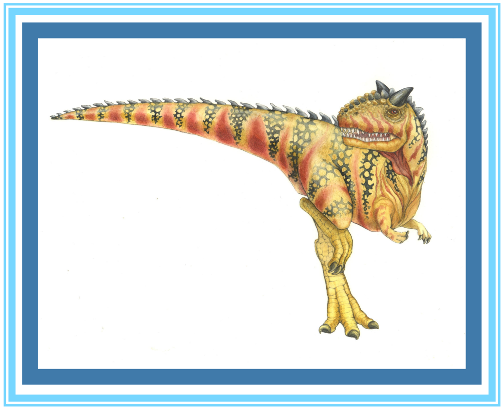
Chapter 7: Deadlocks



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 , ... , R_m

  CPU cycles, memory space, I/O devices
- Each resource type R_i has W_i instances
- A lock mechanism (e.g., mutex, semaphore) is assigned its own resource class; locks are also system resources
- Each process utilizes a resource as follows:
  - **request**
  - **use**
  - **release**
- **request** and **release** may be system calls; a system table records if a resource is free or allocated, and if so, to which process; a queue of waiting processes for one resource

Deadlock with Mutex Locks

- Deadlocks can occur via system calls, locking, etc.
- See example box in textbook (pages 317-318) for mutex deadlock
  - a first thread requests mutex1 and mutex2
  - a second thread requests mutex2 and mutex1
  - they each acquire their first mutex and then wait for their second mutex, acquired by the other

Deadlock Characterization

- Deadlock can arise if all **four** conditions hold **simultaneously**
  - **Mutual exclusion**
    - only one process at a time can use a resource ; other processes requesting this resource must be delayed
  - **Hold and wait**
    - a process holding at least one resource is waiting to acquire additional resources held by other processes

Deadlock Characterization (cont.)

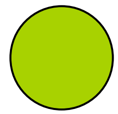
- Deadlock can arise if all **four** conditions hold **simultaneously**
  - **No preemption**
    - a resource can be released only voluntarily by the process holding it, after that process has completed its task
  - **Circular wait**
    - there exists a set $\{P_0, P_1, \ldots, P_n\}$ of waiting processes 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

Resource-Allocation Graph

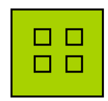
- Directed graph: a set of vertices V and a set of edges E
- V is partitioned into two sets:
  - $P = \{ P_1 , P_2 , \ldots, P_n \}$, set of all the processes in the system
  - $R = \{ R_1 , R_2 , \ldots, R_m \}$, set of all resource types in the system
- **request edge** – directed edge $P_i \rightarrow R_j$
- **assignment edge** – directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph (cont.)

