Announcements

- Assignment 1:
  - Average: 80.5
  - Standard Deviation: 24
- Important clarification for assignment 3 online regarding the extra credit part (fairness policy).

Chapter 8: Deadlocks

- Background.
- System Model.
- Deadlock Conditions.
- Methods for Handling Deadlocks.
- Deadlock Prevention.
- Deadlock Avoidance.
- Deadlock Detection.
- Recovery from Deadlock.

Background

- A set of blocked processes each holding a resource and waiting to acquire a resource held by another process in the set.

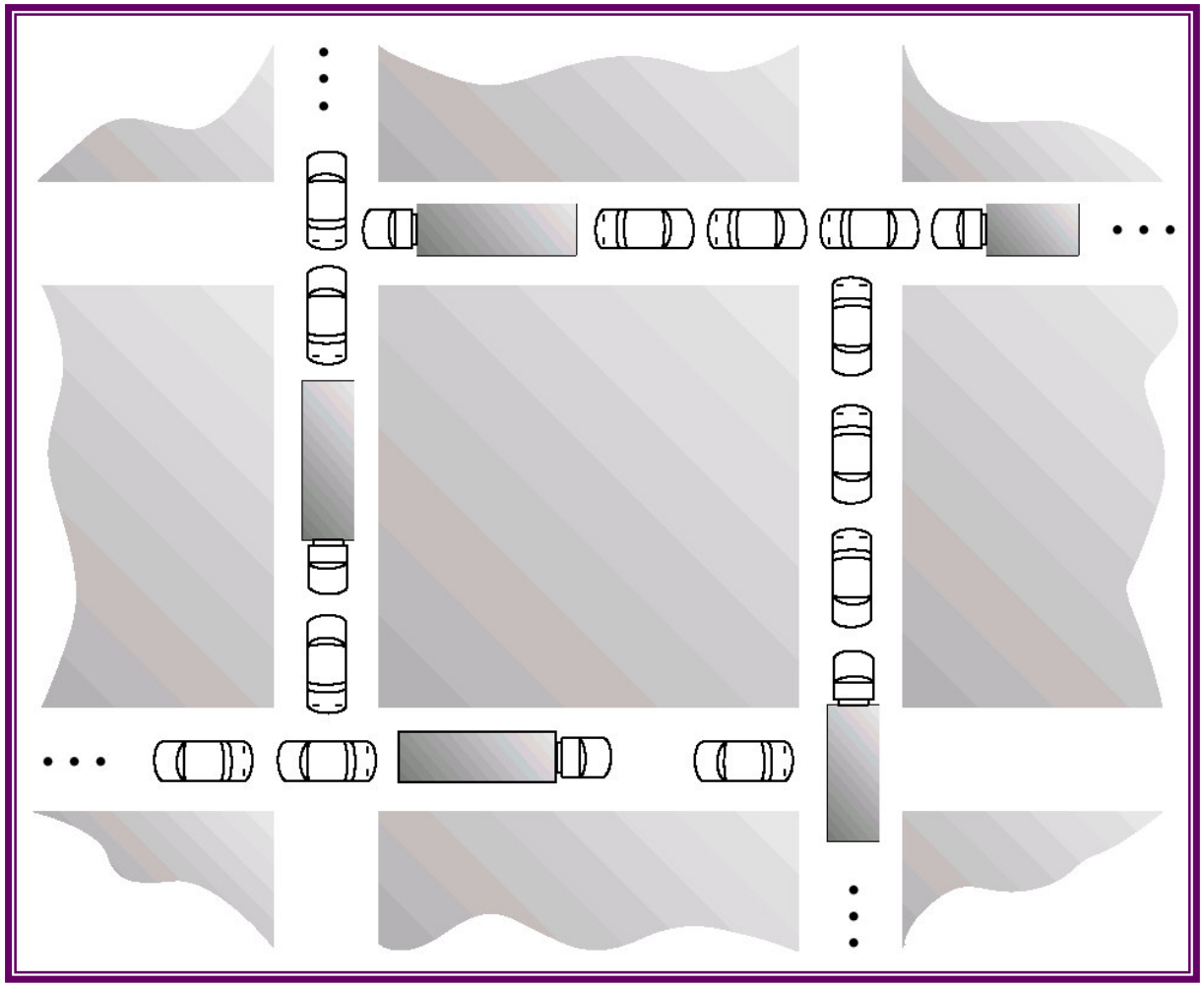
- Example:
  - System has 2 tape drives.
  - P_1 and P_2 each hold one tape drive and each needs another one.

