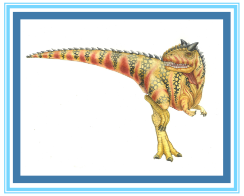
Chapter 7: Deadlocks



Chapter 7: Deadlocks

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

Chapter 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**

Deadlock Characterization

Deadlock can arise if four conditions hold simultaneously – necessary but not sufficient conditions

- **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

  $P_2, \ldots, P_{n-1}$ 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.

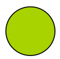
Resource-Allocation Graph

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 $R_j \rightarrow P_i$

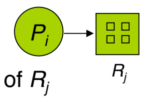
Resource-Allocation Graph (Cont.)

- Process

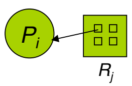


- Resource Type with 4 instances

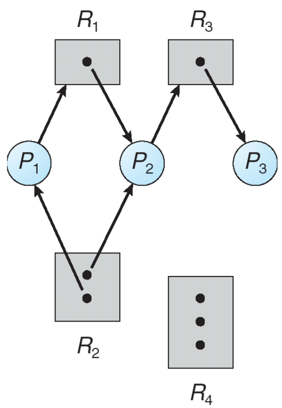
- P_i requests instance of R_j



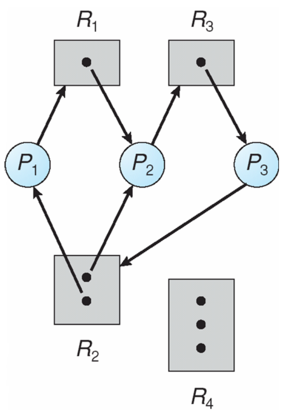
- P_i is holding an instance of R_j



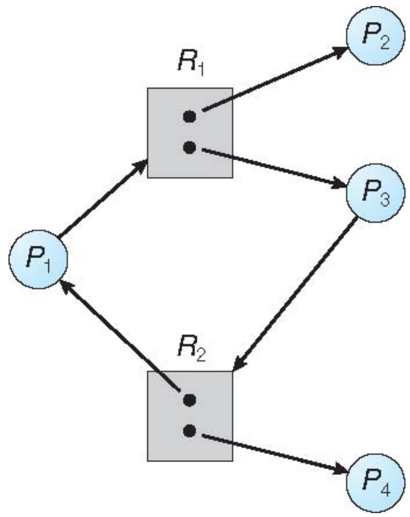
Example of a Resource Allocation Graph



Resource Allocation Graph With A Deadlock



Graph With A Cycle But No Deadlock



Basic Facts

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

Three Methods for Handling Deadlocks

- Use a protocol to prevent or avoid deadlocks, ensuring that the system will ***never*** enter a deadlock state
- Allow the system to enter a deadlock state, detect it, and then recover
- Ignore the problem and pretend that deadlocks never occur in the system; used by most operating systems, including UNIX

Methods for Handling Deadlocks (Cont.)

- Deadlock Prevention: it provides a set of methods to ensure at least one of the necessary conditions cannot hold
- Deadlock Avoidance: this requires additional information given in advance concerning which resources a process will request and use during its lifetime. Within this knowledge, the operating system can decide for each resource request whether or not a process should wait
- If a system does not employ either of the above two methods, a deadlock situation may arise. In this environment, the system can provide an algorithm that examines the state of the system to determine whether a deadlock has occurred and an algorithm to recover from the deadlock

Deadlock Prevention

Restrain the ways request can be made

- **Mutual Exclusion** – not required for sharable resources; must hold for nonsharable 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
  - 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
  - This can only be applied to resources whose state can be easily saved and restored such as registers and memory space. It cannot generally be applied to resources such as locks and semaphores
- **Circular Wait** – impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration – R = {<R_1, R_2, …, R_m},

Deadlock Example

```
/* 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);
}
```

Deadlock Example with Lock Ordering

```
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);
}
```


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 a circular-wait condition can never exist
- **Resource-allocation state** is defined by the number of available and allocated resources, and the maximum demands of the processes

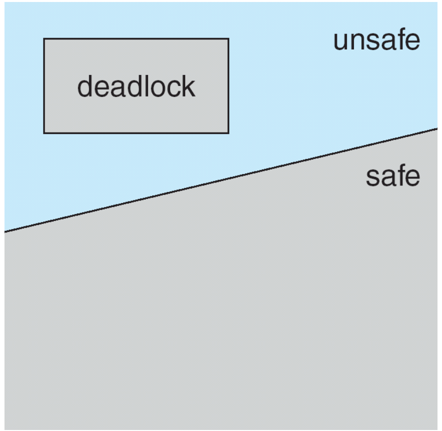
Safe State

- 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 sequence $<P_1, P_2, …, P_n>$ of **all 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 plus resources held by all the P_j, with $j < i$
- That is:
  - 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

Basic Facts

- 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
  - In this scheme, if a process requests a resource that is currently available, it may still have to wait (if the allocation leads to unsafe state). This, resource utilization may be lower than it would be otherwise

