CIS 415
Operating Systems
Deadlocks

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Logistics

- Lab 5 posted
  - Signal processing in C
- Decision on lab/project zoom meeting
  - Use first 30 minutes of Grayson's Wednesday office hours for questions and clarifications
- Decision on lab solutions
  - Lab exercises are aligned very closely to projects
  - Providing coding solutions could transfer directly to project development making it difficult to evaluate individual work
  - Try to understand errors in exercises and seek further help
- Midterm next Tuesday
  - Midterm review in Thursday's lecture
- Read Chapter 8

Outline

- System Model
- Deadlock Characterization
- Methods for Handling Deadlocks
- Deadlock Prevention
- Deadlock Avoidance
- Deadlock Detection
- Recovery from Deadlock

Objectives

- To develop a description of deadlocks, which prevent sets of concurrent processes from completing their tasks
- To present a number of different methods for preventing or avoiding deadlocks in a computer system

System Model

- System consists of resources
- Resource types $R_1, R_2, \ldots, R_m$
  - CPU cycles, memory space, I/O devices, …
- Each resource type R_i has W_i instances
- Each process utilizes a resource as follows:
  - Request
  - Use
  - Release
- We want a general way to think about problems like the dining philosophers

Deadlock Characterization

- Deadlock can arise if four conditions hold simultaneously:
  1. *Mutual exclusion*: only one process at a time can use a resource
  2. *Hold and wait*: a process holding at least one resource is waiting to acquire additional resources held by other processes
  3. *No preemption*: a resource can be released only voluntarily by the process holding it, after that process has completed its task using the resource
  4. *Circular wait*: there exists a set $\{P_1, P_2, \ldots, P_n\}$ of waiting processes such that P_1 is waiting for a resource that is held by P_2, P_2 is waiting for a resource that is held by P_3, …, 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_1

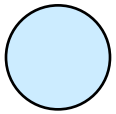
Resource Allocation Graph

- 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 $P_i \rightarrow R_j$
- *Assignment edge*
  - Directed edge $R_j \rightarrow P_i$
- A resource allocation graph is used to determine "state" of the resource system