- Example:
  - Semaphores *A* and *B*, initialized to 1:

	P_0	P_1	
Execute first →	`wait(A)`	`wait(B)`	← Execute second
Execute third →	`wait(B)`	`wait(A)`	← Execute fourth

Traffic Deadlock

- Very heavy fines in US if you block an intersection. If you can't cross to the other side, don't enter intersection.



System Model

- Resource *types* R_1, R_2, . . ., R_m: CPU cycles, memory space, I/O devices, printers.
- Each resource type R_i has W_i *instances*: 2 printers, 5 item containers in a buffer.
- Each process utilizes a resource as follows:
  1. Allocate (request/acquire).
  2. (Hold/own and) use.
  3. Release (deallocate).
- A single, *atomic* allocation request can be for:
  - Any one instance of one resource.
  - Any number of instances of one resource.
  - Any number of instances of many resources (different number for each resource).

Deadlock Conditions

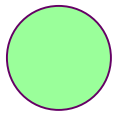
- **Mutual exclusion:** only one process at a time can use a resource instance, e.g. a printer.
- **Hold and wait:** a process holding at least one resource instance is waiting to acquire additional resource instances, which are currently *held by* or *accumulated for* other processes:
  - Held by: another process is using the resource instances.
  - Accumulated for: nobody is using them, but somebody else has requested many instances a long time ago and we are setting aside instances a few at a time to satisfy that big request (*fairness policy*).
- **No preemption:** a resource instance 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 an instance of a resource and P_1 is holding instances of that resource,
  - P_1 is waiting for ... and P_2 is holding ...
  - …,
  - P_{n-1} is waiting for ... and P_n is holding ...
  - P_n is waiting for ... and P_0 is holding ...

Circular wait is necessary condition, but not *sufficient!*

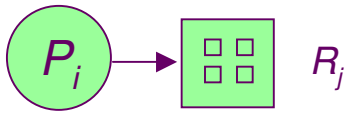
Resource-Allocation Graph

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

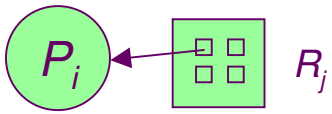
- V is partitioned into two types:
  - $P = \{P_1, P_2, \ldots, P_n\}$: all the processes.
  - $R = \{R_1, R_2, \ldots, R_m\}$: all resource *types*.
    - Instances are squares inside each resource type vertex.



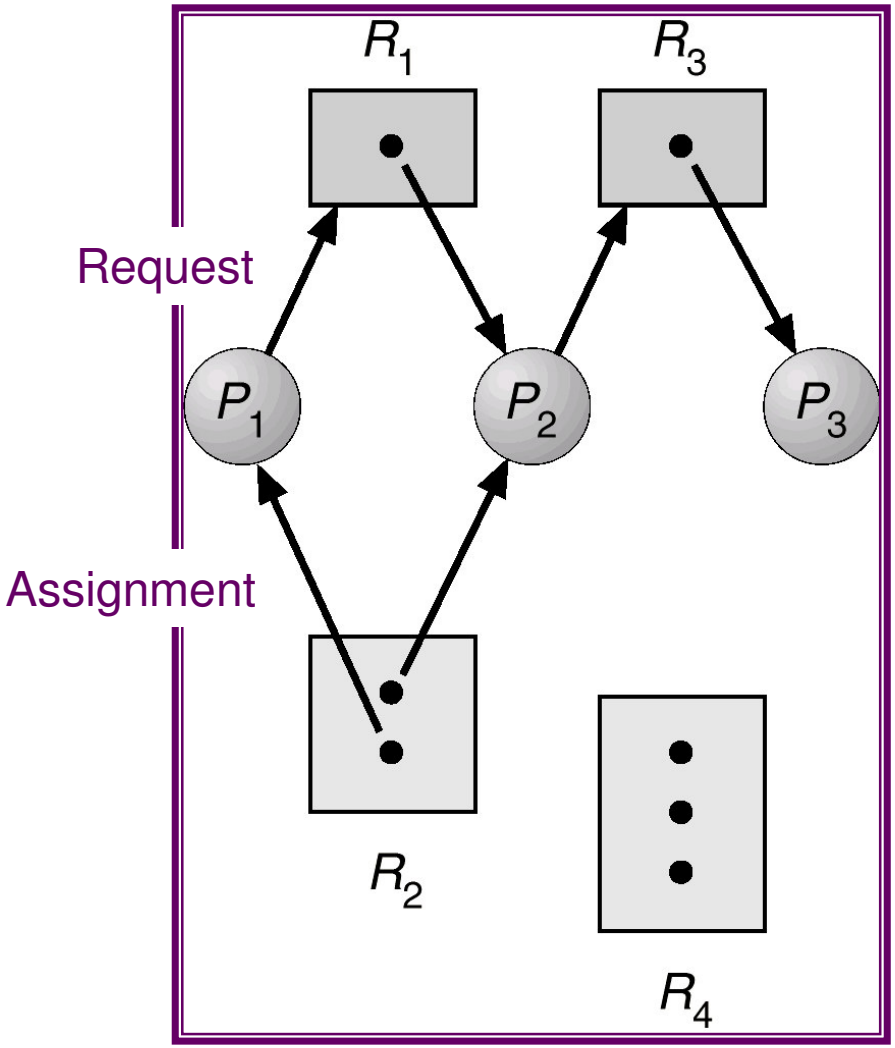
- *Request* edge: directed edge $P_i \rightarrow R_j$: P_i is waiting to acquire one or more instances of R_j.



