

Assignment edge

Request edge

Claim edge

Claim edge

# Unsafe State In Resource-Allocation Graph




Assignment edge

Request edge

Claim edge

Assignment edge

# Resource-Allocation Graph Algorithm



- Suppose that process $P_i$ requests a resource $R_j$
- The request can be granted only if converting the request edge to an assignment edge does not result in the formation of a cycle in the resource allocation graph

# Banker's Algorithm

- Used when there exists **multiple** instances of a resource type
- 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***: $n \times m$ matrix. If $Max[i,j] = k$, then process $P_i$ may request at most $k$ instances of resource type $R_j$.
- ***Allocation***: $n \times m$ matrix. If $Allocation[i,j] = k$ then $P_i$ is currently allocated $k$ instances of $R_j$.
- ***Need***: $n \times m$ 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*$_i$ ≤ *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 $P_i$



$Request_i$ = 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 $Request_i \le Need_i$ go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim.
2. If $Request_i \le Available$, 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 ⇒ the resources are allocated to $P_i$.*
- *If unsafe ⇒ $P_i$ must wait, and the old resource-allocation state is restored*

# 7.6 Deadlock Detection

# Deadlock Detection

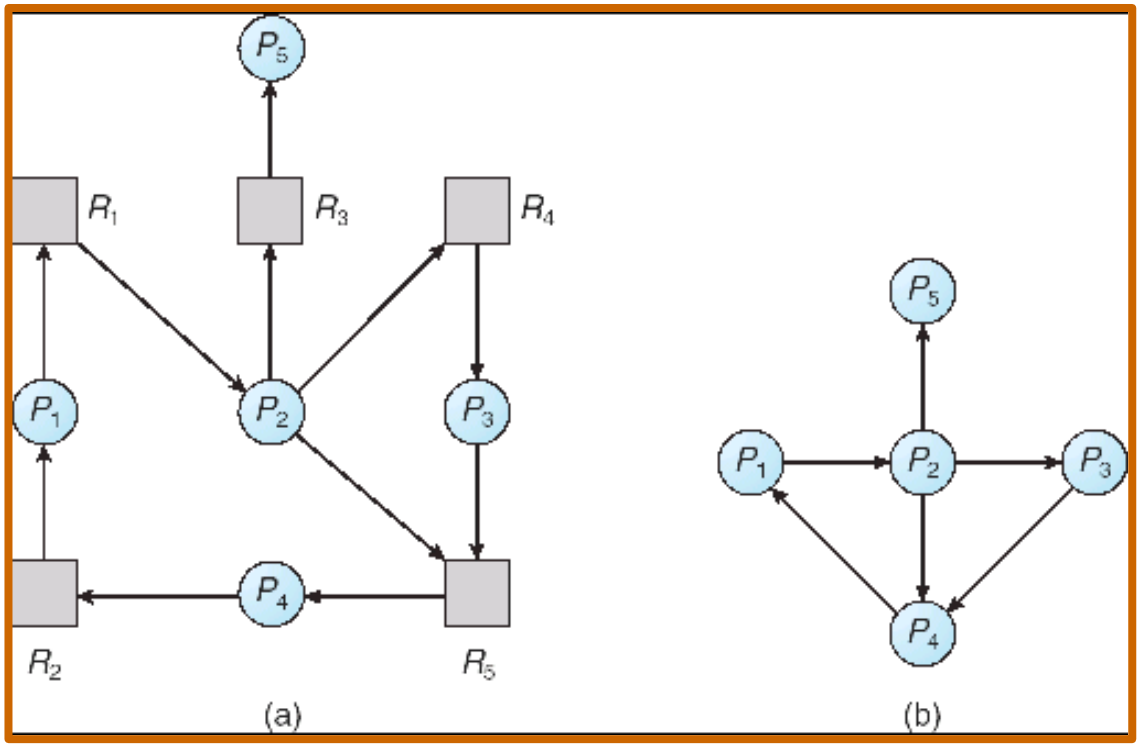


- For deadlock detection, the system must provide
  - An algorithm that examines the state of the system to detect whether a deadlock has occurred
  - And an algorithm to recover from the deadlock
- A detection-and-recovery scheme requires various kinds of overhead
  - Run-time costs of maintaining necessary information and executing the detection algorithm
  - Potential losses inherent in recovering from a deadlock

# Single Instance of Each Resource Type

- Requires the creation and maintenance of a *wait-for* graph
  - Consists of a variant of the resource-allocation graph
  - The graph is obtained by **removing** the resource nodes from a resource-allocation graph and **collapsing** the appropriate edges
  - Consequently; all 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
  - If there is a cycle, there exists a deadlock
  - 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

# Multiple Instances of a Resource Type



Required data structures:

- ***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 Usage

- When, and how often, to invoke the detection algorithm depends on:
  - How often is a deadlock likely to occur?
  - How many processes will be affected by deadlock when it happens?

- If the detection algorithm is invoked arbitrarily, there may be **many** cycles in the resource graph and so we would not be able to tell **which one** of the many deadlocked processes "caused" the deadlock
- If the detection algorithm is invoked for every resource request, such an action will incur a considerable **overhead** in computation time
- A less expensive alternative is to invoke the algorithm when CPU utilization drops **below 40%**, for example
  - This is based on the observation that a deadlock eventually cripples system throughput and causes CPU utilization to drop

# 7.7 Recovery From Deadlock

# Recovery from Deadlock

- Two Approaches
  - Process termination
  - Resource preemption

# Recovery from Deadlock: Process Termination

- **Abort all deadlocked processes**
  - This approach will break the deadlock, but at great expense
- **Abort one process at a time until the deadlock cycle is eliminated**
  - This approach incurs considerable overhead, since, after each process is aborted, a deadlock-detection algorithm must be re-invoked to determine whether any processes are still deadlocked
- **Many factors may affect which process is chosen for termination**
  - What is the priority of the process?
  - How long has the process run so far and how much longer will the process need to run before completing its task?
  - How many and what type of resources has the process used?
  - How many more resources does the process need in order to finish its task?
  - How many processes will need to be terminated?
  - Is the process interactive or batch?

# Recovery from Deadlock: Resource Preemption

- With this approach, we successively preempt some resources from processes and give these resources to other processes until the deadlock cycle is broken
- When preemption is required to deal with deadlocks, then three issues need to be addressed:
  - **Selecting a victim** – Which resources and which processes are to be preempted?
  - **Rollback** – If we preempt a resource from a process, what should be done with that process?
  - **Starvation** – How do we ensure that starvation will not occur? That is, how can we guarantee that resources will not always be preempted from the same process?

# Summary

- Four necessary conditions must hold in the system for a deadlock to occur
  - Mutual exclusion
  - Hold and wait
  - No preemption
  - Circular wait
- Four principal methods for dealing with deadlocks
  - Use some protocol to (1) **prevent** or (2) **avoid** deadlocks, ensuring that the system will never enter a deadlock state
  - Allow the system to enter a deadlock state, (3) **detect** it, **and** then **recover**

    Recover by **process termination** or **resource preemption**
  - **(4) Do nothing;** ignore the problem altogether and pretend that deadlocks never occur in the system (used by Windows and Unix)
- To prevent deadlocks, we can ensure that **at least one** of the four necessary conditions **never holds**