Operating Systems

Deadlocks

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Deadlocks

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

Deadlock

- A process requests resources; if the resources are not available at that time, the process enters a waiting state. Sometimes, **a waiting process is never again able to change state**, because the resources it has requested are held by other waiting processes. This situation is called a deadlock.

- OSes typically do not provide deadlock-prevention facilities, and it remains the responsibility of programmers to ensure that they design **deadlock-free programs**.

System Model

- System consists of resources
- Resource types $R_1, R_2, \ldots, R_m$

  CPU cycles, memory space, I/O devices;

  files, mutex, semphores,
- Each resource type R_i has W_i instances.
- Each process utilizes (e.g. via syscalls) 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 of waiting processes $\{P_0, P_1, \ldots, P_n\}$ 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.

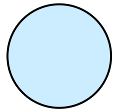
Resource-Allocation Graph

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

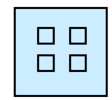
- V is partitioned into two types:
  - $P = \{P_1, P_2, \ldots, P_n\}$, all the **processes** in the system
  - $R = \{R_1, R_2, \ldots, R_m\}$, all **resource** types in the system
- **request edge** – directed edge $P_i \rightarrow R_j$
- **assignment edge** – directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph (Cont.)

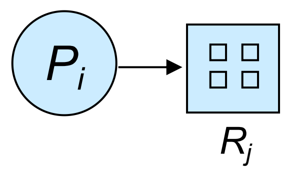
- Process



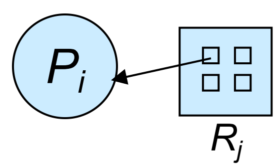
- Resource Type with 4 instances



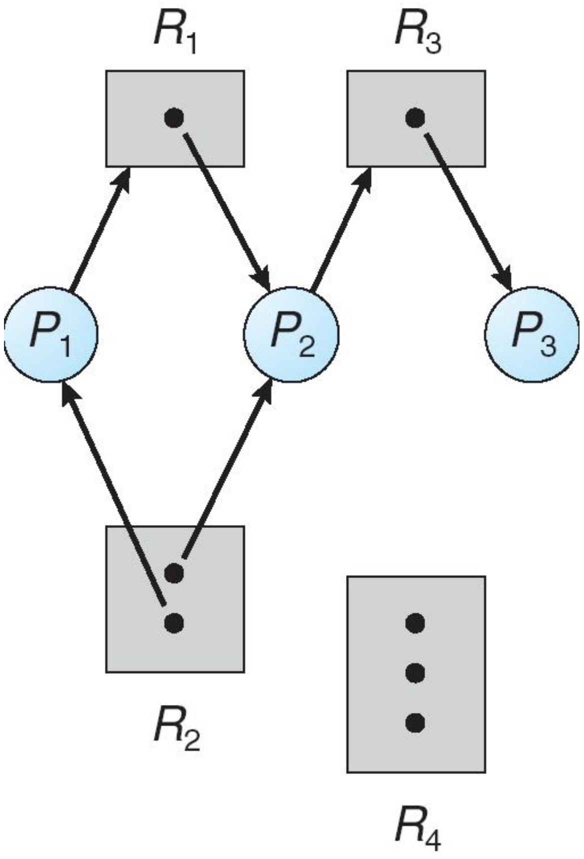
- P_i requests instance of R_j



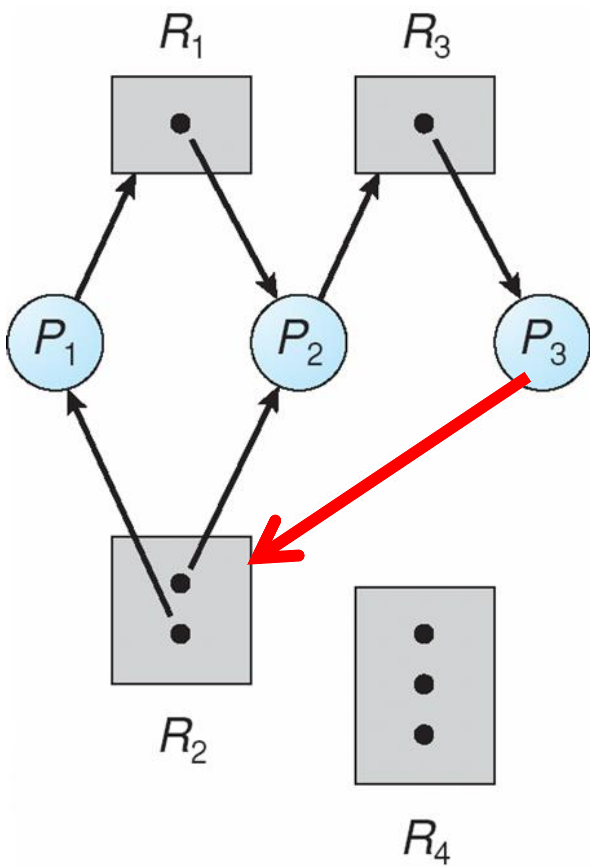
- P_i is holding an instance of R_j



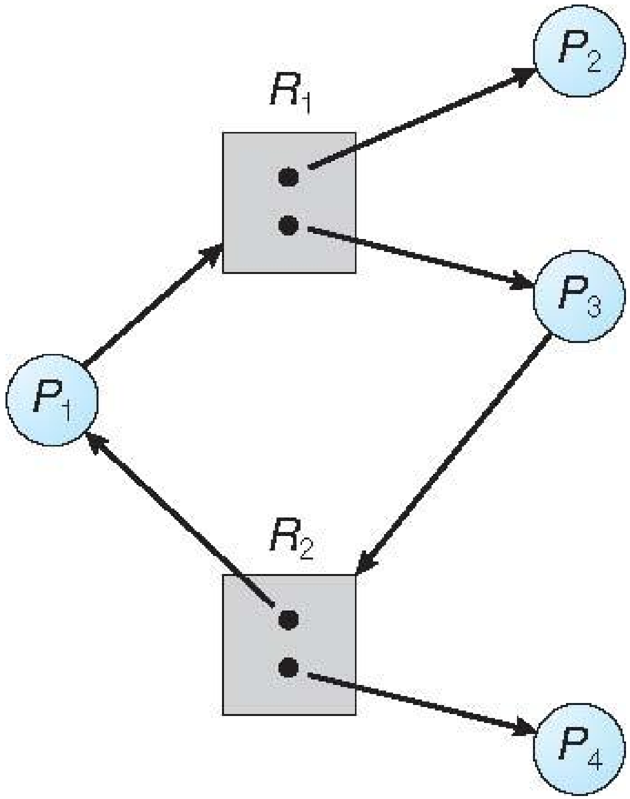
Example of a Resource Allocation Graph



Resource Allocation Graph With A Deadlock



Graph With A Cycle But No Deadlock



Basic Facts

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

Methods for Handling Deadlocks

- Ensure that the system will ***never*** enter a deadlock state:
  - Deadlock **prevention**
  - Deadlock **avoidence**
- 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 Linux and Windows.
  - It is then up to the **application developers** to write programs that handle deadlocks.

Deadlock Prevention

Restrain the ways that requests can be made

- **Mutual Exclusion** – it must hold for non-sharable resources. Thus, we cannot deny the mutual-exclusion condition 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 allocated to it. (**all-or-nothing**)
  - Disadvantages: 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 and 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.

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);
}
```

Transactions 1 and 2 execute concurrently as follows.