- *Assignment* edge: directed edge $R_j \rightarrow P_i$: P_i is holding one or more instances of R_j.

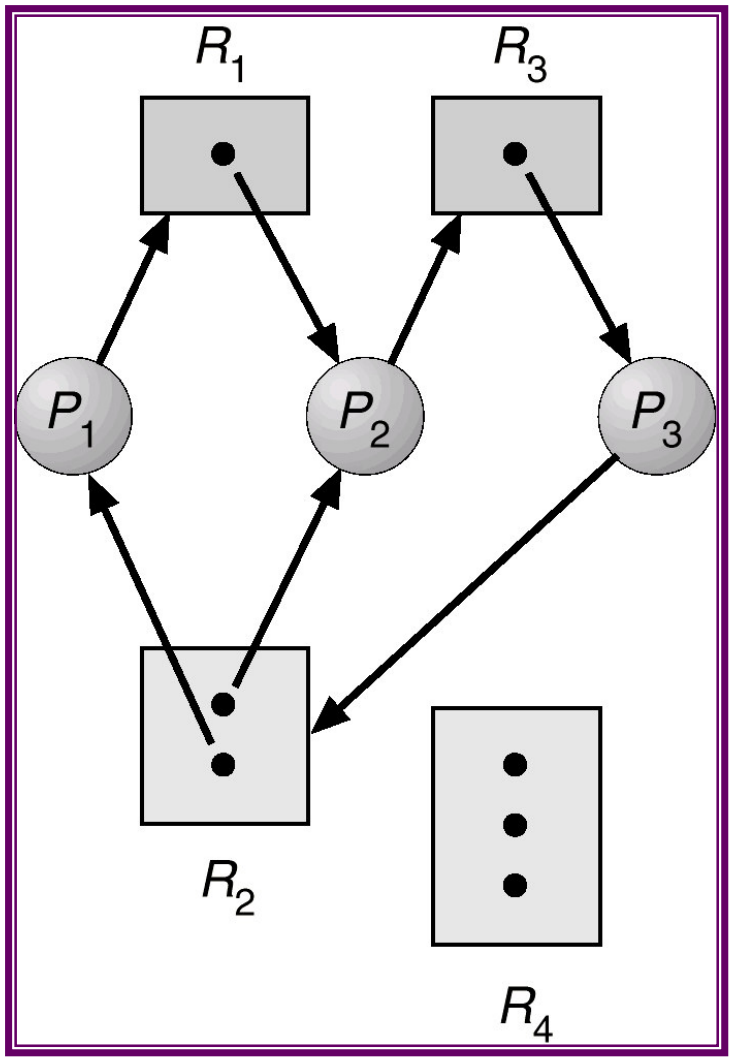


Resource-Allocation Graph (Cont.)

