Chapter 7
Deadlocks

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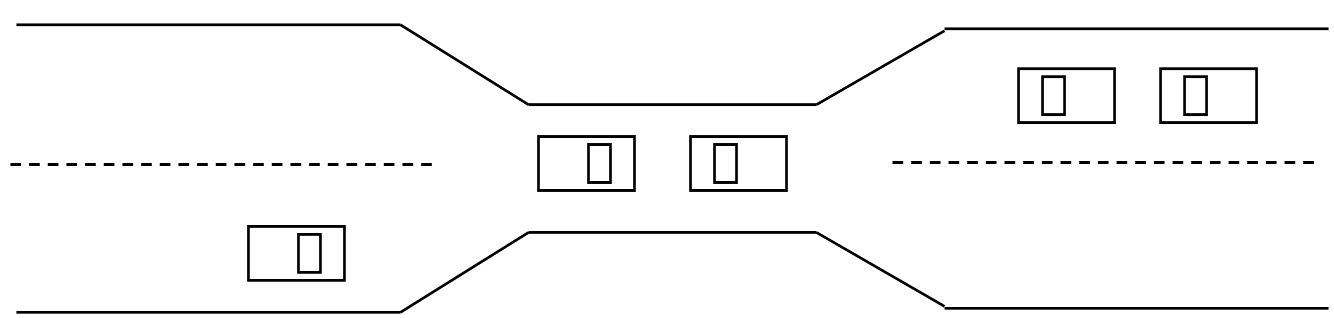
The Deadlock Problem

- **Deadlock**: a set of blocked processes each holding a resource and waiting to acquire a resource held by another process in the set
- Examples:
  - a system has 2 disk drives, P_1 and P_2 each hold one disk drive and each needs another one
  - semaphores A and B, initialized to 1

P_1	P_2
wait (A);	wait(B)
wait (B);	wait(A)

Bridge Crossing Example

- Traffic only in one direction, each section 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
  - starvation is possible
- Note: most OSes do not prevent or deal with deadlocks



System Model

- Resources: $R_1, R_2, . . ., R_m$
  - each represents a different **resource type**
    - e.g., CPU cycles, memory space, I/O devices
  - each resource type R_i has W_i **instances**.
- Each process utilizes a resource in the following pattern
  - request
  - use
  - release

Four Conditions of Deadlock

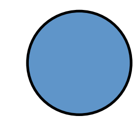
- **Mutual exclusion**: only one process at a time can use a resource
- **Hold and wait**: a process holding at least one resource is waiting to acquire additional resources held by other processes
- **No preemption**: a resource can be released only **voluntarily** by the process holding it, after it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

Resource-Allocation Graph

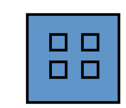
- Two types of nodes:
  - $P = \{P_1, P_2, \ldots, P_n\}$, the set of all the **processes** in the system
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set of all **resource** types in the system
- Two types of edges:
  - **request edge**: directed edge $P_i \rightarrow R_j$
  - **assignment edge**: directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph

