Comments are Welcome

- Online feedback systems are open (Due soon)
  - https://venus2.wis.ntu.edu.sg/SFT/Login.aspx
- Your comments are **VERY important**:
  - To have a self-assessment process
  - To improve teaching and course content/structure
- Speak out:
  - If you like my lecture (Score 5), I will treasure the good teaching experience
  - If you think of any improvements that you can suggest, that would be great feedback as well

Part 5: Deadlocks and Starvation

- **Deadlock Problem**
- System Model
- Deadlock Conditions
- Deadlock Prevention
- Deadlock Avoidance
- Deadlock Detection – not examinable

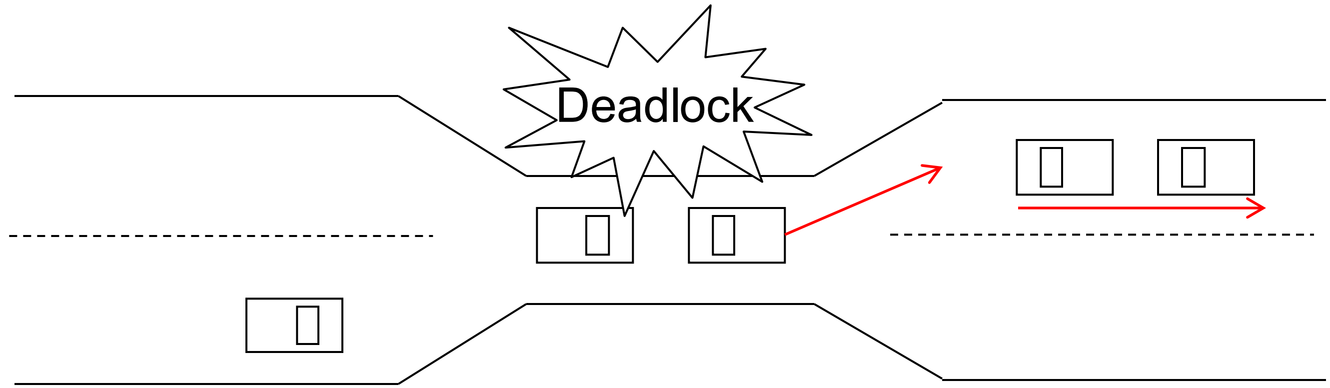
The Deadlock Problem

- Deadlock: A set of blocked processes each holding a resource and waiting to acquire a resource held by another process in the set
- Example 1:
  - System has two different types of tape drives; both P1 and P2 need the two tapes to finish execution
  - P_1 and P_2 each hold one tape drive and need the other
- Example 2: Semaphores *A* and *B*, initialized to 1

P_0	P_1
wait (A);	*wait (B);*
wait (B);	*wait (A);*

Context switch points

Bridge Crossing Example



- Only one car is allowed on the bridge
- The bridge can be viewed as a shared resource
- If a deadlock occurs, it can be resolved if one car backs up (release resource, i.e., the bridge, and rollback)
- Several cars may have to be backed up if a deadlock occurs

Part 5: Deadlocks and Starvation

- Deadlock Problem
- **System Model**
- Deadlock Conditions
- Deadlock Prevention
- Deadlock Avoidance
- Deadlock Detection

System Model

- Resource types R_1, R_2, . . ., R_m
  - – Memory space, I/O devices, semaphores, etc.

- Each resource type R_i has W_i identical instances

- Each process utilizes a resource as follows:
  1. Request for a specific number of instances
  2. Use
  3. Release all the instances

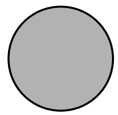
Resource-Allocation Graph

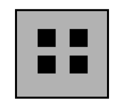
Graph → A set of vertices *V* and a set of edges *E*

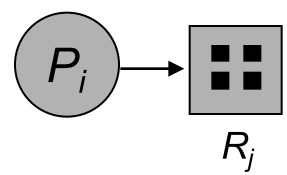
- V is partitioned into two types
  1. $P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system
  2. $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system

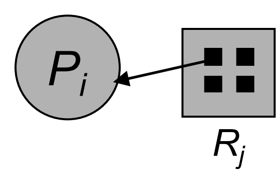
- E is partitioned into two types
  - Request Edge: Directed edge $P_i \rightarrow R_j$
    - When the request is granted, this edge is removed
  - Assignment Edge: Directed edge $R_j \rightarrow P_i$
    - When the resource is released, this edge is removed

Resource-Allocation Graph (Cont.)

