Chapter 7: Deadlocks

肖 卿 俊
办公室：计算机楼212室
电邮：csqjxiao@seu.edu.cn
主页：http://cse.seu.edu.cn/PersonalPage/csqjxiao
电话：025-52091022

Chapter 7: Deadlocks

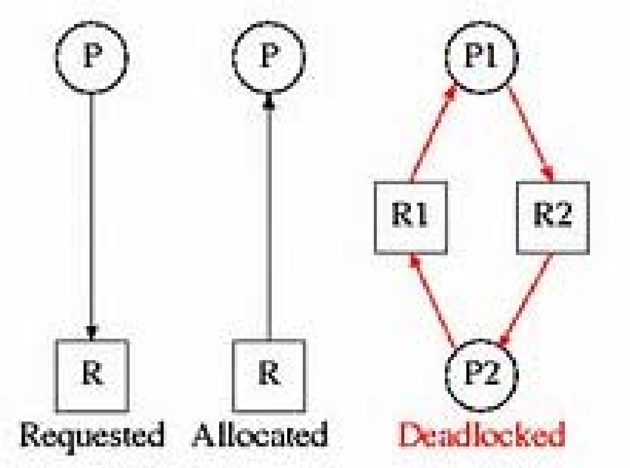
- System Model
- Deadlock Characterization
- Methods for Handling Deadlocks
- Deadlock Prevention (死锁预防)
- Deadlock Avoidance (死锁避免)
- Deadlock Detection (死锁检测)
- Recovery from Deadlock (死锁恢复)

What Is a Deadlock?

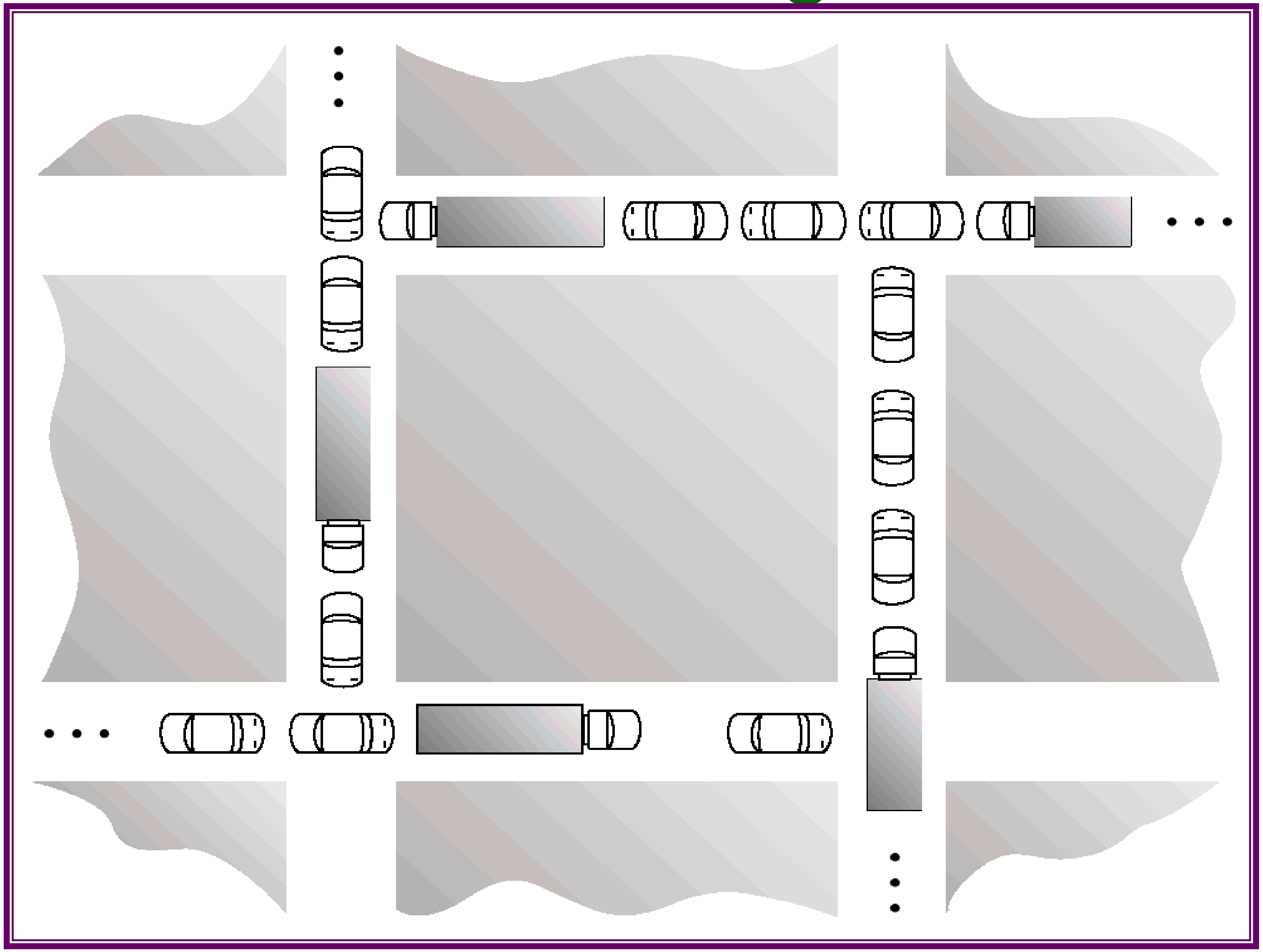
- Deadlock (死锁) is a special phenomenon of resource scarcity among a group of processes (or threads)
- A set of blocked processes each holding a resource and waiting to acquire a resource held by another process in the set.
- A Simple Example
  - System has 2 tape drives.
  - P_1 and P_2 each hold one tape drive and each needs another one.