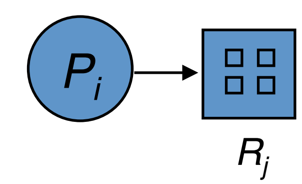
- Process



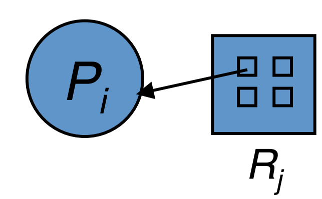
- Resource Type with 4 instances



- Pi requests instance of Rj

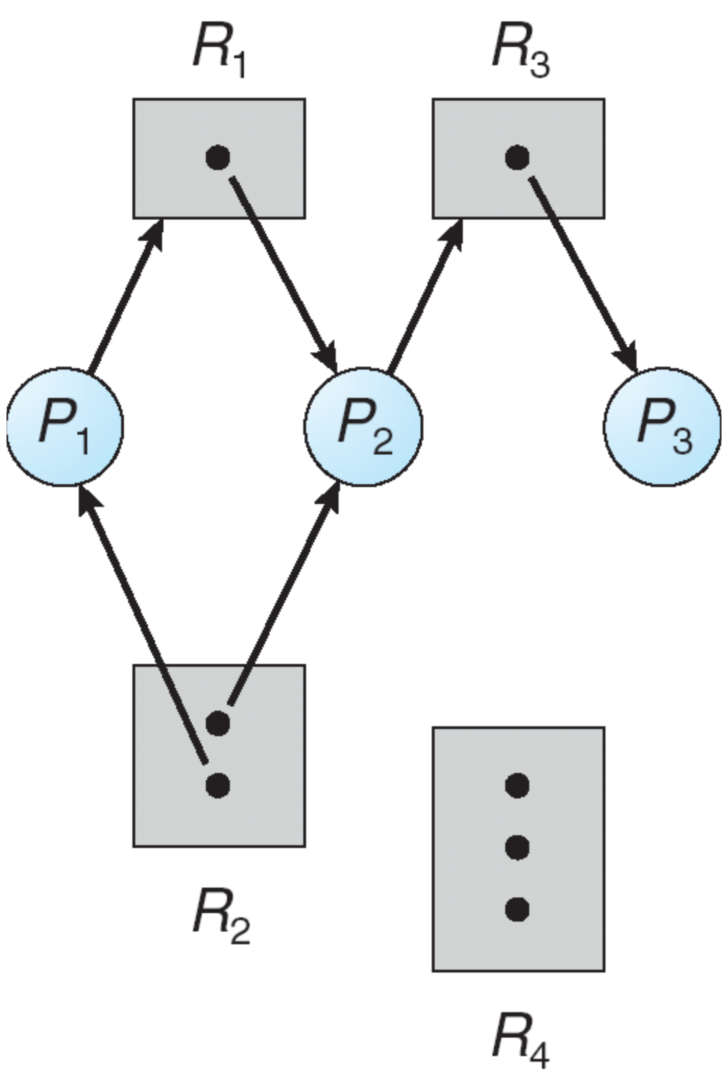


- Pi is holding an instance of Rj



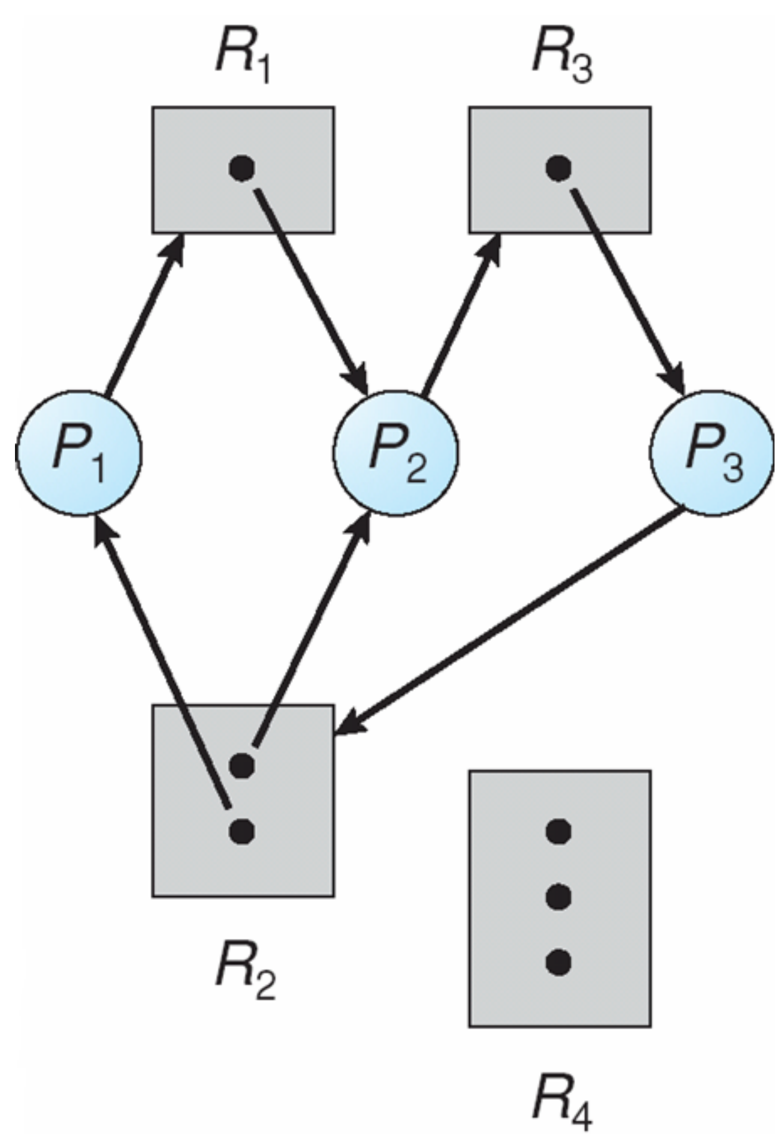
Resource Allocation Graph

- Is there a deadlock?



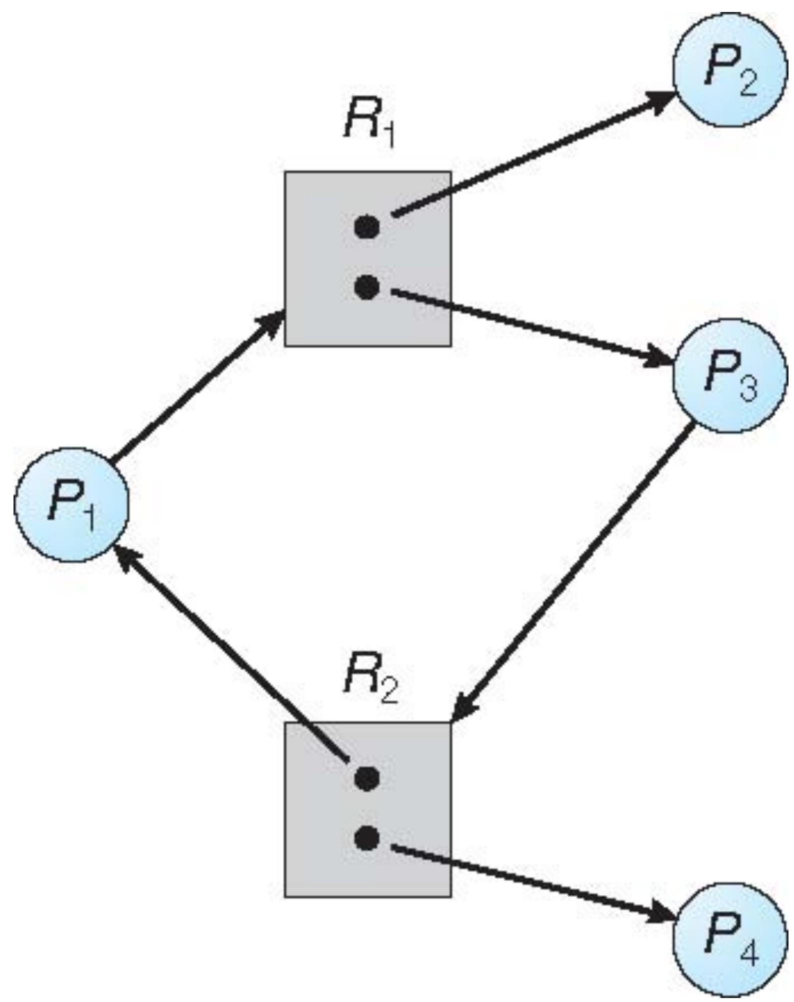
Resource Allocation Graph

- Is there a deadlock?



Resource Allocation Graph

- Is there a deadlock?
  - **circular wait does not necessarily lead to deadlock**



Basic Facts

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

How to Handle Deadlocks

- **Deadlock prevention**: ensure that the system will never enter a deadlock state
- **Deadlock detection and recovery**: allow the system to enter a deadlock state and then recover
- **Ignore the problem** and pretend deadlocks never occur in the system

Deadlock Prevention

- How to prevent **mutual exclusion**
  - not required for sharable resources
  - must hold for non-sharable resources
- How to prevent **hold and wait**
  - whenever a process requests a resource, it doesn't hold any other resources
    - require process to request *all* its resources before it begins execution
    - allow process to request resources only when the process has none
  - low resource utilization; starvation possible

