Chapter 7: Deadlocks

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Chapter 7: Deadlocks

- System Model
- Deadlock Characterization
- Deadlock Prevention
- Deadlock Avoidance

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.

```c
/* 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);
}
```

```c
/* 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);
}
```

SYSTEM MODEL & DEADLOCK CHARACTERIZATION

System Model

- Resource $R_1, R_2, \ldots, R_m$
  - CPU cycles, memory objects, I/O devices
- Each resource type R_i has W_i instances.
  - For example, DMA channels
- Each process utilizes a resource as follows:
  1. request
  2. use
  3. release

Deadlock Characterization

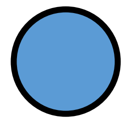
- If a deadlock arises, then the four conditions hold *simultaneously*
  - Mutual exclusion: only one process at a time can use a resource
  - Hold and wait: a process holding at least one resource is waiting to acquire additional resources held by other processes
  - No preemption: a resource can be released only voluntarily by the process holding it, after that process has completed its task
  - Circular wait: there exists a set $\{P_0, P_1, \ldots, P_n\}$ 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

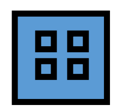
- A set of vertices V and a set of edges E.
- V is partitioned into two types:
  - $P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system.
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system.
- request edge – directed edge $P_1 \rightarrow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

Resource-Allocation Graph (Cont.)