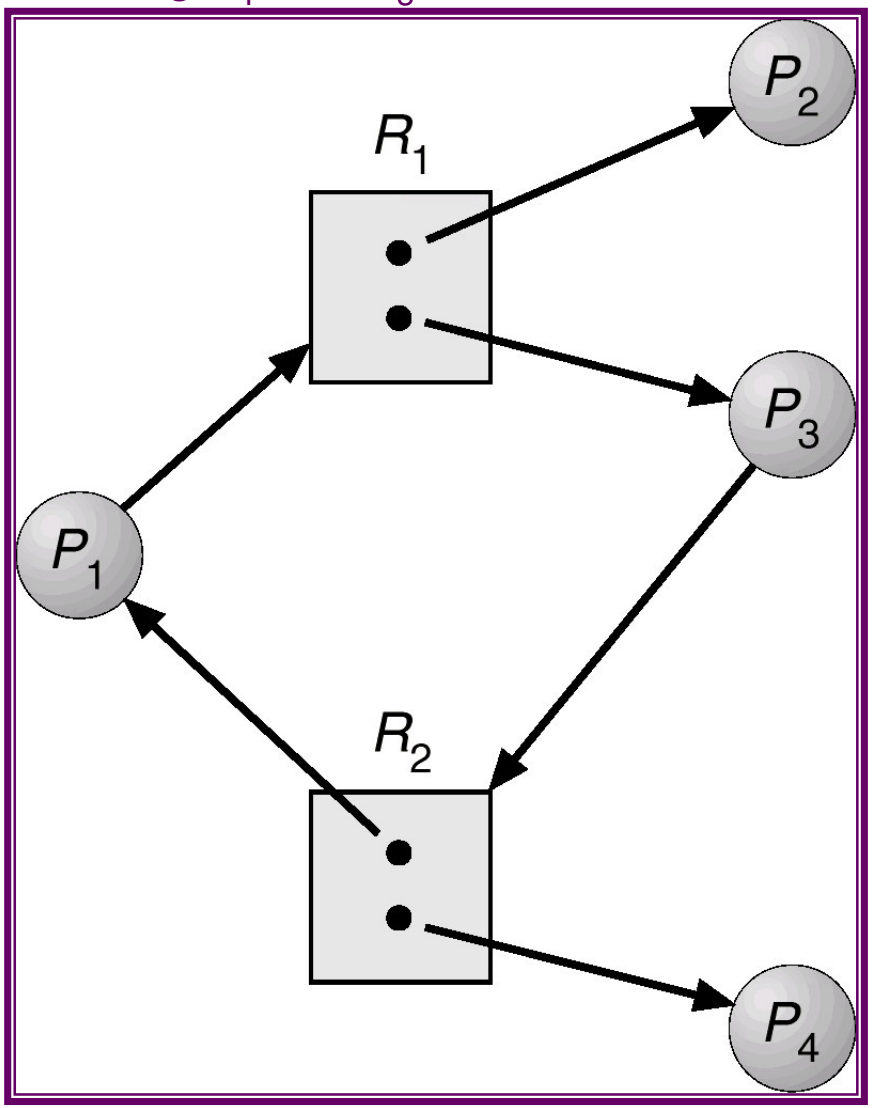


Resource-Allocation Graph With Cycles

Deadlock



No deadlock: P_4 or P_2 can finish, enabling P_1 and P_3 to finish.



Resource-Allocation Graph (Cont.)

- If graph contains no cycles then no deadlock: no circular wait.
- If graph contains a cycle then there is circular wait. Also:
  - If only one instance per resource type, deadlock has occured. (Circular wait is necessary *and* sufficient condition.)
  - If several instances per resource type, deadlock is possible but not certain.

Methods for Handling Deadlocks

1. *Prevention & avoidance*: ensure that the system will *never* enter a deadlock state.

2. *Detection*: allow the system to enter a deadlock state and then recover: CenterRun plan execution engine:
   - Host update plan starts on one host (WebLogic slave), may move to another (WebLogic master) temporarily before finishing with first.
   - Hosts locked by a plan while it runs on them.
   - Multiple plans run at the same time. Plan that would cause deadlock gets aborted as soon as it attempts to lock a host.

3. 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: ensure that at least one of the four conditions cannot be met.

- **Mutual exclusion**: make sure system doesn't have nonsharable resources.
  - For example, create printer spooler to provide inifite virtual printers; hence printer never needs to be locked.
  - Some resources inherently nonshareable, e.g. full-screen monitor mode.

- **Hold and wait**: whenever a process requests a resource instance, it should not hold any other resources instances.
  - Require process to request and be allocated all its resources before it begins execution in a single atomic allocation request, or allow process to request resources only when the process has none.
  - 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.
  - Process will be restarted only when it can regain its old resources, as well as the new ones that it is requesting.
  - Doesn't apply to some resource types: can't stop printer half-way, let other process go, and then return.

- **Circular wait:** impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration:
  - E.g. scanner must always be requested before printer.

P_0	P_1	
`wait(S)`	`wait(P)`	Illegal
`wait(P)`	`wait(S)`	order.

