Deadlocks

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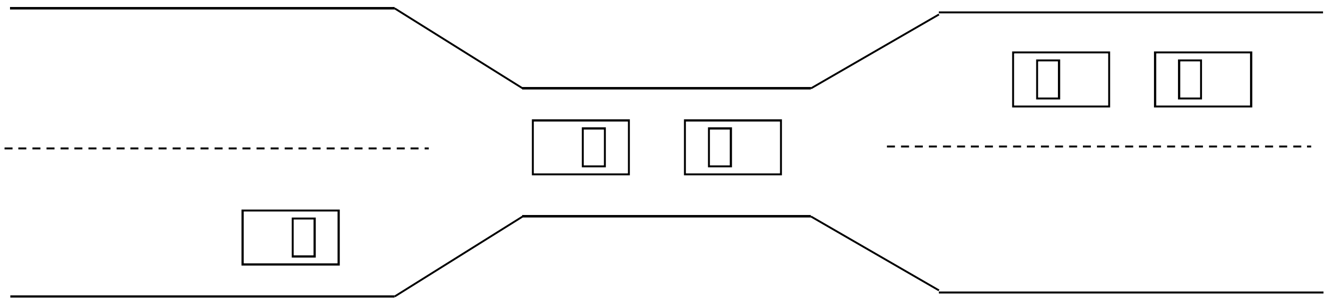
Bridge Crossing Example



- Traffic only in one direction
- Each section of a bridge can be viewed as a resource
- A deadlock occurs when two cars get on the bridge from different directions at the same time

The Problem of Deadlock

- Example
  - System has 2 disk drives
  - P_1 and P_2 each hold one disk drive and each needs another one
- Example
  - semaphores *S* and *Q*, initialized to 1

P_0	P_1
① wait (S);	② wait (Q);
③ wait (Q);	④ wait (S);

- Deadlock: A set of blocked processes each holding some resources and waiting to acquire the resources held by another process in the set

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 $\{P_0, P_1, \ldots, P_n\}$ 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.

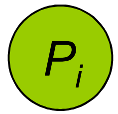
System Model

- Processes $P_1, P_2, \ldots, P_n$
- Resource types $R_1, R_2, \ldots, R_m$

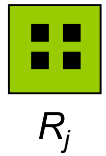
  e.g., CPU, memory space, I/O devices
- Each resource type R_i has W_i instances.
- Each process utilizes a resource as follows:
  - **request**
  - **use**
  - **release**

Resource-Allocation Graph

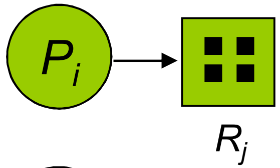
- Deadlocks can be identified with system resource-allocation graph.
  - A set of vertices *V* and a set of edges *E*.
  - *V* is partitioned into two types:
    - $P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system



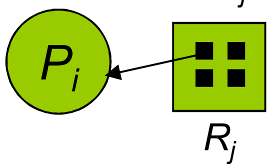
    - $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system



  - *E* has two types:
    - **request edge** – directed edge $P_i \rightarrow R_j$

