Operating Systems
COMP2006

Deadlocks
Lecture 5

Deadlocks

References:

Silberschatz, Galvin, and Gagne, *Operating System Concepts*, Chapter 7.

Topics:

– Deadlock system model and characterization.
– Methods for handling deadlocks.
– Deadlock prevention, avoidance, and detection.
– Recovery from deadlock.
– Combined approach to deadlock handling.

Introduction

- Several processes may compete for a finite number of resources, and some of them may wait for the resources forever because the resources are held by other waiting processes → deadlock.
- A set of processes is in a deadlock state if every process in the set is waiting for an event that can be caused only by another process in the set.

Example

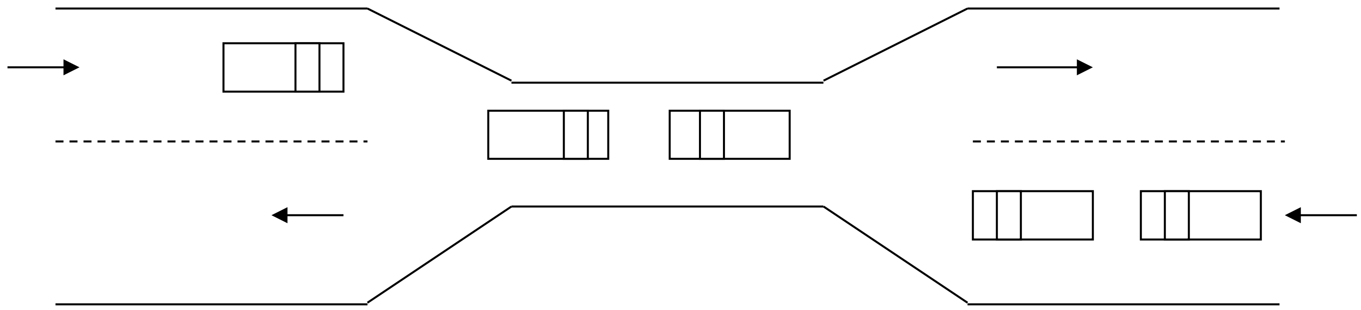
- System has two tape drives.
- P1 and P2 each hold one tape drive and each needs another one.

Example

- Semaphores A and B, initialized to 1.

P0	P1
wait (*A*)	*wait* (*B*)
wait (*B*)	*wait* (*A*)

Example (bridge crossing)



- 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 back up if a deadlock occurs.
- Starvation is possible.

System Model

- Resources are partitioned into several types, each consists of some number of identical *instances*.
  - **Identical**: allocation of *any* instance of the type will satisfy process's request.
  - Resources may be physical resources (printers, tape drives, CPU cycles), or logical resources (files, semaphores, and monitors).
  - A **pre-emptible** resource is one that can be taken away from a process with no ill effect to the process; e.g., memory.
  - A **non-preemptible** resource is one that cannot be taken away from its user since it will make the user fails; e.g., printers
    - In general, potential deadlocks involve this resource type.
- Each process uses a resource as follows:
  - **Request** the resource; a process must wait if the resource is being used by another process.
  - **Use** the resource; e.g., the process can print on the printer.
  - **Release** the resource.

Necessary conditions for deadlock

Four conditions must hold for a deadlock to occur (Coffman et al.):

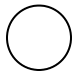
1. **Mutual exclusion condition**. Only one process at a time can use the resource.
   - **or** each resource is either currently assigned to exactly one process or is available.
2. **Hold and wait condition**. A process holding at least one resource is waiting to acquire additional resources held by other processes.
3. **No pre-emption condition**. A resource can be released only voluntarily by the process holding it after that process has completed its task.
4. **Circular wait condition**. 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.

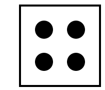
Note: the four conditions are not completely independent, e.g., the circular-wait condition implies the hold-and-wait condition.

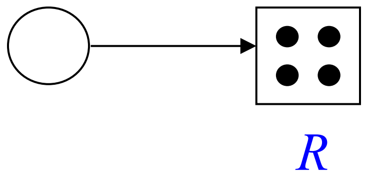
Deadlock Modelling

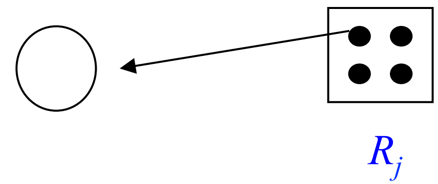
- Deadlocks can be described more precisely in terms of a directed graph $G(V, E)$
  - called *System resource-allocation graph*
- V is partitioned into two types:
  - Set of processes in the system: $P = \{P_1, P_2, \ldots, P_n\}$.
  - Set of all resource types in the system: $R = \{R_1, R_2, \ldots, R_n\}$
- *Request edge* – directed edge $P_i \rightarrow R_j$
  - process P_i requests an instance of resource R_j
- *Assignment edge* – directed edge $R_j \rightarrow P_i$
  - an instance of resource R_j has been allocated to process P_i