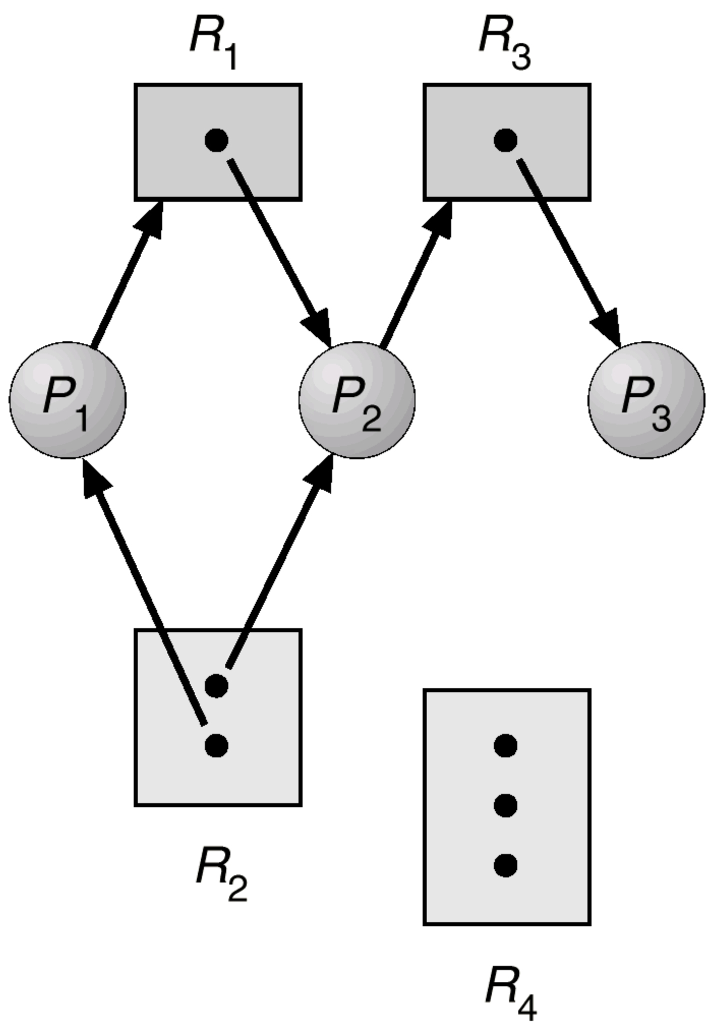
- Process 

- 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



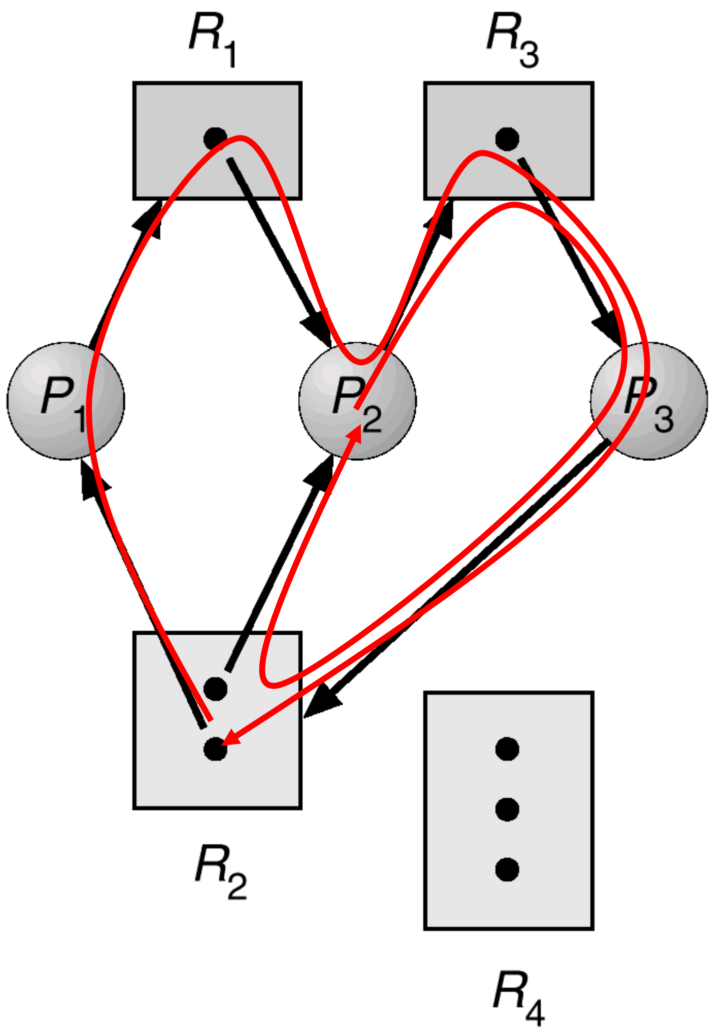
Is there a deadlock?

No deadlock

Can you identify a sequence of process executions so that all requests are met?

