

# CS420: Operating Systems

## Deadlocks & Deadlock Prevention

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# The Deadlock Problem

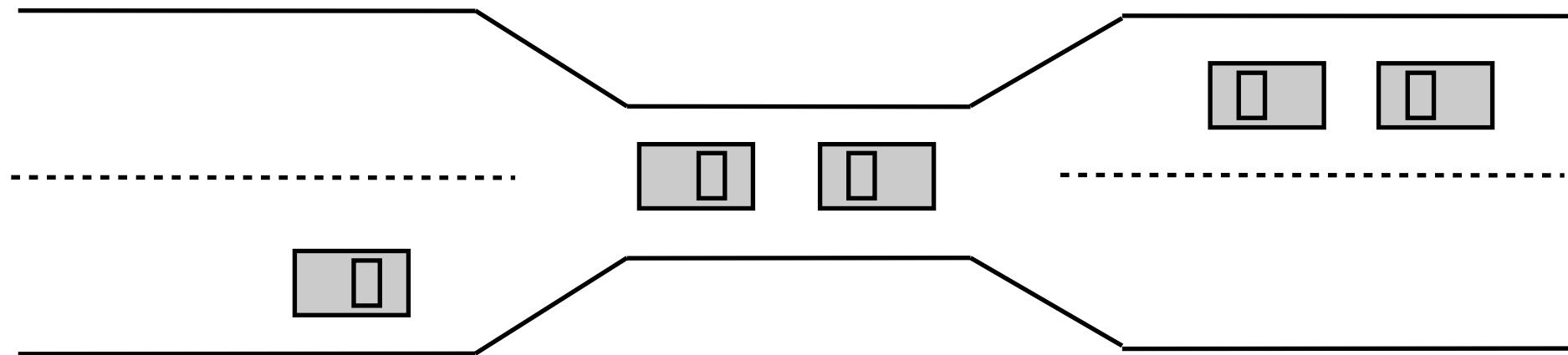
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- **Deadlock** - A condition that arises when two or more processes are waiting indefinitely for an event that can only be caused by one of the waiting processes
  - The events that the processes are waiting for will never happen :-(
  - Other processes in the system that need the resources that are currently locked will never get access to them
- **Operating systems do not typically provide deadlock-prevention facilities**
  - It is up to the programmer to design deadlock-free programs
- **Deadlock will become an even greater problem with the trend toward more processor cores and more threads**

# Bridge Crossing Example

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- Traffic can only pass bridge 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



# Deadlock Characterization

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- **Deadlock can arise if the 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 of resources** - 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  $\{P_0, P_1, \dots, P_n\}$  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  $P_2$ , ...,  $P_{n-1}$  is waiting for a resource that is held by  $P_n$ , and  $P_n$  is waiting for a resource that is held by  $P_0$

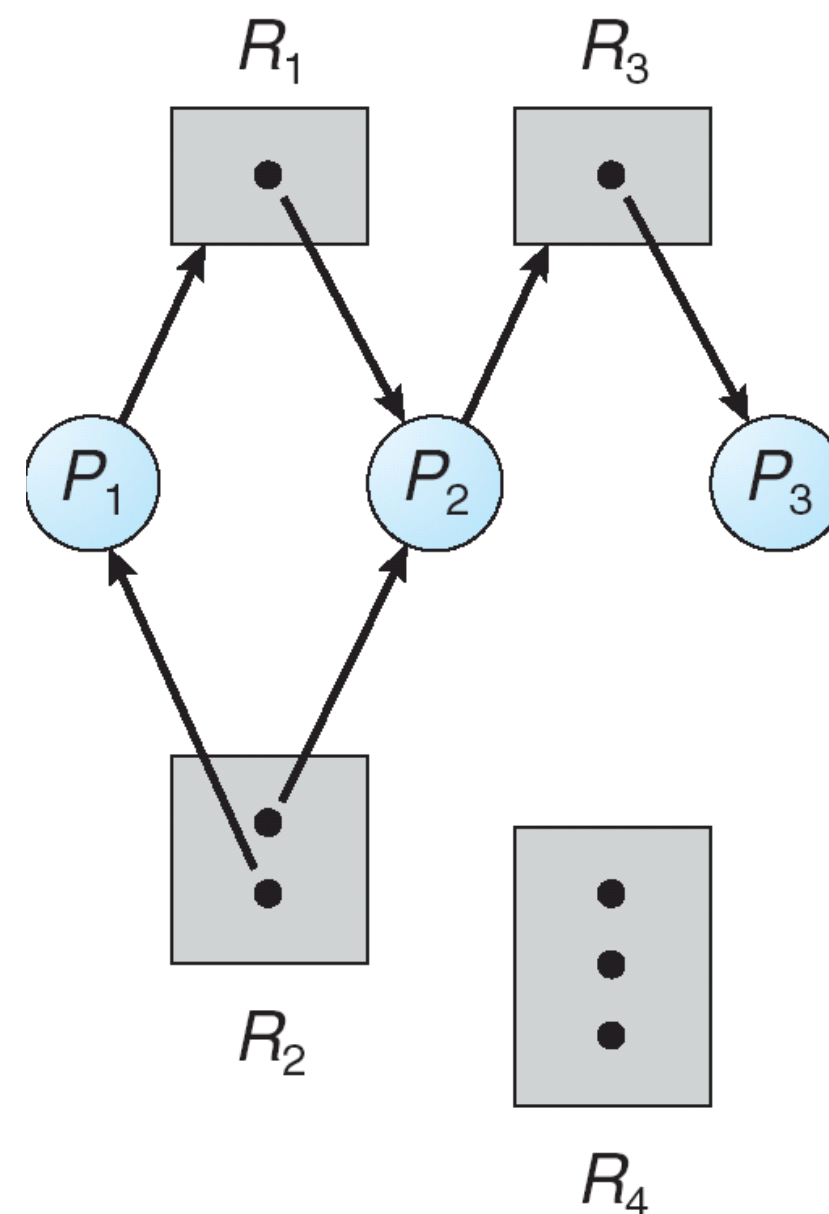
# Resource-Allocation Graph

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- **Deadlocks can be described precisely using system resource-allocation graphs**
- **A resource-allocation graph consists of a set of vertices  $V$  and a set of edges  $E$** 
  - $V$  is partitioned into two sets:
    - $P = \{P_1, P_2, \dots, P_n\}$ , the set consisting of all the processes in the system
    - $R = \{R_1, R_2, \dots, R_m\}$ , the set consisting of all resource types in the system
  - There are also two different types of edges:
    - **Request edge** – directed edge  $P_i \rightarrow R_j$ , a process  $P_i$  is requesting a resource of type  $R_j$
    - **Assignment edge** – directed edge  $R_j \rightarrow P_i$ , a resource of type  $R_j$  has been assigned to a process  $P_i$