Formalize the Simple Example of Deadlock

- A simple example of deadlock between two processes P1 and P2
  - P1 holds R1 and needs R2
  - P2 holds R2 and needs R1



Deadlock can be of a much larger scale



System Model

- Resource types $R_1, R_2, \ldots, R_m$

  CPU cycles, memory space, I/O devices, etc.

- Each resource type R_i has W_i instances.

- Each process utilizes a resource as follows:
  - Request
  - Use
  - Release

System Model

- System resources are used in the following way:
  - Request: If a process makes a request to use a system resource which cannot be granted immediately, then the requesting process must block until it can acquire the resource.
  - Use: The process can operate on the resource.
  - Release: The process releases the resource.
- ***Deadlock***: A set of process is in a deadlock state when every process in the set is waiting for an event that can only be caused by another process in the set.

Four Necessary Conditions for a Deadlock Situation

- ***For a deadlock to occur, each of the following four conditions must hold.***
  - **Mutual exclusion:** only one process at a time can use a resource.
  - **Hold and wait:** A process must be holding a resource and waiting for another.
  - **No preemption:** a resource can be released only voluntarily by the process holding it, after that process has completed its task.
  - **Circular wait:** A waits for B, B waits for C, C waits for A.

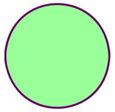
Resource-Allocation Graph

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

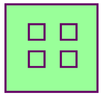
- Vertices V is partitioned into two types:
  - $P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system.
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system.
- Edges E is also partitioned into two types:
  - Resource request edge – directed edge $P_i \rightarrow R_j$
  - Resource assignment edge – directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph (Cont.)