Model Symbols

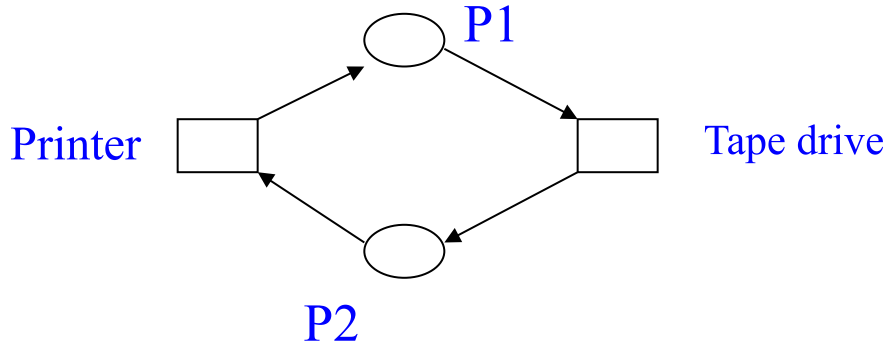
- Process: 

  Resource type with 4 instances: 

- P_i requests R_j: 

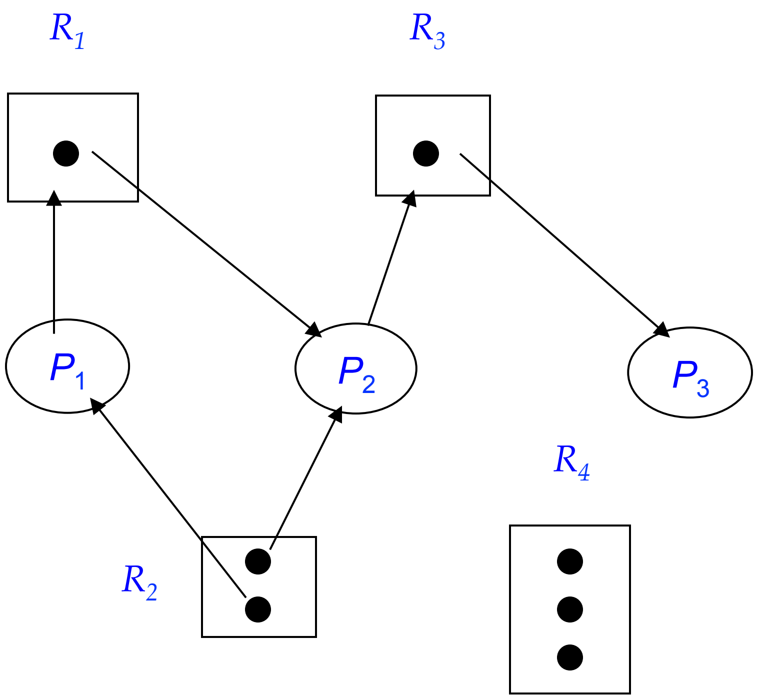
  P_i uses R_j: 

Example: Deadlock



- If the graph contains **no cycles**, no process in the system is deadlocked.
- If the graph contains **a cycle**, deadlock *may* exist.
  - If each resource type has **one instance**, **cycle means deadlock**.
  - If each resource type has **several instances**, cycle is necessary but **not sufficient condition for deadlock**.

Example: resource allocation graph (with no cycles)



The sets P, R, and E:

$P = \{P_1, P_2, P_3\}$
$R = \{R_1, R_2, R_3, R_4\}$

$E = \{P_1 \rightarrow R_1, P_2 \rightarrow R_3, R_1 \rightarrow P_2, R_2 \rightarrow P_2, R_2 \rightarrow P_1, R_3 \rightarrow P_3\}$

Resource instances:

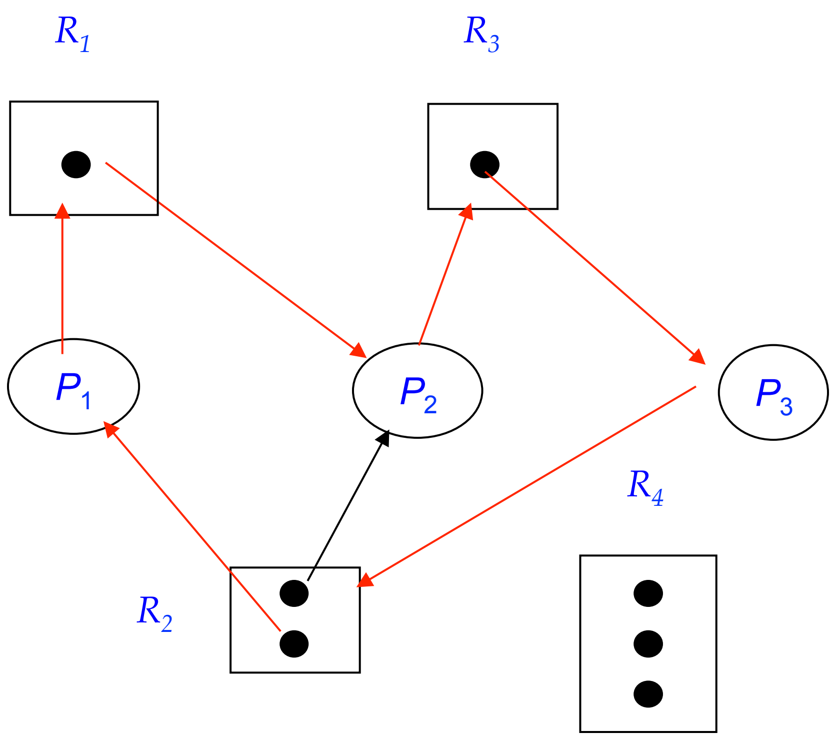
- One instance of resource type R_1
- Two instances of resource type R_2
- One instance of resource type R_3
- Three instances of resource type R_4

Process states:

- P_1 is holding an instance of R_2, and waiting for an instance of R_1
- P_2 is holding an instance of R_1 and R_2, and is waiting for an instance of R_3
- P_3 is holding an instance of R_3

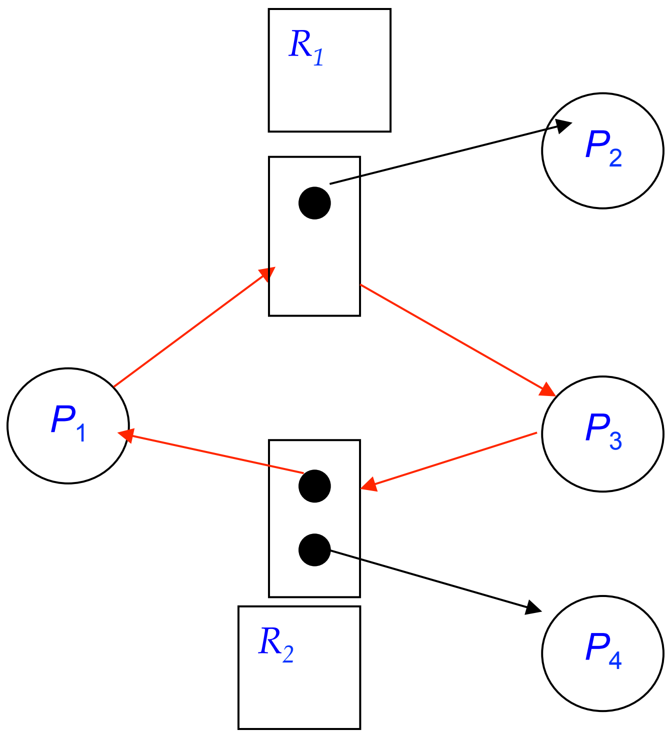
Example

A cycle and deadlock



A cycle but no deadlock

P_4 can release R_2 which gets allocated to P_3; breaking the cycle



Example: how deadlock occurs and how to avoid it

Consider:

- Three resources: R, S, and T
- Three processes: A, B, and C
- The following is sequences of resource requests/releases:

A	B	C
Request R	Request S	Request T
Request S	Request T	Request R
Release R	Release S	Release T
Release S	Release T	Release R

Example (cont.)

(a) Request/release order:

(1) A requests R,

(2) B requests S,

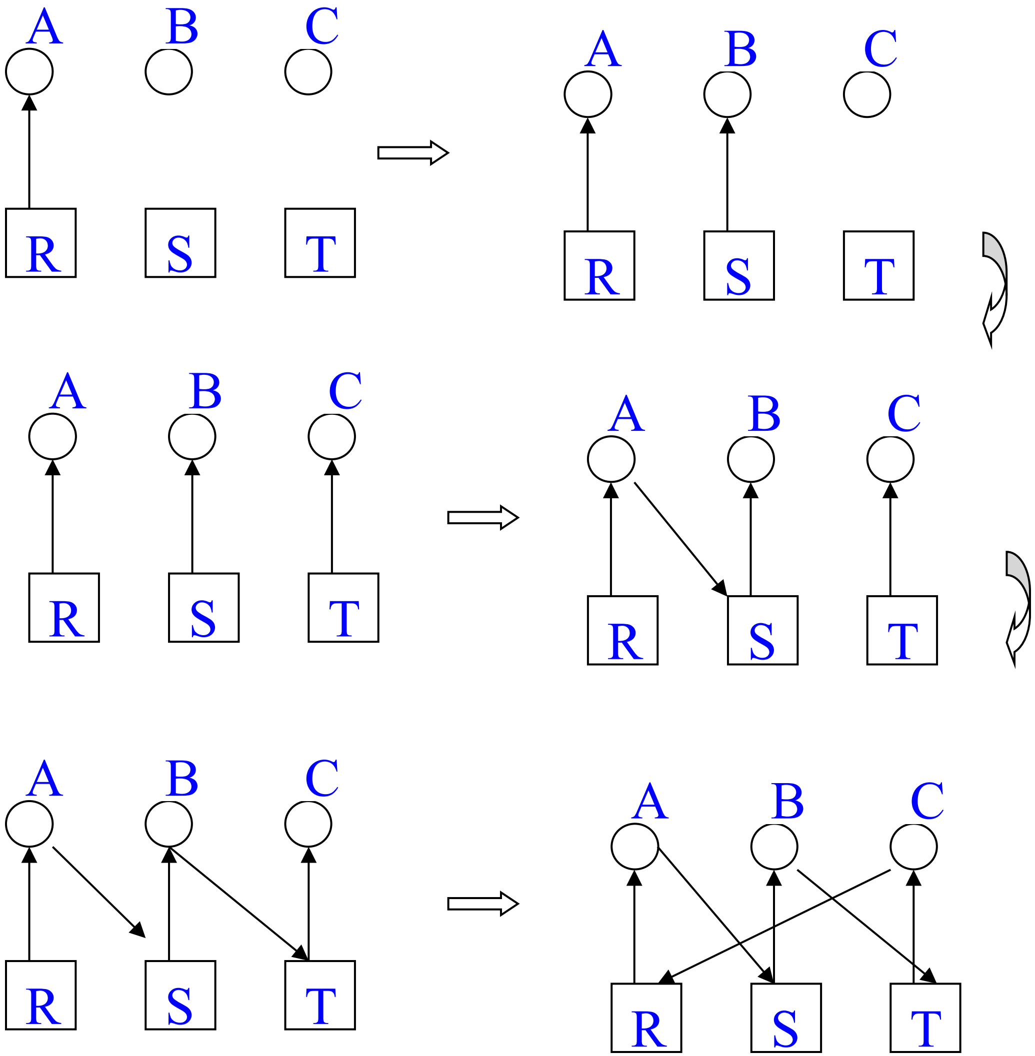
(3) C requests T,

(4) A requests S,

(5) B requests T,

(6) C requests R

→ **deadlock.**



Example (cont.)

(b) Request/release order:

(1) A requests R,

(2) C requests T,

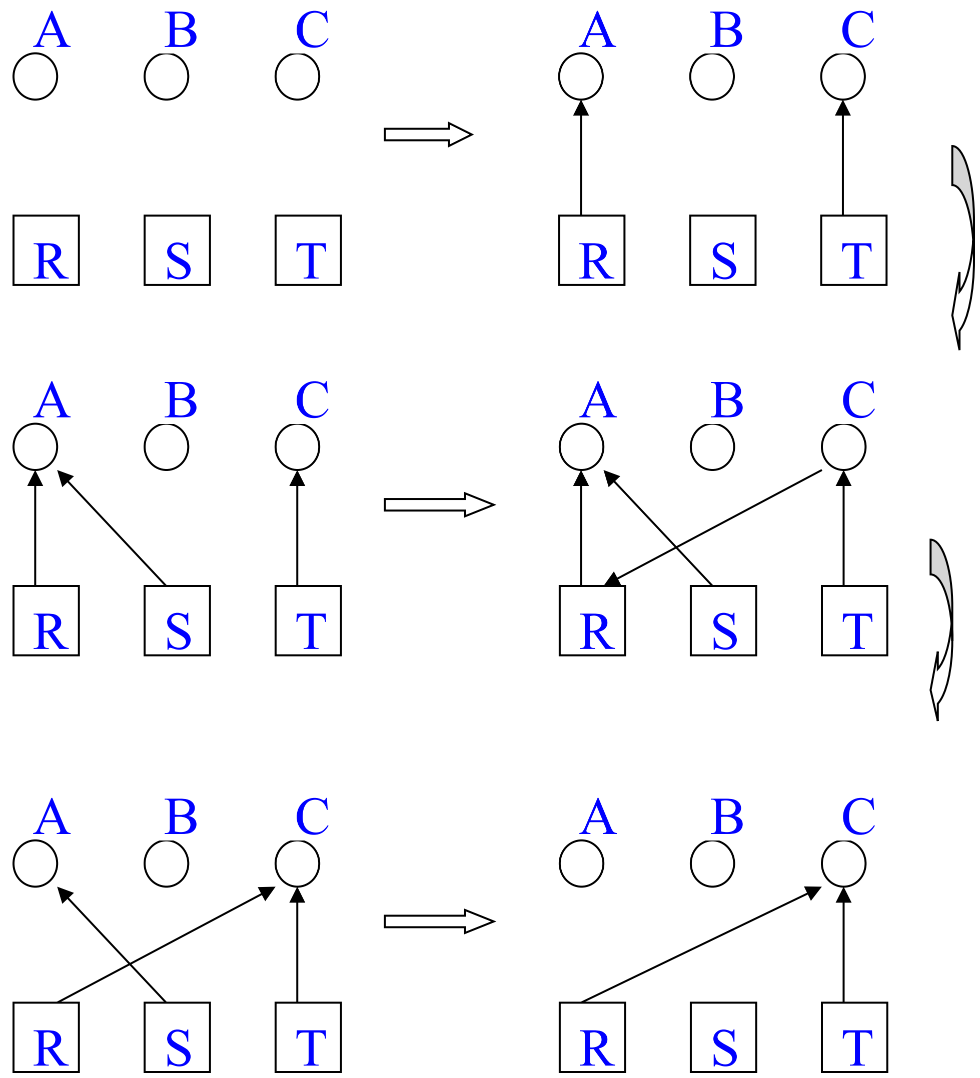
(3) A requests S,

(4) C requests R ,

(5) A release R,

(6) A release S

→ **no deadlock.**



Three Methods for handling deadlock

- Use a protocol to ensure that the system will *never* reaches deadlock
  - Using *deadlock prevention* and/or *deadlock avoidance* techniques
- Allow the system to enter a deadlock state and then recover
  - needs *deadlock detection* and *deadlock recovery* algorithms
- Ignore the problem and pretend that deadlocks never occur in the system
  - used by most OS, including UNIX
  - Also called the **ostrich** algorithm!

Deadlock prevention

- Restrain the ways resource requests can be made
  - Use a set of methods to ensure that **any one** of the four deadlock conditions cannot hold

(1) Deny mutual exclusion

- Not required for sharable resources (e.g., read-only files, cannot be in deadlock)
- Must hold for non-sharable resources (a printer cannot be simultaneously shared by several processes)
- **In general**, it is not possible to prevent deadlock by denying mutual-exclusion condition since some resources are non-sharable

(2) Deny hold and wait

- Must guarantee that whenever a process requests a resource, it does not hold any other resources

<u>Options:</u>

- Each process is granted all resources before it starts
- Allows a process to request resources only when it has none
  - If a process needs more resources, release all resources before requesting new ones

<u>Problem:</u>

- Resource utilisation is low
- Possible starvation.
  - A process that needs popular resources may have to wait indefinitely

Deadlock prevention (cont.)

(3) Prevent no pre-emption (i.e., allow pre-emption)

- When a process holding some resources requests other resource that cannot be immediately allocated, it must release all resources currently being held
  - The pre-empted resources are added to the process's list of requested resources
  - The process is restarted when it regains its old resources and obtains the new one it is requesting

Problem:

- Can be applied easily to resources whose state can be saved easily (e.g., memory), but not so easily for others (e.g., printer)

Deadlock prevention (cont.)

(4) Deny circular wait

- All resource types are ordered, e.g.,
  - F(card reader) = 1 F(disk drive) = 5
  - F(tape drive) = 7 F(printer) = 12
- Each process must request increasing order of resources
- Protocol:
  - Each process requests resources in increasing order
  - Initially a process can request for any R_i
  - After that, it can request R_j only if $F(R_j) > F(R_i)$
- **Problem:** It may be impossible to find a resource ordering that satisfies everyone

Deadlock avoidance

- The system must have some additional a *priori* information about which resources a process will request and use during its lifetime
  - With the additional information, the system can decide for each request whether or not the process should wait
  - The 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**
- A resource-allocation *state* is defined by:
  - The number of **available** and **allocated** resources, and
  - The **maximum demands** of the processes