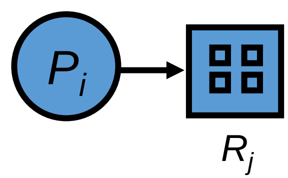
- Process



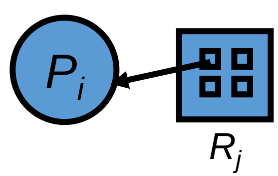
- Resource Type with 4 instances



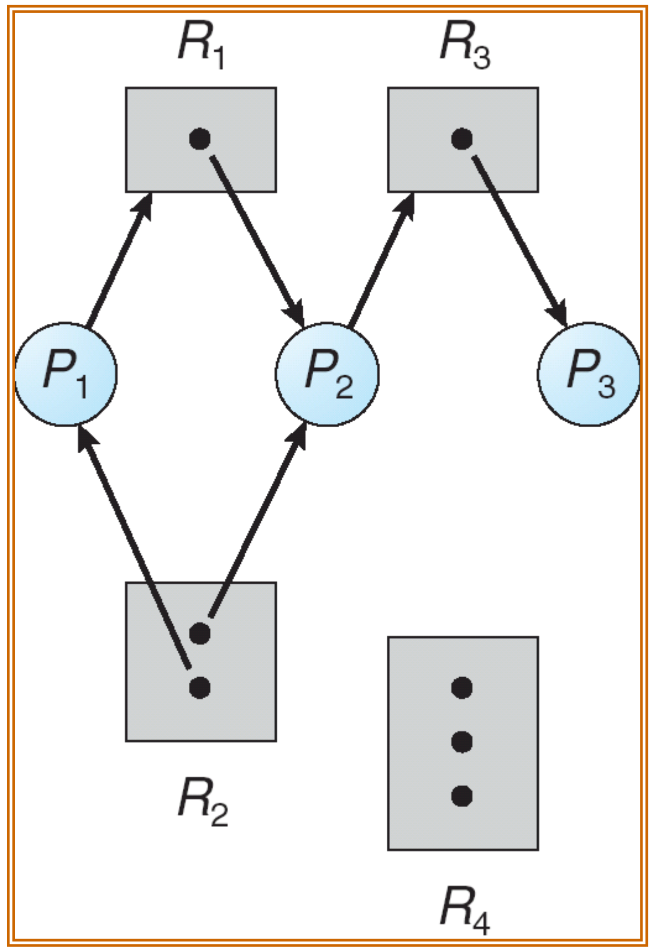
- P_i requests instance of R_j



- P_i is holding an instance of R_j



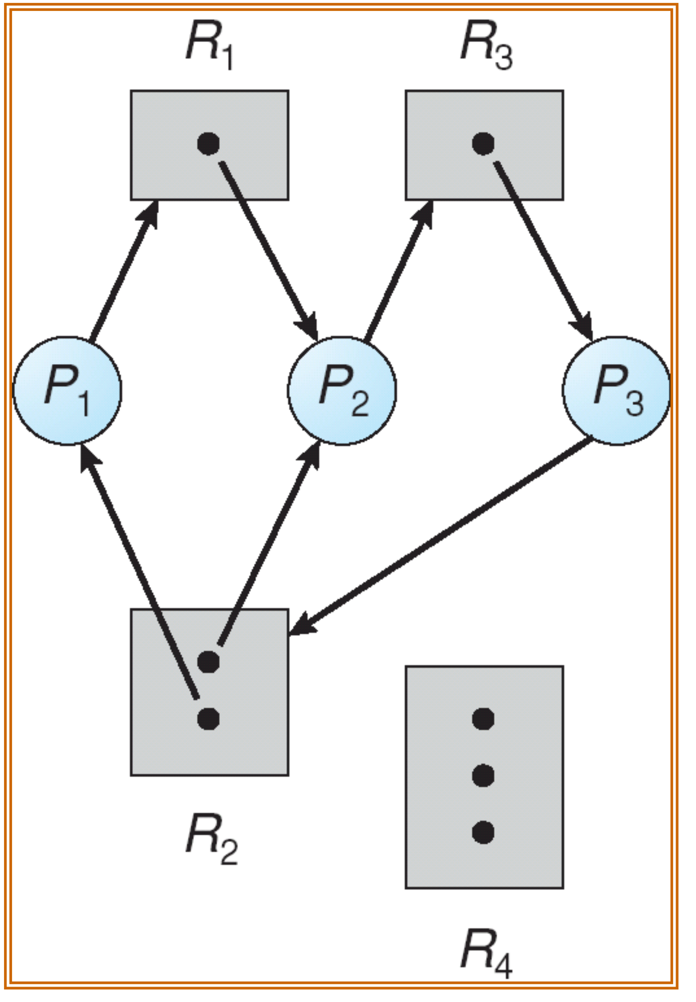
Example of a Resource Allocation Graph



Resource Allocation Graph With A Deadlock

The system is deadlocked

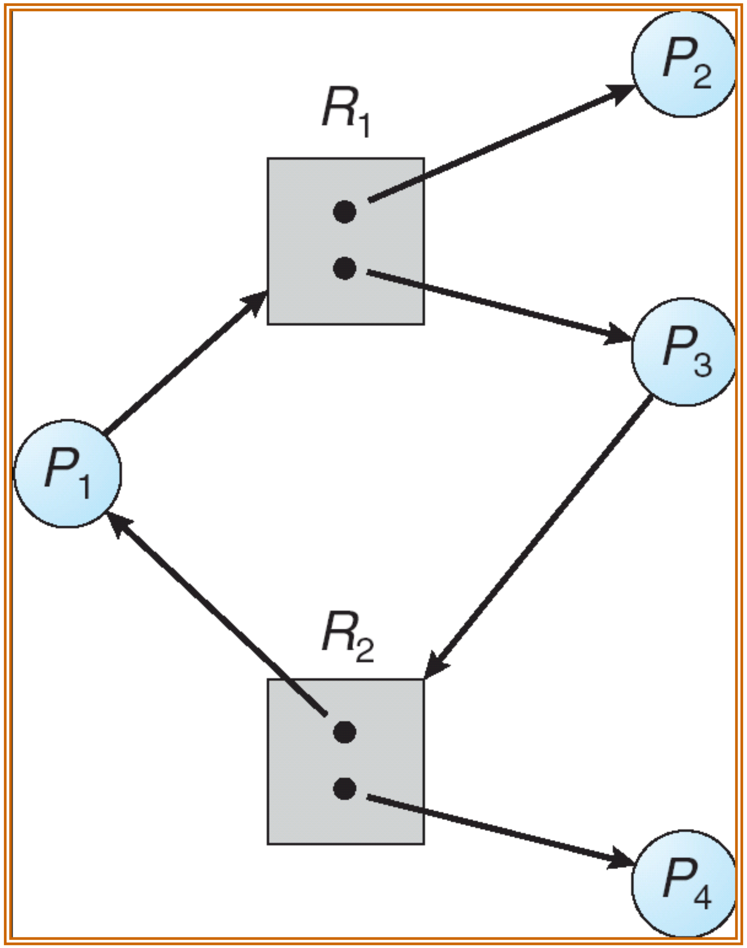
There is a cycle in the graph



Resource Allocation Graph With A Cycle But No Deadlock

The system is not deadlocked

There is a cycle in the graph



Basic Facts

- Resources have multiple instances
  - Deadlock → there is a cycle
- Resources have single instance
  - Deadlock ←→ there is a cycle