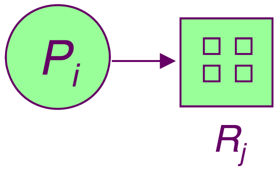
- Process



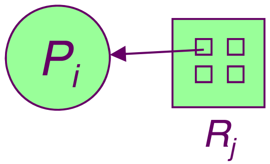
- Resource Type with 4 instances



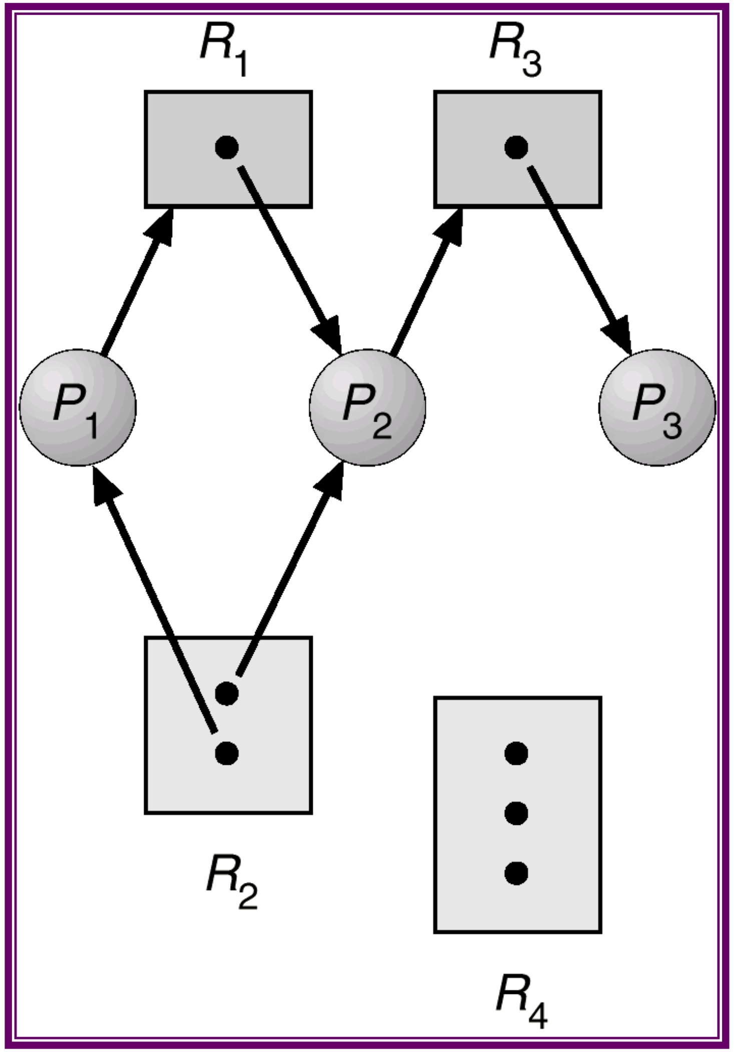
- P_i requests instance of R_j



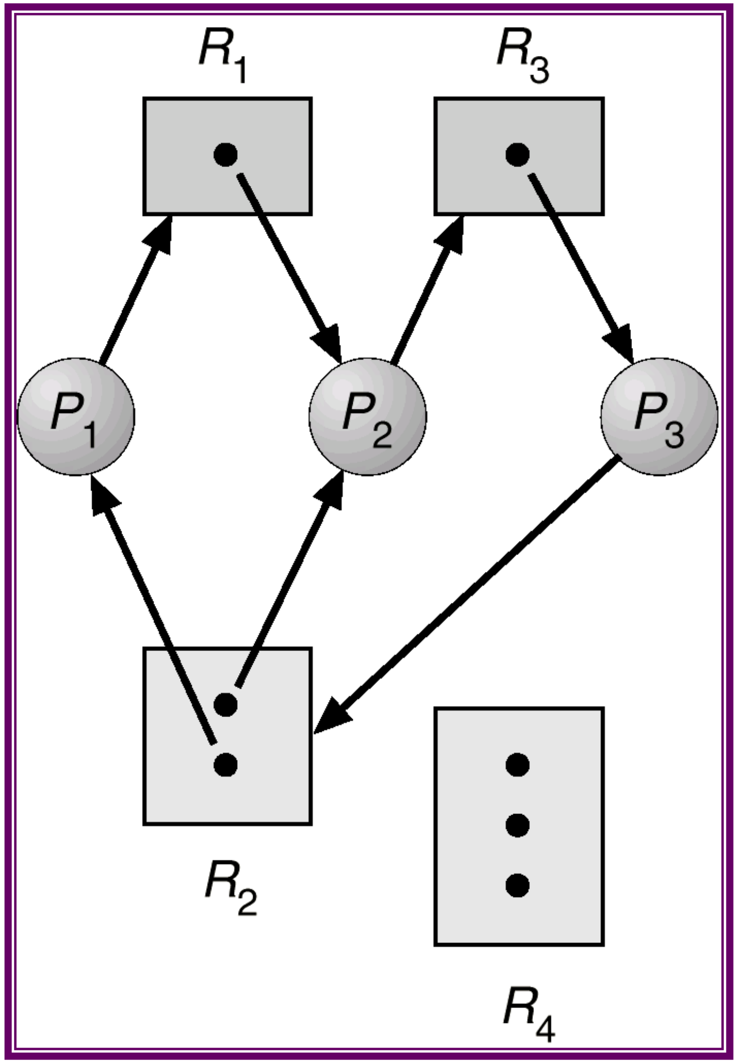
- P_i is holding an instance of R_j



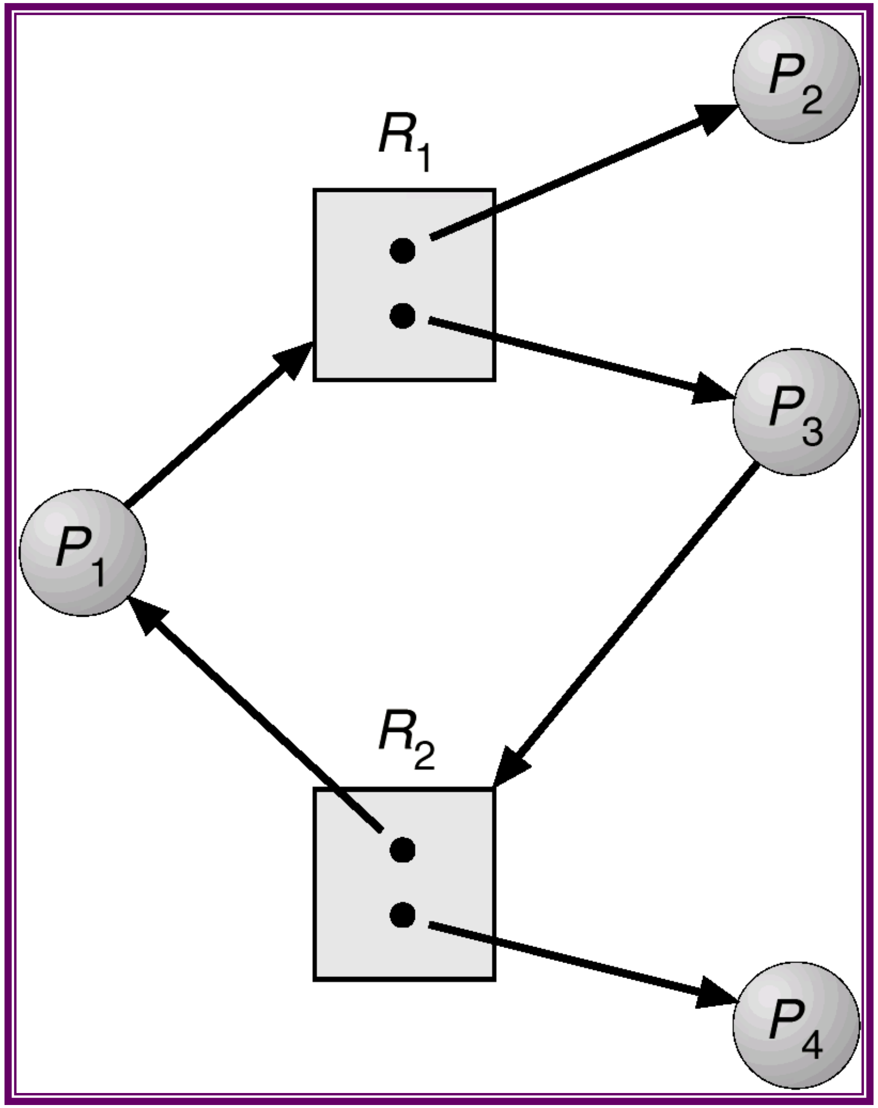
An Example of Resource Allocation Graph



Resource Allocation Graph With A Deadlock



Resource Allocation Graph With A Cycle But No Deadlock



Basic Facts about Deadlock Detection

- 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.

Methods for Handling Deadlocks

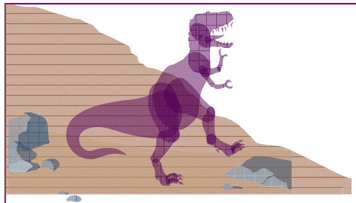
- Ignore the problem and pretend that deadlocks never occur in the system.
- Allow the system to enter a deadlock state, detect it, and recover from it, typically by killing the processes that hold the popular resources
- Ensure that the system will *never* enter a deadlock state.
  - **Prevention:** Ensure one of the four conditions fails.
  - **Avoidance:** The OS needs more information so that it can determine if the current request can be satisfied or delayed.

Deadlock Prevention: Mutual Exclusion

- By ensuring that at least one of the four conditions cannot hold, we can prevent the occurrence of a deadlock.

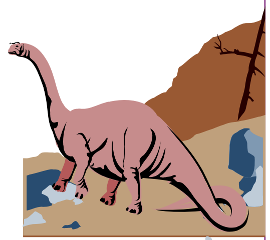
- **Mutual Exclusion:** Some sharable resources must be accessed exclusively (e.g., printer), which means we cannot deny the mutual exclusion condition.