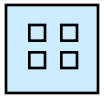
Resource-Allocation Graph Symbols

Graphic representation

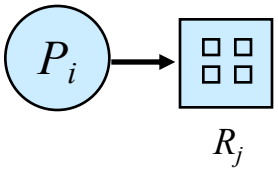
- Process



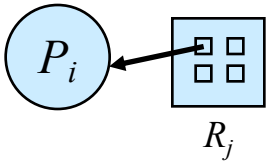
- Resource type with 4 instances



- P_i requests instance of R_j

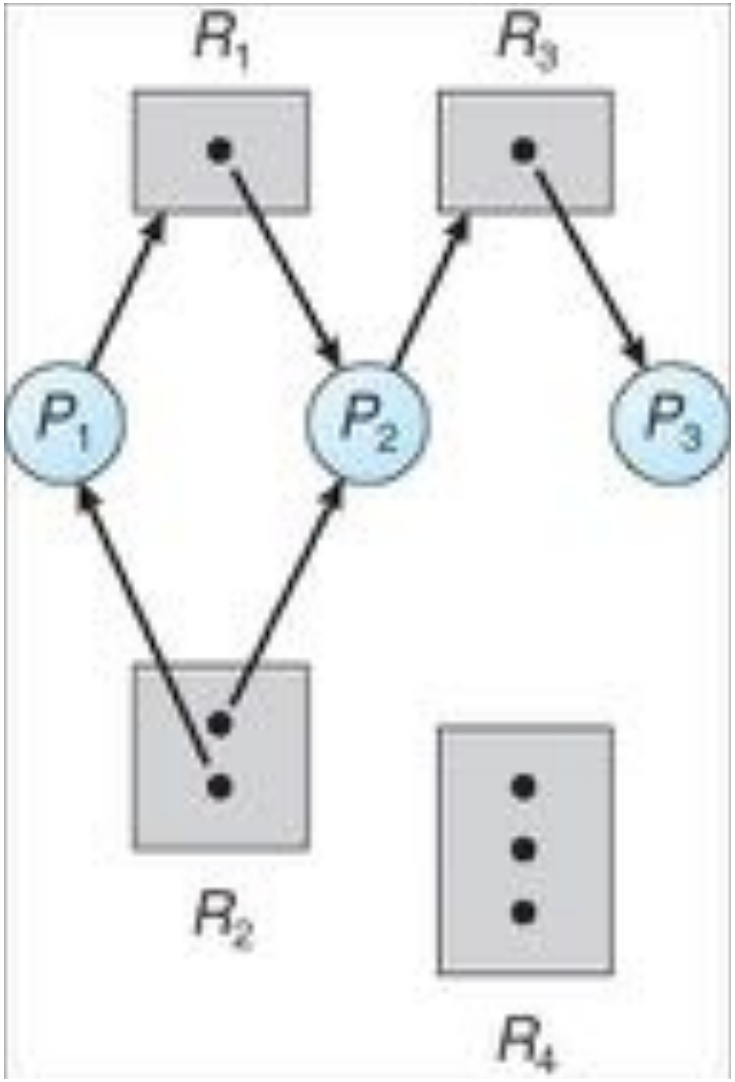


- P_i is holding an instance of R_j



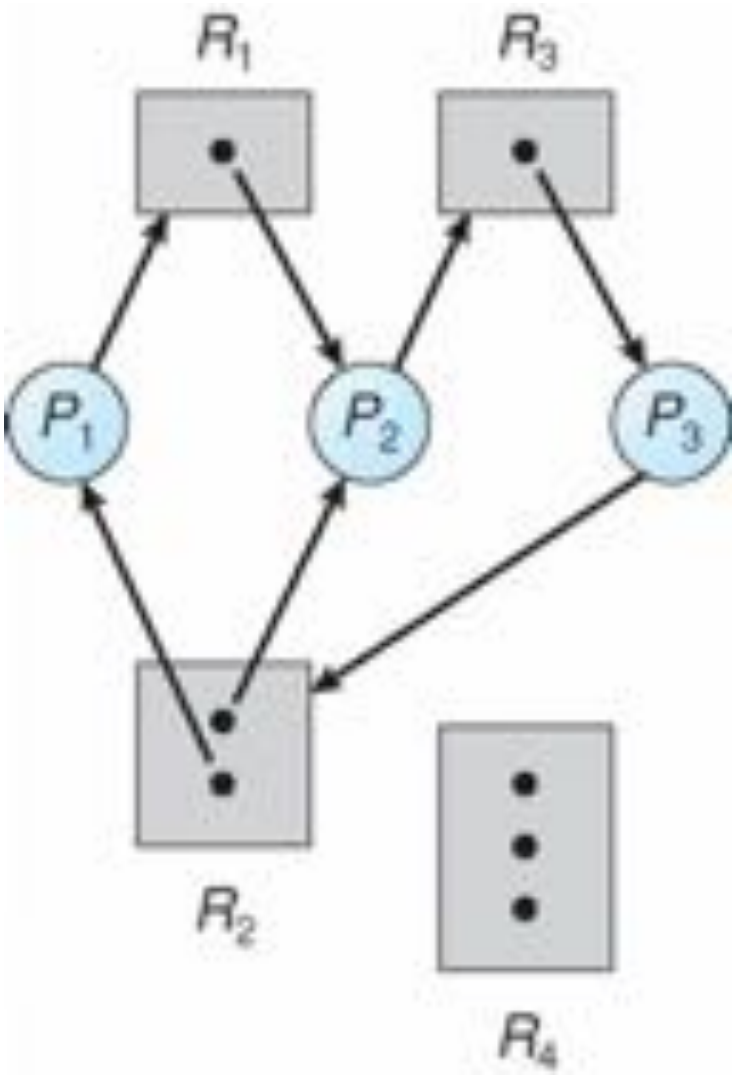
Example of a Resource Allocation Graph

- P_1 is requesting R_1 and holding an instance of *R2*
- P_2 is holding an instance of R_1 and R_2 and is requesting R_3
- P_3 is holding an instance of R_3
- Resource allocation graph shows the "hold" and "wait" conditions
- Is there a deadlock?