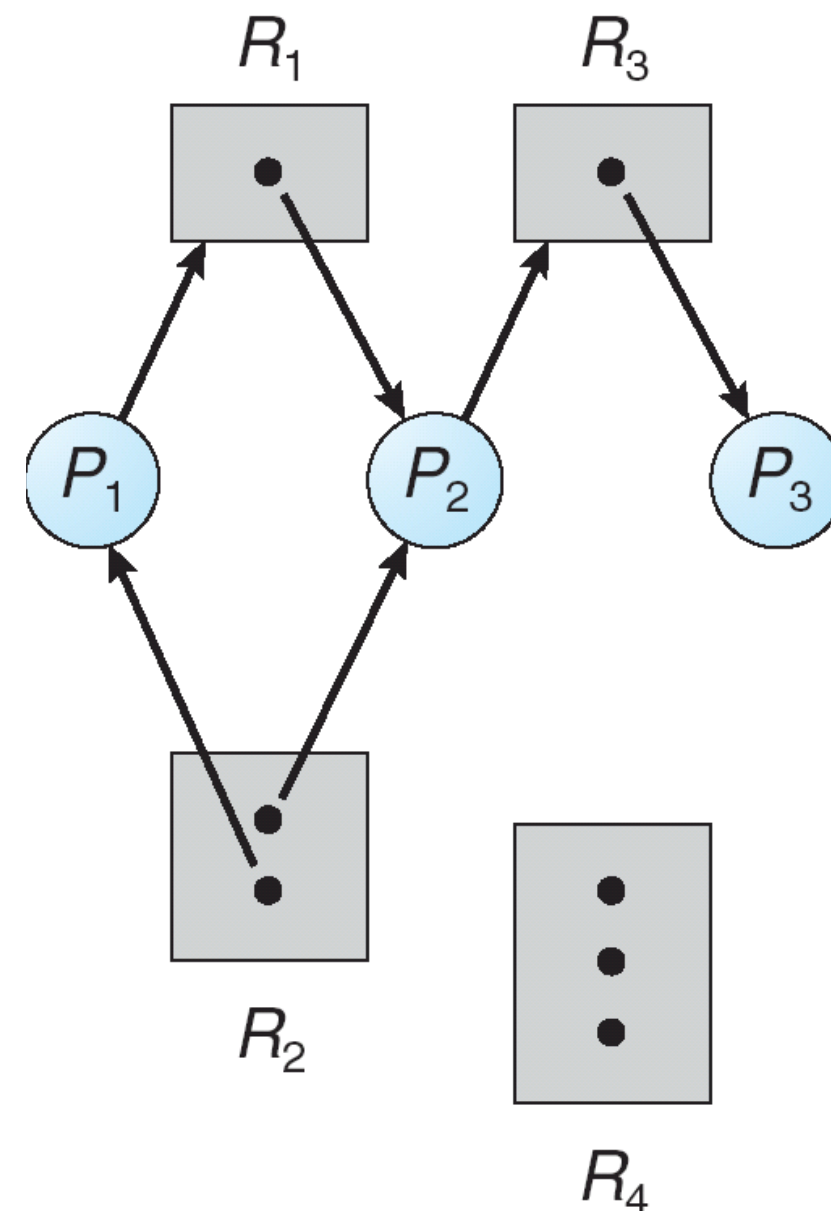
# Resource-Allocation Graph (Cont.)

- A process is represented as a circular vertex in the graph
- A resource type is represented as a square vertex in the graph
  - Because there may be multiple instances of some resources (i.e. two disks), each instance of a resource is represented using a dot
- A directed edge from a process  $P_i$  to a resource  $R_j$  is a request from  $P_i$  for a resource of type  $R_j$
- A directed edge from a resource instance to a process  $P_i$  indicates that the resource has been allocated to  $P_i$



# Resource-Allocation Graph (Cont.)

- If the graph contains no cycles, then no process in the system is deadlocked
- If the graph does contain cycles, then deadlock **may exist**, but is not guaranteed to exist
  - If a resource type has exactly one instance then a cycle implies that a deadlock has occurred
  - If a resource type has several instances, then a cycle does not necessarily imply that a deadlock has occurred



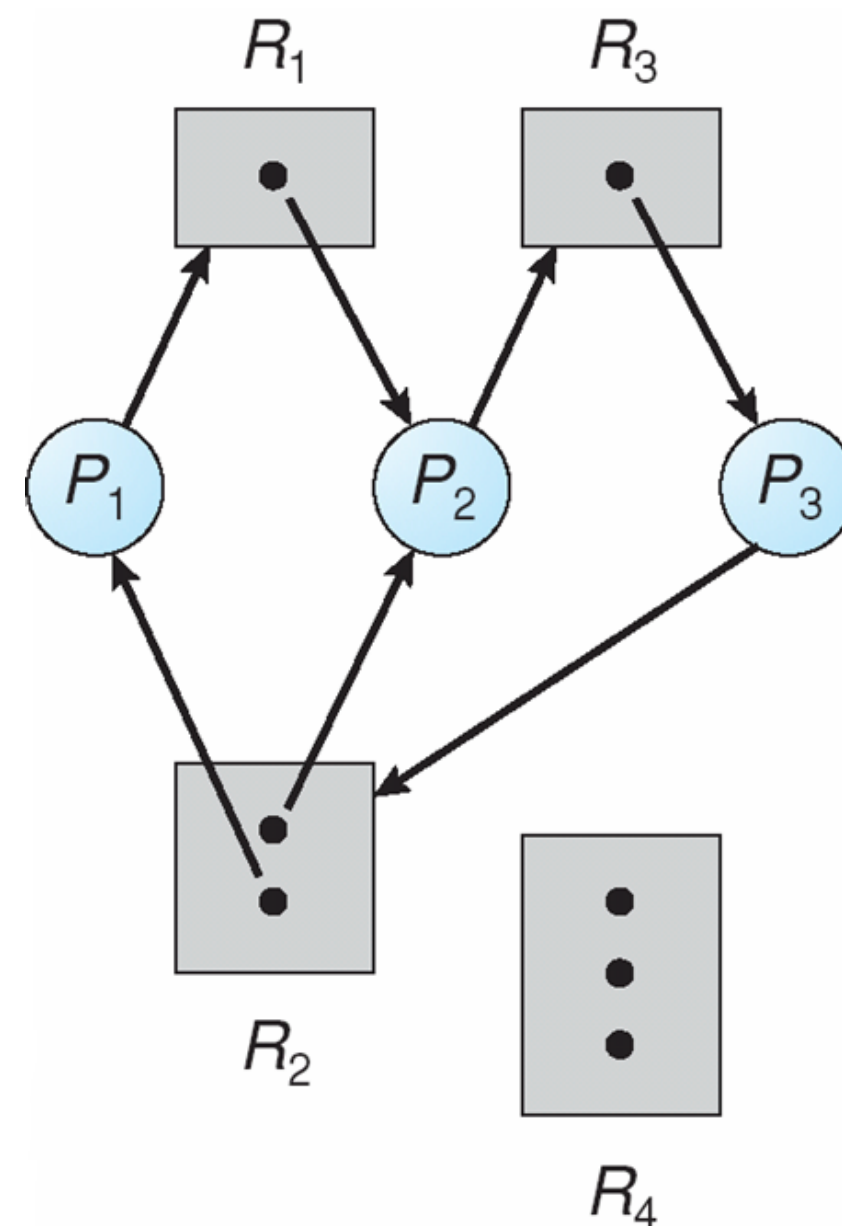
# Resource Allocation Graph With A Deadlock