- Reader-Writer Lock may bring some inspirations



Deadlock Prevention: Hold and Wait

- No process can hold some resources and then request for other resources.
- Two strategies are possible:
  - A process must acquire *all* resources before it runs.
  - When a process requests for resources, it must hold none (*i.e.*, return resources before requesting for more).
- Resource utilization may be low, since many resources will be held and unused for a long time
- Starvation is possible. A process that needs some popular resources may have to wait indefinitely.



Deadlock Prevention: Hold and Wait

- No process can hold some resources and then request for other resources.
- Two strategies are possible:
  - A process must acquire *all* resources before it runs.
  - When a process requests for resources, it must hold

The dining philosopher problem can be solved, if we wrap the taking of left chopstick and the taking of right chopstick as an atomic operation. WHY?

- Re
  res ne
- Starvation is possible. A process that needs some popular resources may have to wait indefinitely.

Deadlock Prevention: 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.
- If the requested resources are not available:
  - If they are being held by processes that are waiting for additional resources, these resources are preempted and given to the requesting process.
  - Otherwise, the requesting process waits until the requested resources become available. While it is waiting, its resources may be preempted.

Deadlock Prevention: Circular Wait

- To break the circular waiting condition, we order all resource types (*e.g.*, tapes, printers)
- A process can only request resources higher than the resource types it holds.
- Suppose the ordering of tapes, disks, and printers are 1, 4, and 8. If a process holds a disk (4), it can only ask a printer (8) and cannot request a tape (1). A process must release some higher order resources to request a lower order resource. To get tapes (1), a process must release its disk (4).
- **In this way, there will be no cycle. Why?**

Deadlock Prevention: Circular Wait

- To break the circular waiting condition, we order all resource types (*e.g.*, tapes, printers)
- A process can only request resources higher than the resource types it holds.
- Su… pri… a dis… cannot request a tape (1). A process must release some higher order resources to request a lower order resource. To get tapes (1), a process must release its disk (4).

The dining philosopher problem can be solved by imposing an ordering to the five chopsticks. But HOW?

- **In this way, there will be no cycle. Why?**

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.
- Deadlock-avoidance algorithm examines the resource-allocation state dynamically to ensure that there will never be a circular-wait condition (when only one instance per resource type).
- Resource-allocation *state* is defined by the number of available and allocated resources, and the maximum demands of the processes.

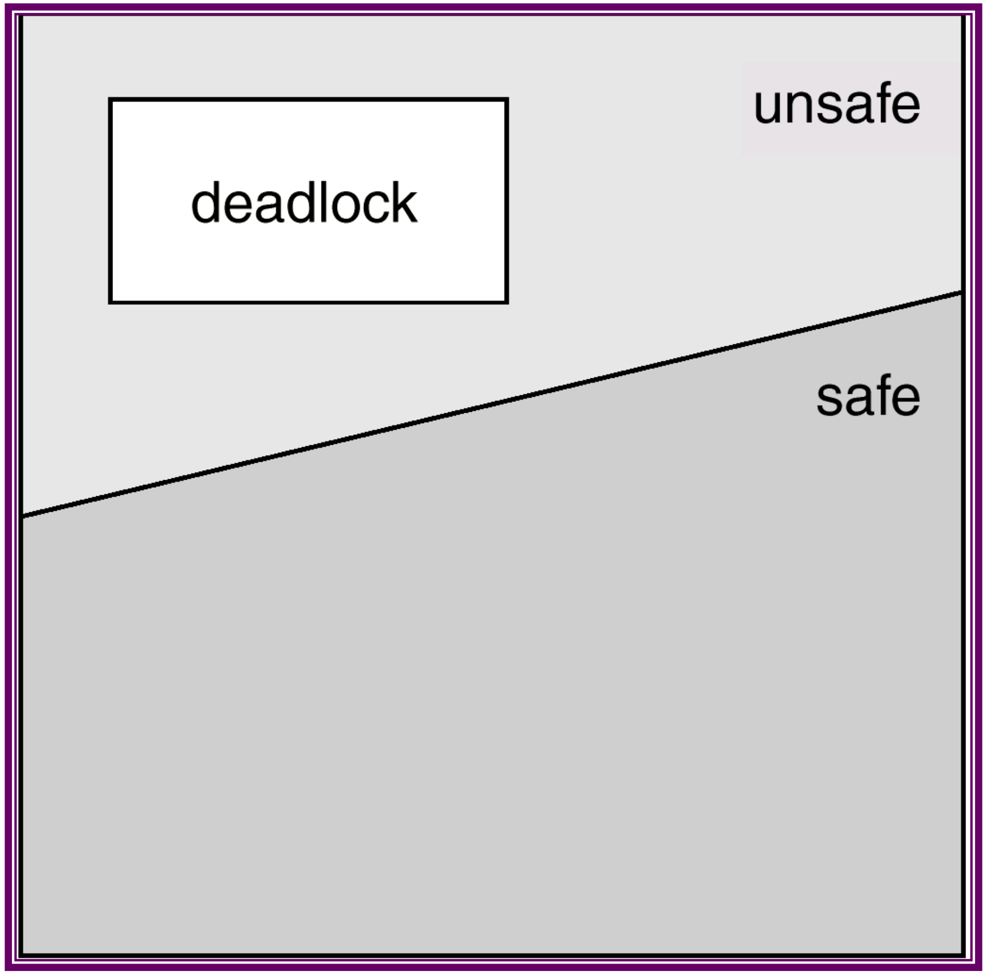
Safe State

- 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 safe sequence of all processes.
- Sequence $<P_1, P_2, \ldots, P_n>$ is safe if 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, and so on.