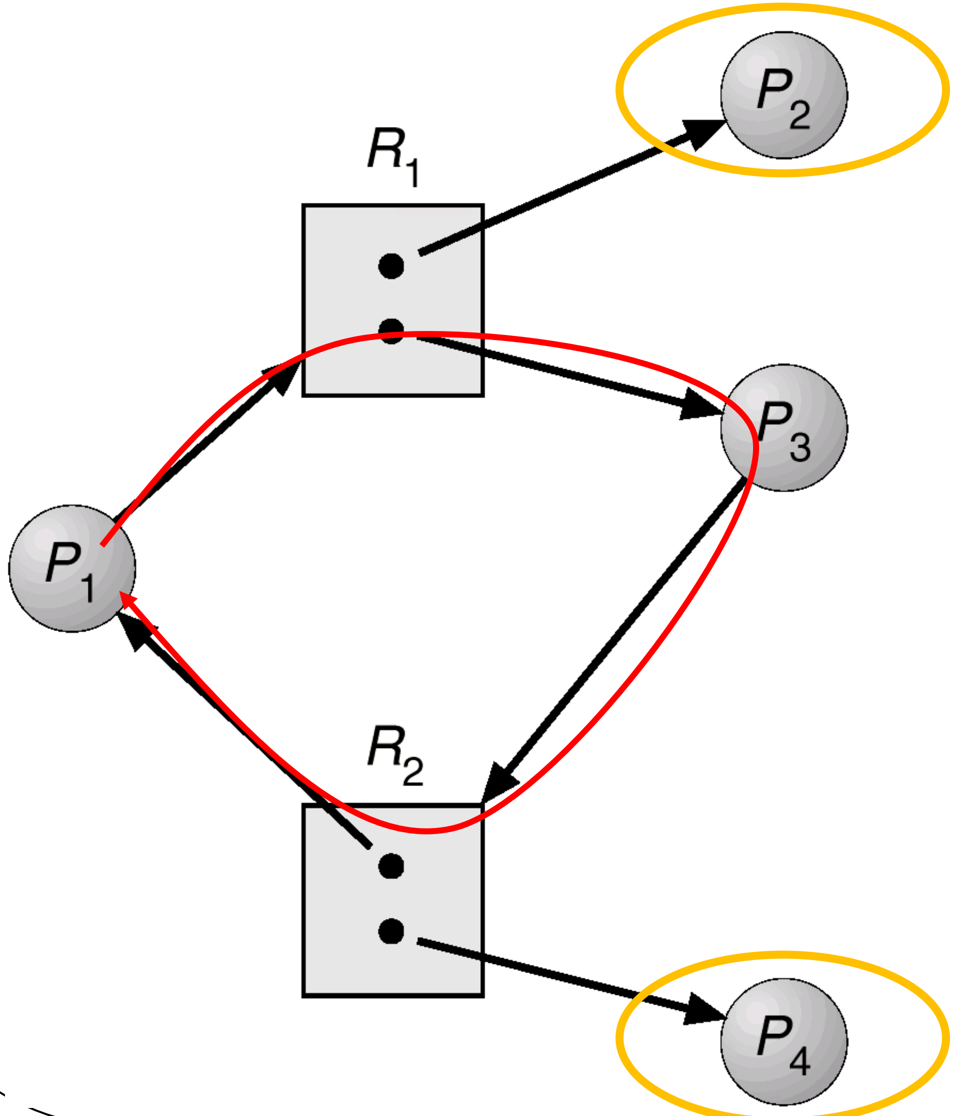
P3->P2->P1

Resource Allocation Graph With A Deadlock



Does this mean a cycle in the graph always indicates a deadlock?

Resource Allocation Graph With A Cycle But No Deadlock



Process execution order that avoids a deadlock

P2->P4->P3->P1

Basic Facts

- 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

Part 5: Deadlocks and Starvation

- Deadlock Problem
- System Model
- **Deadlock Conditions**
- Deadlock Prevention
- Deadlock Avoidance
- Deadlock Detection

Deadlock Conditions

Deadlock **may** arise if the following four conditions hold **simultaneously**
(necessary, but not sufficient)

1. Mutual exclusion: Only one process at a time can use a resource instance

2. Hold and wait: A process holding at least one resource is waiting to acquire additional resources held by other processes

Deadlock Conditions (Cont.)

3. **No preemption:** A resource can be released only voluntarily by the process holding it, after that process has completed its task

4. **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 P_2, …, P_{n-1} is waiting for P_n, and P_n is waiting for P_0