- If graph contains no cycles $\Rightarrow$ no deadlock
- If graph contains a cycle $\Rightarrow$
  - Resources have single instance, then deadlock
  - Resources have multiple instances, then *possible* deadlock

METHODS FOR HANDLING DEADLOCKS

Methods for Handling Deadlocks

- Ensure that the system will never enter a deadlock state (prevention or avoidance), e.g., RTOS,
- allow the system to enter a deadlock state and then recover (detection and recovery), or
- ignore the problem and pretend that deadlocks never occur in the system; used by most operating systems, e.g., UNIX & Windows

Methods for Handling Deadlocks

- Deadlock prevention: new rules to guarantee that one or more of the necessary conditions never happens
  - usually involving a new programming model, less practical
- Deadlock avoidance: to test whether a request to resources is safe or not; an unsafe request is delayed (even if the resource is available)

DEADLOCK PREVENTION

Deadlock Prevention

- Mutual Exclusion – this must be true for serially reusable resources
- Hold and Wait – a process cannot request for a new resource if it is currently holding one
  - All or none
  - [R1----[R2----]-----] ➔ [Rv------------------]
  - Low concurrency among processes due to long critical sections

Deadlock Prevention (Cont.)

- No Preemption –
  - If a process (victim) holds a resource R but is waiting for another resource, R will be preempted when another process tries to acquire R
  - The victim process will be restarted when R is available again
  - Requiring a checkpoint mechanism; computationally expensive
- Circular Wait – impose a total ordering or a partial ordering of allocation on resources
  - E.g., R1→R2 but no R2→R1
  - Can be "implemented" by the programmers

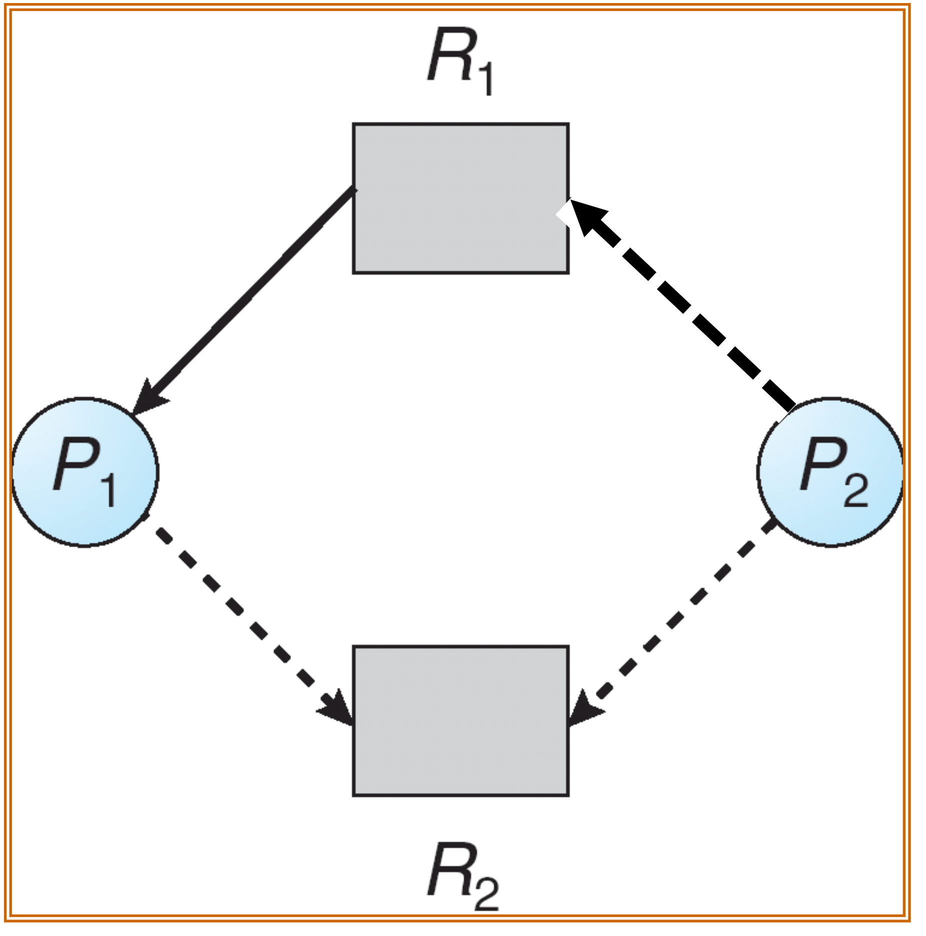
DEADLOCK AVOIDENCE

Deadlock Avoidance with single-instance resources

Deadlock Avoidance

- 1 instance per resource
  - Deadlock ←→ cycle (s)
  - Resource acquisition must not create cycle(s) in the resource allocation graph
- Deadlock avoidance based on cycle detection in resource allocation graphs