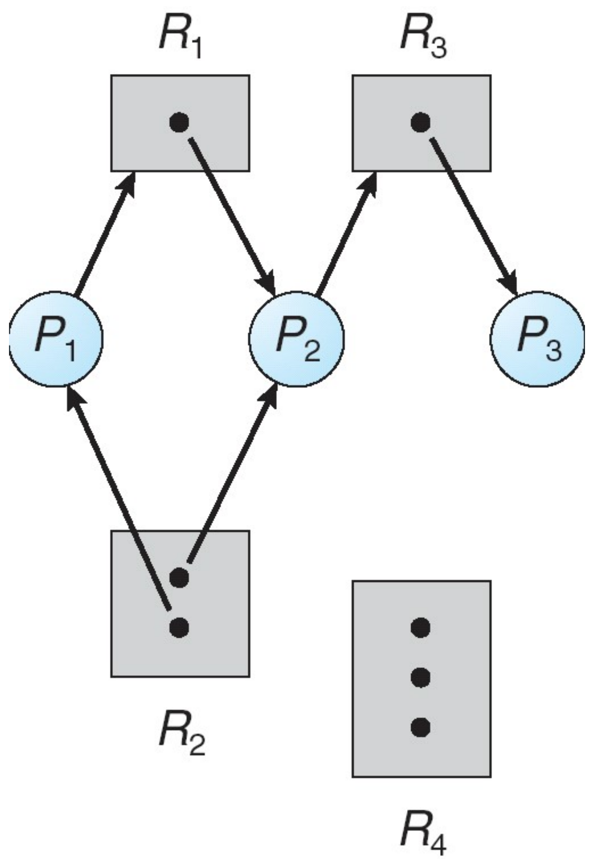


    - **assignment edge** – directed edge $R_j \rightarrow P_i$



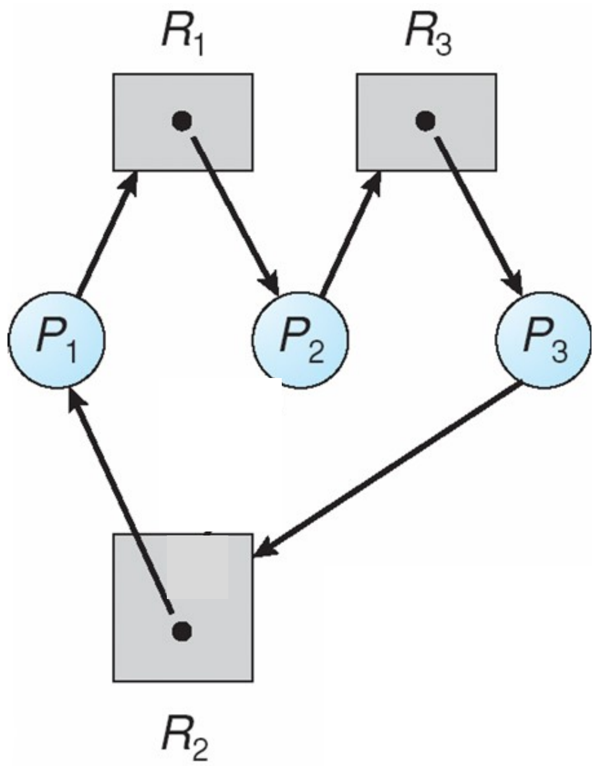
Example of a Resource Allocation Graph

- $P = \{P_1, P_2, P_3\}$
- $R = \{R_1, R_2, R_3, R_4\}$
- Resource instances:
  - $W_1=W_3=1$
  - $W_2=2$
  - $W_4=3$
- $E = \{P_1 \rightarrow R_1, P_2 \rightarrow R_3, R_1 \rightarrow P_2, R_2 \rightarrow P_2, R_2 \rightarrow P_1, R_3 \rightarrow P_3\}$



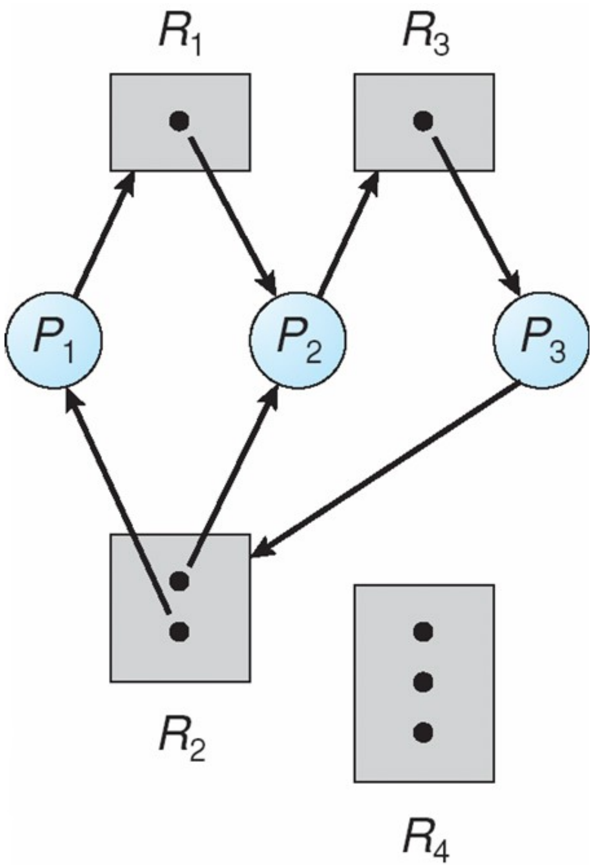
Resource Allocation Graph With A Deadlock