Basic Facts

- If a system is in safe state $\Rightarrow$ definitely not in deadlock states.
- If a system is in unsafe state $\Rightarrow$ possibility of deadlock.
- Avoidance $\Rightarrow$ ensure that a system will never enter an unsafe state.

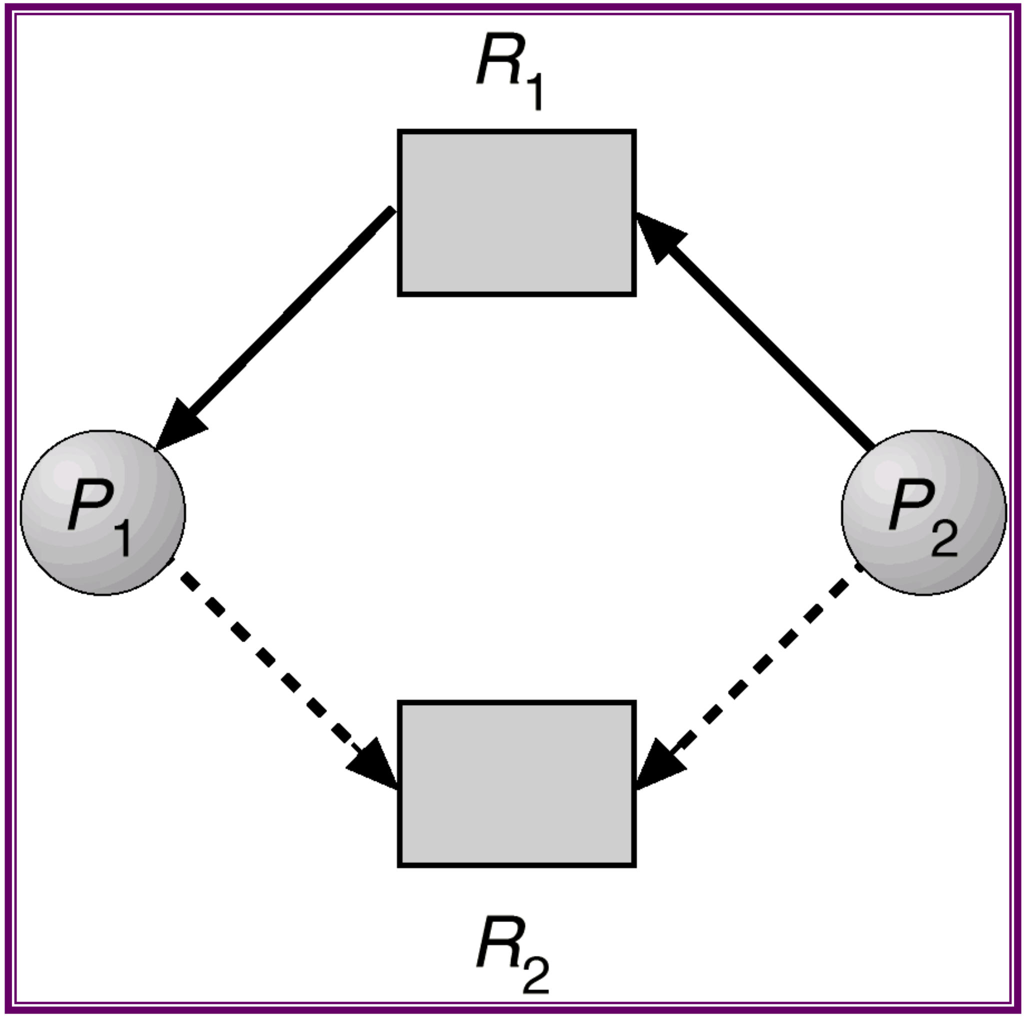
Safe, Unsafe , Deadlock State



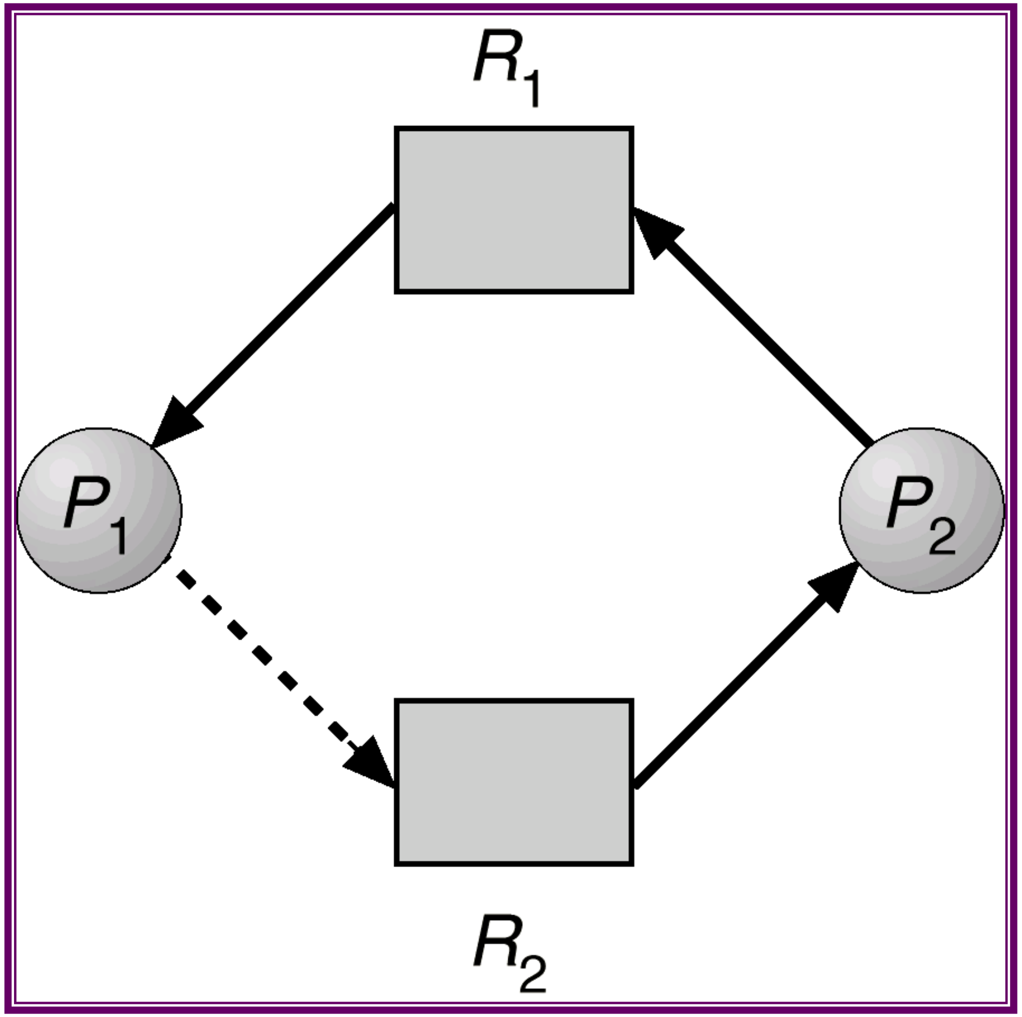
One Instance Per Resource Type: Resource-Allocation Graph Algorithm