Part 5: Deadlocks and Starvation

- Deadlock Problem
- System Model
- Deadlock Conditions
- **Deadlock Prevention**
- Deadlock Avoidance
- Deadlock Detection

Methods for Handling Deadlocks

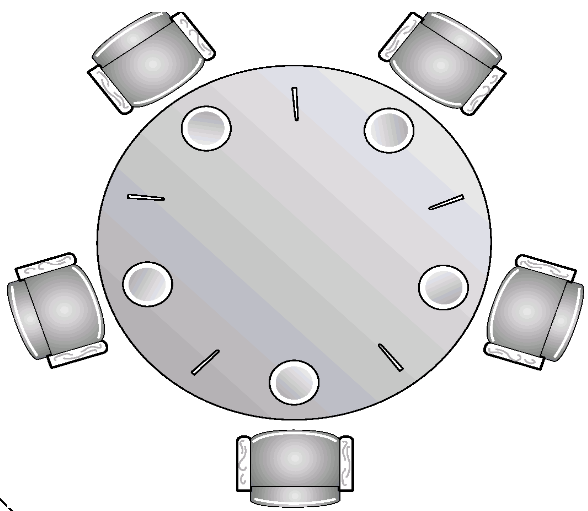
- Ensure that the system will never enter a deadlock state
- Allow the system to enter a deadlock state and then recover
- Ignore the problem and pretend that deadlocks never occur in the system
  - Used by most operating systems, including UNIX

Deadlock Prevention

Prevent at least one of the four deadlock conditions

We will illustrate using Dining-Philosophers Problem

- Recall dining-philosopher solution using semaphores
  - Each chopstick is a shared resource protected by a binary semaphore (**chopstick [5];**)
  - Initially, for all i, **chopstick [i] = 1;**
  - Code (Process Philosopher i)



```
while (1) {
    wait(chopstick [ i ]);
    wait(chopstick [ (i+1)%5 ]);
        eat
    signal(chopstick [ i ]);
    signal(chopstick [ (i+1)%5 ]);
        think
}
```

Deadlock Prevention (Cont.)