Deadlock Prevention

- How to handle **no preemption**
  - if a process requests a resource not available
    - release all resources currently being held
    - preempted resources are added to the list of resources it waits for
    - process will be restarted only when it can get all waiting resources
- How to handle **circular wait**
  - **impose a total ordering of all resource types**
  - require that each process requests resources in an increasing order
  - **Many operating systems adopt this strategy for some locks.**

Deadlock Avoidance

- Each process declares a **max** number of resources it may need
- Deadlock-avoidance algorithm ensure there can **never** be a **circular-wait** condition
- Resource-allocation state:
  - the number of **available** and **allocated** resources
  - the **maximum demands** of the processes

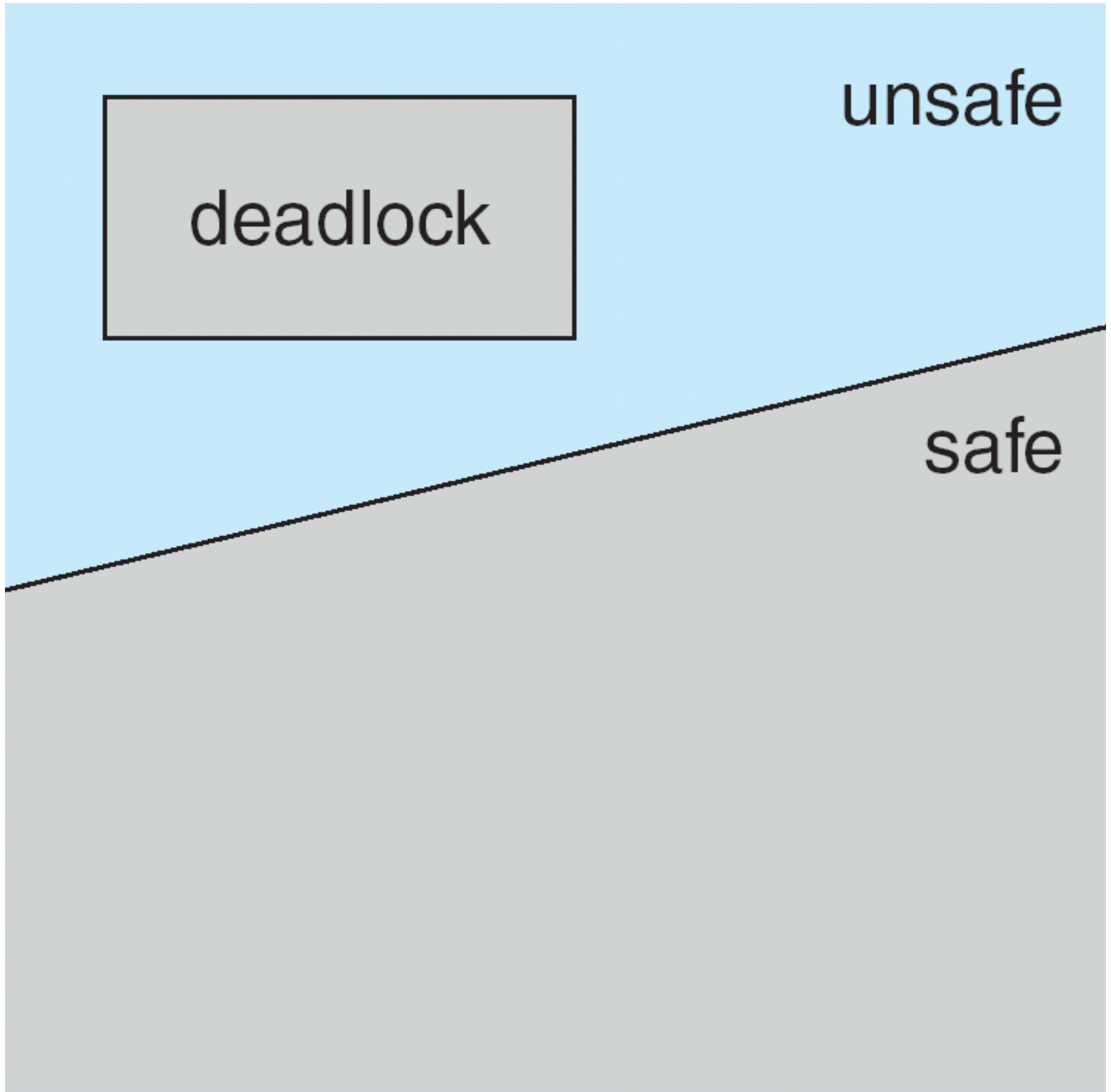
Safe State

- When a process requests an available resource, system must decide if immediate allocation leaves the system in a **safe state**:
  - there exists a sequence **$<P_1, P_2, \ldots, P_n>$** of all processes in the system
  - for each P_i, resources that P_i can still request can be satisfied by currently **available resources** + **resources held by all the P_j, with $j < i$**
- **Safe state can guarantee no deadlock**
  - if P_i's resource needs are not immediately available:
    - wait until all P_j have finished ($j < i$)
    - when P_j ($j < i$) has finished, P_i can obtain needed resources,
  - when P_i terminates, P_{i+1} can obtain its needed resources, and so on

Basic Facts

- If a system is in **safe state** ➠ **no deadlocks**
- If a system is in **unsafe state** ➠ **possibility of deadlock**
- **Deadlock avoidance** ➠ ensure a system **never enters an unsafe state**

Deadlock Avoidance



Deadlock Avoidance Algorithms

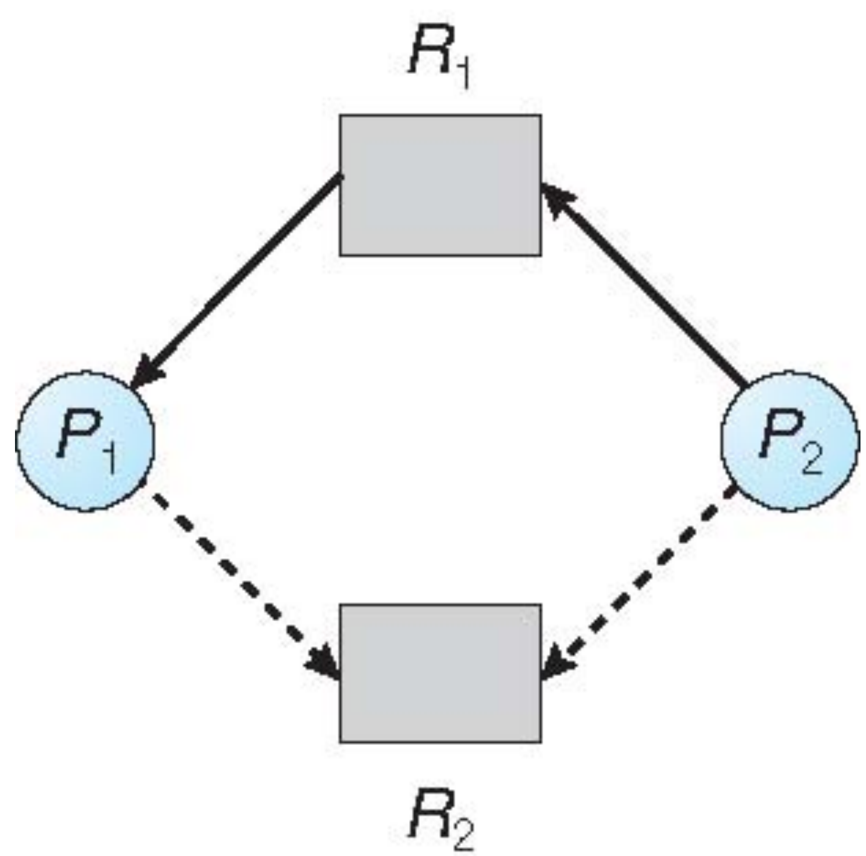
- Single instance of each resource type ➠ use **resource-allocation graph**
- Multiple instances of a resource type ➠ use the **banker's algorithm**

Single-instance Deadlock Avoidance

- Resource-allocation graph can be used for **single instance resource** deadlock avoidance
  - one new type of edge: **claim edge**
    - claim edge $P_i \rightarrow R_j$ indicates that process P_i *may* request resource R_j
    - claim edge is represented by a dashed line
  - **resources must be claimed a priori in the system**
- Transitions in between edges
  - ***claim edge*** converts to ***request edge*** when a process requests a resource
  - ***request edge*** converts to an ***assignment edge*** when the resource is allocated to the process
  - ***assignment edge*** reconverts to a ***claim edge*** when a resource is released by a process