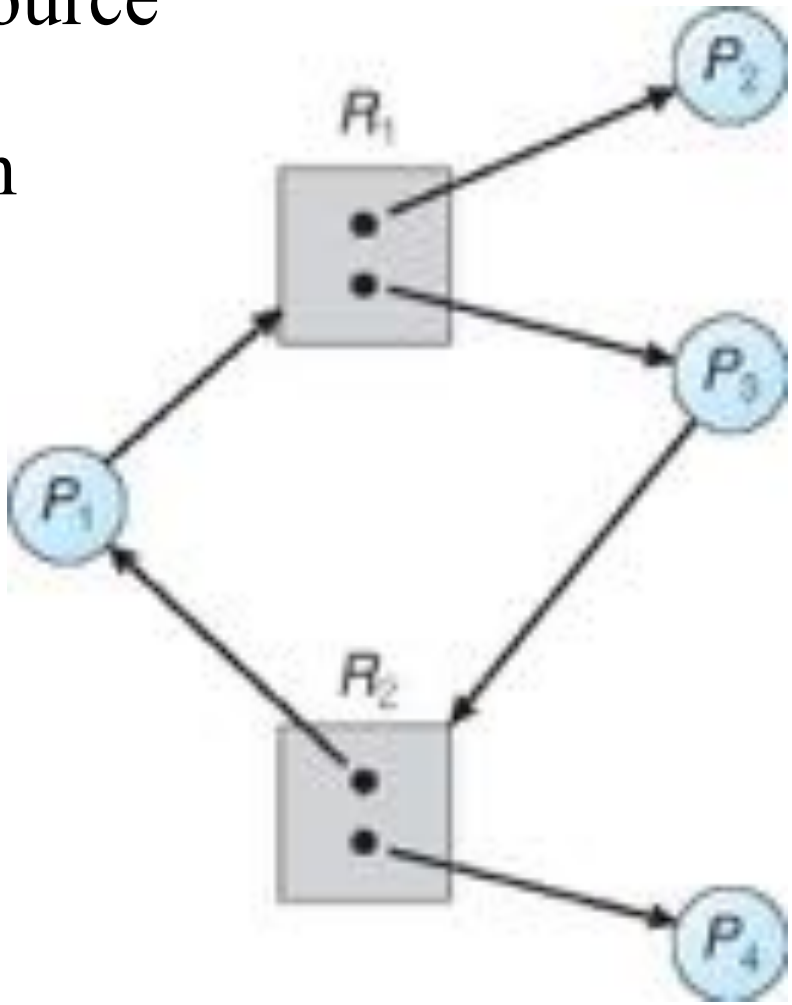
Resource Allocation Graph With A Deadlock

- Look for hold and wait conditions that create a circular waiting state
  - Every process is waiting on a resource that is being held by another process in the cycle
- If there is a circular wait state, then no process can proceed because they are all blocked
- Every process is waiting indefinitely because no resource will be released



Graph With A Cycle But No Deadlock

- It is possible for there to be a cycle in the resource allocation graph, but the resource system is not deadlocked
- Does this resource allocation graph have a deadlock?
- There exist a resource that is held by a process that is not in the cycle
- A resource can be released by a process that is not in the cycle, allowing for a process in the cycle to proceed



Basic Facts

- If resource allocation graph contains no cycles:
  - There can be no deadlock
- If resource allocation graph contains a cycle:
  - If there is only one instance per resource type
    $\Rightarrow$ deadlock
  - If there are several instances per resource type
    $\Rightarrow$ possibility of deadlock

Methods for Handling Deadlocks

- Basically, we need to ensure that the system will never enter a deadlock state
- This can be done in 2 ways:
  - *Deadlock prevention*
  - *Deadlock avoidance*
- However, you could also allow the system to enter a deadlock state and then recover
  - Need to guarantee that recovery is possible and valid
- Or, you could ignore the problem and pretend that deadlocks never occur in the system
  - Used by most operating systems, including UNIX

Deadlock Prevention – Requirements (1)