Safe, Unsafe, Deadlock State



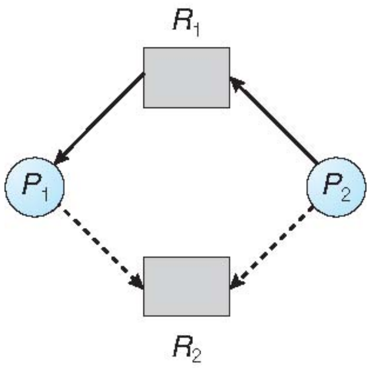
Avoidance algorithms

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

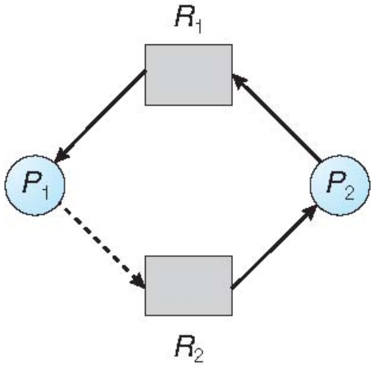
Resource-Allocation Graph Scheme

- **Claim edge** $P_i \rightarrow R_j$ indicated that process P_j may request resource R_j; represented by a dashed line
- Claim edge converts to 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



Unsafe State In Resource-Allocation Graph



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

Banker's Algorithm

- Multiple instances
- Each process must declare a priori maximum use
- When a process requests a resource it may have to wait – check to see is this allocation results in a safe state or not
- 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) $\boldsymbol{Need_i \le Work}$

   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 = 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 $\boldsymbol{Request_i \le Need_i}$ go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim
2. If $\boldsymbol{Request_i \le Available}$, go to step 3. Otherwise P_i must wait, since resources are not available
3. Pretend to have allocated requested resources to P_i by modifying the state as follows:

   Available = Available – Request;

   $\boldsymbol{Allocation_i = Allocation_i + Request_i}$;

   $\boldsymbol{Need_i = Need_i - Request_i}$;

   - If safe: the resources are allocated to P_i
   - If unsafe: 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:

	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) ≤ (3,3,2) ≤ 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 $\boldsymbol{P_4}$ be granted? – resource not available
- Can request for (0,2,0) by $\boldsymbol{P_0}$ be granted? – state is not safe

Deadlock Detection

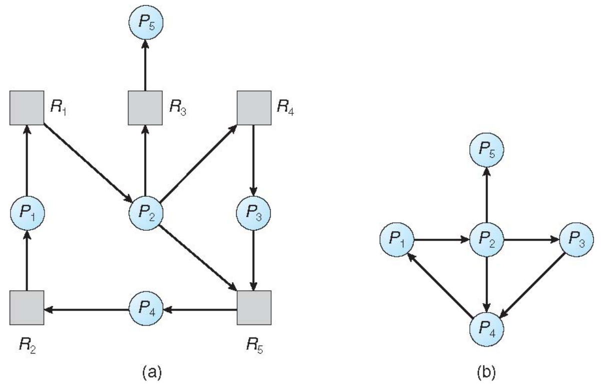
If a system does not use either a deadlock-prevention, or deadlock-avoidance algorithm, then a deadlock situation may occur. In this environment, the system may provide

- An algorithm that examines the state of the system to determine whether a deadlock has occurred
- An algorithm to recover from the deadlock

Single Instance of Each Resource Type

- Maintain **wait-for** graph
  - Nodes are processes
  - $\boldsymbol{P_i \rightarrow P_j}$ if $\boldsymbol{P_i}$ is waiting for $\boldsymbol{P_j}$
- 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 $\boldsymbol{n^2}$ operations, where $\boldsymbol{n}$ is the number of vertices in the graph
- The wait-for graph scheme is not applicable to a resource-allocation system with multiple instances of each resource type

Resource-Allocation Graph 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, …, *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 ≤ ***I*** ≤ ***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	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 be affected by a deadlock when it occurs
    - 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.
- Invoking the deadlock detection algorithm for every resource request will incur considerable overhead in computation. A less expensive alternative is to invoke the algorithm at defined intervals – for example, once per hour or whenever CPU utilization drops below 40 percent

Recovery from Deadlock: Process Termination

- **Abort all deadlocked processes**: This clearly break the deadlock cycle, but at great expense
- **Abort one process at a time until the deadlock cycle is eliminated**: This incurs considerable overhead, since after each process is aborted, the deadlock-detection algorithm needs to run
- In which order should we choose to abort? – many factors:
  1. Priority of the process
  2. How long process has computed, and how much longer to completion
  3. Resources the process has used
  4. Resources process needs to complete
  5. How many processes will need to be terminated
  6. Is process interactive or batch?

Recovery from Deadlock: Resource Preemption

To successively preempt some resources from processes and give these resources to other processes until the deadlock cycle is broken

- **Selecting a victim** – minimize cost (which resources and which processes are to be preempted)
- **Rollback** – return to some safe state, restart process for that state
- **Starvation** – same process may always be picked as victim, including the number of rollback in cost factor might help to reduce the starvation