- **Two cycles exist in the graph to the right**

- $P_1 \rightarrow R_1 \rightarrow P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2$
- $P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_2$

- **Processes  $P_1$ ,  $P_2$  and  $P_3$  are **deadlocked****

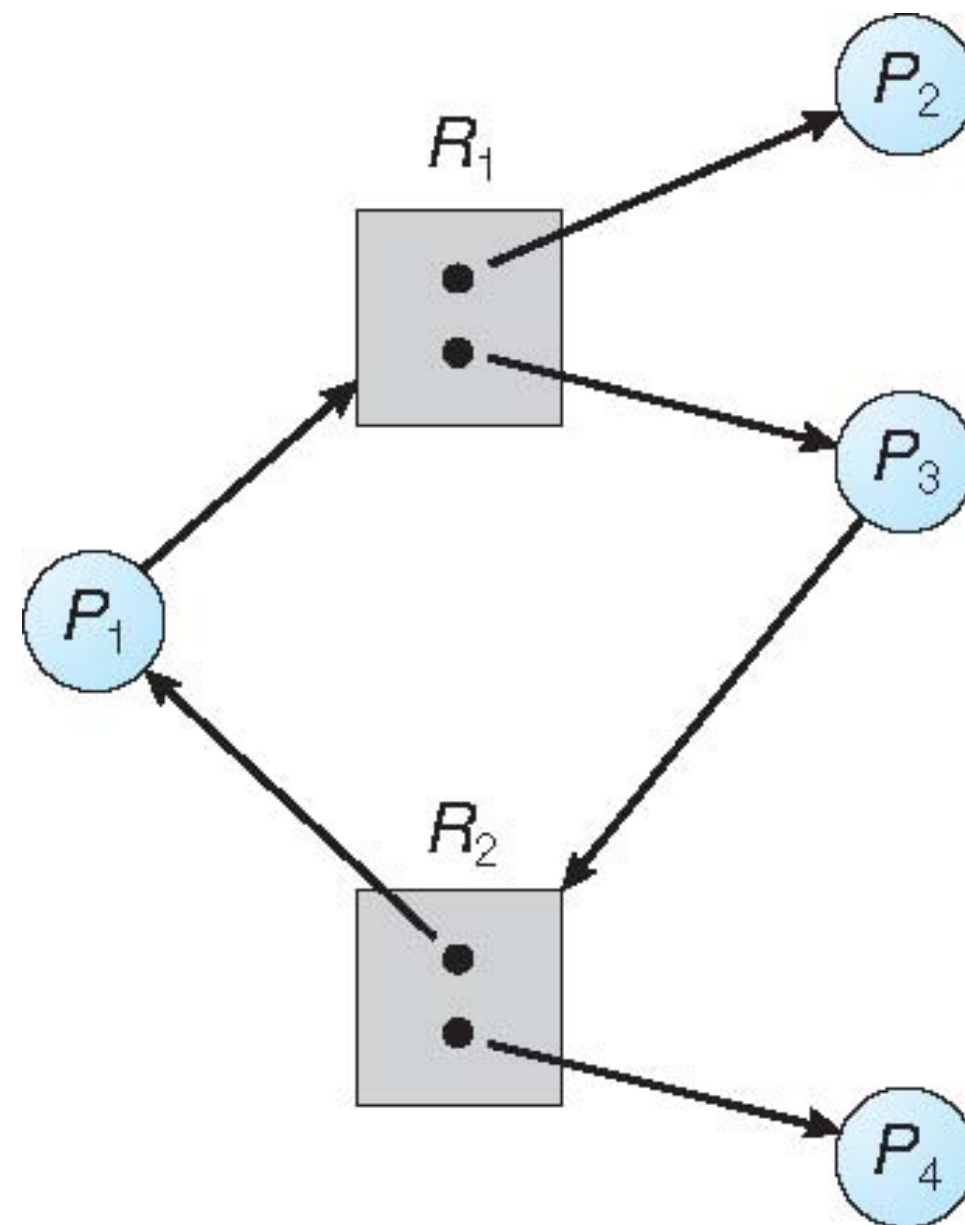
- $P_2$  is waiting for  $R_3$  (held by  $P_3$ )
- $P_3$  is waiting for  $R_2$  (held by  $P_1$  and  $P_2$ )
- $P_1$  is waiting for  $R_1$  (held by  $P_2$ )





# Graph With a Cycle But No Deadlock

- **A cycle exists in the graph to the right**
  - $P_1 \rightarrow R_1 \rightarrow P_3 \rightarrow R_2 \rightarrow P_1$
- **Processes  $P_3$  is waiting for resource  $R_2$** 
  - $P_4$  should eventually release  $R_2$
- **Process  $P_1$  is waiting for resource  $R_1$** 
  - $P_2$  should eventually release  $R_1$



# Resource Allocation Graph Recap

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- **If graph contains no cycles then no deadlock possible**
- **If graph contains a cycle then,**
  - If only one instance per resource type, then deadlock exists
  - If several instances per resource type, then deadlock is possible

# Methods for Handling Deadlocks

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- **Possible for OS to deal with deadlock in one of three ways:**
  - 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)
    - Requires that application developers write programs that avoid deadlock