- Idea is to restrain the ways request can be made
- *Mutual exclusion*
  - Not required for sharable resources (e.g., read-only files)
  - 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 (strict)
  - Require process to request and be allocated ALL of its resources before it begins execution
  - Allow process to request resources only when the process has none allocated to it
  - Low resource utilization and starvation possible

Deadlock Prevention– Requirements (2)

- *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 by that process 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
- *Circular wait*
  - Impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration

Example using Pthread Mutex Locks

- Think of the mutex locks as representing a resource being requested
- Does this code generate a deadlock?
- Why or why not?
- What is wrong?
- Hint: order matters

```
/* thread one runs in this function */
void *do_work_one(void *param) {
   pthread_mutex_lock(&first_mutex);
   pthread_mutex_lock(&second_mutex);
   /** * Do some work */
   pthread_mutex_unlock(&second_mutex);
   pthread_mutex_unlock(&first_mutex);
   pthread_exit(0);
}
/* thread two runs in this function */
void *do_work_two(void *param) {
   pthread_mutex_lock(&second_mutex);
   pthread_mutex_lock(&first_mutex);
   /** * Do some work */
   pthread_mutex_unlock(&first_mutex);
   pthread_mutex_unlock(&second_mutex);
   pthread_exit(0);
}
```

An Account Transaction Example

- Transactions 1 and 2 execute concurrently
  - Transaction 1 transfers $25 from account A to account B
  - Transaction 2 transfers $50 from account B to account A
- Locks are locked in an order, unlocked in reverse

```
void transaction(Account from, Account to, double amount) {
   mutex lock1, lock2;
   lock1 = get_lock(from);
   lock2 = get_lock(to);
   acquire(lock1);
      acquire(lock2);
         withdraw(from, amount);
         deposit(to, amount);
      release(lock2);
   release(lock1);
}
```

Does it work?

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
- Resource allocation state is defined by the number of available and allocated resources, and the *maximum* possible demands of the processes

Safe State

- When a process requests an available resource, it must be decided if immediate allocation of the resource to the process leaves the system in a *safe state*
- System is in safe state if there exists a sequence

$$<P_1, P_2, \ldots, P_n> \text{ of ALL the processes in the system}$$

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 $j < i$

  - 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

Basic Facts

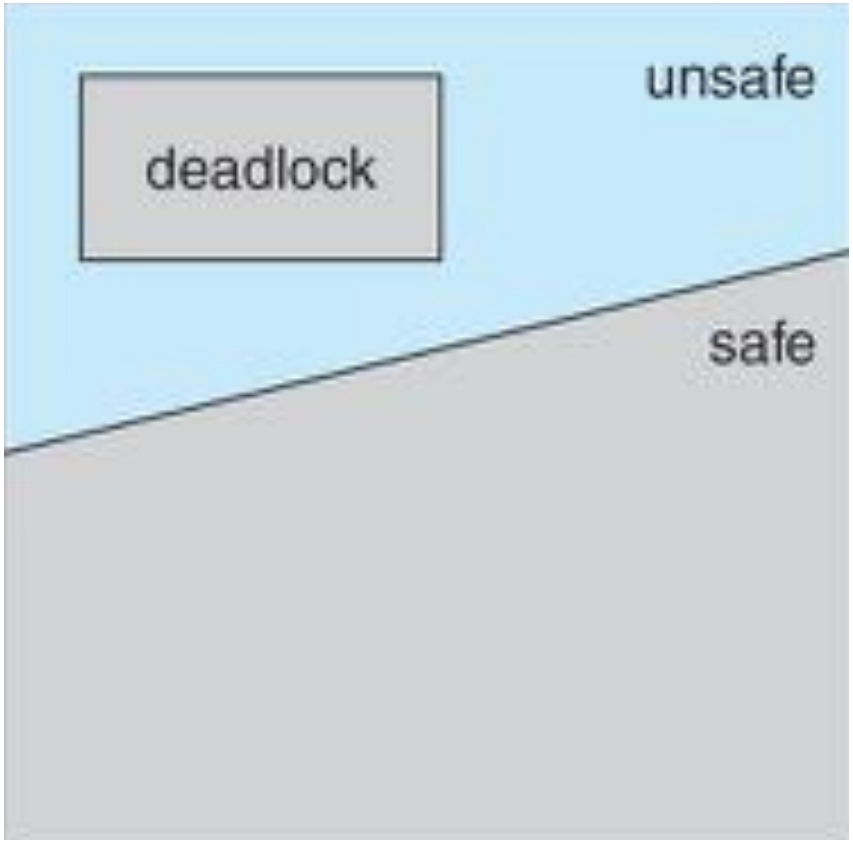
- If a system is in safe state
  $\Rightarrow$ no deadlocks