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

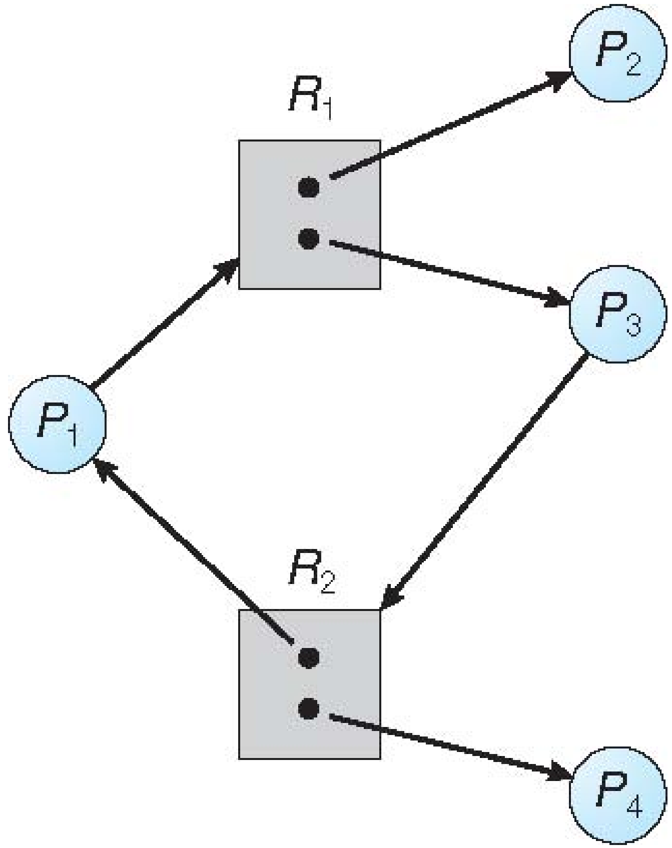


Resource Allocation Graph With A Deadlock

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



Graph With A Cycle But No Deadlock



Basic Facts

- If graph contains no circle $\Rightarrow$ no deadlock
- If graph contains a circle $\Rightarrow$
  - if only one instance per resource type, then deadlock
  - if several instances per resource type, possibility of deadlock
- Question:
  - Can you find a way to determine whether there is a deadlock, given a resource allocation graph with several instances per resource type?

Methods for Handling Deadlocks

- Ensure that the system will ***never*** enter a deadlock state
  - Deadlock prevention
  - Deadlock avoidance

- ***Allow*** the system to enter a deadlock state and then recover
  - Deadlock detection
  - Deadlock recovery

Deadlock Prevention

Restrain the ways request can be made

- **Mutual Exclusion** – not required for sharable resources; must hold for non-sharable 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 (has released all its resources)
  - 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 preempted
  - 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