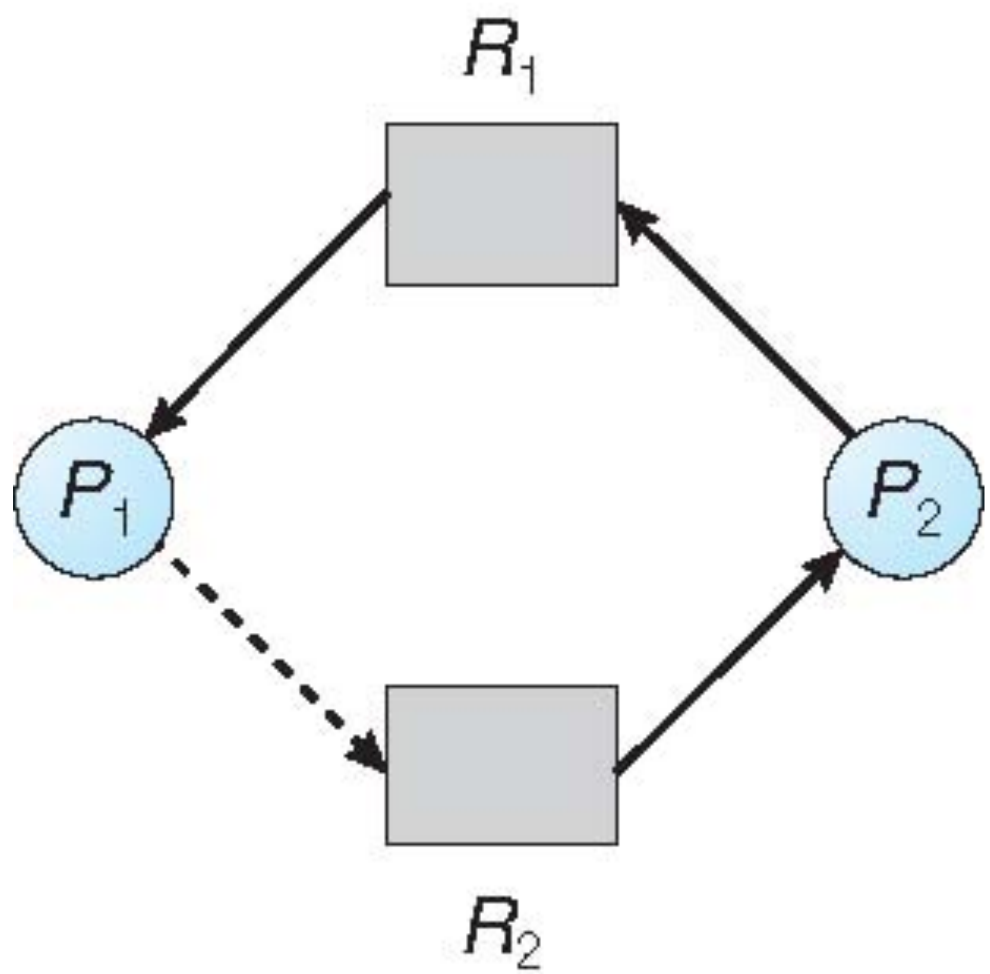
Single-instance Deadlock Avoidance

- Is this state safe?



Single-instance Deadlock Avoidance

- Is this state safe?



Single-instance Deadlock Avoidance

- 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**
  - **no cycle ➠ safe state**

Banker’s Algorithm

- Banker’s algorithm is for **multiple-instance resource deadlock avoidance**
  - each process must a priori claim **maximum** use of each resource type
  - when a process requests a resource it may have to wait
  - when a process gets all its resources it must release them in a finite amount of time

Data Structures for the Banker's Algorithm

- **n** processes, **m** types of resources
  - **available**: an array of length ***m***, instances of available resource
    - available[j] = k: k instances of resource type R_j available
  - **max**: a ***n x m*** matrix
    - max [i,j] = k: process P_i may request at most k instances of resource R_j
  - **allocation**: ***n x m*** matrix
    - allocation[i,j] = k: P_i is currently allocated k instances of R_j
  - **need**: ***n x m*** matrix
    - need[i,j] = k: 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: **Safe State**