- If a system is in unsafe state
  $\Rightarrow$ possibility of deadlock

- Avoidance achieved by ensuring that a system will never enter an unsafe state

State Relationships

- A resource allocation graph can be in 2 mutually exclusive states: safe, unsafe
- In the unsafe state, a resource allocation graph can be vulnerable to deadlock or in a deadlocked condition

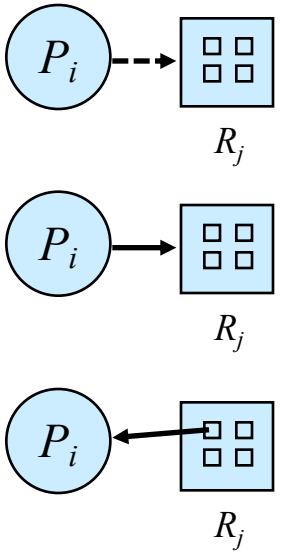


Deadlock Avoidance Algorithms

- Avoidance algorithms prevent deadlocks from ever happening
  - Never allowing an unsafe state to be entered)
- Approaches depend on assumptions about the resource allocation graph
- Single instance of a resource type
  - Use a resource allocation graph to evaluate
- Multiple instances of a resource type
  - Must run an algorithm on the resource allocation graph
  - Use the *Banker's algorithm*