  - Interactive programs are unpredictable.

Deadlock Avoidance

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

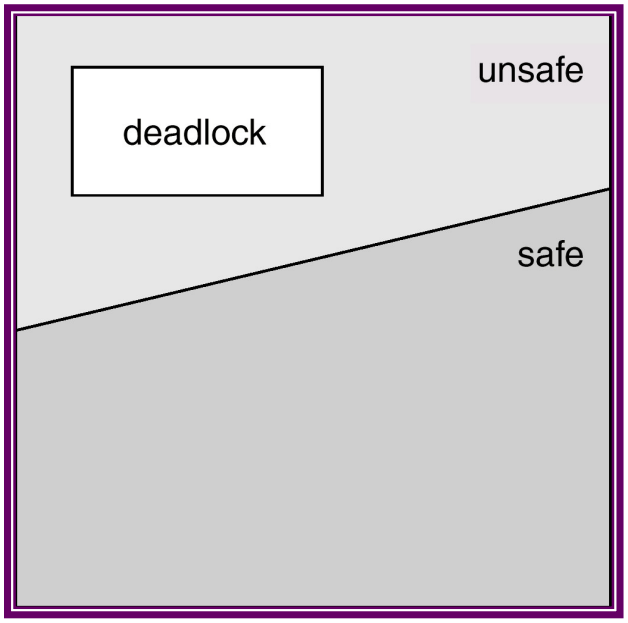
- Simplest and most useful model requires that each process declares the *maximum number* of instances of each resource type that it may need during its execution.
- The deadlock-avoidance algorithm dynamically examines the resource-allocation state to ensure that there can never be a circular-wait condition.
- Resource-allocation *state* is defined by the number of available and allocated resources, and the maximum demands of the processes.
- We don't care who is currently waiting! Algorithms assume worst-case: we treat each process as if it is blocked waiting for whatever it still doesn't have allocated.

Safe State

- When a process issues allocation request, system must decide if immediate allocation leaves the system in a *safe state*. Who is actually waiting is irrelevant.
- System is in safe state if there exists a safe sequence of all processes.
- Sequence $<P_1, P_2, \ldots, P_n>$ 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.

Safe State (Cont.)

- If a system is in safe state then deadlock is impossible.
- If a system is in unsafe state then deadlock is possible (but not certain; see two slides ahead).
- Avoidance: ensure that a system will never enter an unsafe state, hence keeping deadlock impossible:
  - One instance per resource type: resource-allocation graph algorithm.
  - Multiple instances per resource type: banker's algorithm.