```
transaction(A, B, 25);
transaction(B, A, 50);
```

Deadlock Avoidance

Requires that the system has a priori information available (先验信息)

- 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 demands of the processes

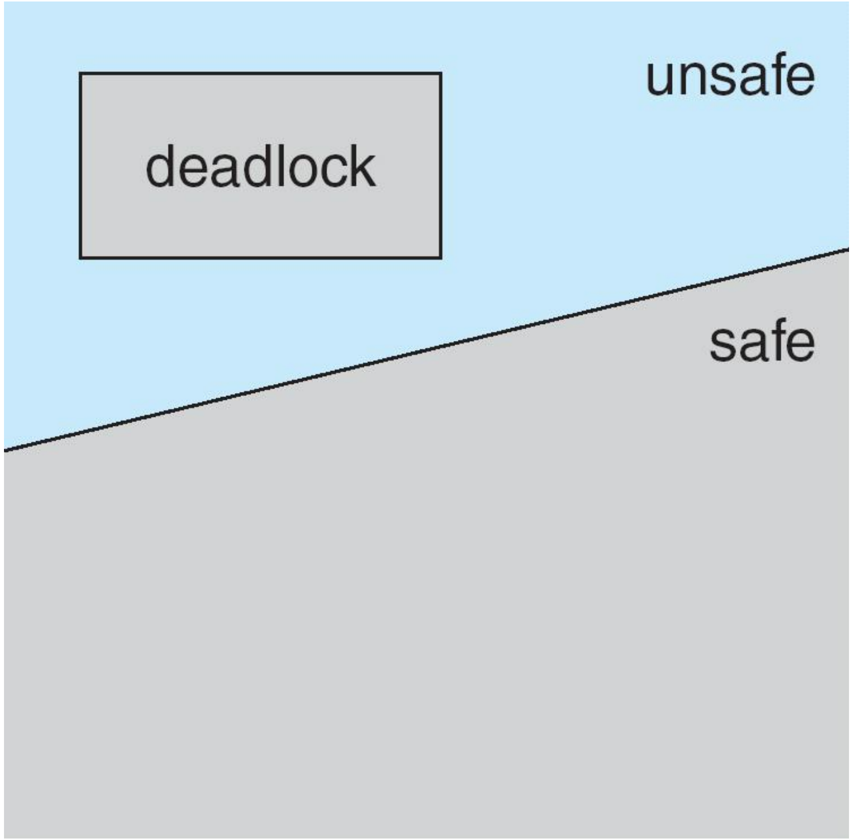
Safe State

- 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 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.

Safe, Unsafe, Deadlock State



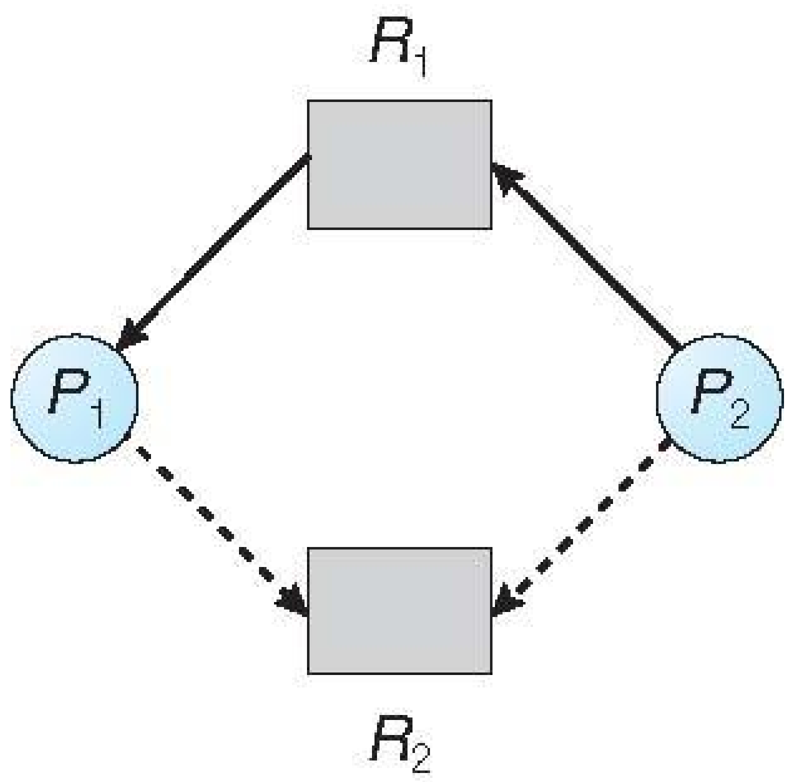
Avoidance Algorithms

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

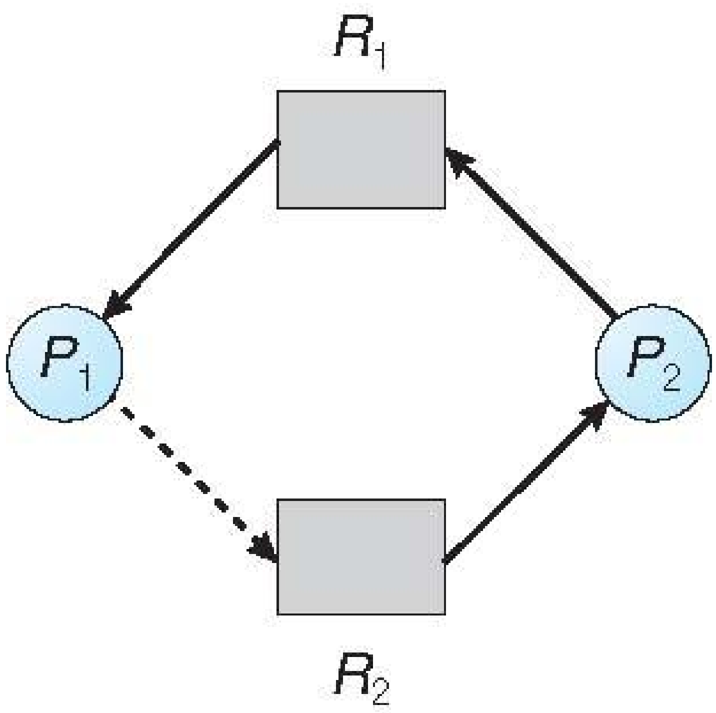
Resource-Allocation Graph Scheme

- **Claim edge** $P_i \rightarrow R_j$ indicated that process P_i may request resource R_j at some time in the future. represented by a dashed line
- Claim edge **converts** to request edge when a process requests a resource
- Request edge **converts** 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 a **cycle** in the resource allocation graph
- An algorithm for detecting a cycle in this graph requires an order of n^2 operations, where n is the number of processes.

Banker's Algorithm

- Multiple instances per resource type
- 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

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**: $n \times m$ 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 *work: dynamic avail. resource*

   ***Finish[i] = false* for *i* = 0, 1, …, *n*- 1** The proc. finished

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

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

   (b) ***Need$_i$* ≤ *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