- *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.
- When a resource is released by a process, assignment edge reconverts to a claim edge.
- Resources must be claimed *apriori* in the system.

Resource-Allocation Graph For Deadlock Avoidance



Unsafe State In Resource-Allocation Graph



Multiple Instances per Resource Type: Banker's Algorithm

- Three Assumptions of Banker's Algorithm
  - Each process must apriori claim its maximum use of each resource type.
  - When a process requests for a particular amount of resources, it may have to wait, even if the system has the resources available.
  - When a process gets all its needed resources, it must return them in a finite amount of time.

http://en.wikipedia.org/wiki/Banker%27s_algorithm

Data Structures for the Banker's Algorithm

n = number of processes, 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 finish its task.

An 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).
- System snapshot at the 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

Resource-Request Algorithm for Process P_i

Request = request vector for process P_i.

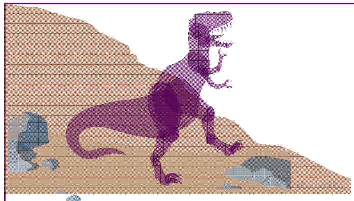
If $Request_i[j] = k$, then the process P_i wants k instances of resource type R_j.

Three-Step Algorithm

Step 1. If $Request_i \leq Need_i$, then go to step 2. Otherwise, raise error condition, since the process P_i has exceeded its maximum claim.

Step 2. If $Request_i \leq Available$, then go to step 3. Otherwise, the process P_i must wait, since the requested resources are not available.

Step 3. Pretend to allocate requested resources to P_i by simulating the resource allocation:



Resource-Request Algorithm for Process P_i

Explain the Step 3 in More Details

Step 3. Pretend to allocate requested resources to process P_i by modifying the state as follows:

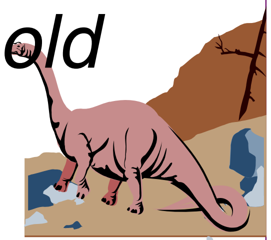
For each j^{th} type of resource with $0 \le j < m$,

$$Available_j = Available_j - Request_i[j];$$

$$Allocation_i[j] = Allocation_i[j] + Request_i[j];$$

$$Need_i[j] = Need_i[j] - Request_i[j];$$

- *If safe $\Rightarrow$ the resources are allocated to process P_i, and P_i goes to Ready state*
- *If unsafe $\Rightarrow$ process P_i must wait, and the old resource-allocation state is restored*



Safety Algorithm

- Purpose: Differentiate the safe and unsafe states

- Pessimistic Assumption: all processes will eventually attempt to acquire their stated maximum resources and terminate soon afterward
  - If a process terminates without acquiring its maximum resource it only makes it easier on the system

Safety Algorithm (cont.)

- How to differentiate between safe and unsafe system states?
  - Determines if a state is **safe** by trying to find a hypothetical sequence of requests by the processes that would allow each to acquire its maximum resources and then terminate (returning its resources to the system).
  - Any state where no such sequence exists is an **unsafe** state.

Safety Algorithm (cont.)

Step 1. Let *Work* and *Finish* be vectors of length *m* and *n*, respectively. Initialize them as