# Methods for Handling Deadlocks

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- To ensure that deadlocks never occur, a system can use either **deadlock-prevention** or **deadlock-avoidance**
- **Deadlock Prevention** - ensure that at least one of the four necessary conditions for deadlock cannot hold
- **Deadlock Avoidance** - requires that the operating system be given comprehensive information about which resources a process will request during its lifetime
  - Operating system can then make intelligent decisions about when a process should be allocated a resource

# Methods for Handling Deadlocks

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- **If a system does not use either deadlock-prevention or deadlock-avoidance, a deadlock situation may eventually arise**
  - Need some way to detect these situations -- **deadlock detection**
  - Need some way to recover from these situations -- **deadlock recovery**
- **If a system does not use deadlock-detection/deadlock-avoidance, and does not use deadlock-detection/deadlock-recovery, then the system performance may eventually deteriorate**
  - Reboot

# Deadlock Prevention

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- **For deadlock to occur, each of the four necessary conditions must hold true**
- **To prevent deadlock, ensure that at least one of these four conditions does not hold true**

## (1) Mutual Exclusion

- Not required for sharable resources (i.e. read-only files)
- Must hold true for non-sharable resources :-(
- In general, cannot prevent deadlock by denying the mutual-exclusion condition because some resources are non-sharable

# Deadlock Prevention (Cont.)

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- **For deadlock to occur, each of the four necessary conditions must hold true**
- **To prevent deadlock, ensure that at least one of these four conditions does not hold true**
  - (2) Hold-and-wait
    - To ensure the hold-and-wait condition never occurs, must guarantee that whenever a process requests a resource, it does not hold any other resources
      - One approach requires a process to request and be allocated all its resources before it begins execution
        - Low resource utilization because resources may allocated but unused for a long time
        - Starvation is possible if at least one of the resources that a process needs is always allocated to some other process
      - Another approach allows a process to request resources only when it has none

# Deadlock Prevention (Cont.)

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- **For deadlock to occur, each of the four necessary conditions must hold true**
- **To prevent deadlock, ensure that at least one of these four conditions does not hold true**

## (3) No Preemption of Resources

- **To ensure that the no preemption condition never occurs:**
  - 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
  - All 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



# Deadlock Prevention (Cont.)

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- For deadlock to occur, each of the four necessary conditions must hold true
- To prevent deadlock, ensure that at least one of these four conditions does not hold true

## (4) Circular Wait

- To ensure that a circular waiting condition never occurs, impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration
  - Each resource type is given an integer value, must request desired resource in increasing order

LAN Port = 1  
Disk Drive = 2  
Printer = 3

If a process needs both the LAN and the printer, it must request the LAN first, and then request the printer

# Deadlock Avoidance

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- **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
  - A 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

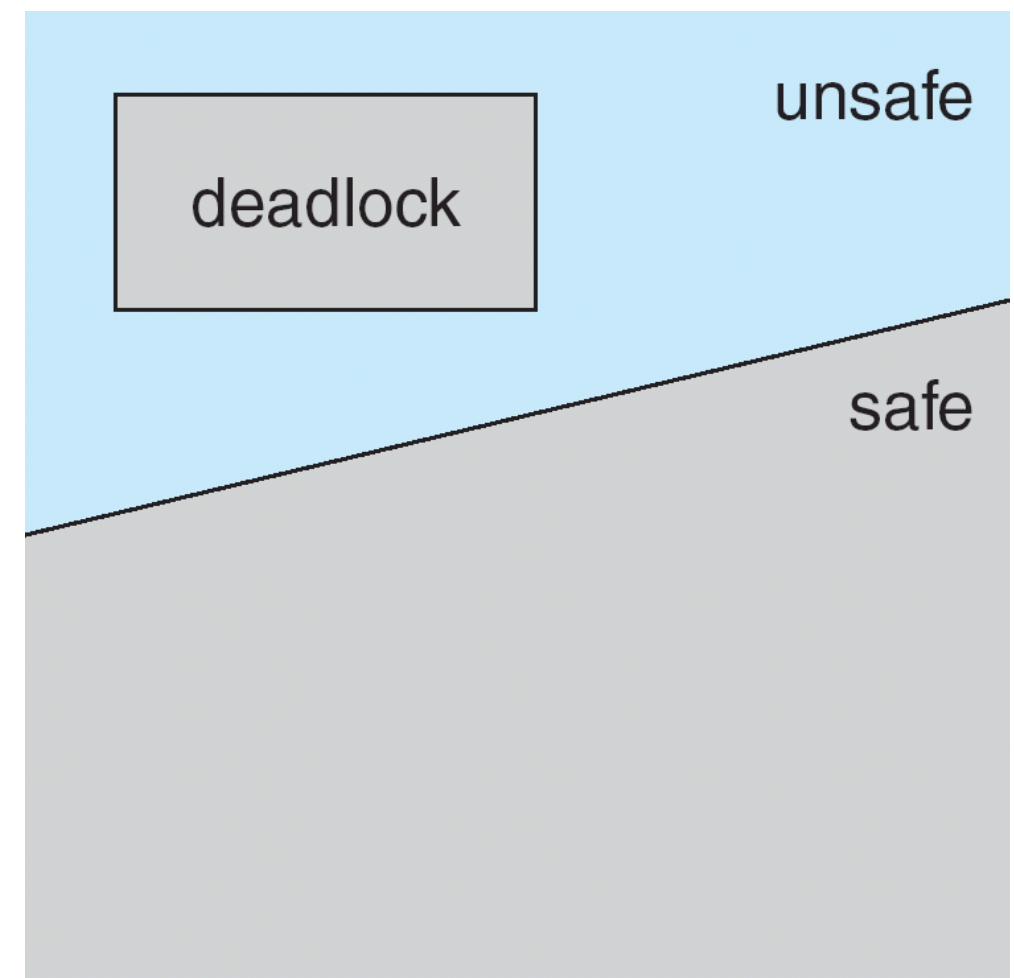
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- When a process requests an available resource, system must decide if immediate allocation leaves the system in a safe state
- In a **safe state** if the system can allocate resources to each process (up to its maximum) in some order and still avoid deadlock
- System is in **safe state** if there exists a sequence  $\langle P_1, P_2, \dots, P_n \rangle$  of ALL the processes in the systems such that for each  $P_i$ , the resources that  $P_i$  can still request can be satisfied by currently available resources plus resources held by all the  $P_j$ , with  $j < i$
- That is:
  - If resources needed by  $P_i$  are not immediately available, then  $P_i$  can wait until all  $P_j$  have finished
  - When  $P_j$  is finished,  $P_i$  can obtain the resources it needs, execute, return allocated resources, and terminate
  - When  $P_i$  terminates,  $P_{i+1}$  can obtain the resources it needs, and so on