- Data structure to compute whether the system is in a safe state
  - use **work** (a vector of length *m*) to track **allocatable resources**
    - **unallocated** + **released by finished processes**
  - use **finish** (a vector of length n) to track whether process has finished
  - initialize: **work** = **available**, **finish[i]** = **false** for i = 0, 1, …, n- 1
- Algorithm:
  - find an i such that **finish[i] = false && need[i] ≤ work** if no such i exists, go to step 3
  - **work = work + allocation[i]**, **finish[i] = true**, go to step 1
  - if finish[i] == true for all i, then the system is in a safe state

Bank's Algorithm: **Resource Allocation**

- Data structure: request vector for process P_i
  - **request**[j] = k then process P_i wants k instances of resource type R_j
- Algorithm:

1. if $request_i \leq$ need[i] go to step 2; otherwise, raise error condition (the process has exceeded its maximum claim)
2. if $request_i \leq$ available, go to step 3; otherwise P_i must wait (not all resources are not available)
3. pretend to allocate requested resources to P_i by modifying the state:

   available = available – $request_i$

   allocation[i] = allocation[i] + $request_i$

   need[i] = need[i] – $request_i$
4. use **previous algorithm** to test if it is a safe state, if so ➟ allocate the resources to P_i
5. if unsafe ➟ P_i must wait, and the old resource-allocation state is restored

Banker’s Algorithm: Example

- System state:
  - **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	

Banker's Algorithm: Example

- **need** = **max** – **allocation**

	need	available
	A B C	A B C
P_0	7 4 3	3 3 2
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

Banker's Algorithm: Example

- Next, P_1 requests (1, 0, 2), try the allocation. The updated state is:

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

- Sequence $< P_1, P_3, P_4, P_0, P_2 >$ satisfies safety requirement
- Can request for (3,3,0) by P_4 be granted?
- Can request for (0,2,0) by P_0 be granted?