- 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

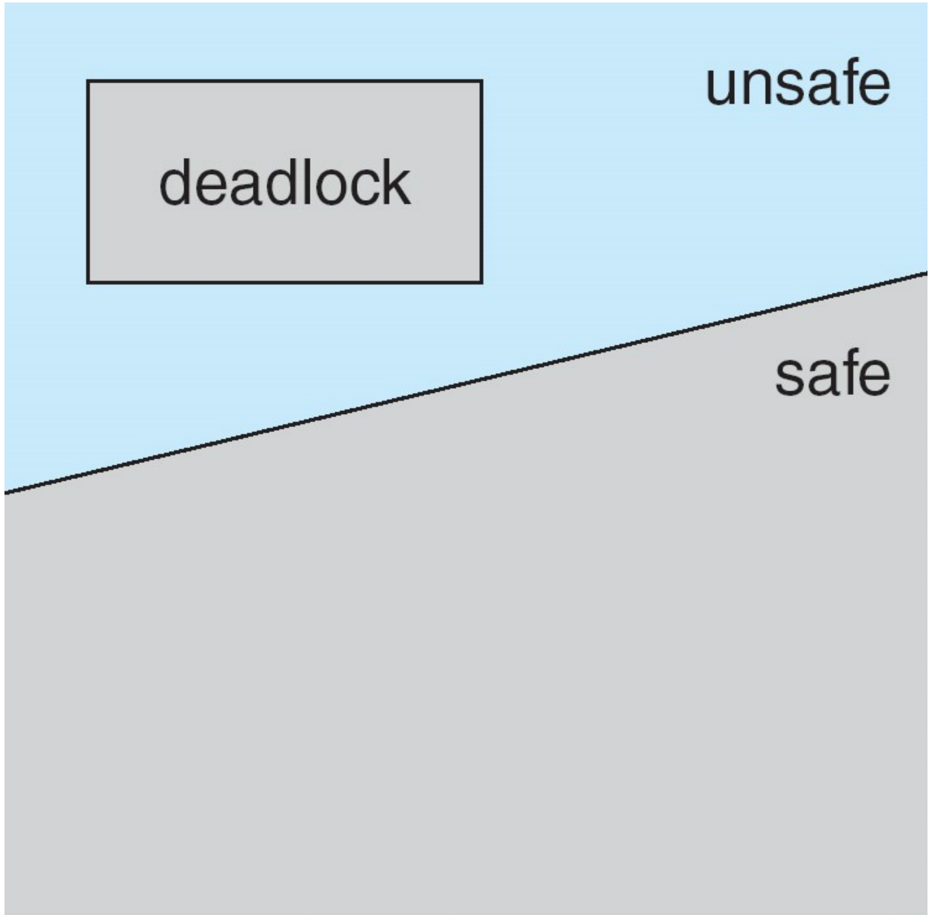
Safe State

- 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** <P_1, P_2, …, P_n> 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 + resources held by all the P_j, with $j < i$
- That is:
  - If P_i's resource needs are not immediately available, then P_i can wait until all P_j have finished
  - When all P_j are 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
- Otherwise, system is in **unsafe state**

Safe, Unsafe, Deadlock State

- 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 States

	Maximum Needs	Holds	Needs
P_0	10	5	5
P_1	4	2	2
P_2	9	2	7

Available
3

Safe sequence: ?

Safe & Unsafe States

	Maximum Needs	Holds	Needs
P_0	10	5	5
P_1	4	4	0
P_2	9	2	7

Available
1

Safe sequence: P_1

Safe & Unsafe States

	Maximum Needs	Holds	Needs
P_0	10	5	5
P_1	4	--	--
P_2	9	2	7

Available
5

Safe sequence: P_1

Safe & Unsafe States

	Maximum Needs	Holds	Needs
P_0	10	10	0
P_1	4	--	--
P_2	9	2	7

Available
0

Safe sequence: $P_1 \rightarrow P_0$

Safe & Unsafe States

	Maximum Needs	Holds	Needs
P_0	10	--	--
P_1	4	--	--
P_2	9	2	7

Available
10

Safe sequence: $P_1 \rightarrow P_0$

Safe & Unsafe States

	Maximum Needs	Holds	Needs
P_0	10	--	--
P_1	4	--	--
P_2	9	9	0

Available
3

Safe sequence: $P_1 \rightarrow P_0 \rightarrow P_2$

Safe & Unsafe States

	Maximum Needs	Holds	Needs
P_0	10	--	--
P_1	4	--	--
P_2	9	--	--

Available
12

Safe sequence: $P_1 \rightarrow P_0 \rightarrow P_2$

Safe & Unsafe States

	Maximum Needs	Holds	Needs
P_0	10	5	5
P_1	4	2	2
P_2	9	3	6

Available
2

Safe sequence: ?

