CAS CS552
Intro to Operating Systems

Richard West

Deadlocks

Objectives

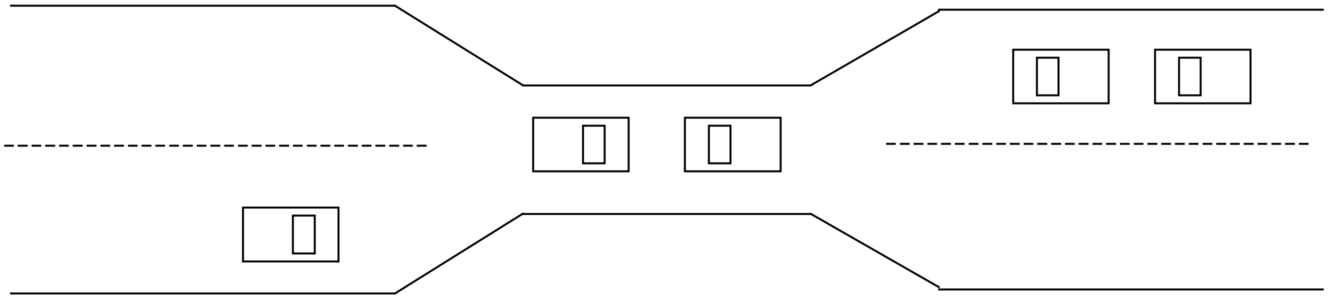
- To develop a description of deadlocks, which prevent sets of concurrent processes from completing their tasks
- To present a number of different methods for preventing or avoiding deadlocks in a computer system.

The Deadlock Problem

- A set of blocked processes each holding a resource and waiting to acquire a resource held by another process in the set
- Example
  - semaphores *A* and *B*, initialized to 1

P_0	P_1
wait (A);	wait(B);
wait (B);	wait(A);

Bridge Crossing Example



- Traffic only 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

System Model

- Resource types $R_1, R_2, . . ., R_m$

  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

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 $\{P_0, P_1, \ldots, P_{n-1}\}$ 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_0

Resource-Allocation Graph

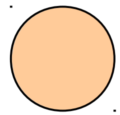
A set of vertices *V* and a set of edges *E*

- 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

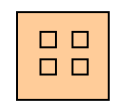
- Each edge in set E can be either:
  - a request edge – directed edge $P_i \rightarrow R_j$
  - an assignment edge – directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph (Cont.)