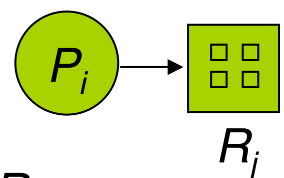
- Process



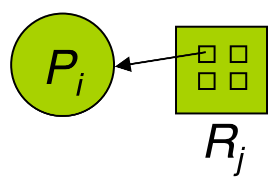
- Resource type with 4 instances



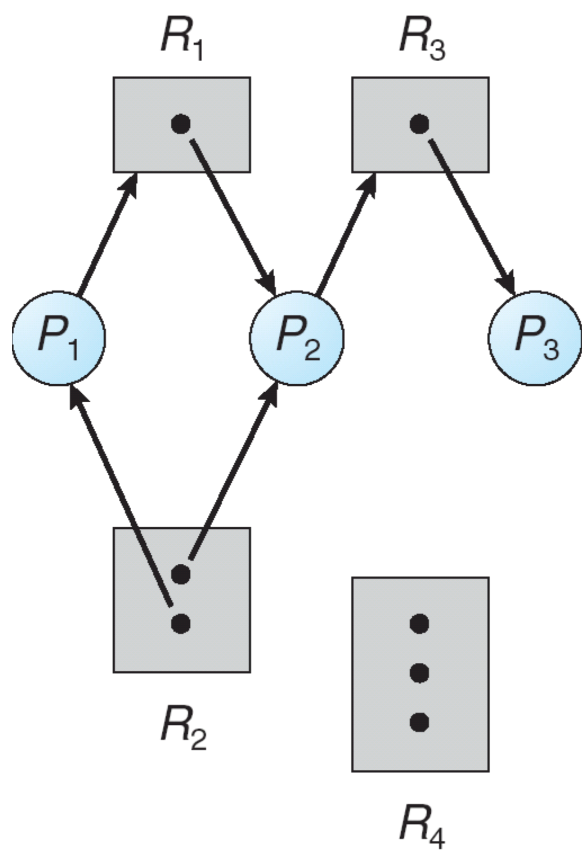
- P_i requests instance of R_j



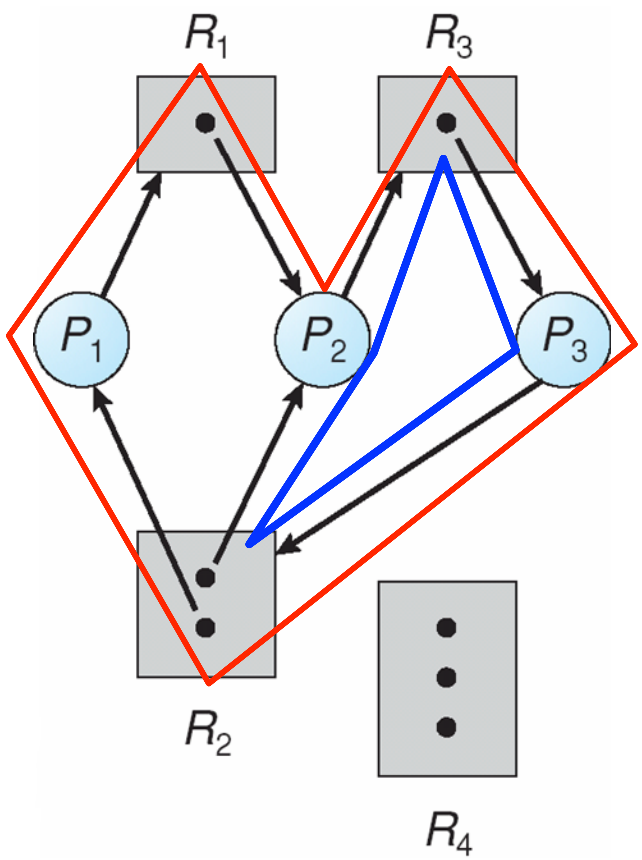
- P_i holds an instance of R_j



Example of a Resource Allocation Graph

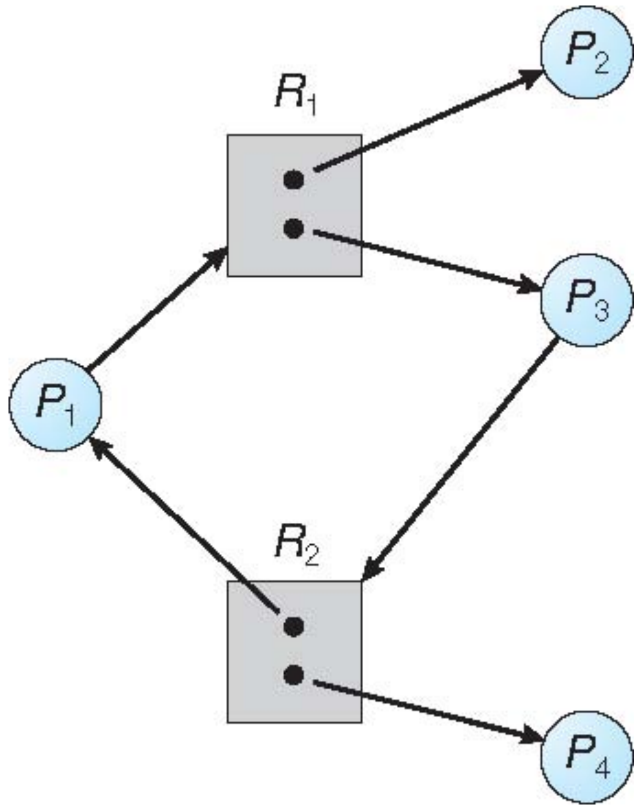


Resource Allocation Graph with a Deadlock



two minimal cycles

Graph with a Cycle But No Deadlock



Basic Facts

- If graph contains no cycles ⇒ no deadlocks
- If graph contains a cycle ⇒ a deadlock *may* or *may not* exist
  - if only one instance per resource type, then deadlock
    - necessary and sufficient condition
  - if several instances per resource type, possibility of deadlock
    - necessary but not sufficient condition

Methods for Handling Deadlocks

- Ensure that the system will ***never*** enter a deadlock state
- Allow the system to enter a deadlock state and then recover
- Ignore the problem and pretend that deadlocks never occur in the system
  - used by most operating systems, including UNIX and Windows

Deadlock Prevention

- Restrain the ways request can be made (release at least 1 of the 4 necessary conditions)
  - **Mutual Exclusion** – not required for sharable resources, but must hold for nonsharable resources
  - **Hold and Wait** – must guarantee that whenever a process requests a resource, it does not hold any other resources