Work = *Available* (*copy the array of available resources)*

Finish [*i*] = *false,* for each *i* = 0, 1, …, *n-1.*

Step 2. Find an *i* such that both conditions satisfy

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

(b) $Need_i \leq Work$

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

Step 3. *Finish*[*i*] = *true;*

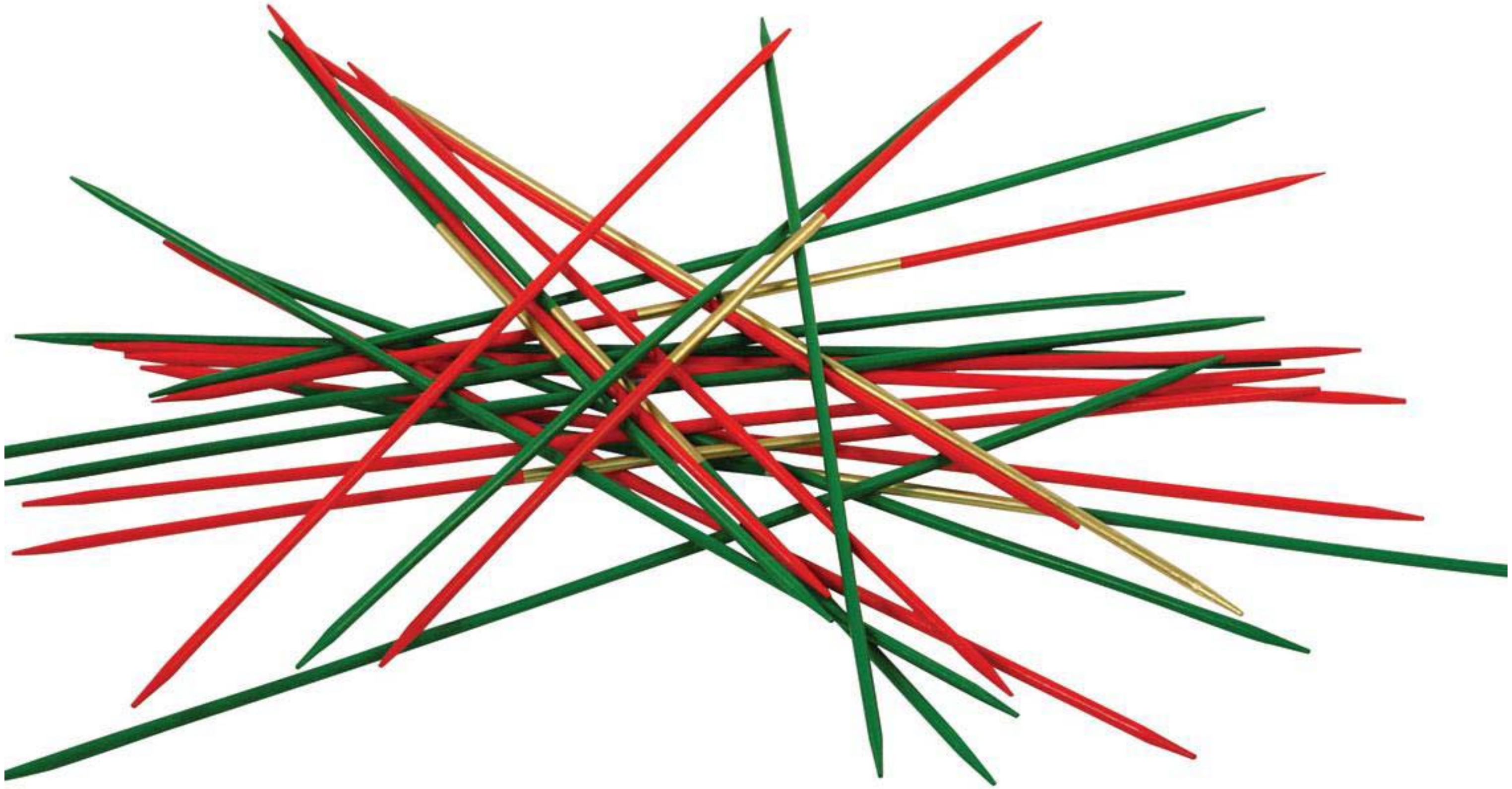
$Work = Work + Allocation_i$ *// reclaim resources*

go to step 2.

Step 4. If *Finish* [*i*] == true for all *i*,

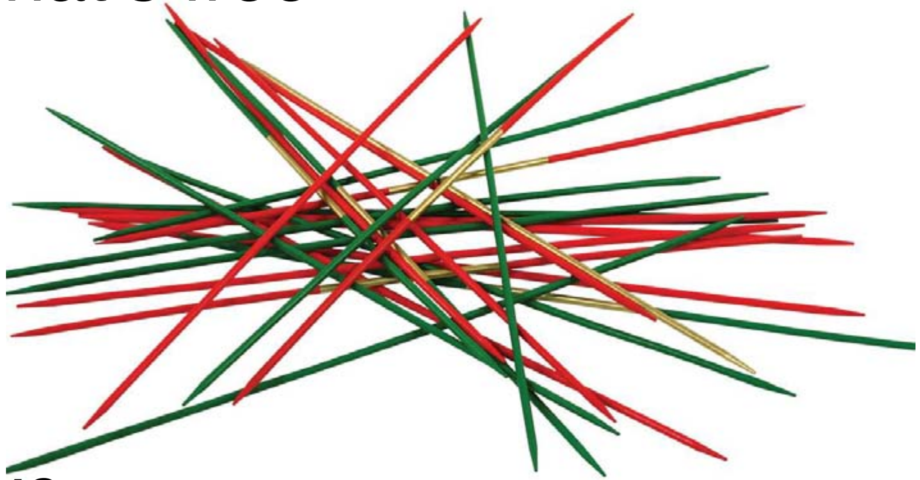
then the system is in a **safe** state.

Inspiration



Playing Pickup Sticks with Processes

- Pickup
  - Find a stick on top
    = Find a process that can finish with what it has plus what's free
  - Remove a stick
    = Process releases its resources
- Repeat
  - Until all processes have finished, Answer: safe
  - Or we get stuck,
    Answer: unsafe



Notes for Safety Algorithm

- These requests and acquisitions are *hypothetical*. The algorithm generates them to check the safety of the state, but no resources are actually given and no processes actually terminate.

- The order in which these requests are generated – if several can be fulfilled – doesn't matter, since safety is checked for each resource request

An Example: P_1 Request for (1,0,2)

- Snapshot at time T_0:

	Allocation	*Max*	*Available*	*Need*
	A B C	*A B C*	*A B C*	*A B C*
P_0	0 1 0	7 5 3	3 3 2	7 4 3
P_1	2 0 0	3 2 2		1 2 2
P_2	3 0 2	9 0 2		6 0 0
P_3	2 1 1	2 2 2		0 1 1
P_4	0 0 2	4 3 3		4 3 1

- Firstly, Check that Request $\leq$ Need1.
  That is, $(1,0,2) \leq (1,2,2) \Rightarrow$ *true*.