Prevent at least one of the four deadlock conditions

We will illustrate using Dining-Philosophers Problem

1. Mutual Exclusion
   – Chopsticks are not shareable (simultaneously), hence this condition cannot be eliminated

2. Hold and Wait: Must guarantee that whenever a process requests a resource, it does not hold any other resource
   – Allow a philosopher to pick up chopsticks only if both the required chopsticks are available

Deadlock Prevention (Cont.)

Prevent at least one of the four deadlock conditions

We will illustrate using Dining-Philosophers Problem

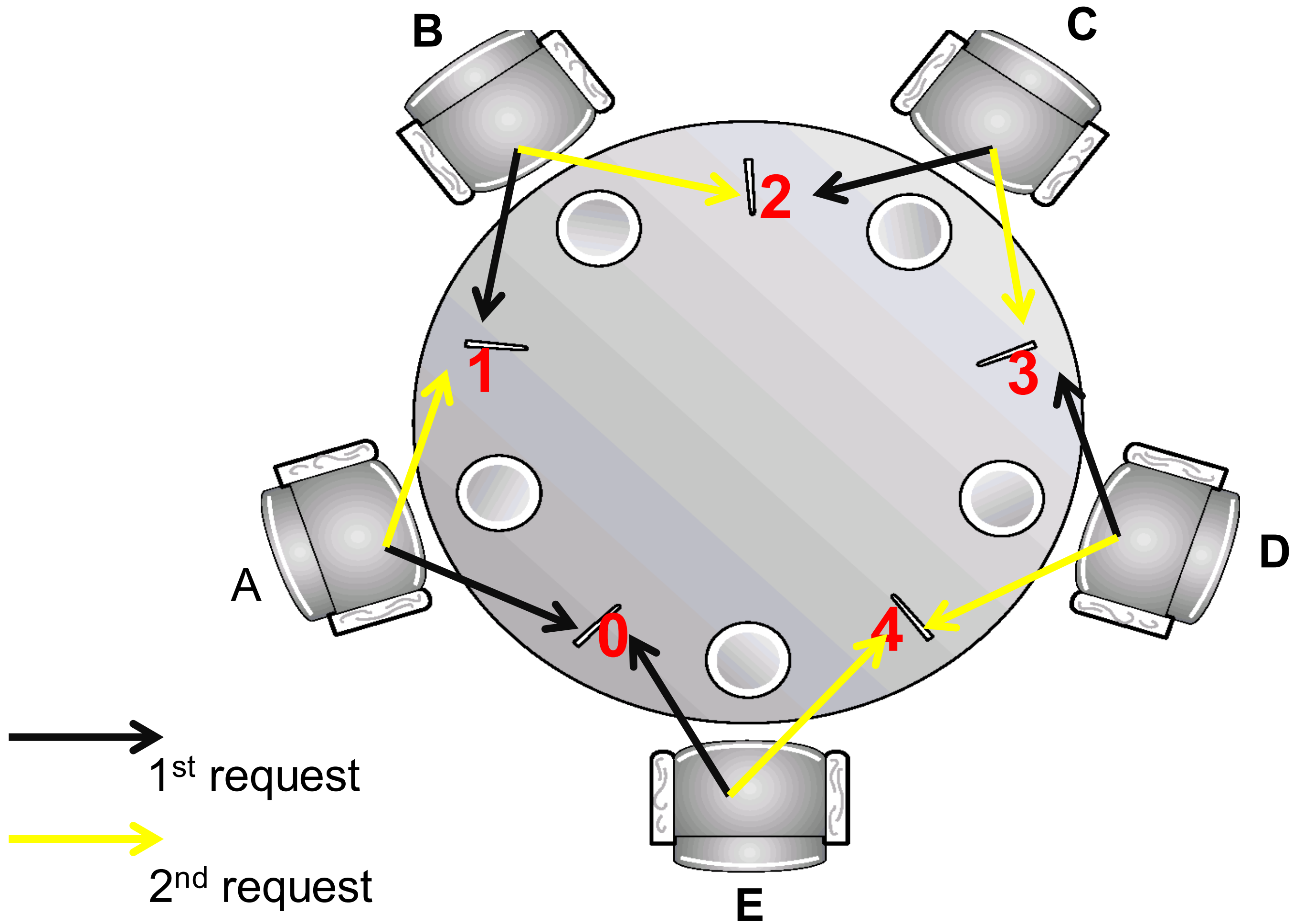
3. No Preemption

– If a philosopher cannot get the second chopstick, then preempt and release the chopstick that is being held

4. Circular Wait

1. Allow at most **four** philosophers to be hungry simultaneously
2. Odd-Even solution (see previous lecture)
3. Chopsticks can only be acquired in order (next slide)

Chopstick Ordering to Prevent Circular Wait



Part 5: Deadlocks and Starvation

- Deadlock Problem
- System Model
- Deadlock Conditions
- Deadlock Prevention
- **Deadlock Avoidance**
- Deadlock Detection

Deadlock Avoidance

- The deadlock-avoidance algorithm dynamically examines the resource-allocation state to ensure that the system never goes into unsafe state