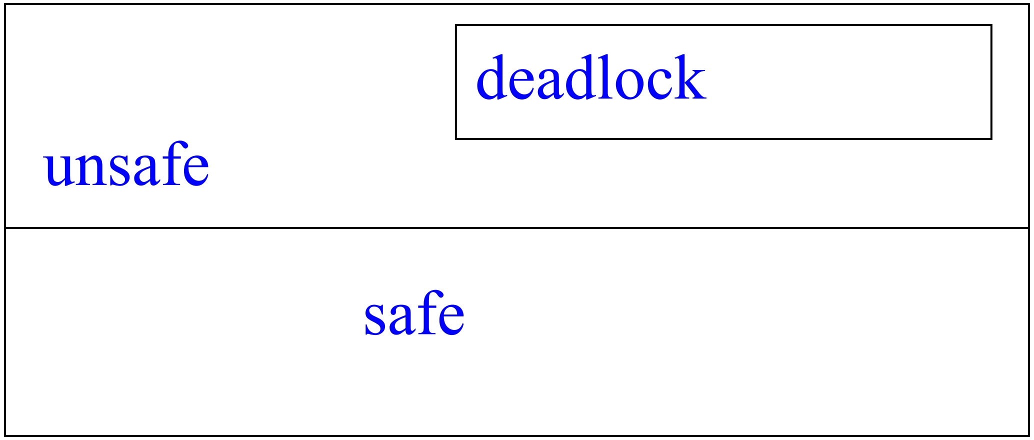
Safe State

- When a process requests an available resource, the system checks if its allocation keeps the system in ***safe state***
- The system is in *safe state* if there exists a ***safe sequence*** of all processes
- A sequence <P_1, P_2, … P_n> is *safe* if, for each P_i, the resources requested by P_i can be allocated from the currently available resources + resources held by all P_j, with $j < i$
  - If P_i's resource needs are not immediately available, P_i waits until all P_j have finished
  - When all P_j are finished, P_i obtains the needed resources, executes, returns the allocated resources, and terminates
  - When P_i terminates, P_{i+1} can obtain its needed resources, and so on

Safe State (cont.)

Basic facts

- If a system is in safe state → no deadlocks
- If a system is in unsafe state → possibility of deadlock
- Avoidance ensures that the system never enters an unsafe state
- A process requesting for a currently available resource may have to wait
  - Thus, resource allocation is lower than without deadlock avoidance algorithm



Example

Consider a system with 12 resources of the same type, and 3 processes with the following resource needs and allocation

	Maximum needs	Allocation	Current need
P_0	10	5	5
P_1	4	2	2
P_2	9	2	7

- At time t_0, **available resource = 3**, and the system is in safe state
  - There is a safe sequence <P_1, P_0, P_2>
- What if at t_1 one more resource is allocated to process P_2?
  - The system is in unsafe state
    - Deadlock can occur

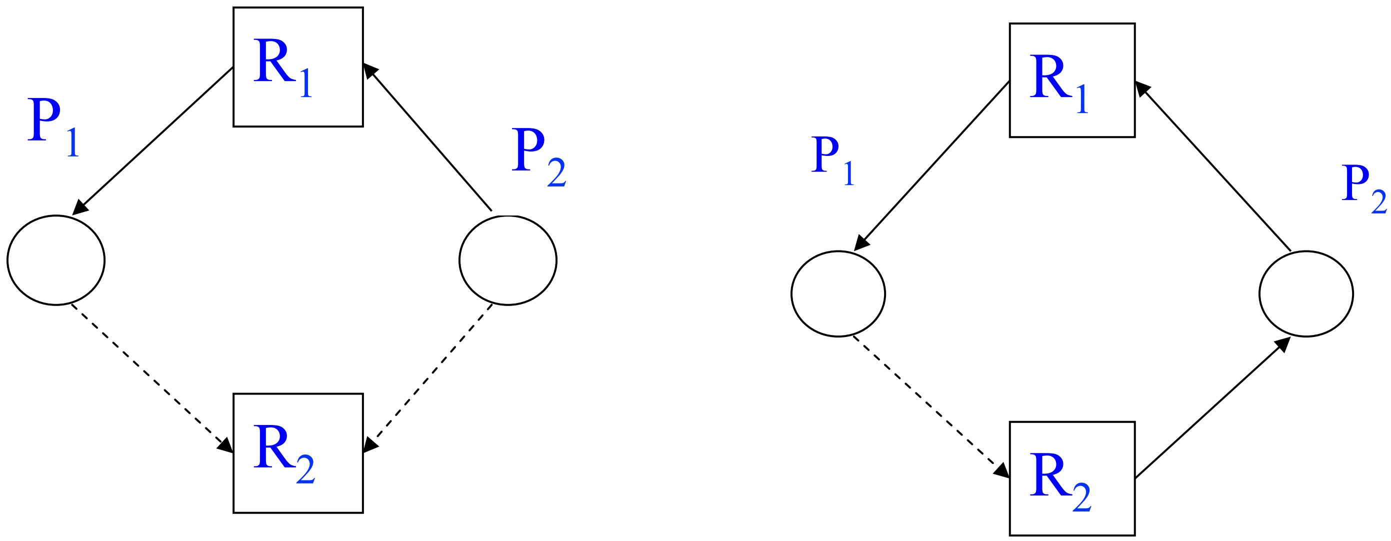
Resource-Allocation Graph Algorithm

- *Claim edge* $P_i \rightarrow R_j$ indicates that process P_i 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* converts to a *claim edge*
- Resources must be claimed a *priori* in the system
- Need a cycle detection algorithm → $O(n^2)$
- This algorithm **can not be used** for system comprising resource types with **multiple instances**

Example

Suppose P_2 requests R_2

Although R_2 is currently free, allocating it to P_2 may lead to unsafe state (a cycle in right figure)



Banker's Algorithm

- The algorithm for a system comprising resource types with **multiple instances**
- Similar to a bank: never allocates its available cash if it can no longer satisfy the needs of all customers
- Each process must a *priori* claim maximum number of instances of each resource type that it may need
- When a process requests a resource:
  - It may have to wait (if resource allocation may lead to unsafe state) until some other process releases enough resources
- When a process gets all its resources:
  - It must return them in a finite amount of time

Banker's Algorithm (cont.)