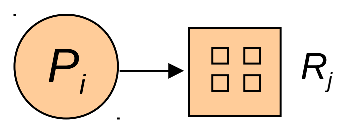
- Process



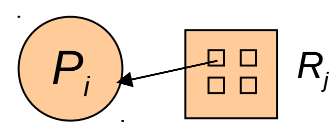
- Resource Type with 4 instances



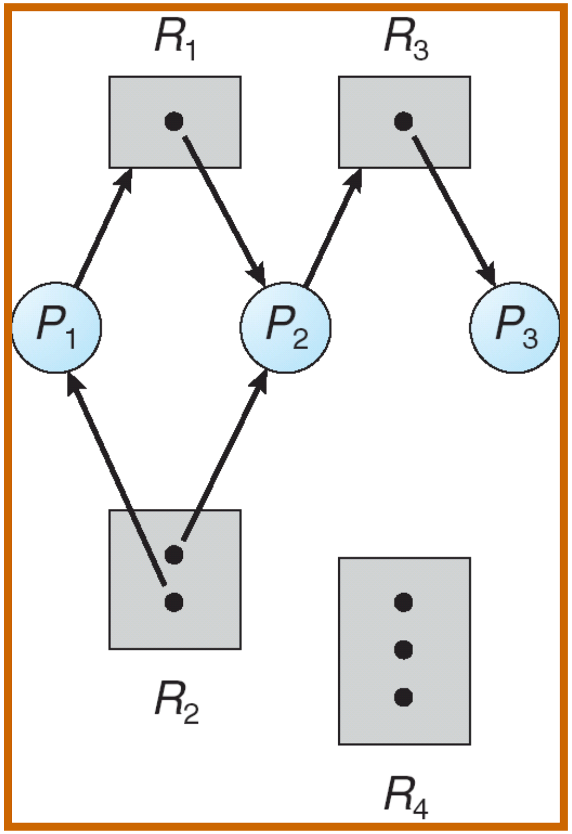
- P_i requests instance of R_j



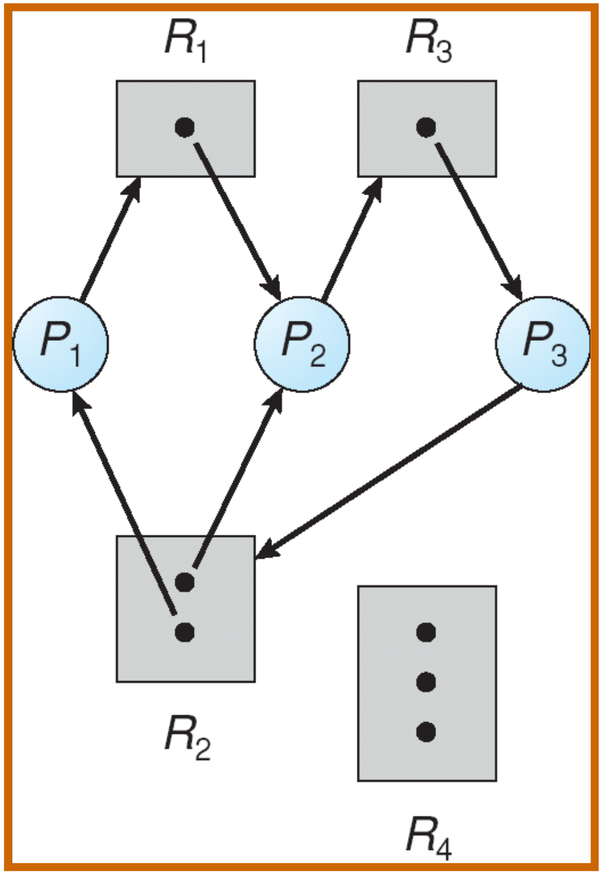
- P_i is assigned an instance of R_j



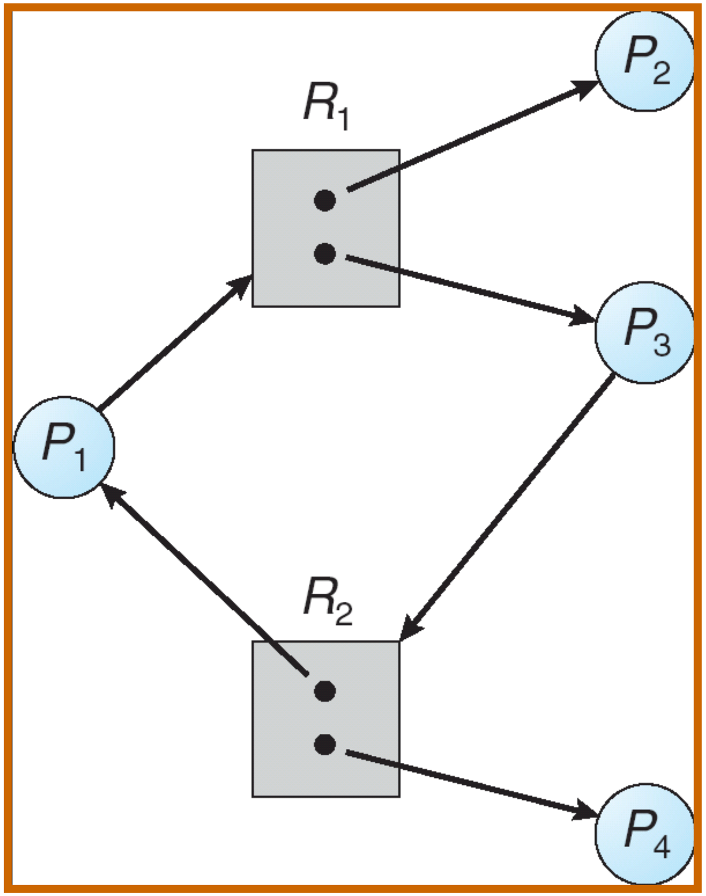
Example Resource Allocation Graph



Resource Allocation Graph with a Deadlock



Another Graph with a Cycle



Is there a deadlock?

Observations

- If graph contains no cycles $\Rightarrow$ no deadlock

- If graph contains a cycle $\Rightarrow$
  - if only one instance per resource type, then deadlock
  - if several instances per resource type, possibility of deadlock but not necessarily

Methods for Handling Deadlocks

- Ensure that the system will *never* enter a deadlock state
  - prevention versus avoidance
- Allow the system to enter a deadlock state and then recover
  - detection and recovery
- Ignore the problem and pretend that deadlocks never occur in the system (e.g. UNIX approach)
  - the Ostrich method! :-)

Deadlock Prevention

Prevent any one of the four necessary conditions:

- **Mutual Exclusion** – must hold for resources required in exclusive manner
- **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 it 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

- **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

Observe pattern of allocation of resources given current system state and decide whether or not it is safe to allocate resources