  - When a process requests an available resource, system must decide if immediate allocation leaves the system in a safe state
  - If safe, the request is granted, and otherwise, the process must wait

- System is in safe state if **there exists a *safe completion sequence*** of all processes without deadlock

Safe State

- A process completion sequence $<P_1, P_2, \ldots, P_n>$ is safe, if for each P_i, the resources that P_i requests can be satisfied by currently available resources **+** resources held by all the P_j, $j< i$
  - If $\mathrm{P_i}$'s needs cannot be immediately met, then P_i can wait until all P_j, $j<i$ have finished
  - When all P_j (j<i) are finished, P_i can obtain needed resources, execute, return allocated resources, and terminate
  - When P_i terminates, P_{i+1} can obtain its resources, and so on
  - All processes in the sequence can finish

Example of Safe Process Sequence

Available: 1

Processes	Hold	Request
P1	1	1
P2	1	2
P3	1	3

Q1: Is <P1, P2, P3> safe?

Yes

P1.request<=Available

P2.request<=P1.Hold+Available

P3.request<=P1.Hold+P2.Hold+Available

Q2: <P3, P2, P1> safe?

No

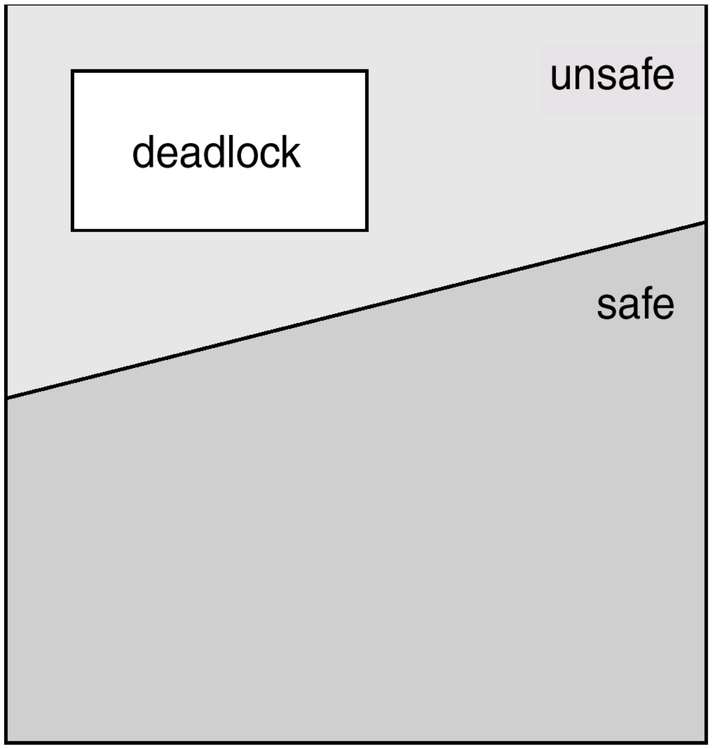
P3.request>Available

Q3: Is the system safe?