# Safe, Unsafe, Deadlock State

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- If a system is in **safe state**  $\Rightarrow$  no deadlocks
- If a system is in **unsafe state**  $\Rightarrow$  possibility of deadlock
- To avoid deadlock, ensure that a system will never enter an unsafe state



# Avoidance Algorithms

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- **Two main avoidance algorithms ... choice depends on how many instances of available resource types exist**
  - **Single instance** of a resource type
    - Use a resource-allocation graph
  - **Multiple instances** of a resource type
    - Use the Banker's Algorithm

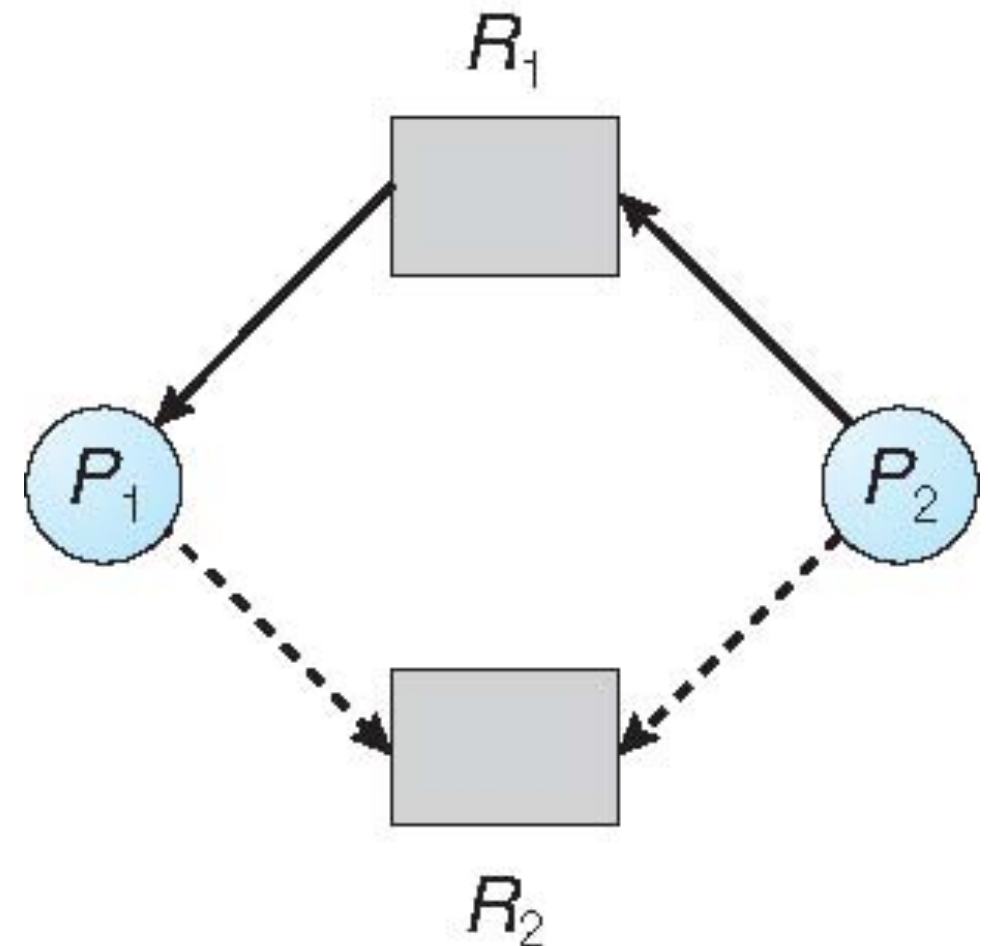
# Resource-Allocation Graphs for Deadlock Avoidance

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- **Introduce a new type of edge to the resource-allocation graph, the claim edge**
  - A **claim edge**  $P_i \rightarrow R_j$  indicates that process  $P_i$  may request a resource  $R_j$
  - A **claim edge** is represented as dashed lines in resource-allocation graph
  - Resources must be claimed a priori in the system, so all claim edges are known
- **A claim edge converts to request edge when a process actually requests a resource**
- **A request edge is converted to an assignment edge when the resource is allocated to the process**
- **When a resource is released by a process, an assignment edge converts back to a claim edge**