Algorithm

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

Data structures:

- *Available*: Vector of length m
  - *available*$[j] = k$; means k instances of resource type R_j are available
- *Max*: $n \times m$ matrix
  - *Max*$[i, j] = k$; means process P_i may request at most k instances of resource type R_j.
- *Allocation*: $n \times m$ matrix
  - *Allocation*$[i, j] = k$; means process P_i is currently allocated k instances of resource type R_j
- *Need*: $n \times m$ matrix
  - *Need*$[i, j] = k$; means process P_i may need k more instances of resource type R_j to complete its task.
  - *Need*$[i, j]$ = *max*$[i, j]$ – *allocation* $[i, j]$

Implementation of the safety algorithm

// Time complexity = $O(mn^2)$

1. Let *work* and *finish* be vectors of length m and n, respectively

   initialise:
   $work = available$
   $finish\,[i] = false$ for $i = 1, 2, \ldots, n$

// Find an unfinished process i; it still needs resources

2. Find a value of i such that both:
   - $finish[i] = false$, and
   - $need_i \leq work$
   - If no such i exists, go to step 4

// process i pretends to finish, so it releases its resources i.e., $allocation_i$

3. $work = work + allocation_i$

   $finish[i] = true$
   go to step 2

4. If $finish[i] = true$ for all i, the system is in safe state.

Resource-request algorithm for process P_i

$Request_i$ = 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 $request_i \leq need_i$, go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim.
2. If $request_i \leq available$, go to step 3. Otherwise P_i must wait, since resources are not available.
3. The system pretends to allocate requested resources to 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 resulting state is safe, resources are allocated to P_i
   – else 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*			*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

- The content of matrix *Need* is defined to be *Max* – *Allocation*
- The system is in a safe state since the sequence <P_1, P_3, P_4, P_2, P_0> satisfies the safety criteria

Example (P_1 requests (1,0,2)):

- Check that *request* ≤ *need* (that is, (1, 0, 2) ≤ (1, 2, 2)) → true
- Check that *request* ≤ *available* (that is, (1, 0, 2) ≤ (3, 3, 2)) → true

Before Adjustment

	Allocation		
	A	B	C
P_0	0	1	0
P_1	2	0	0
P_2	3	0	2
P_3	2	1	1
P_4	0	0	2

After Adjustment

	Alloc.			Need			Avail.		
	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			

- $<P_1, P_3, P_4, P_0, P_2>$ or $<P_1, P_4, P_3, P_0, P_2>$ satisfies safety requirement
- Can request for (3, 3, 0) by P_4 be granted? (0, 2, 0) by P_0 ?

Deadlock detection

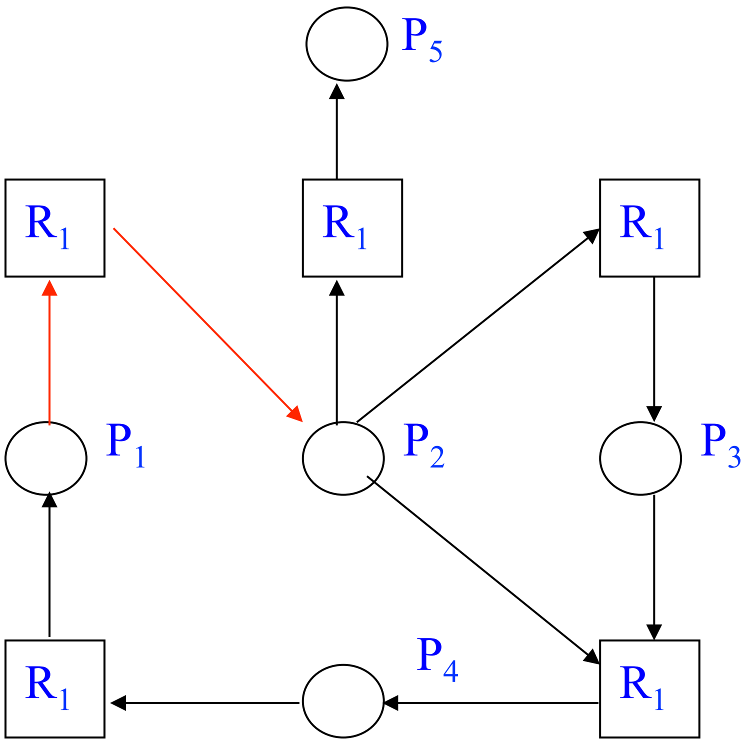
- If a system does not employ either a deadlock-prevention or a deadlock-avoidance algorithm, then a deadlock situation may occur
- Need a *deadlock detection* algorithm that examines the state of the system to determine whether a deadlock has occurred
- Need a *recovery* algorithm to recover from deadlock