Resource-Allocation Graph For Deadlock Avoidance



Claim edge: may use a resource at some time
Request edge: is requesting a resource
Assignment edge: is holding a resource

Resource-Allocation Graph Algorithm

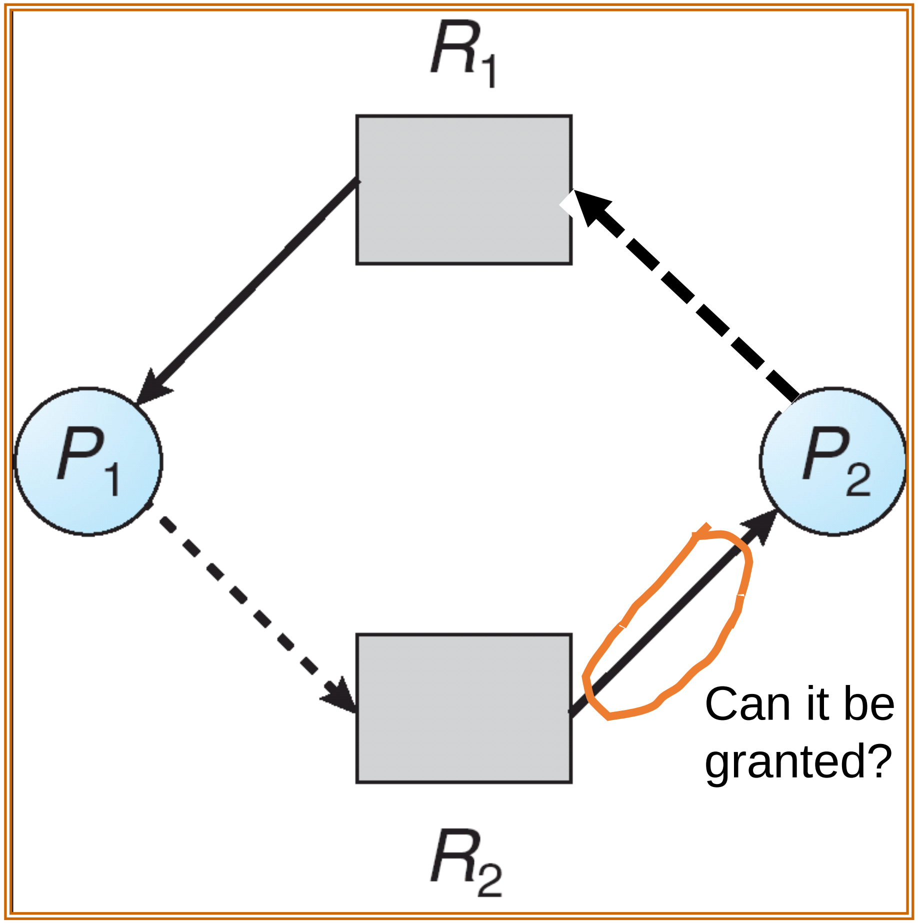
- Claim edge Pi → Rj indicated that process Pj may request resource Rj; represented by a dashed line
- Claim edge converts to request edge when a process requests a resource
- When a resource is released by a process, assignment edge reconverts to a claim edge

- Resources must be claimed *a priori* in the system.

Deadlock Avoidance for 1-Instance Resources

1. Initially, put all claim edges
2. When a process requests a resource, convert the claim edge into request edge
3. If the resource is available, tentatively change the request edge into assignment edge and check if there are any new cycles(s) in the resource-allocation graph
4. If new cycle(s) exist, revert the allocation edge back to request edge and put the process waiting; Otherwise, the resource is allocated to the process