    1. Require process to request and be allocated all its resources *before* it begins execution, or
    2. Allow process to request resources *only* when the process has *none*
       - it must release its current resources before requesting them back again
    - Disadvantages:
      - low resource utilization: unnecessarily unused
      - possible starvation: always waiting...

Deadlock Prevention (cont.)

- **No Preemption** –
  - If a process, that is holding some resources, does request another resource that cannot be immediately allocated to it, then all its 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
  - require that each process requests resources in an increasing order of enumeration, or release resources of *higher or equal* order
    - several instances of one resource type must be requested in a single request
  - a *witness* may detect a wrong order and emit a warning

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 declares 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

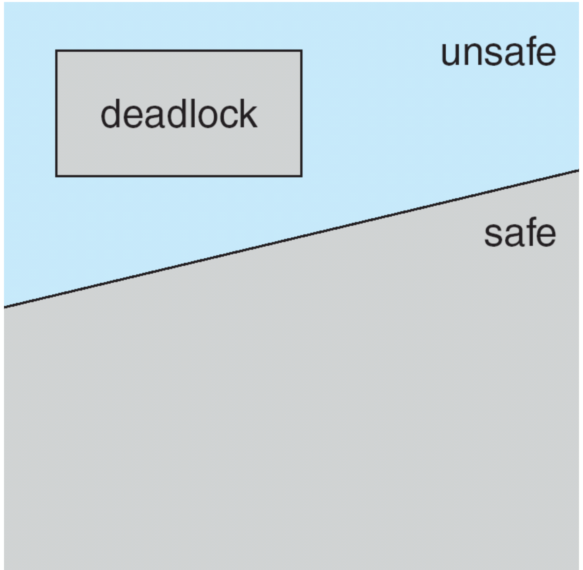
- When a process requests an available resource, system must decide if immediate allocation leaves the system in a safe state

- System is in **safe state** if there exists a sequence $< P_1, P_2, \ldots, P_n >$ 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 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 $\Rightarrow$ 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