Safe & Unsafe States

	Maximum Needs	Holds	Needs
P_0	10	5	5
P_1	4	--	--
P_2	9	3	6

Available
4

Safe sequence: $P_1 \rightarrow$?

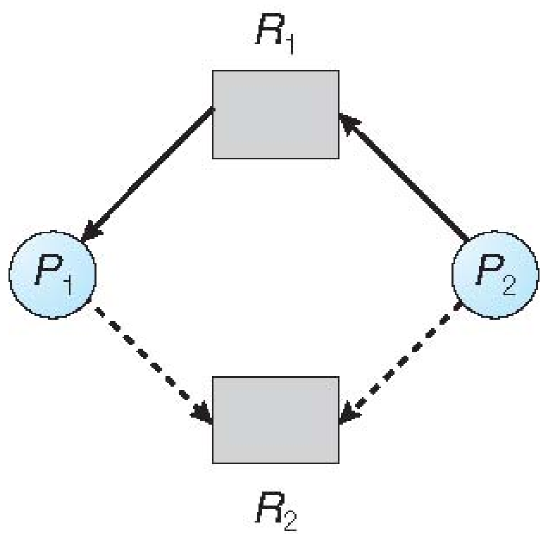
Avoidance Algorithms

- Avoidance algorithms ensure that the system will never deadlock.
  - Whenever a process requests a resource, the request is granted only if the allocation leaves the system in a safe state.

- Two avoidance algorithms
  - Single instance of a resource type
    - Use a resource-allocation graph
  - Multiple instances of a resource type
    - Use the banker's algorithm

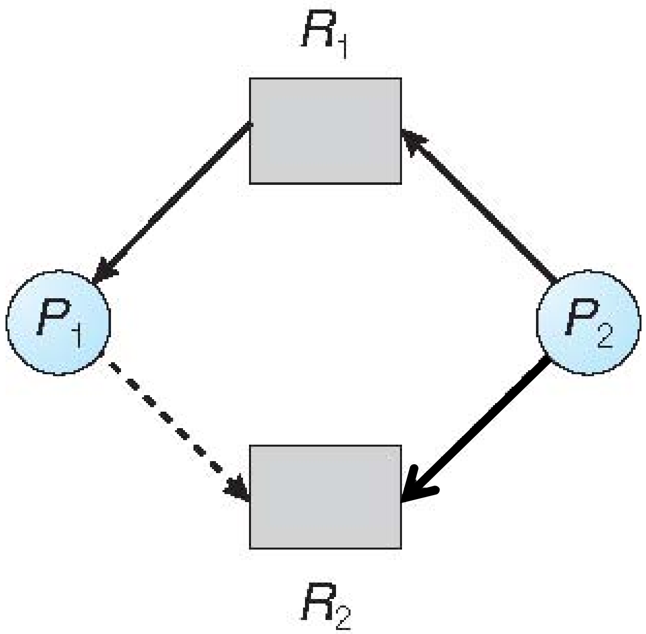
Resource-Allocation-Graph Algorithm

- **Claim edge** $P_i \rightarrow R_j$ indicates that process P_j may request resource R_j; represented by a **directed dashed line**
- Resources must be claimed *a priori* in the system
- 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
- When a resource is released by a process, assignment edge reconverts to a claim edge (the edge is removed if the process finishes)