$\boldsymbol{Request_i}$ = request vector for process $\boldsymbol{P_i}$. If $\boldsymbol{Request_i[j] = k}$ then process $\boldsymbol{P_i}$ wants $\boldsymbol{k}$ instances of resource type $\boldsymbol{R_j}$

1. If $\boldsymbol{Request_i \leq Need_i}$ go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim
2. If $\boldsymbol{Request_i \leq Available}$, go to step 3. Otherwise $\boldsymbol{P_i}$ must wait, since resources are not available
3. Pretend to allocate requested resources to $\boldsymbol{P_i}$ by modifying the 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 $\boldsymbol{P_i}$
- If unsafe $\Rightarrow$ $\boldsymbol{P_i}$ must wait, and the old resource-allocation state is restored

Example of Banker's Algorithm

- 5 processes: P_0 ~ 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***

	<u>*Need*</u>
	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. Pretending that this request is fulfilled will cause a new state:

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

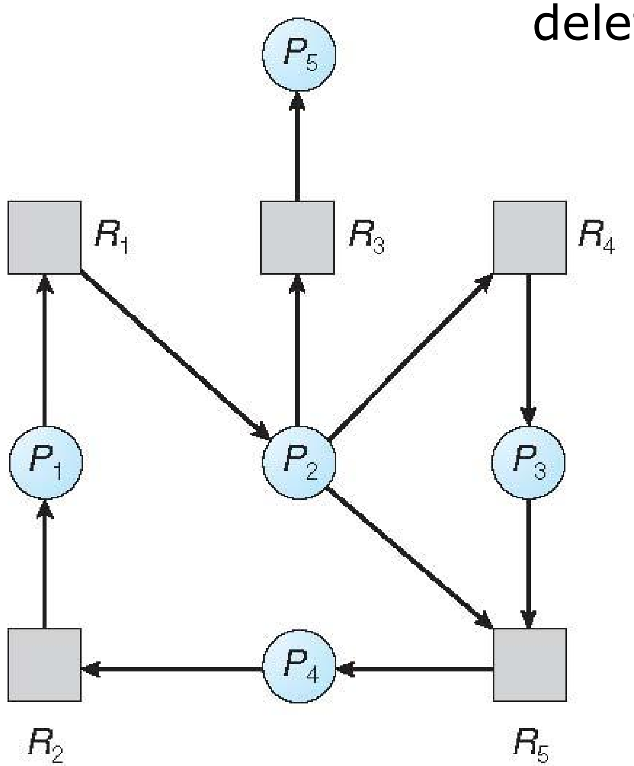
- Allow system to enter deadlock state
- Detection algorithm
- Recovery scheme

Single Instance per Resource Type

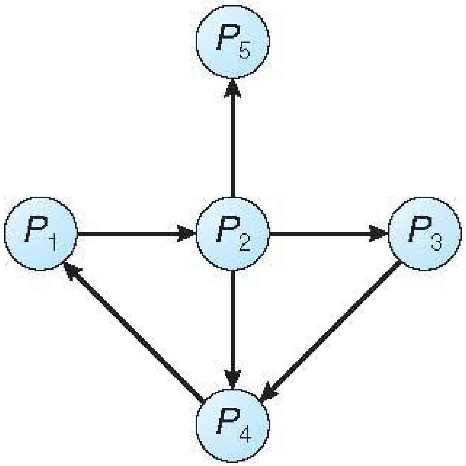
- Maintain **wait-for** graph
  - Nodes are processes
  - $P_i \rightarrow P_j$ if P_i is waiting for P_j
- **Periodically** invoke an algorithm that searches for a **cycle** in the graph. If there is a cycle, there exists a **deadlock**
- An algorithm to detect a cycle in a graph requires an order of n^2 operations, where n is the number of vertices in the graph

Resource-Allocation Graph and Wait-for Graph

delete Resource nodes



(a)



(b)

Resource-Allocation Graph

Corresponding Wait-for Graph

Several Instances per 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 $\boldsymbol{i}$ **= 1,2, …,** $\boldsymbol{n}$, if $\boldsymbol{Allocation_i \neq 0}$, then ***Finish[i] = false****;* otherwise*,* ***Finish[i] = true***

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

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

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

   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***, $1 \leq \boldsymbol{i} \leq \boldsymbol{n}$, then the system is in deadlock state. Moreover, if ***Finish[i] == false***, then $\boldsymbol{P_i}$ 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: $\boldsymbol{P_0} \sim \boldsymbol{P_4}$; three resource types: A (7 instances), *B* (2 instances), and *C* (6 instances)
- Snapshot at time $\boldsymbol{T_0}$:

	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 <$\boldsymbol{P_0, P_2, P_3, P_1, P_4}$> 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 need to be rolled back?

- Invoking the deadlock-detection algorithm for every resource request will incur considerable overhead. A less expensive alternative is simply to invoke the algorithm at defined **intervals**, e.g., once per hour or whenever **CPU utilization** drops below 40 percent.
- 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

- 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** – roll back the process to some safe state, restart it from that state
- **Starvation** – same process may always be picked as victim, a solution is to include number of rollback in cost factor (roll back in a finite number of times)

Review Part 2: Process management

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