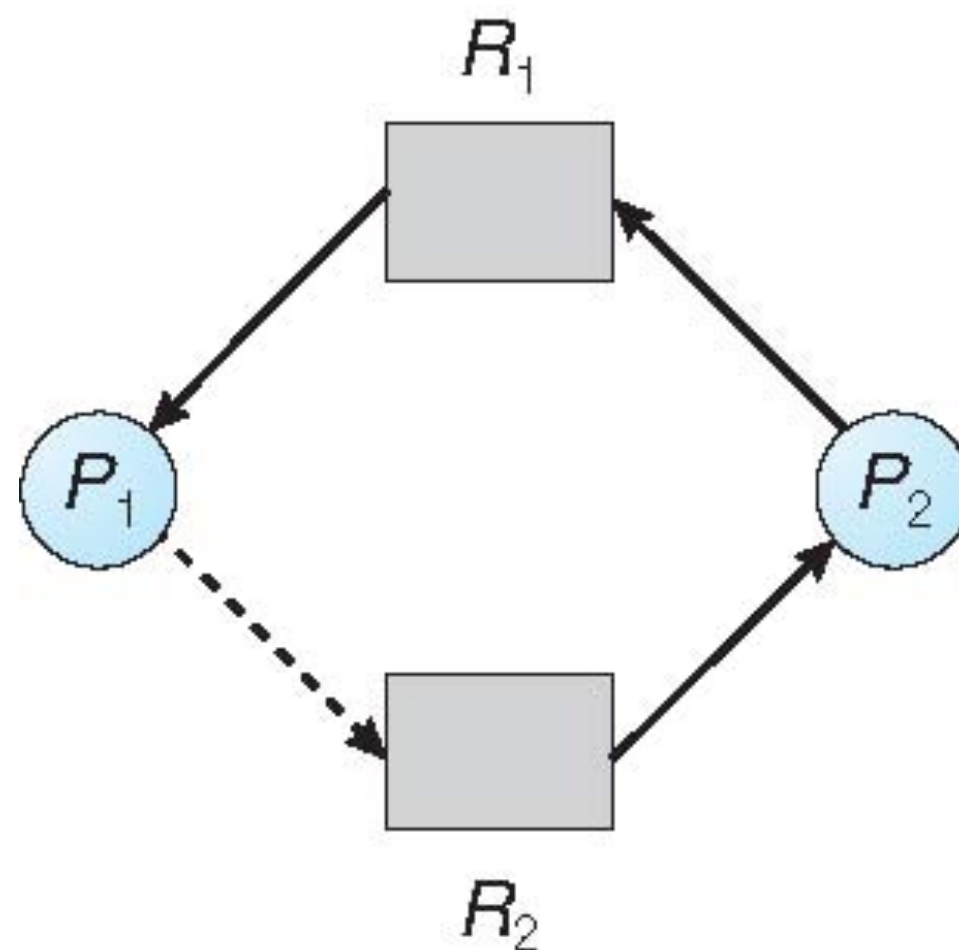
# Resource-Allocation Graph

- In this graph, both processes  $P_1$  and  $P_2$  may eventually want to request resource  $R_2$ 
  - Claim edges exists, because the system knows in advance that  $P_1$  and  $P_2$  may both want to request  $R_2$
- Currently, there are no cycles in the graph so the system is in a **safe state**
- If process  $P_2$  were to request resource  $R_2$  and be granted that resource then ...



# Unsafe State In Resource-Allocation Graph

- If process  $P_2$  were to request resource  $R_2$  and be granted that resource then a cycle is formed in the resource-allocation graph
- The system is not yet deadlocked, but is in an **unsafe state**
- If process  $P_1$  were to request resource  $R_2$ , then the system would be in a deadlocked state
- To prevent an unsafe state and the possibility of deadlock,  $P_2$  should not be allocated resource  $R_2$  when it makes the request,  $P_2$  must wait for  $P_1$  to release  $R_1$  so that no cycles are created





# Banker's Algorithm

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- **Use for deadlock avoidance when multiple instances of resources exist**
- **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**
- **Banker's algorithm needs to know three things to work:**
  - How much of each resource each process could possibly request
  - How much of each resource each process is currently holding
  - How much of each resource the system currently has available

# Data Structures for the Banker's Algorithm

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- **Let  $n$  = number of processes, and  $m$  = number of resource types**
  - **Available** -- Vector of length  $m$  that indicates the number of available resources of each type. If  $Available[j] = k$ , there are  $k$  instances of resource type  $R_j$  available
  - **Max** --  $n \times m$  matrix that defines the maximum demand of each process on each resource type. 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 that defines the number of resources of each type currently allocated to each process. If  $Allocation[i,j] = k$  then  $P_i$  is currently allocated  $k$  instances of  $R_j$
  - **Need** --  $n \times m$  matrix that indicates the remaining resource needs of each process. If  $Need[i,j] = k$ , then  $P_i$  may need  $k$  more instances of  $R_j$  to complete its task

$$Need[i,j] = Max[i,j] - Allocation[i,j]$$

# Banker's Algorithm -- Safety Procedure

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- **Used to determine whether or not a system is in a safe state**
- **Local Data Structures**
  - *Finish* -- a vector[1 .. n] , initialize as *false* for each process  $P_i$
- **The procedure to check for a safe state:**
  - (1) Find a process  $P_i$  such that  $Finish[i] = false$  and  $Need_i \leq Available$   
If  $P_i$  exists do the following:  
*Available = Available + Allocation<sub>i</sub>*  
*Finish[i] = true*  
Go back to Step #1
  - (2) If no such process  $P_i$  exists  
If  $Finish[i] = true$  for all processes  $P_i$  for  $i=1 .. n$ , then the system is in a safe state  
Otherwise, processes with a  $Finish[i]$  value of *false* are in an unsafe state and can potentially deadlock

# Example of Banker's Algorithm-Check Safe State

- **Consider a system with**
  - Five processes  $P_0 - P_4$
  - Three resource types, A (10 instance), B (5 instances), and C (7 instances)
- **At some time  $t_0$ , the system looks like the following:**

	<u>Allocation</u>			<u>Max</u>		
	<u>A</u>	<u>B</u>	<u>C</u>	<u>A</u>	<u>B</u>	<u>C</u>
$P_0$	0	1	0	7	5	3
$P_1$	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

<u>Available</u>		
<u>A</u>	<u>B</u>	<u>C</u>
3	3	2

- **Is this a safe state?**

# Example of Banker's Algorithm-Check Safe State (Cont.)

- The  $n \times m$  matrix *Need* is defined as
  - $Need[i,j] = Max[i,j] - Allocation[i,j]$
- The sequence  $\langle P_1, P_3, P_0, P_2, P_4 \rangle$  is a safe sequence (there are other safe sequences as well)

	<u>Allocation</u>	<u>Max</u>	<u>Need</u>
	<u>A B C</u>	<u>A B C</u>	<u>A B C</u>
$P_0$	0 1 0	7 5 3	7 4 3
$P_1$	2 0 0	3 2 2	1 2 2
$P_2$	3 0 2	9 0 2	6 0 0
$P_3$	2 1 1	2 2 2	0 1 1
$P_4$	0 0 2	4 3 3	4 3 1

<u>Available</u>
<u>A B C</u>
3 3 2

# Banker's Algorithm -- Resource-Request

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- **Used to determine whether requests for resources can be safely granted**
- **Local Data Structure**
  - *Request<sub>i</sub>* -- a vector[1 .. m], is a request vector for process  $P_i$ , the number of additional resources, of each type 1..m, that process  $P_i$  is requesting
- **The procedure to determine if resource can be safely granted**
  - (1) If ( $Request_i > Need_i$ ) then raise an error -- process  $P_i$  is trying to get more resources than it initially declared it would need
  - (2) If ( $Request_i > Available_i$ ) then process  $P_i$  must wait because there are not currently sufficient resources available to satisfy the request
  - (3) Pretend to allocate the requested resources to process  $P_i$ 
    - $Available = Available - Request_i$
    - $Allocation_i = Allocation_i + Request_i$
    - $Need_i = Need_i - Request_i$
  - (4) Check the safety of the state that would result from step #3
    - If step#3 produces a safe state, then the resources are allocated for real
    - If step#3 produces an unsafe state, then don't allocate the resources to process  $P_i$ , the process must wait

# Example of Banker's Algorithm - $P_1$ Request

- Since the system is in a safe state, use the **Resource Request procedure** to determine if the following request can be granted
  - $P_1$  requests one instance of resource A, and two instances of resource C  
The request vector looks like -->  $Request_1 = (1, 0, 2)$
  - First note if the resources are available to fulfill this request:  $Request_1 \leq Available$

	<u>Allocation</u>	<u>Max</u>	<u>Need</u>
	<u>A B C</u>	<u>A B C</u>	<u>A B C</u>
$P_0$	0 1 0	7 5 3	7 4 3
$P_1$	2 0 0	3 2 2	1 2 2
$P_2$	3 0 2	9 0 2	6 0 0
$P_3$	2 1 1	2 2 2	0 1 1
$P_4$	0 0 2	4 3 3	4 3 1

<u>Available</u>
<u>A B C</u>
3 3 2



$(1, 0, 2) \leq (3, 3, 2)$
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## Example of Banker's Algorithm - $P_1$ Request (Cont.)