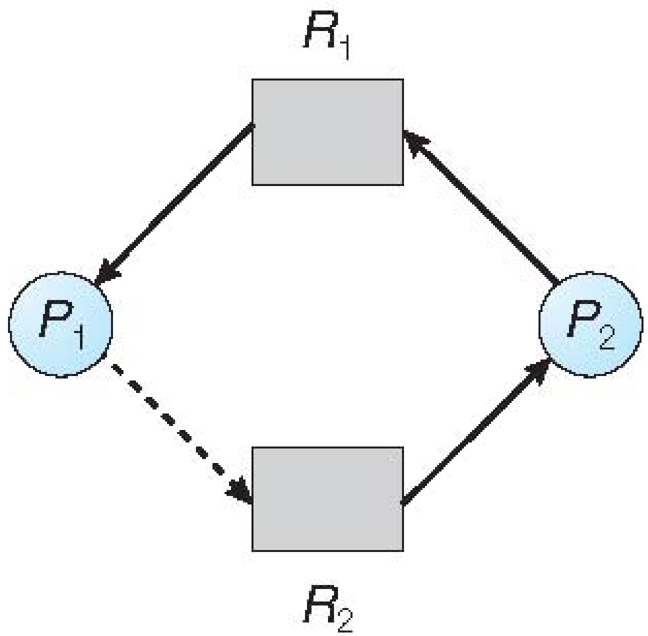


Resource-Allocation Graph Algorithm

- 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 circle in the resource allocation graph



Can we grant P_2's request for R_2?



Circle! Therefore, P_2's request cannot be granted, and P_2 needs to wait.

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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* = 0, 1, …, *n*- 1

2. Find an *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$_i$ = 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 $Request_i \leq Need_i$, 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 P_i*
- *If unsafe $\Rightarrow$ P_i 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* (5 instances), and *C* (7 instances)

Snapshot at time T_0:

	Max	Allocation	Need	Available
	A B C	*A B C*	*A B C*	*A B C*
P_0	7 5 3	0 1 0	7 4 3	3 3 2
P_1	3 2 2	2 0 0	1 2 2	
P_2	9 0 2	3 0 2	6 0 0	
P_3	2 2 2	2 1 1	0 1 1	
P_4	4 3 3	0 0 2	4 3 1	

- Is the system in safe state?

Applying Safety Algorithm

	Max	Allocation	Need	Available
	A B C	*A B C*	*A B C*	*A B C*
P_0	7 5 3	0 1 0	7 4 3	5 3 2
P_2	9 0 2	3 0 2	6 0 0	
P_3	2 2 2	2 1 1	0 1 1	
P_4	4 3 3	0 0 2	4 3 1	

Safe sequence: P_1

Applying Safety Algorithm

	Max	Allocation	Need	Available
	A B C	*A B C*	*A B C*	*A B C*
P_0	7 5 3	0 1 0	7 4 3	7 4 3
P_2	9 0 2	3 0 2	6 0 0	
P_4	4 3 3	0 0 2	4 3 1	

Safe sequence: $P_1 \rightarrow P_3$

Applying Safety Algorithm

	Max	Allocation	Need	Available
	A B C	*A B C*	*A B C*	*A B C*
				7 5 3
P_2	9 0 2	3 0 2	6 0 0	
P_4	4 3 3	0 0 2	4 3 1	

Safe sequence: $P_1 \rightarrow P_3 \rightarrow P_0$

Applying Safety Algorithm

	Max	Allocation	Need	Available
	A B C	*A B C*	*A B C*	*A B C*
				10 5 5
P_4	4 3 3	0 0 2	4 3 1	

Safe sequence: $P_1 \rightarrow P_3 \rightarrow P_0 \rightarrow P_2$

Applying Safety Algorithm

	Max	Allocation	Need	Available
	A B C	*A B C*	*A B C*	*A B C*
				10 5 7

Safe sequence: $P_1 \rightarrow P_3 \rightarrow P_0 \rightarrow P_2 \rightarrow P_4$

Example: P_1 Request (1,0,2)

- Check that Request ≤ Available (that is, (1,0,2) ≤ (3,3,2) ⇒ true)

	Max	Allocation	Need	Available
	A B C	*A B C*	*A B C*	*A B C*
P_0	7 5 3	0 1 0	7 4 3	2 3 0
P_1	3 2 2	3 0 2	0 2 0	
P_2	9 0 2	3 0 2	6 0 0	
P_3	2 2 2	2 1 1	0 1 1	
P_4	4 3 3	0 0 2	4 3 1	

- Executing safety algorithm shows that sequence < P_1, P_3, P_0, P_2, P_4> satisfies safety requirement

Example: P_0 Request (0,2,0)