Unsafe State In Resource-Allocation Graph



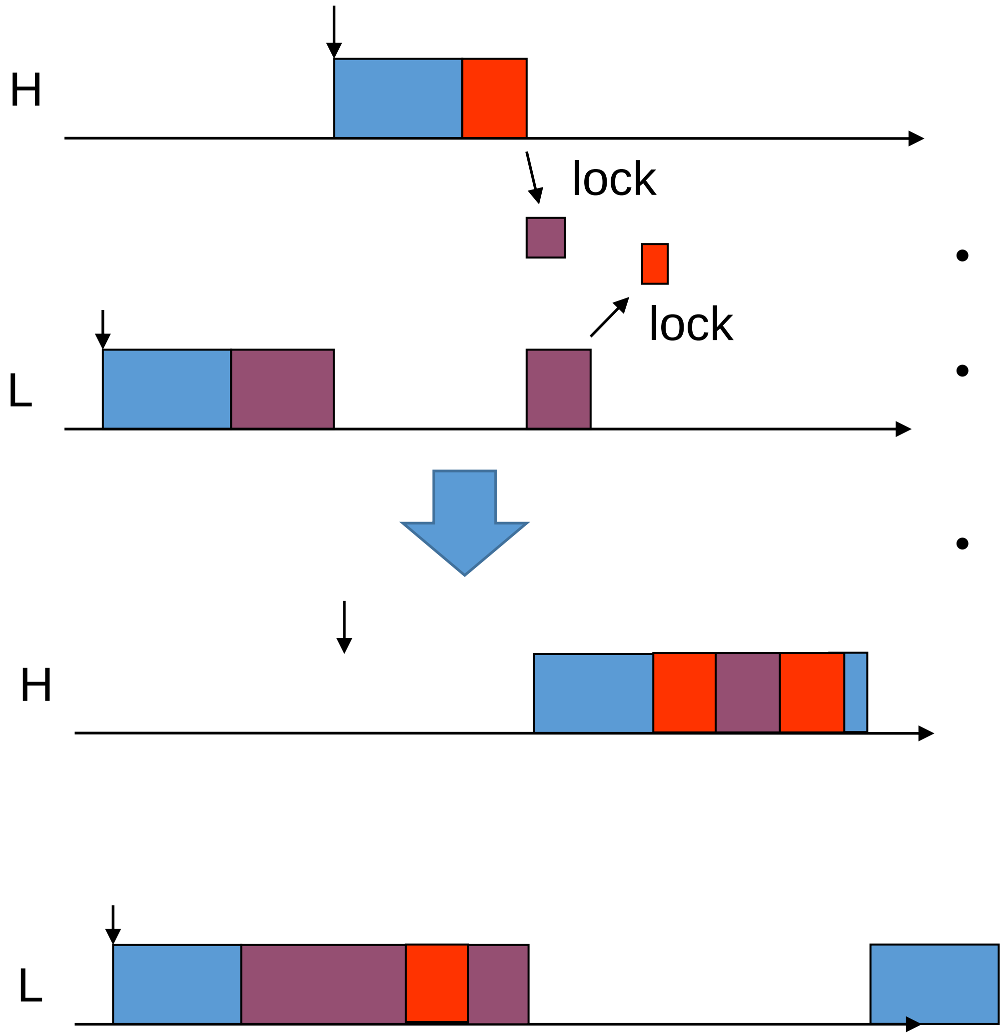
To detect cycles before an request can be granted

How to detect cycle(s) in the resource-allocation graph?

Deadlock Avoidance in Real-Time Systems

- Deadlock management has been dropped by commodity operating systems
  - It becomes the programmer's responsibility to write deadlock-free programs
- However, in real-time systems, the consequence of deadlocks can be catastrophic
  - Deadlines will be missed
  - RTOSes are equipped with resource-synchronization protocols to avoid deadlocks

Example: Highest Locker's Protocol in RTOS



- A process's priority is boosted to the highest lockers' priorities
- This protocol requires that a mutex can only be unlocked by its owner (locker)
- Recall the difference between mutexes and semaphores