Yes

Exists one safe sequence <P1, P2, P3>

Safe, Unsafe and Deadlock States



- If a system is in safe state ⇒ no deadlocks
- If a system is in unsafe state ⇒ possibility of deadlock
  - If a process releases resources much before its completion, then deadlock may not occur
- Deadlock Avoidance: Ensure that a system will never enter an unsafe state

Banker's Algorithm

- An algorithm to check whether satisfaction of a resource request would lead to an unsafe state
  - For multiple instances of each resource type
- When a process requests a resource it may have to wait (if the allocation leads to unsafe state)
- Assumptions
  - Each process must declare the maximum instances of each resource type that it needs
  - When a process gets all its resources it must return them in a finite amount of time

Data Structures for Banker's Algorithm

n = number of processes; *m* = number of resource 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]

Banker's Algorithm Part 1: Safety Algorithm

1. Let **Work** and **Finish** be vectors of length **m** and **n**, respectively; initially
   - **Work = Available**
   - **Finish [i] = false for i = 1,2, …, n**

2. Find an **i** such that (a)**Finish [i] == false** and (b)**Need [i, *] ≤ Work**
   - If no such **i** exists, go to step 4

What if multiple answers?

3. **Work = Work + Allocation [i, *]; Finish[i] = true**
   - Go to step 2

Work= Available + resources held by all P_j (Finish [j] = true)

4. If **Finish [i] == true** for all **i**, then the system is in a safe state
   - Otherwise the system is in a unsafe state

Example of Safety 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 of Safety Algorithm (Cont.)

- Then the matrix **Need** is defined to be **Max – Allocation**

	Allocation	*Max*	***Need***	*Available*
	A B C	*A B C*	*A B C*	*A B C*
P_0	0 1 0	7 5 3	7 4 3	3 3 2
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	

Example of Safety Algorithm (Cont.)

- The working is as follows:

	Need A	Need B	Need C		Allocation A	Allocation B	Allocation C
P_0	7	4	3	✓	0	1	0
P_1	1	2	2	✓	2	0	0
P_2	6	0	0	✓	3	0	2
P_3	0	1	1	✓	2	1	1
P_4	4	3	1	✓	0	0	2

The system is safe (sequence <P_1, P_3, P_4, P_2, P_0>)

	Work A	Work B	Work C	Finished Process
	3	3	2	
+	2	0	0	P_1
	5	3	2	
+	2	1	1	P_3
	7	4	3	
+	0	0	2	P_4
	7	4	5	
+	3	0	2	P_2
	10	4	7	
+	0	1	0	P_0
	10	5	7	

Banker's Part 2: Resource-Request Algorithm

Request$_i$ = Request vector for process **P$_i$**

– If **Request$_i$ [j] == k** then process **P$_i$** wants **k** instances of resource type **R$_j$**

V1<=V2 ≡ V1[j]<=V2[j], for all j

The ith row of the matrix

1. If **Request$_i$ ≤ Need$_i$**, go to step 2
   - Otherwise, raise error condition, since process has exceeded its maximum claim
2. If **Request$_i$ ≤ Available**, go to step 3
   - Otherwise P_i must wait, since resources are not available

Resource-Request Algorithm (Cont.)