- Simplest and most useful model requires that each process declare the *maximum number* of resources of each type that it may need (a-priori)
- 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

- System is in safe state if there exists a sequence <P_1, P_2, …, P_n> 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 $j < i$

- That is:
  - If P_i's 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

Observation

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

Avoidance algorithms

- Single instance of a resource type
  - Use a resource-allocation graph

- Multiple instances of a resource type
  - Dijkstra’s banker’s algorithm

Banker's Algorithm

- Each process must (a-priori) claim maximum use of each resource it needs
- 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 Data Structures

Let n = number of processes, and m = number of resources types

- ***Available****:* Vector of length m
  - Available[j] = k, if 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 $i = 0, 1, \ldots, n-1$

2. Find and 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

- Let *Request* = request vector of length *m* for process P_i
  - If $Request_i[j] = k$, process P_i wants *k* instances of resource type R_j

1. If $Request_i \leq Need_i$ go to step 2; else raise error condition, since process has exceeded its maximum claim!
2. If $Request_i \leq Available$, go to step 3; else P_i must wait, since not all resources are available!
3. Consider allocation of requested resources to P_i by modifying the system 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 (instances in brackets):
  - *A* (10), *B* (5), and *C* (7)
- 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 (Cont.)

- The content of the matrix *Need* is defined to be:
  Max – Allocation

	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> satisfies safety criteria

Example: P_1 Request (1,0,2)

- Check that Request ≤ Available (that is, $(1,0,2) \le (3,3,2) \Rightarrow$ true

	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 (0,1,0) by P_0 be granted?

Deadlock Detection

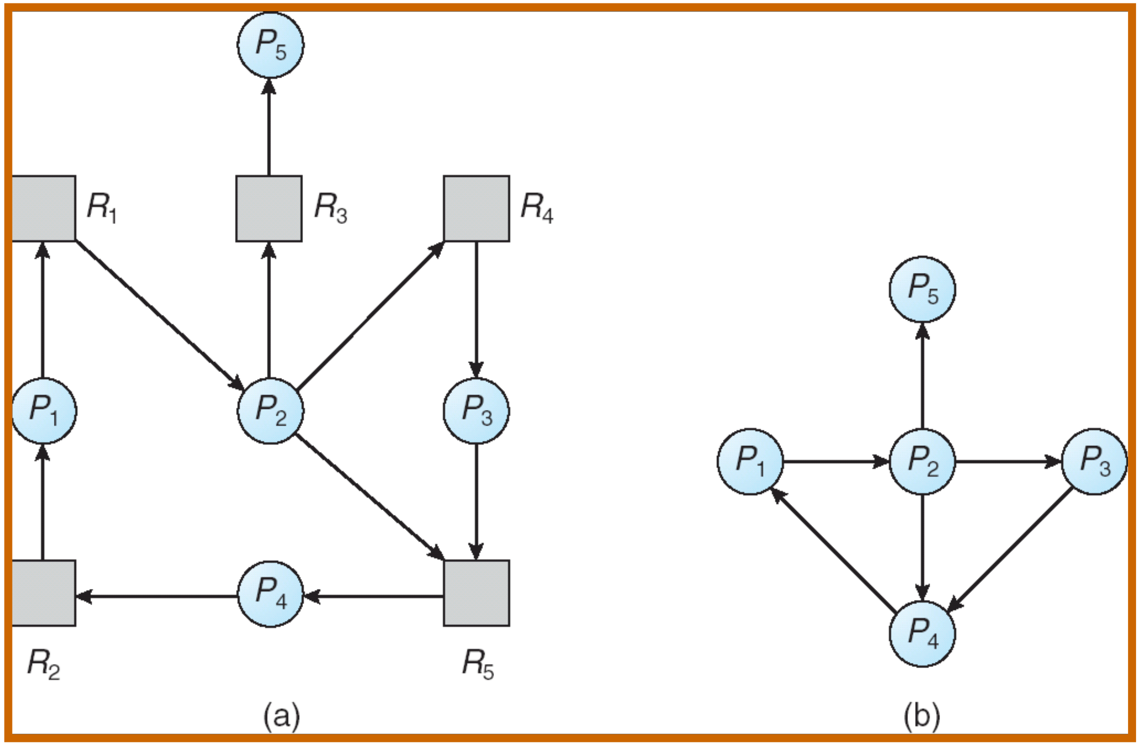
- Allow system to enter deadlock state
- Detection algorithm
- Recovery scheme

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

- 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 & Wait-For Graphs



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.

Detection Algorithm (Cont.)

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.

Algorithm requires an order of O(m x 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 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.

	Request
	A B C
P_0	0 0 0
P_1	2 0 1
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

- 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 – 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