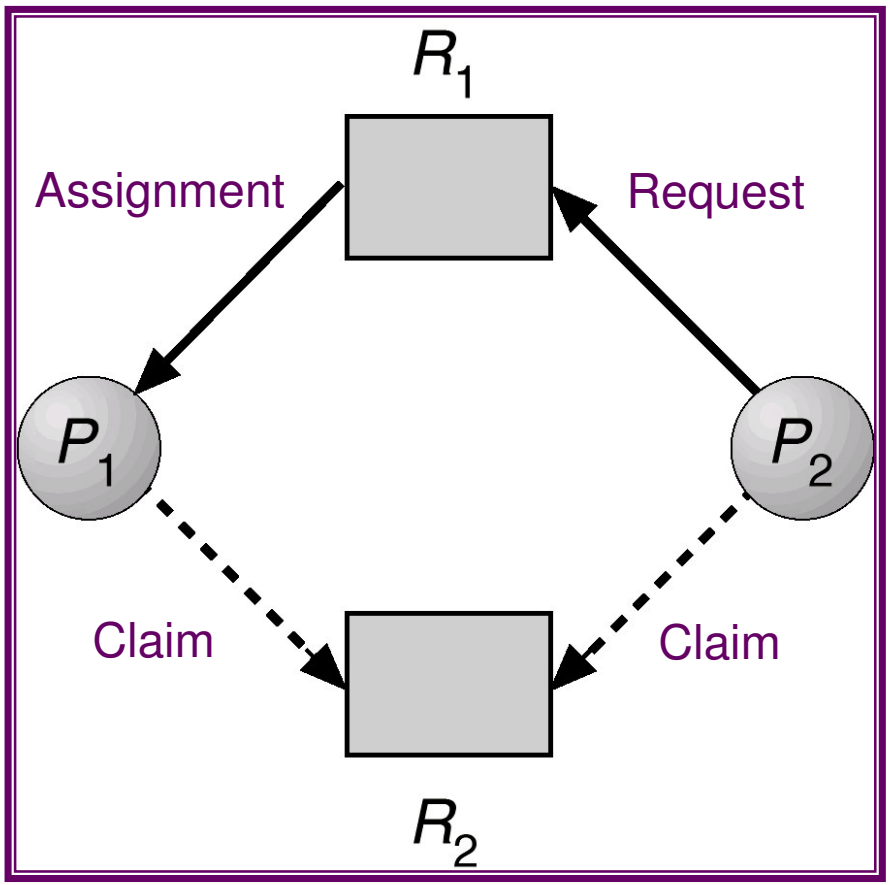


Resource-Allocation Graph Algorithm

- *Claim edge* $P_i \rightarrow R_j$ indicates that process P_i 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.
- System is in safe state as long as the graph doesn't have a cycle.
  - ☞ We treat claim edges as if they are request edges, i.e. as if resource is already waiting for those resource instances.

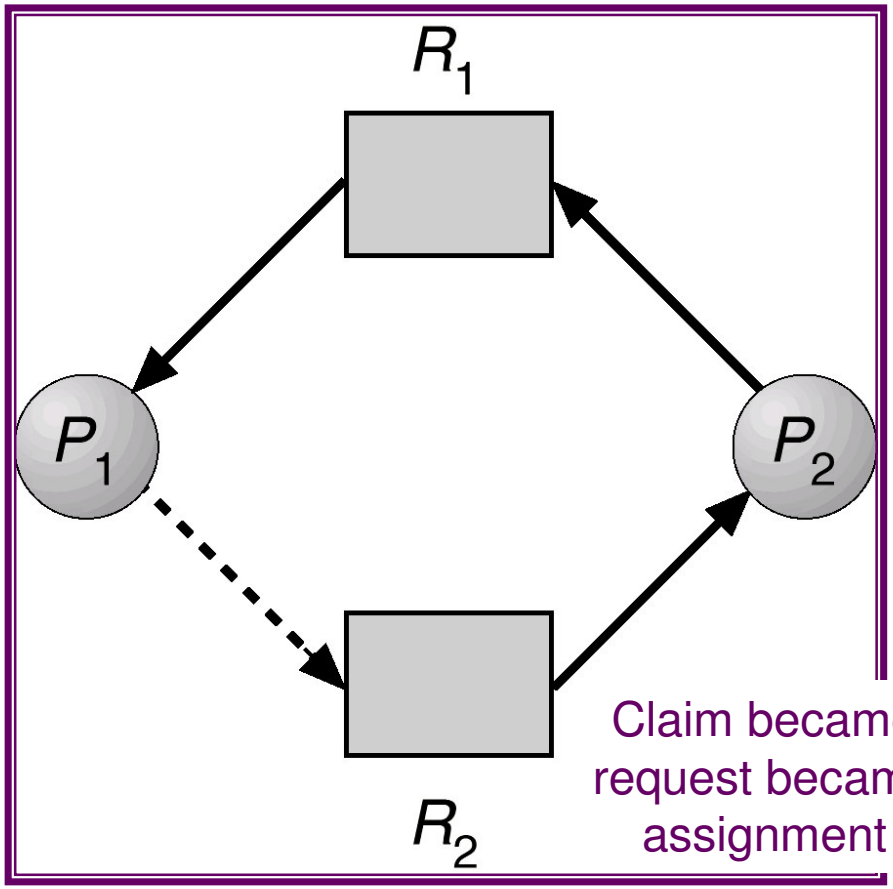
Resource-Allocation Graph Algorithm (Cont.)

Safe state



P_2 requests R_2 and receives it (it won't if system runs deadlock avoidance).

Unsafe state: no deadlock since P_1 may terminate before it asks for R_2.



P_2 releases R_2.

Banker's Algorithm: Data Structures

- n = number of processes.
- m = number of resources types.
- *Available:* m-element vector.
  - Available[j] = k: there are k instances of resource type R_j available.
- *Max:* n x m matrix.
  - *Max*[i,j] = k: process P_i may request at most k instances of resource type 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: Safety Check

Intuition: we look for a safe sequence. If we find one, the state is safe. If not, it is unsafe.

1. k^{th} iteration: we found first k processes in sequence.

2. The available instances per resource after the first k processes are finished.

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

   $Work = Available$

   $Finish[i] = (Allocation_i == 0)$ for $i = 1,2, \ldots, n$.