3. Pretend to allocate requested resources to P_i by modifying the state as follows:
   - **Available = Available – $Request_i$;**
   - **$Allocation_i$ = $Allocation_i$ + $Request_i$;**
   - **$Need_i$ = $Need_i$ – $Request_i$;**

4. Run the safety algorithm
   - Safe ⇒ the resources are allocated to P_i
   - Unsafe ⇒ P_i must wait, and the old resource-allocation state is restored

Example of Resource-Request Algorithm

- Suppose P_1 requests (1, 0, 2) resources
- Step1: Check $Request_1 \leq Need_1$, $(1,0,2) \leq (1,2,2) \Rightarrow$ *true*
- Step2: Check that $Request_1 \leq Available$, i.e. $(1,0,2) \leq (3,3,2) \Rightarrow$ *true*
- Steps 3 & 4:

	Allocation	*Max*	*Need*	*Available*
	A B C	*A B C*	*A B C*	*A B C*
P_0	0 1 0	7 5 3	7 4 3	~~3 3 2~~ **2 3 0**
P_1	~~2 0 0~~ **3 0 2**	3 2 2	~~1 2 2~~ **0 2 0**	
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	

Step 3: Pretend to allocate requested resources

Step 4: Executing safety algorithm shows that sequence <P_1, P_3, P_4, P_0, P_2> is safe

Example of Resource-Request Algorithm

- Can a further request for (1,0,2) by P_1 be granted?
  - Step 1: Check if $\text{Request}_1 \le \text{Need}_1$, $(1,0,2) \nleq (0,2,0) \Rightarrow$ *false*
- Can a further request for (0,2,0) by P_0 be granted?
  - Step 1: Check if $\text{Request}_0 \le \text{Need}_0$, $(0,2,0) \le (7,4,3) \Rightarrow$ *true*
  - Step 2: Check if $\text{Request}_0 \le \text{Available}$, $(0,2,0) \le (2,3,0) \Rightarrow$ *true*

	Allocation	*Need*	*Available*
	A B C	*A B C*	*A B C*
P_0	~~0 1 0~~ 0 3 0	~~7 4 3~~ 7 2 3	~~2 3 0~~ 2 1 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	

☹We cannot find Need_i < Available
→ Restore the state

- How about a request for (2,3,0) by P_4?

Part 5: Deadlocks and Starvation

- Deadlock Problem
- System Model
- Deadlock Conditions
- Deadlock Prevention
- Deadlock Avoidance
- **Deadlock Detection**

Deadlock Detection

- Allow system to enter deadlock state
- Then invoke detection algorithms
  - For single instance of each resource type (in textbook based on identifying cycle in resource-allocation graph)
  - For multiple instances of each resource type (next few slides)
- Then invoke recovery algorithm (in textbook)

This slide and the later slides in this chapter are not examinable

Multiple Instances of Each Resource Type

- Available: A vector of length *m* indicates the number of available resource types
- 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; initially
   - **Work = Available**
   - For i = 1,2, …, n, if **$Allocation_i$!= 0**, then **Finish[i] = false**, else **Finish[i] = true**

2. Find an **i** such that (a)**Finish [i] == false** and (b)**Request [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] == false** for some **i**, then system (process **P_i**) is deadlocked

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> results in Finish[i] = true for all i

Example of Detection Algorithm (Cont.)

Suppose P_2 requests an additional instance of type C

	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 1	☹	
P_3	2 1 1	1 0 0	☹	
P_4	0 0 2	0 0 2	☹	

Work

$A\ B\ C$

$$\begin{array}{r} 0\ 0\ 0 \\ +\ \ 0\ 1\ 0 \\ \hline 0\ 1\ 0 \end{array}$$

Finished

P_0

Example of Detection Algorithm (Cont.)

- State of system?
  - Can reclaim resources held by process P_0, but insufficient resources to fulfill other process requests
  - Deadlock exists, consisting of processes P_1, P_2, P_3, and P_4

Advanced Readings

- "The Deadlock Problem: An Overview", By Sreekaanth S. Isloor, T. Anthony Marsland. (pdf in NTULearn)
- Other readings
  - Java Concurrency, http://docs.oracle.com/javase/tutorial/essential/concurrency/index.html
  - Deadlock, http://en.wikipedia.org/wiki/Deadlock