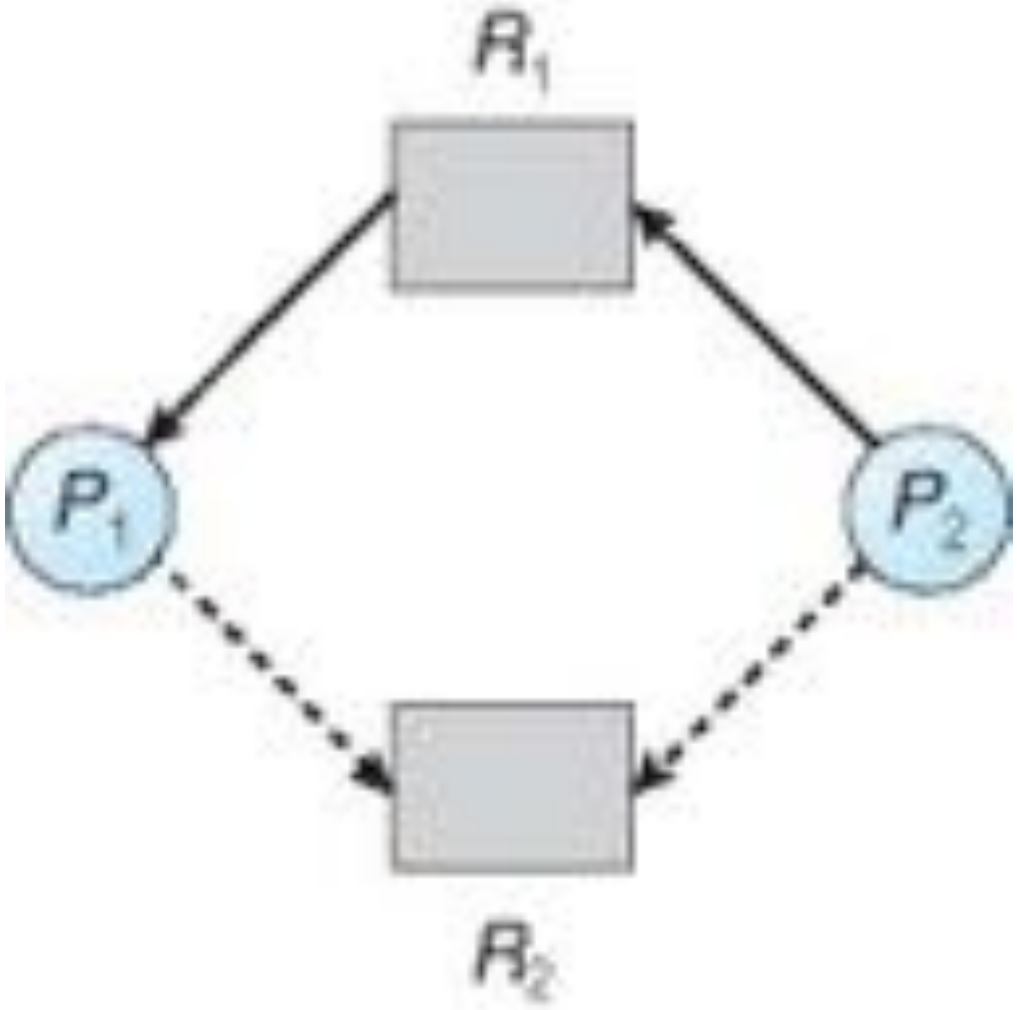
Resource Allocation Graph Scheme

- *Claim edge* $P_i \rightarrow R_j$ indicates that process P_j may request resource R_j
  - Represented by a dashed line
- Claim edge converts to a *request edge* when a process requests a resource
- Request edge converted 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
- Resources must be claimed *a priori* in the system