2. Find an i such that both:

   (a) $Finish[i] == false$ and

   (b) $Need_i \leq Work$ (All elements are ≤).

   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.

3. After initialization, $Finish[i]$ is *true* iff process P_i is one of the first k processes in the safe sequence. *During*, it is *true* iff process P_i is at the tail end of the sequence.

4. We haven't included P_i in the sequence.

5. P_i can become the $k+1^{st}$ process in the safe sequence.

6. Otherwise, we built a partial safe sequence, which means the remaining processes can possibly deadlock.

Example of Banker's Algorithm

- 5 processes P_0 through P_4
- Resource types:
  - *A* (10 total instances),
  - *B* (5 total instances), and
  - *C* (7 total 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	

Example of Banker's Algorithm (Cont.)

- The *Need* matrix.

	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

$$< P_1, P_3, P_4, P_2, P_0 >$$

is a safe sequence.

Resource-Request Algorithm for Process P_i

- *Request*: *m*-element vector.
  - *Request* [*j*] = *k*: process P_i wants *k* instances of resource type R_j.
- Resource allocator algorithm, i.e. what to do with this request (grant, enqueue, deny):
  1. If *Request* ≤ $Need_i$ go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim.
  2. If *Request* ≤ *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 resource-allocation state as follows:

     Available = *Available* - *Request;*

     $Allocation_i$ = $Allocation_i$ + *Request*;

     $Need_i$ = $Need_i$ - *Request*

     - If safe then the resources are allocated to P_i and make the temporary changes to the state permanent.
     - If unsafe then P_i must wait and the temporary changes are discarded.

Example of Banker's Algorithm (Cont.)

- P_1 issues request (1,0,2).
- Is Request ≤ Need? Yes: (1,0,2) ≤ (1,2,2).
- Is Request ≤ Available? Yes: (1,0,2) ≤ (3,3,2).
- Modify state temporariry, run banker's algorithm:

	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	

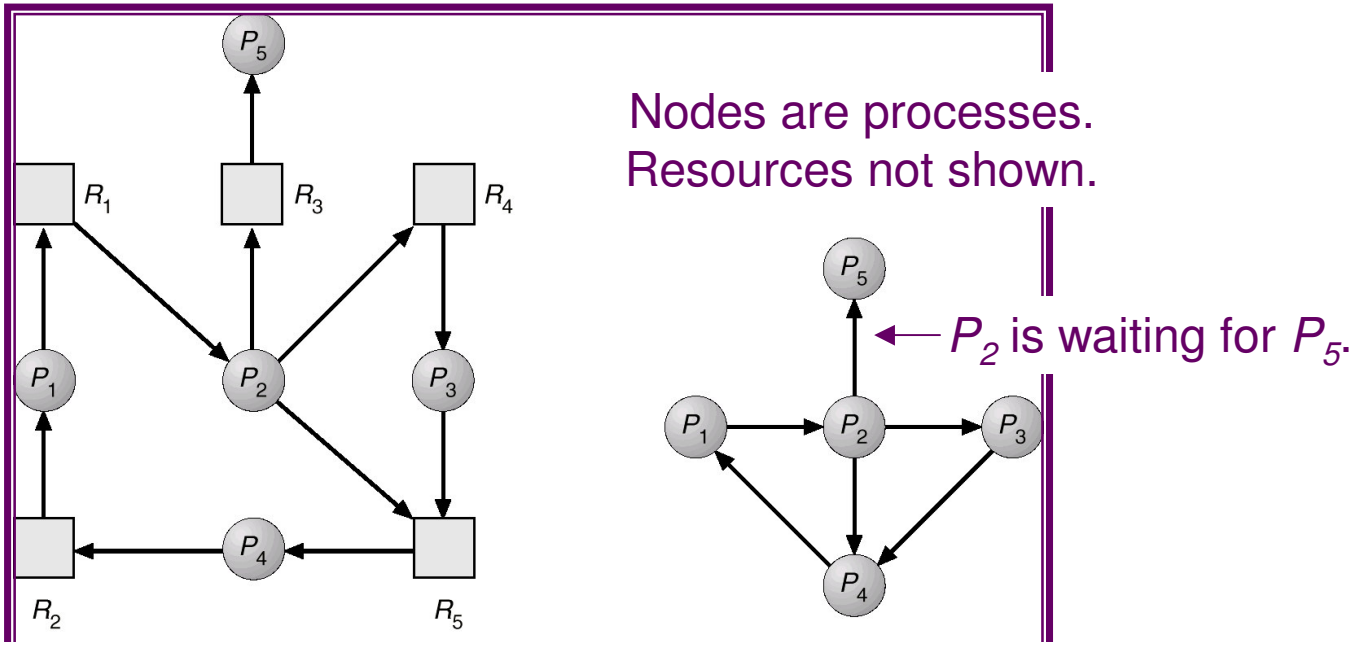
- Sequence <P_1, P_3, P_4, P_0, P_2> is safe. Request is granted.
- Requests enqueued (waiting):
  - P_4 for (3,3,0) because resources unavailable.
  - P_0 for (0,2,0) because state unsafe.