- After determining that the resources are actually available, pretend to allocate them to process  $P_1$
- Update the *Allocation*, *Need* and *Available* values
- Check to see if this new state is safe, if yes, then allocate resources for real

	<u>Allocation</u>	<u>Max</u>	<u>Need</u>
	<u>A B C</u>	<u>A B C</u>	<u>A B C</u>
$P_0$	0 1 0	7 5 3	7 4 3
$P_1$	2 0 0	3 2 2	1 2 2
$P_1$	3 0 2	3 2 2	0 2 0
$P_2$	3 0 2	9 0 2	6 0 0
$P_3$	2 1 1	2 2 2	0 1 1
$P_4$	0 0 2	4 3 3	4 3 1

<u>Available</u>
<u>A B C</u>
3 3 2
2 3 0

- Is this a safe state?

The sequence  $\langle P_1, P_3, P_4, P_0, P_2 \rangle$  is a safe sequence



# Example of Banker's Algorithm - $P_1$ Request (Cont.)

- What if  $P_4$  requests (3, 3, 0) ?

Request cannot be granted, not enough resources available

- What if  $P_0$  requests (0,2,0) ?

Request cannot be granted, system ends up in an unsafe state

	<u>Allocation</u>			<u>Max</u>	<u>Need</u>
	<u>A B C</u>	<u>A B C</u>	<u>A B C</u>	<u>A B C</u>	
$P_0$	0 1 0	7 5 3	7 4 3		
$P_1$	3 0 2	3 2 2	0 2 0		
$P_2$	3 0 2	9 0 2	6 0 0		
$P_3$	2 1 1	2 2 2	0 1 1		
$P_4$	0 0 2	4 3 3	4 3 1		

<u>Available</u>		
<u>A</u>	<u>B</u>	<u>C</u>
2	3	0

# Deadlock Detection

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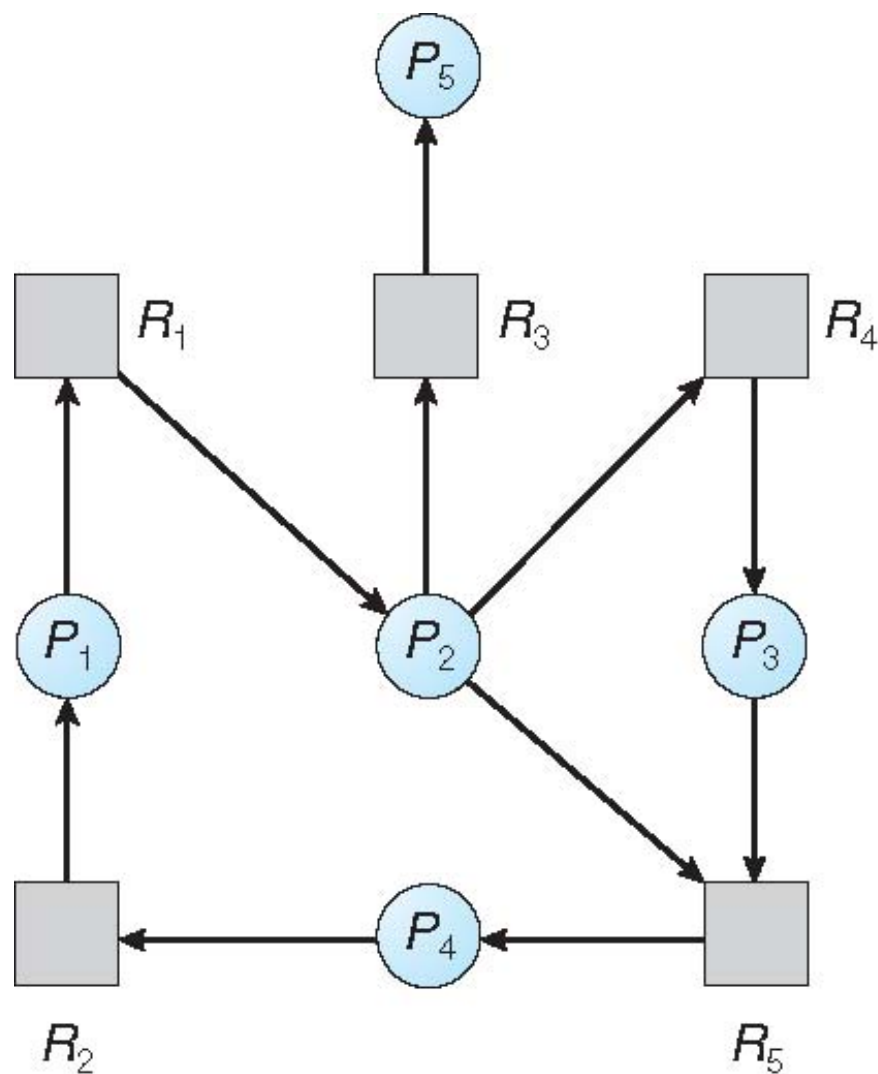
- In systems that don't use **deadlock-prevention** or **deadlock-avoidance**, deadlock may occur
- Such a system may provide:
  - A **deadlock detection** algorithm that determines if a deadlock has occurred in the system
  - A **deadlock recovery** algorithm to recover from deadlock if it has occurred
- As with deadlock avoidance, systems with multiple instances of a single resource type must be considered differently than systems with only single instance resources