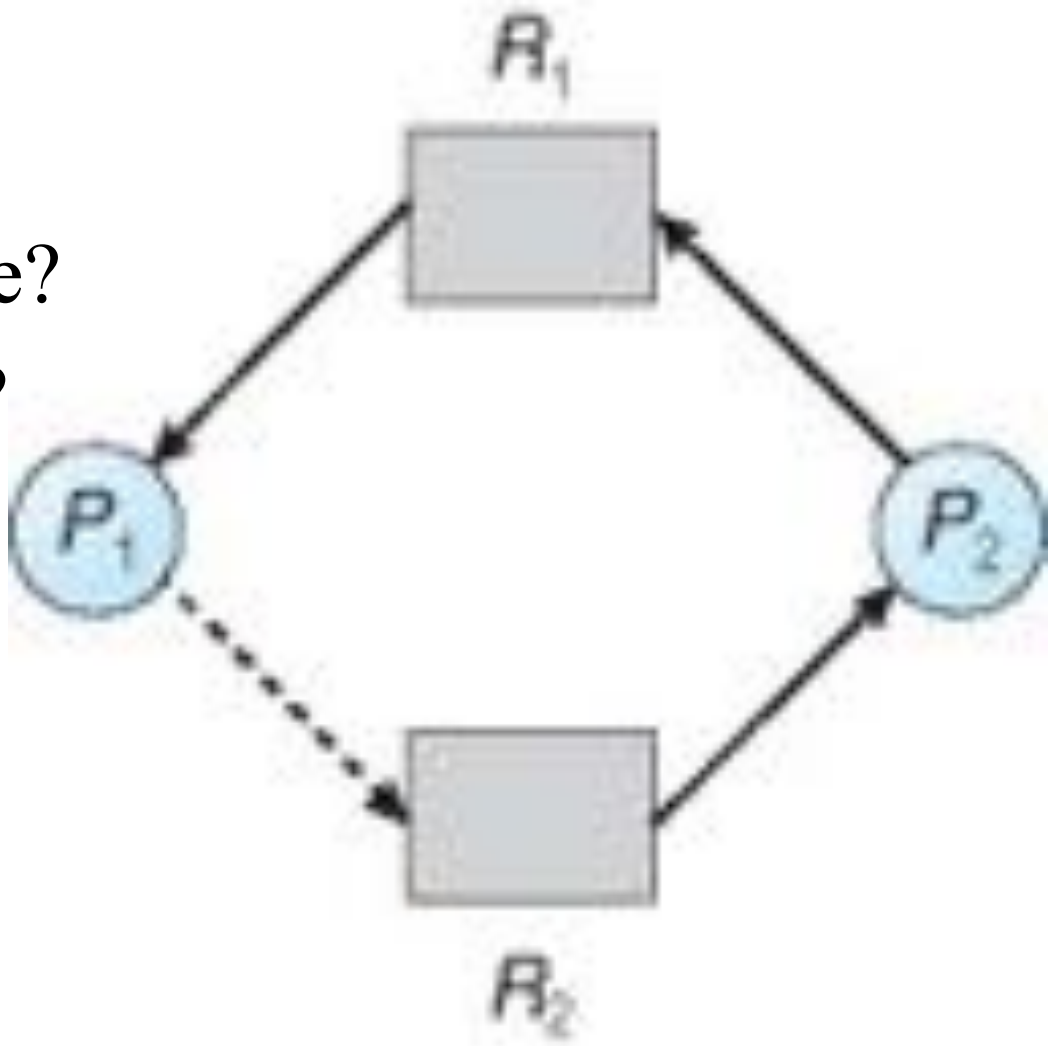
Resource Allocation Graph

- Is this in a safe state?



Unsafe State In Resource Allocation Graph

- What about this?
- Is this in a safe state?
- If it is unsafe, why?



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
- Cycles are evaluated using all types of edges, including claim edges

Banker's Algorithm

- Suppose we have multiple instances
- Requirements:
  - 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 algorithms is a bookkeeping method for tracking and assigning resources

Data Structures for 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 $i = 0, 1, \ldots, n\text{-}1$

2. Find an *i* such that both:
   Finish[i] = *false*
   $Need_i \leq Work$
   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:
   $Available = Available - Request_i$;
   $Allocation_i = Allocation_i + Request_i$;
   $Need_i = Need_i - Request_i$;
   If safe $\Rightarrow$ the resources are allocated to P_i
   If unsafe $\Rightarrow$ P_i must wait, restore old resource allocation

Example of Banker's Algorithm

- 5 processes P_0 through P_4
- 3 resource types:
  - A (10 instances), B (5 instances), C (7 instances)
- Snapshot at time T_i:

Process	*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	

Check for Safety

- Matrix *Need* is defined to be *Max – Allocation*

Process	Need
	A B C
P0	7 4 3
P1	1 2 2
P2	6 0 0
P3	0 1 1
P4	4 3 1

Process	*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	

- The system is in a safe state since the sequence $< P_1, P_3, P_4, P_2, P_0>$ satisfies safety criteria

P_1 Requests (1,0,2)

- Let's advance the system with P_1 making request (1,0,2)
- Check that *Request* $\leq$ *Available* (that is, (1,0,2) $\leq$ (3,3,2) $\Rightarrow$ true)

Process	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	

- Executing safety algorithm shows that 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?