Deadlock detection for single instance of each resource type

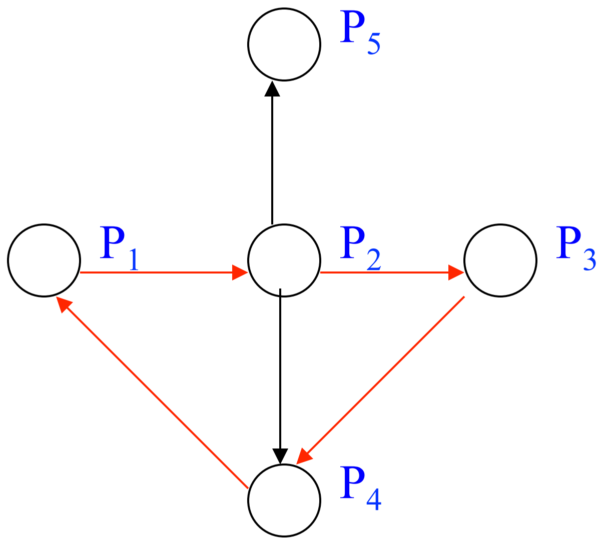
- Maintain a *wait-for graph*
  - Nodes are processes
  - $P_i \rightarrow P_j$ if P_i is waiting for P_j
- Periodically invoke an algorithm that searches for a cycle in the graph
  - An algorithm to detect a cycle in a graph requires $O(n^2)$ operations,
    - n is the number of vertices in the graph

Example

Resource Allocation Graph



Wait for Graph



Deadlock detection (cont.)

Deadlock detection for several instances of a resource type

Data structures:

Available: Vector of length m

Indicates the number of available resources of each type

Allocation: $n \times m$ matrix

Defines the number of resources of each type currently allocated to each process

Request: $n \times m$ matrix

Indicates the current request of each process

request $[i, j] = k$; // means P_i is requesting k more instances of resource R_j

Detection algorithm

// Requires an $O(mn^2)$ operations to detect if the system is in a deadlocked state

1. Let *work* and *finish* be vectors of length m and n, respectively.

   initialise: $work = available$

   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 $finish[i] = false$ and $request_i \leq work$

   if no such i exists, go to step 4

3. $work = work + allocation_i$

   $finish[i] = true$; go to step 2

4. if $finish[i] = false$, for some i, $1 \leq i \leq n$, then the system is in a deadlock state.

   Moreover, $finish[i] = false \rightarrow P_i$ is deadlocked.

Example of detection algorithm

- Five processes: P_0 through P_4
- Resources: 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* → no deadlock

Example (cont.)

What if 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 fulfil requests from other processes
  - **Deadlock exists, consisting of processes P_1, P_2, P_3, and P_4**

Detection algorithm usage

- When should the algorithm be invoked? It depends on:
  - How often we believe deadlocks occur
  - How many processes will be affected by deadlock when it occurs
- Invoke every time a process makes a request → expensive
  - But it can identify the processes that caused the deadlock
    - Good for debugging
- Invoke at less frequent intervals
  - E.g., when CPU utilisation falls below 40% (perhaps because of deadlock), or every hour.

Deadlock recovery

1) Terminate processes

- Kill (abort) all deadlocked processes
- Kill one process at a time until deadlock cycle eliminated

- In which order should we choose process to abort?
  - The process with lowest priority
  - How long the process has computed, and how much longer to completion
  - Resources the process has used
  - Resources the process needs to complete
  - How many processes will need to be terminated
  - Is process interactive or batch?

Problem: what if the process is in the middle of updating a file?

Aborting the process may lead to incorrect file

Deadlock recovery

2) Pre-empt a resource from a process.

- How to select a victim (process) to minimize cost?

- Roll back the process to some safe state and restart from there
  - How do we find a safe state?
    - Easiest way: destroy the process and restart
    - Use checkpoints during execution
- Starvation – same process may always be picked as victim
  - How do we ensure no starvation?
    - Include number of rollbacks in cost factor

Combined approach to deadlock handling

- Combine the three basic approaches
  - Prevention
  - Avoidance
  - Detection
- Allow the use of the optimal approach for each class of resources in the system
  - Partition resources into hierarchically ordered classes
  - Use most appropriate technique for handling deadlocks within each class.