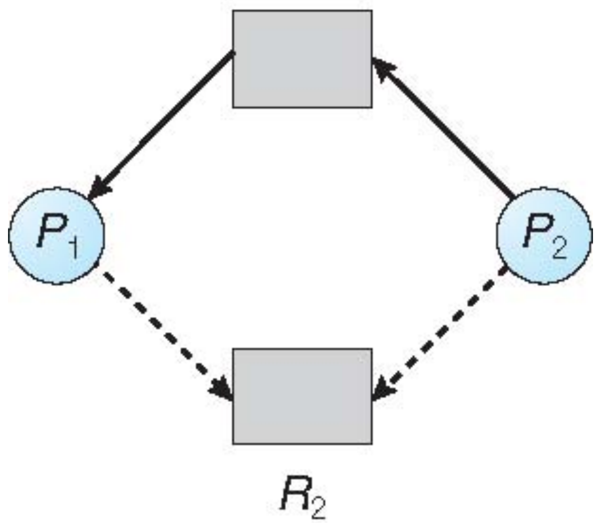
- Single instance of a resource type
  - Use a resource-allocation graph
- Multiple instances of a resource type
  - Use the banker's algorithm

Resource-Allocation Graph Scheme

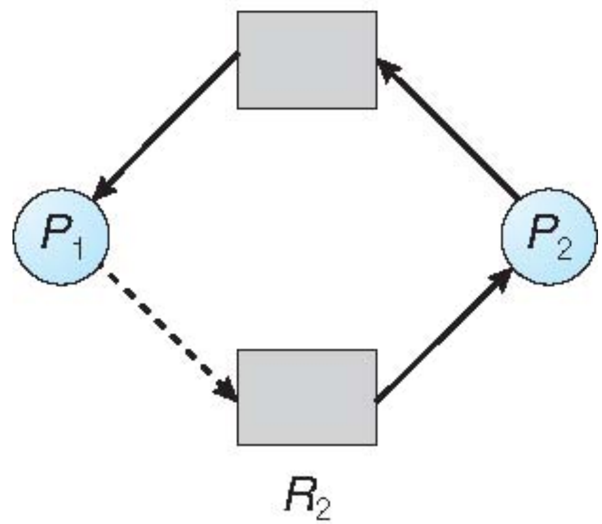
- **Claim edge** $P_i \rightarrow R_j$ indicates that process P_j *may* request resource R_j ; represented by a dashed line
- Claim edge is converted to request edge when a process requests a resource
- Request edge is converted to an assignment edge when the resource is allocated to the process
- When a resource is released by a process, assignment edge is reconverted to a claim edge
- Resources must be claimed *a priori* in the system, i.e., from the start, claim edges must be entered

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 (an $O(n^2)$ task)



safe state



allocate R_2 to P_2
if P_1 requests R_2, unsafe state

Banker's Algorithm

- Multiple instances
- Less efficient than the resource-allocation graph algorithm
- Each process must *a priori* claim maximum number of instances of each resource type
- 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 $i = 0, 1, \ldots, n - 1$

2. Find an *i* such that both:

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

    (b) $\boldsymbol{Need_i \leq Work}$ (P_i needs less resources than still available)

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

3. $\boldsymbol{Work = Work + Allocation_i}$ (release resources of P_i back into available)
    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

P_i requests resources:

1. If $Request_i \le Need_i$ go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim
2. If $Request_i \le Available$, 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:

$$Available = Available - Request$$

$$Allocation_i = Allocation_i + Request_i$$

$$Need_i = Need_i - Request_i$$

- 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:

	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

Available
3 / 3 / 2
P1 ok; releases 2 / 0 / 0
5 / 3 / 2
P3 ok; releases 2 / 1 / 1
7 / 4 / 3
P4 ok; releases 0 / 0 / 2
7 / 4 / 5
P2 ok ; releases 3 / 0 / 2
10 / 4 / 7
P0 ok ; releases 0 / 1 / 0
10 / 5 / 7

- 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 < $\boldsymbol{P_1, P_3, P_4, P_0, P_2}$ > satisfies safety requirement
- Can request for (3,3,0) by $\boldsymbol{P_4}$ be granted? no, (2,3,0) < (3,3,0)
- Can request for (0,2,0) by $\boldsymbol{P_0}$ be granted? no, further state unsafe