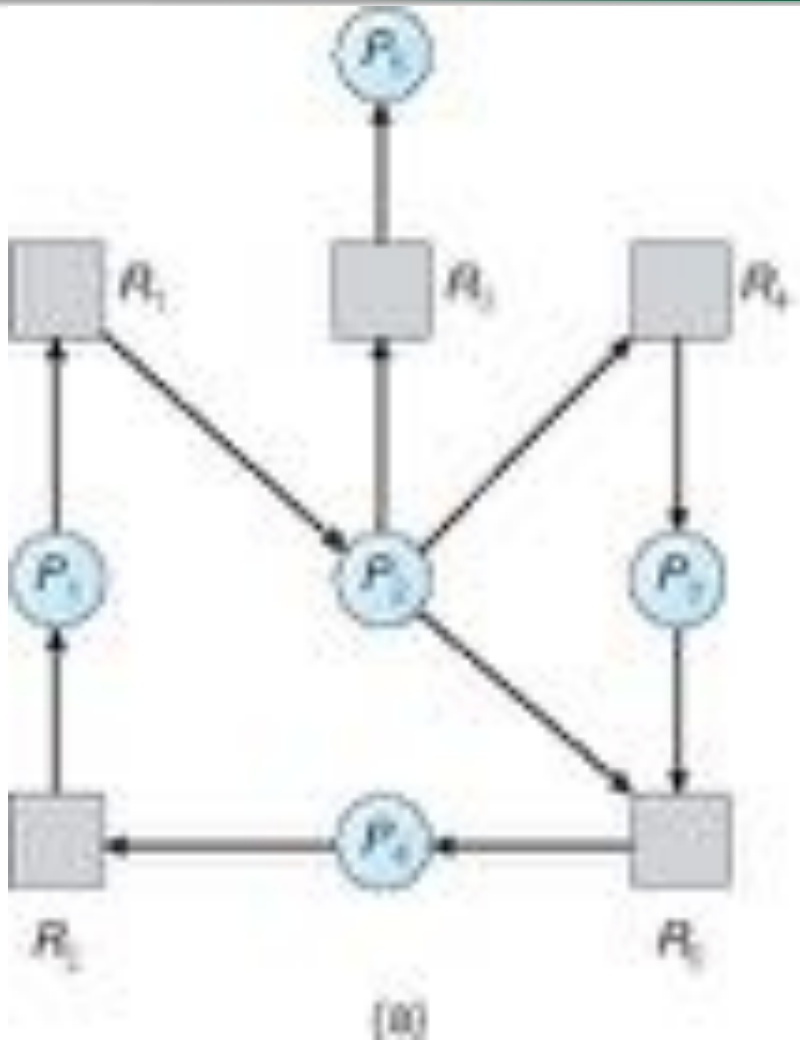
Deadlock Detection

- Allow system to enter deadlock state
- Detection algorithm determines if the resource allocation graph is in a deadlock state
- If it is, a recovery scheme is used to get out of it
  - Assume that it is possible to, in fact, recover
  - It is possible that this might require a rollback to a prior consistent state

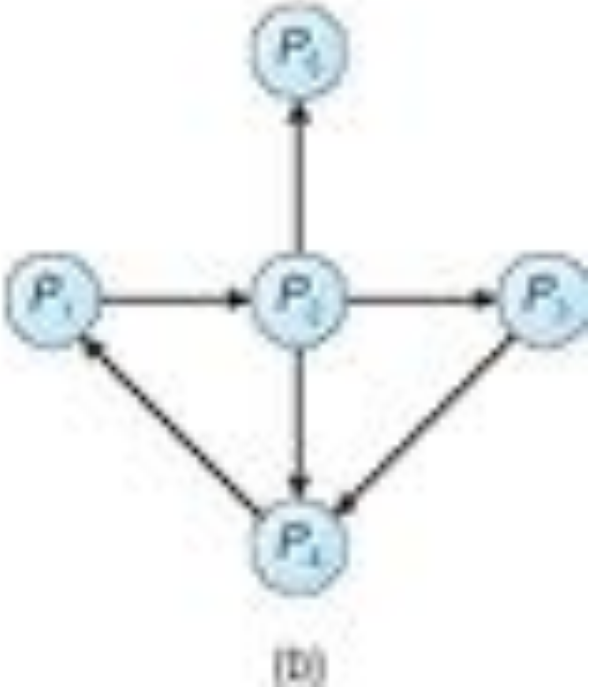
Single Instance of Each Resource Type

- Need to 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 wait-for 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 and Wait-for Graph



Resource-Allocation Graph



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*, respectively 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
   If $Finish[i] == false$, then P_i is deadlocked

Algorithm requires an order of $O(m \times n^2)$ operations to detect whether the system is in deadlocked state

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 T0:

Process	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> gives *Finish[i] = true* for all *i*

Deadlock?

- P_2 requests an additional instance of type C

Process	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

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

- If detection algorithm is invoked arbitrarily, there may be many cycles in the resource graph and so we would not be able to tell which of the many deadlocked processes "caused" the deadlock

Deadlock Recovery – Process Termination

- Aborting 1 or more processes will release their resources
- Different schemes
  - 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?

Deadlock Recovery – Resource Preemption

- Selecting a victim
  - Attempt to minimize cost
- Rollback
  - Return to some safe state
  - Restart process for that state
- Starvation
  - Same process may always be picked as victim, include number of rollback in cost factor

Next Class

- Midterm review