- Check that Request ≤ Available (that is, (0,2,0) ≤ (2,3,0) ⇒ true)

	Max	Allocation	Need	Available
	A B C	*A B C*	*A B C*	*A B C*
P_0	7 5 3	0 3 0	7 2 3	2 1 0
P_1	3 2 2	3 0 2	0 2 0	
P_2	9 0 2	3 0 2	6 0 0	
P_3	2 2 2	2 1 1	0 1 1	
P_4	4 3 3	0 0 2	4 3 1	

- Does there a safe sequence exist?
  - No

Pop Quiz

- 5 processes P_0 through P_4;

  3 resource types:

  A (10 instances), *B* (5 instances), and *C* (7 instances)

  Snapshot at time T_0:

	Max	Allocation	Need	Available
	A B C	*A B C*	*A B C*	*A B C*
P_0	7 5 3	0 1 0	7 4 3	3 3 2
P_1	3 2 2	2 0 0	1 2 2	
P_2	9 0 2	3 0 2	6 0 0	
P_3	2 2 2	2 1 1	0 1 1	
P_4	4 3 3	0 0 2	4 3 1	

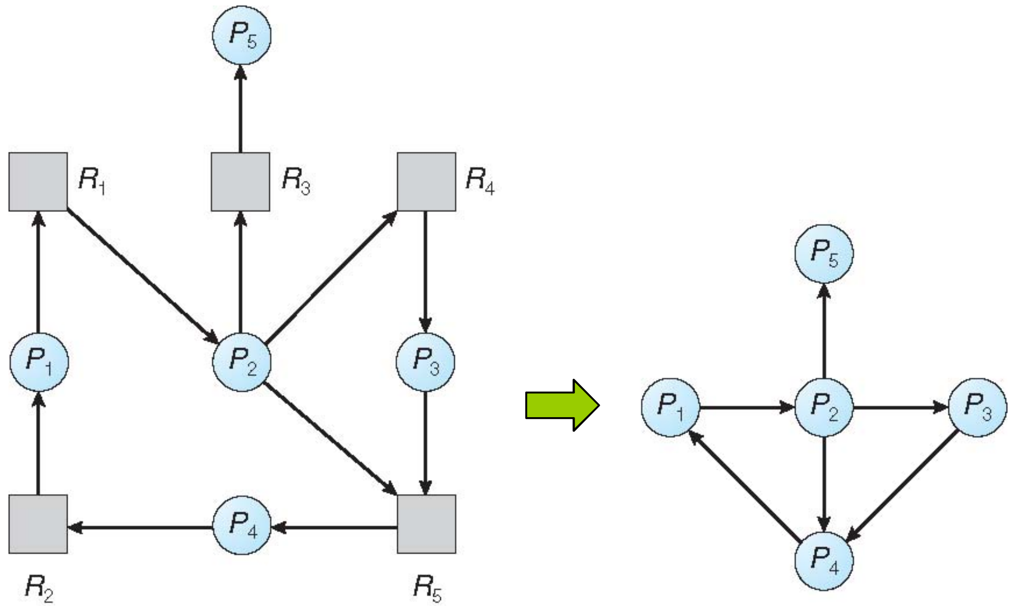
- Can P4's request (2, 1, 0) be granted?
- Can P4's request (2, 1, 2) be granted?

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. If there is a cycle, there exists a deadlock



(a) Resource-Allocation Graph

(b) 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

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

3. $Work = Work + Allocation_i$
   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

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*

Example (Cont.)

- P_2 requests an additional instance of type C

	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 1	
P_3	2 1 1	1 0 0	
P_4	0 0 2	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

Recovery from Deadlock

- Process Termination
  - abort one or more processes to break the circular wait

- Resource Preemption
  - preempt some resources from one or more of the deadlocked processes

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 compete
  - How many processes will need to be terminated
  - Is process interactive or batch?

Resource Preemption

- Selecting a victim – minimize cost
- Rollback – return to some safe state, restart process from that state
- Starvation – same process may always be picked as victim, include number of rollback in cost factor

Homework

- Reading
  - Chapter 7

- Exercise
  - See course website