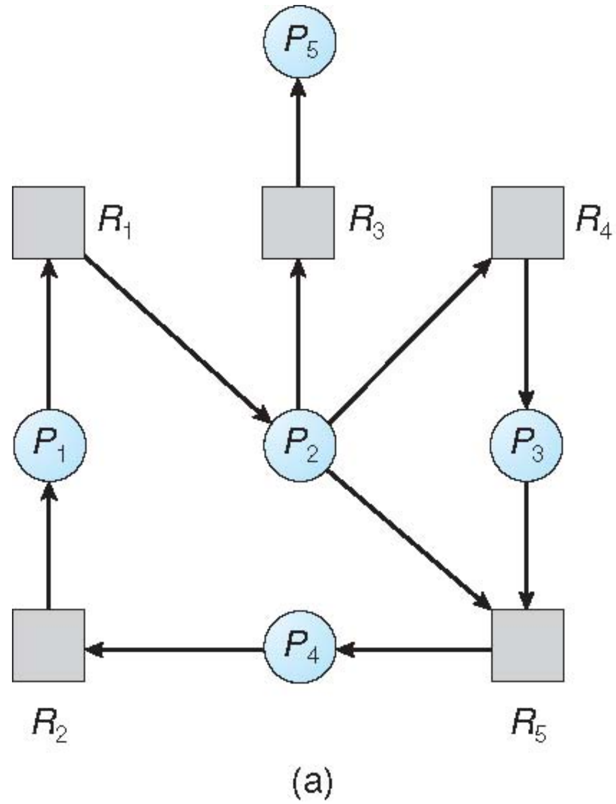
Deadlock Detection

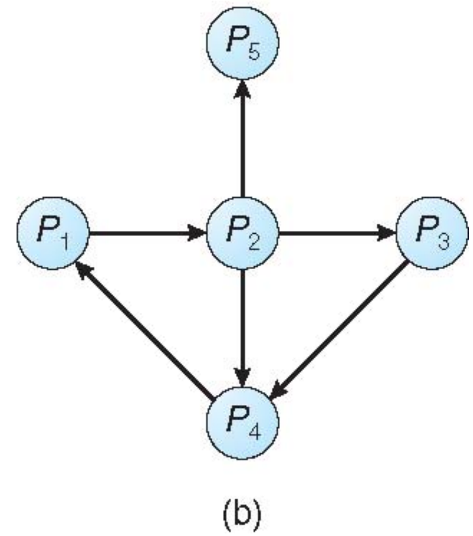
- Allow system to enter deadlock state
- Detection algorithm
- Recovery scheme

Single Instance of Each Resource Type

- Maintain **wait-for** graph
  - Nodes are processes (collapse resources nodes in resource-allocation graph)
  - $P_i \rightarrow P_j$ if P_i is waiting for P_j (to release a requested resource)
- 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 nodes in the graph

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 $\boldsymbol{Allocation_i} \neq \mathbf{0}$, then
   Finish*[i] = *false; otherwise, ***Finish*[i] = *true***

2. Find an index *i* such that both:

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

   (b) $\boldsymbol{Request_i} \leq \boldsymbol{Work}$

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

Detection Algorithm (Cont.)

3. ***Work* = *Work* + *Allocation*$_i$** (hoping P_i will return soon its resources)
   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 requests of the other processes
  - 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

Recovery from Deadlock: Process Termination

- Abort all deadlocked processes
- Ask the operator to resolve manually the deadlock
- Abort one process at a time until the deadlock cycle is eliminated

- In which order should we choose to abort?
  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

- **Selecting a victim** – minimize cost
- **Rollback** – return to some safe state, restart process for that state, but must keep data on the states of running processes
- **Starvation** – same process may always be picked as victim, include number of rollbacks in cost factor

End of Chapter 7