# Single Instance of Each Resource Type

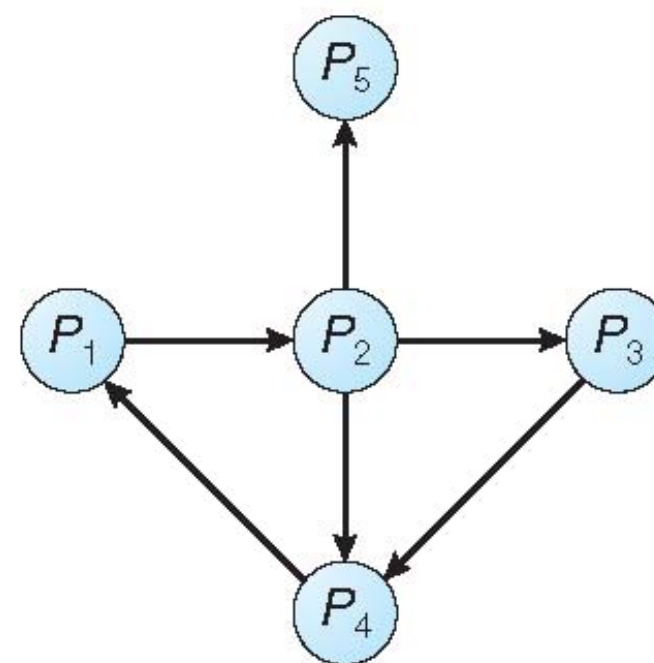
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- **If all resources have only a single instance, use a wait-for graph for deadlock detection**
  - All Nodes are processes
  - An edge  $P_i \rightarrow P_j$  exists if  $P_i$  is waiting for  $P_j$  to release a resource
- **Deadlock exists in the system if and only if the wait-for graph contains a cycle**
- **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

# Several Instances of a Resource Type

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- The wait-for graph cannot be used in systems with multiple instances of each resource type
- The deadlock detection algorithm for several instance contains similar data structures to the Banker's Algorithm
- Let  $n$  = number of processes, and  $m$  = number of resource types
  - *Available* -- Vector of length  $m$  that indicates the number of available resource of each type. If  $available[j] = k$ , there are  $k$  instances of resource type  $R_j$  available
  - *Allocation* --  $n \times m$  matrix that defines the number of resources of each type currently allocated to each process. If  $Allocation[i,j] = k$  then  $P_i$  is currently allocated  $k$  instances of  $R_j$
  - *Request* --  $n \times m$  matrix that indicates the current request of each process. If  $Request[i,j] = k$  then process  $P_i$  is requesting  $k$  more instances of resource type  $R_j$

# Deadlock Detection Algorithm

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- **Used to determine whether or not a system is in a deadlocked state (very similar to Banker's Algorithm safety procedure)**
- **Local Data Structures**
  - *Finish* -- a vector[1 .. n] , initialize as *false* for each process  $P_i$  where  $Allocation_i \neq 0$ , *true* otherwise
- **The procedure to check for a deadlocked state:**
  - (1) Find a process  $P_i$  such that  $Finish[i] = false$  and  $Request_i \leq Available$   
If  $P_i$  exists do the following:  
*Available = Available + Allocation<sub>i</sub>*  
*Finish[i] = true*  
Go back to Step #1
  - (2) If no such process  $P_i$  exists  
If *Finish[i] = false* for a processes  $P_i$  for  $i=1 .. n$ , then  $P_i$  is in a deadlocked state

# Example of Deadlock Detection Algorithm

- Consider a system with
  - Five processes  $P_0 - P_4$
  - Three resource types, A (7 instance), B (2 instances), and C (6 instances)
- At some time  $T_0$ , the system looks like the following:

	<u>Allocation</u>			<u>Request</u>		
	<u>A</u>	<u>B</u>	<u>C</u>	<u>A</u>	<u>B</u>	<u>C</u>
$P_0$	0	1	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

<u>Available</u>		
<u>A</u>	<u>B</u>	<u>C</u>
0	0	0

- Is the system deadlocked?

The sequence  $\langle P_0, P_2, P_3, P_1, P_4 \rangle$  will result in  $Finish[i] = true$  for all processes

## Example of Deadlock Detection Algorithm (Cont.)

- Continuing the previous example, suppose that process  $P_2$  now requests one additional resource of type C
- At some time  $T_0$ , the system looks like the following:

	<u>Allocation</u>			<u>Request</u>		
	<u>A</u>	<u>B</u>	<u>C</u>	<u>A</u>	<u>B</u>	<u>C</u>
$P_0$	0	1	0	0	0	0
$P_1$	2	0	0	2	0	2
$P_2$	3	0	3	0	0	1
$P_3$	2	1	1	1	0	0
$P_4$	0	0	2	0	0	2

<u>Available</u>		
<u>A</u>	<u>B</u>	<u>C</u>
0	0	0

- Is the system deadlocked?

Can only reclaim resources held by  $P_0$ . Insufficient resources to handle the requests from other processes. **Deadlock exists** consisting of processes  $P_1$ ,  $P_2$ ,  $P_3$ , and  $P_4$



# Deadlock Detection Algorithm Usage

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- **When, and how often, to invoke the detection algorithm depends on:**
  - How often a deadlock is likely to occur?
  - How many processes will need to be rolled back?
- **If the detection algorithm is invoked every time a request for allocation cannot be granted:**
  - The algorithm can detect specifically which processes caused the deadlock
  - There is a lot of computational overhead when running the algorithm so frequently
- **If the detection algorithm is invoked less frequently (e.g. once per hour):**
  - It is difficult to determine which processes caused the deadlock
  - The computational overhead can be reduced

# Deadlock Recovery

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- **Once deadlock has been detected in a system there are several options for dealing with deadlock**
  - Notify the system user and let them deal with it
  - Have the system terminate one or more processes
  - Have the system preempt resources from one or more of the deadlocked processes

# Deadlock Recovery: Process Termination

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- **When terminating processes to recover from deadlock, resources are reclaimed from any terminated process**
  - Terminating a process means that work done by that process may be lost
- **Two options:**
  - Abort all deadlocked processes
    - Potential to lose a lot of work / computation time
  - Abort one process at a time until the deadlock cycle is eliminated
    - Lots of overhead since the deadlock-detection algorithm must be run after each process is terminated

# Deadlock Recovery: Process Termination (Cont.)

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- **If terminating processes, in what order should processes be terminated?**
- **Consider:**
  - 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?

# Deadlock Recovery: Resource Preemption

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- **Continually preempt the resources from processes and give those resources to other processes until the system is no longer deadlocked**
- **Must consider the following:**
  - How should victims be selected? And how can cost be minimized?
  - How should a preempted process get rolled back?
    - Would like to return the process to some safe state without having to completely restart the process. To do so requires some fancy bookkeeping by the system to know where the most recent safe state was prior to the deadlock.
  - How to ensure that starvation does not occur?
    - Don't want resources to always get preempted from the same process