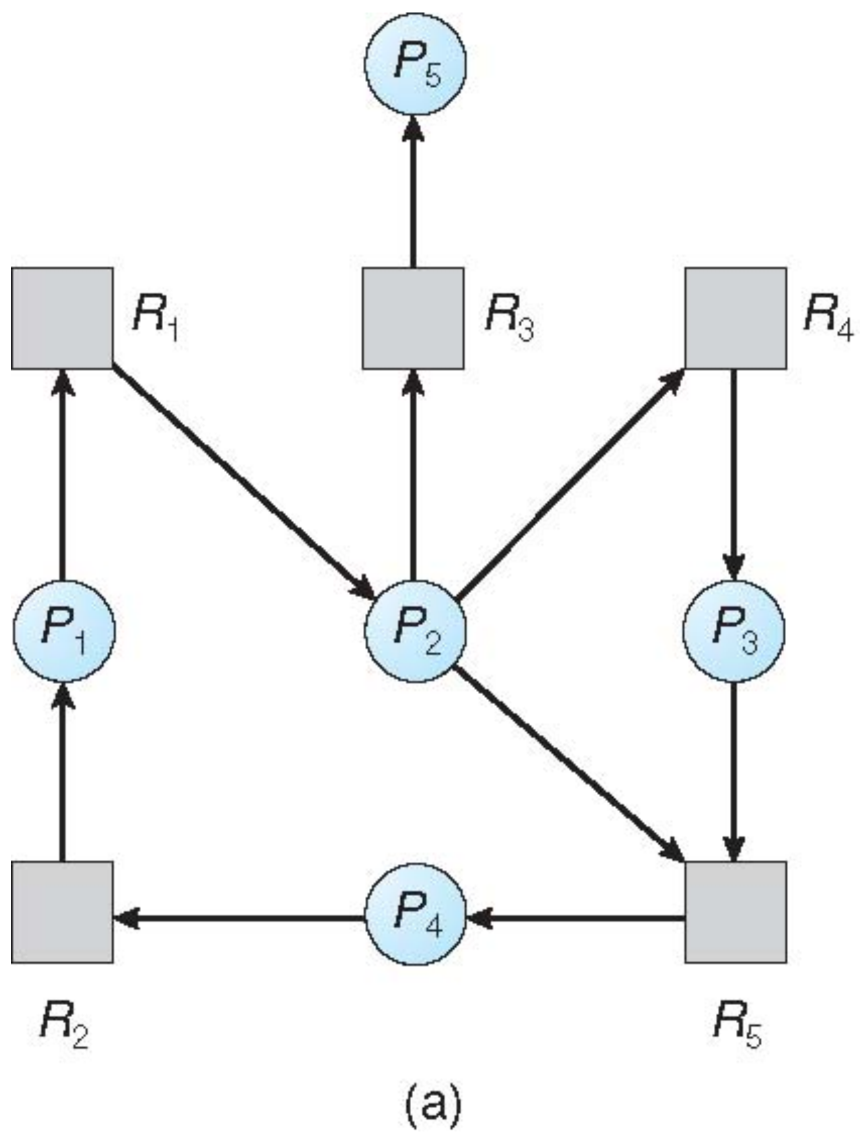
Deadlock Detection

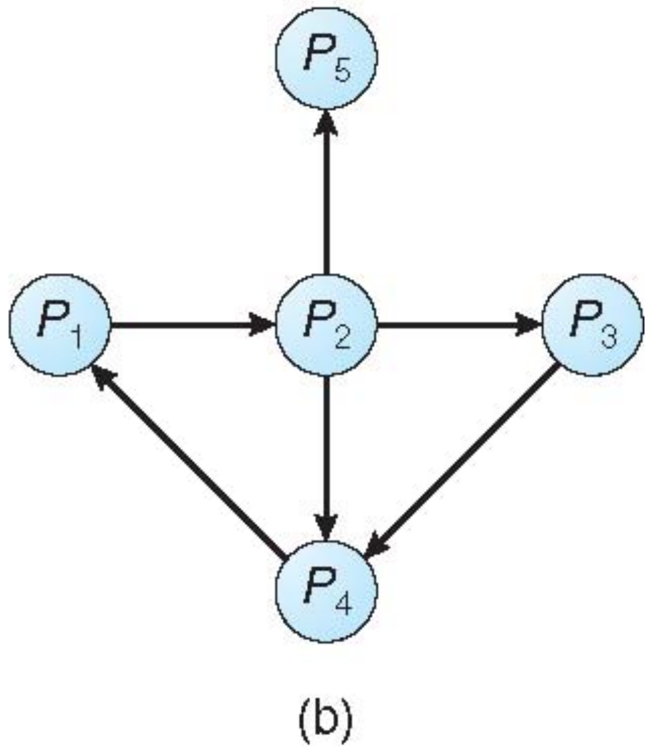
- Allow system to enter deadlock state, but detect and recover from it
- Detection algorithm and recovery scheme

Deadlock Detection: **Single Instance Resources**

- Maintain a 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
  - 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

Wait-for Graph Example





Resource-allocation Graph wait-for graph

Deadlock Detection: **Multi-instance Resources**

- Detection algorithm similar to Banker's algorithm's safety condition
    - to prove it is **not possible** to enter a **safe state**
- Data structure
    - **available**: a vector of length *m,* 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
        - request [i, j] = k: process P_i is requesting k more instances of resource R_j
    - **work**: a vector of *m*, the allocatable instances of resources
    - **finish**: a vector of *m*, whether the process has finished
        - if allocation[i] ≠ 0 ➠ finish[i] = false; otherwise, finish[i] = true

Deadlock Detection: Multi-instance

- Find an process i such that **finish[i] == false && request[i] ≤ work**
  - if no such i exists, go to step 3
- **work = work + allocation[i]**; **finish[i] = true**, go to step 1
- If finish[i] == false, for some i the system is in deadlock state
  - if finish[i] == false, then P_i is deadlocked

Example of Detection Algorithm

- System states:
  - five processes P_0 through P_4
  - three resource types: A (7 instances), B (2 instances), and C (6 instances)
- Snapshot at time T0:

	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

Example (Cont.)

- P2 requests an additional instance of type C

	request
	A B C
P_0	0 0 0
P_1	2 0 2
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

Deadlock Recovery

- Terminate deadlocked processes. options:
  - 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?

End of Chapter 7