An Example: P_1 Request for (1,0,2)

- Secondly, Check that Request ≤ Available. That is, $(1,0,2) \le (3,3,2) \Rightarrow$ *true.*
- Thirdly, Simulate the Resource Allocation

	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 1	6 0 0	
P_3	2 1 1	0 1 1	
P_4	0 0 2	4 3 1	

An Example: P_1 Request for (1,0,2)

- More details about the third step:
  Executing the safety algorithm shows that there exists an execution sequence <P_1, P_3, P_4, P_0, P_2> that can satisfy the safety requirement.

- Further Questions:
  - Can the request for (3,3,0) by P_4 be granted?
  - Can the request for (0,2,0) by P_0 be granted?

Deadlock Detection

- Allow the system to enter deadlock state
- Run deadlock detection algorithm periodically
- Recovery scheme upon the detection of deadlocks

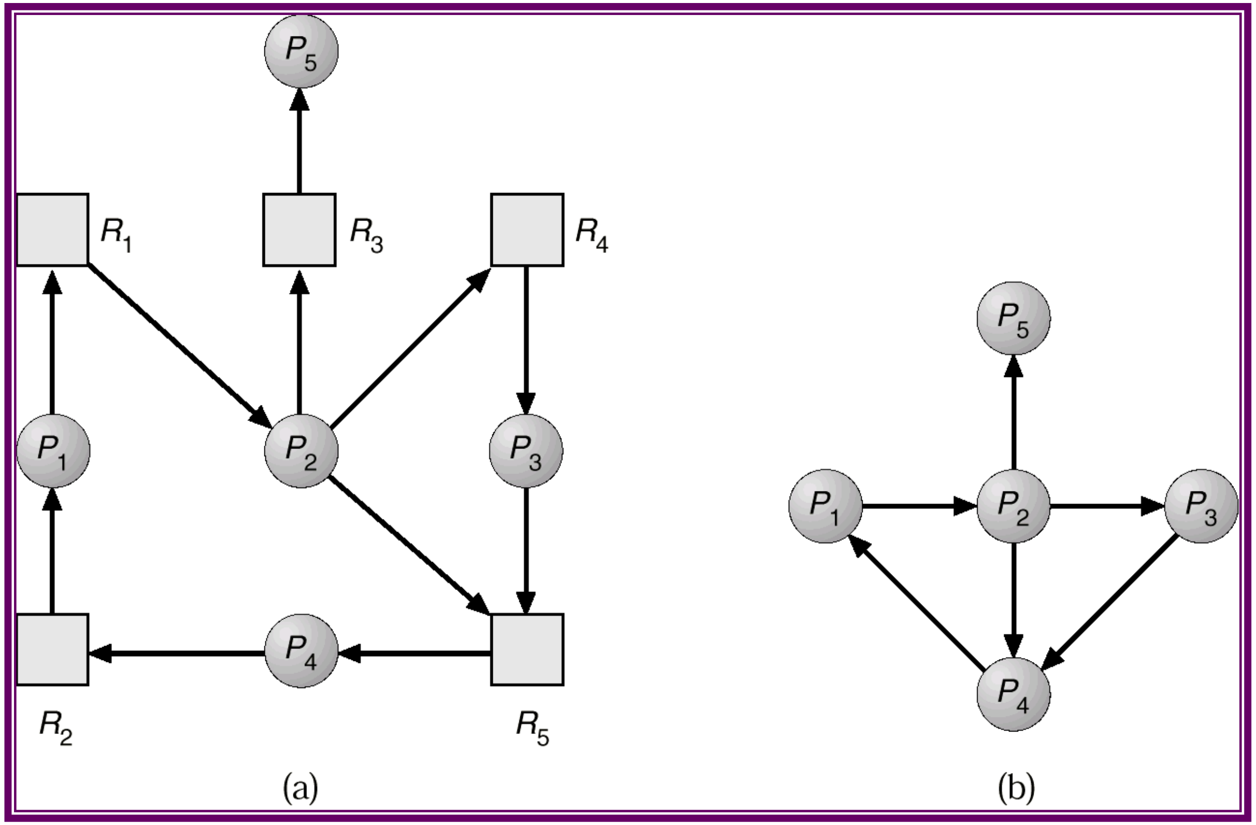
Assumption: Single Instance for Each Resource Type

- Maintain *wait-for* graph
  - Nodes are processes.
  - $P_i \rightarrow P_j$ if P_i is waiting for P_j.

- Periodically invoke a deadlock detection algorithm that searches for a cycle in the graph.

- 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



Resource-Allocation Graph　　Corresponding Wait-for Graph

Assumption: Multiple Instances for 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.

Deadlock Detection Algorithm

Step 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*.

Step 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.)

Step 3. *Finish*[*i*] = *true*
Work = *Work* + $Allocation_i$ // reclaim resource
go to step 2.

Step 4. If *Finish*[*i*] == false, for some *i*, $1 \le i \le n$, then the system is in deadlock state. Moreover, if *Finish*[*i*] == *false*, then P_i is deadlocked.

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

An 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*. So, no deadlock.

An Example of Detection Algorithm

- 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

- What is the state of system? Deadlock or no deadlock?

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 deadlock when it happens?
- 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?
  - 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?

Recovery from Deadlock: 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 the number of rollbacks when calculating the cost factor for victim selection.

Concluding Notes

- In general, deadlock detection or avoidance is expensive
- Must evaluate cost and frequency of deadlock against costs of detection or avoidance
- Deadlock avoidance and recovery may cause indefinite postponement (starvation)
- Unix, Windows use Ostrich Algorithm (do nothing)
- Typical apps use deadlock prevention (order locks)
- Database transaction systems (e.g., credit card systems) need to use deadlock detection/recovery/avoidance/prevention (why?)