Deadlock Avoidance
with Multiple-Instance Resources

Deadlock Avoidance

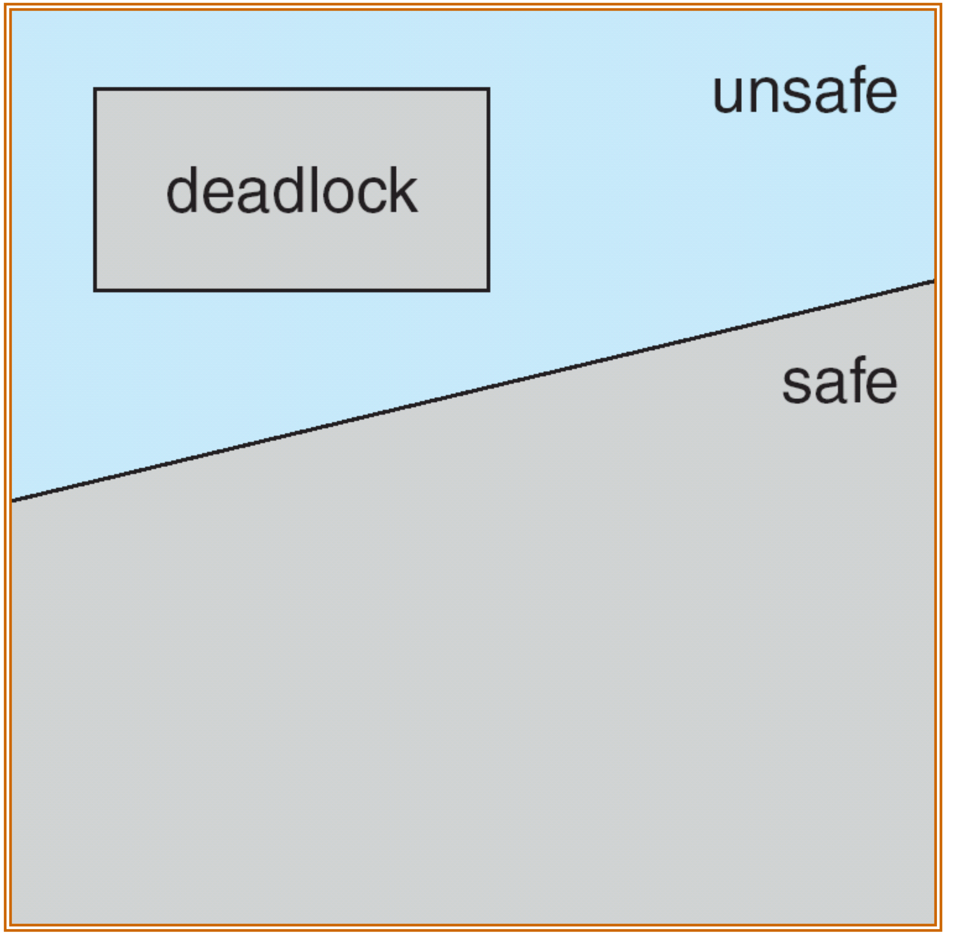
- N instances per resource
  - The graph-based approach is still applicable

- Now introdicing a more general approach
  - Safe/unsafe-state method
  - A system is safe → the system has no deadlock
  - The system must always be in a safe state; resource acquisition cannot put the system in a unsafe state
  - Need a definition on “safe state”

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



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 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 safe sequence of all processes
- Sequence <P1, P2, …, Pn> is safe if for each Pi, the resources that Pi can still request can be satisfied by currently available resources + resources held by all the Pj, with j<i
  - If Pi resource needs are not immediately available, then Pi can wait until all Pj have finished
  - When Pj is finished, Pi can obtain needed resources, execute, return allocated resources, and terminate
  - When Pi terminates, Pi+1 can obtain its needed resources, and so on

Banker's Algorithm

- Multiple instances per resource
- 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 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

n: process #; m: resource #

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

   Work = Available

   Finish [*i*] = *false* for *0~n*

2. Find and *i* such that both:

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

   (b) $Need_i \leq Work$

   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*] == true for all *i*, then the system is in a safe state.

O(n)

O(m)

O(n)

O(m*n²)

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 $Request_i \leq Need_i$ 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. Pretend 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 safe $\Rightarrow$ *the resources are allocated to Pi.*

If unsafe $\Rightarrow$ *Pi 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 (5instances, 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 (Cont.)

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

- Check that Request ≤ Available (that is, R_1(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 1	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 <P1, P3, P4, P0, P2> satisfies safety requirement.
- Can request for (3,3,0) by P4 be granted?
- Can request for (0,2,0) by P0 be granted?

If P0 (0,2,0) was made...

	Allocation	*Need*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 3 0	7 2 3	2 1 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	

Discussions: Safe State

- Why all processes make their largest requests to check safety?
- The allocation problem becomes easier if processes do not make their largest requests

End of Chapter 7

Review Questions

- Create a program of two threads, which are *guaranteed* to be deadlocked
- Why a mutex can only be unlocked by its owner?
- Why deadlock management has been dropped by commodity desktop operating systems?
- Re-run the example of the highest locker’s protocol
- Re-run the example of the banker’s algorithm