Deadlock Detection

- Processes do not state their maximal needs.
- But then a process that starts waiting may wait forever: system may enter deadlock state whenever a new process starts waiting.
- Need:
  - Detection algorithm to identify such states, and
  - Recovery scheme to remove deadlock.
- Detection/recovery executed either:
  - At regular intervals, if complex. More later.
  - Or when process issues request for resource instances and process has to wait. Before we enqueue process we check whether doing so would cause deadlock. If so, request fails with error:
    - Recovery is simple: request is denied.
    - Assignment 3.

Single Instance of Each Resource Type

- Maintain *wait-for* graph:



Resource-allocation graph ═══ Corresponding wait-for graph

- Search for a cycle in the graph.
- Same as avoidance if claim edges are redrawn as active request edges.
- An algorithm to detect a cycle in a graph requires O(*ne*) operations (*n* vertices, *e* edges). But since each process can wait for at most one other, $e \leq n$ hence O(n^2).

Depth-first search.

Several Instances of a Resource Type

- Same as banker's algorithm but we don't assume anything about future needs. Instead, we look at currently waiting processes (pending requests).
- Assignment 3.
- n = number of processes.
- m = number of resources types.
- *Available:* m-element vector.
  - Available[j] = k: there are k instances of resource type R_j available.
- *Request:* $n \times m$ matrix.
  - *Request*[i,j] = k: process P_i is blocked on a request for k (additional) instances of resource type R_j.
- *Allocation:* n x m matrix.
  - Allocation[i,j] = k: P_i is currently allocated k instances of R_j.

Detection Algorithm

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

   Work = *Available*

   Finish[*i*] = (*Allocation*$_i$ == 0) for *i* = 1,2, …, *n.*

2. Find an *i* such that both: ← O(*m n*)

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

   (b) *Request*$_i \leq$ *Work*. ← O(*m*)

   If no such *i* exists, go to step 4.

3. *Work* = *Work* + *Allocation*$_i$

   Finish[*i*] = *true*

   go to step 2. ← O(*m n*^{2})

4. If *Finish*[*i*] == true for all *i*, then the system is in a good state (no deadlock).

Algorithm requires O(*m n*^{2}) operations to detect whether the system is in deadlocked state.

Example of Detection Algorithm

- 5 processes P_0 through P_4
- Resource types:
  - A (7 total instances),
  - B (2 total instances), and
  - C (6 total 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 $<P_0, P_2, P_3, P_1, P_4>$ discovered. No deadlock.

Example of Detection Algorithm (Cont.)

- P_2 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

- No sequence discovered: partial sequence $<P_0>$ means
  - Can reclaim resources held by process P_0 when it dies, but insufficient resources to fulfill other pending requests.
  - Deadlock exists, consisting of processes P_1, P_2, P_3 and P_4 which are mutually dependent.

Detection Algorithm Usage

- Assume regular execution of detection algorithm (by contrast to execution for each request).
- 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?
    - At least one for each disjoint deadlock cycle.
- If detection algorithm is invoked rarely, there may be many cycles and so we would not be able to tell which of the many deadlocked processes “caused” the deadlock.
- If deadlock is detected, we need to recover by either:
  - Terminating processes.
  - Forcing them to release resource instanes (preemption).

Recovery from Deadlock: Process Termination

- Abort all processes that cannot finish (deadlocked, or stuck behind deadlocked ones): the ones with *Finish*[I]==*false*.
- Abort one process at a time until all deadlock cycles are eliminated.
- In which order should we choose to abort?
  - Our options may be limited by detection algorithm.
  - 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

- Algorithm:
  - Select a victim process which will lose some of its resources. Process chosen based on some cost function (priority, resource instances used, etc.).
  - Rollback process: return victim to some safe state, restart process for that state. Usually means termination and restart (previous slide).
- Starvation: same process may always be picked as victim. To avoid, include number of rollbacks in cost factor.