Deadlocks

Operating Systems

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Acknowledgement: some pages are based on the slides from Yajin Zhou.

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- Deadlock problem
- System model
- Handling deadlocks
  - deadlock prevention
  - deadlock avoidance
  - deadlock detection
  - deadlock recovery

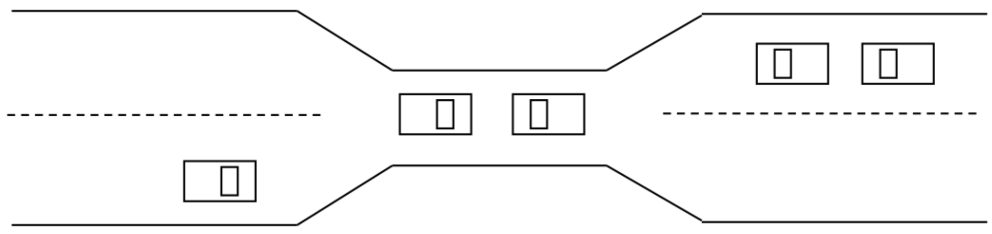
The Deadlock Problem

- **Deadlock**: a set of blocked processes each holding a resource and waiting to acquire a resource held by another process in the set
- Examples:
  - a system has 2 disk drives, P_1 and P_2 each hold one disk drive and each needs another one
  - semaphores A and B, initialized to 1

P_1	P_2
wait (A);	wait(B)
wait (B);	wait(A)

Bridge Crossing Example

- Traffic only in one direction, each section 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 be backed up
  - starvation is possible
- Note: most OSes do not prevent or deal with deadlocks



Deadlock in program

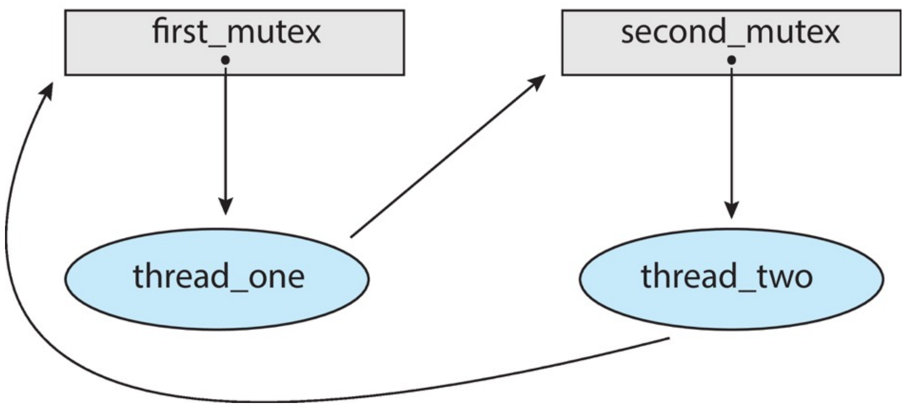
- Two mutex locks are created an initialized:

```
pthread_mutex_t first_mutex;
pthread_mutex_t second_mutex;

pthread_mutex_init(&first_mutex, NULL);
pthread_mutex_init(&second_mutex, NULL);
```

```
/* 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);
}

/* 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);
}
```

Deadlock in program

- Deadlock is possible if thread 1 acquires **first_mutex** and thread 2 acquires **second_mutex**. Thread 1 then waits for **second_mutex** and thread 2 waits for **first_mutex**.
- Can be illustrated with a **resource allocation graph**:



System Model of deadlock

- Resources: $R_1, R_2, \ldots, R_m$
  - each represents a different **resource type**
    - e.g., CPU cycles, memory space, I/O devices
  - each resource type R_i has W_i **instances**
- Each process utilizes a resource in the following pattern
  - request
  - use
  - release

Four Conditions of Deadlock

- **Mutual exclusion**: a resource can only be used by one process at a time
- **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 it has completed its task
- **Circular wait**: there exists a set of waiting processes $\{P_0, P_1, \ldots, P_n\}$
  - 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
  - P_n is waiting for a resource that is held by P_0

Resource-Allocation Graph

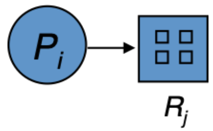
- Two types of nodes:
  - $P = \{P_1, P_2, \ldots, P_n\}$, the set of all the **processes** in the system
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set of all **resource** types in the system
- Two types of edges:
  - **request edge**: directed edge $P_i \rightarrow R_j$
  - **assignment edge**: directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph

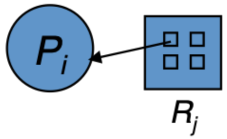
- Process

- Resource Type with 4 instances

- Pi requests instance of Rj

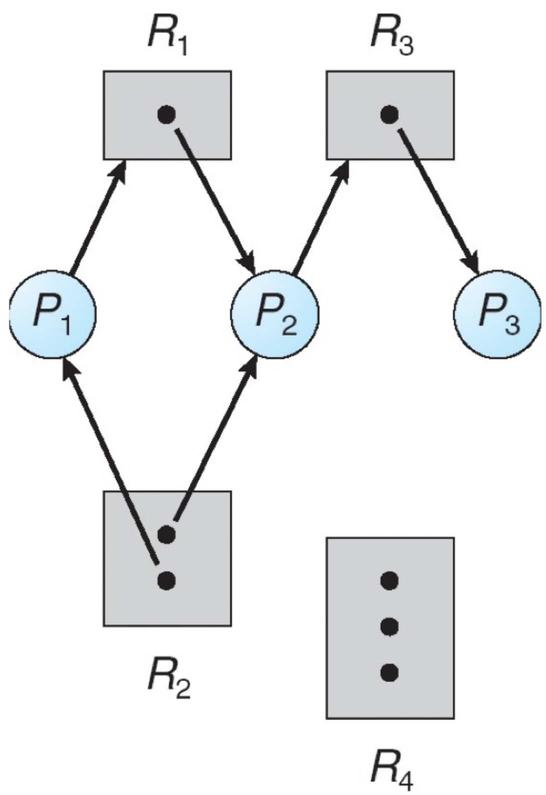


- Pi is holding an instance of Rj



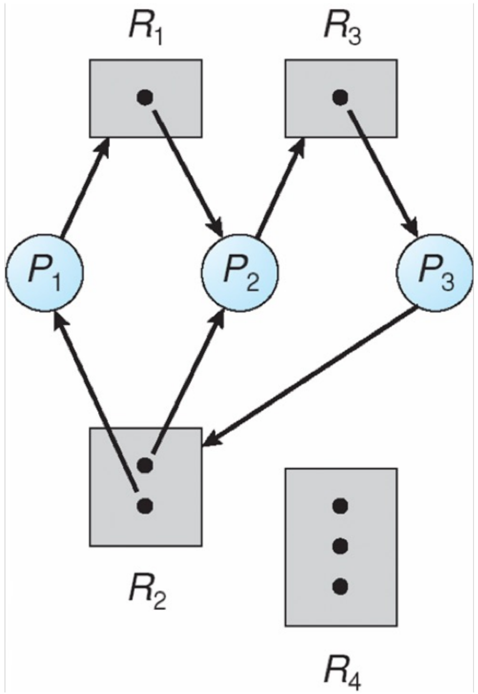
Resource Allocation Graph

- Resources
  - One instance of R1
  - Two instances of R2
  - One instance of R3
  - Three instance of R4
- P1 holds one instance of R2 and is waiting for an instance of R1
- P2 holds one instance of R1, one instance of R2, and is waiting for an instance of R3
- P3 is holds one instance of R3



Resource Allocation Graph

- Is there a deadlock?

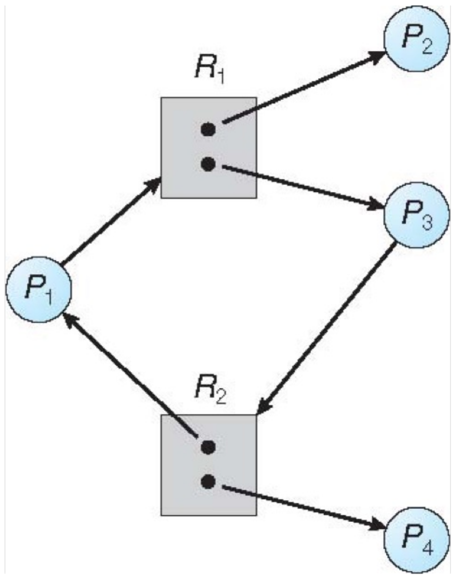


p1->r1->p2->r3->p3->r2->p1

p2->r3->p3->r2->p2

Resource Allocation Graph

- Is there a deadlock?
  - **circular wait does not necessarily lead to deadlock**



p1->r1->p3->r2->p1

P4 releases first

Basic Facts

- If graph contains **no cycles** ➠ **no deadlock**
- If graph contains a cycle
  - if only **one instance per resource type**, ➠ **deadlock**
  - if **several instances** per resource type ➠ **possibility** of deadlock

How to Handle Deadlocks

- Ensure that the system will never enter a deadlock state
  - **Prevention**
  - **Avoidance**
- Allow the system to enter a deadlock state and then recover - database
  - **Deadlock detection and recovery**
- **Ignore the problem** and pretend deadlocks never occur in the system

Deadlock Prevention

- How to prevent **mutual exclusion**
  - not required for sharable resources
  - must hold for non-sharable resources
- How to prevent **hold and wait**
  - whenever a process requests a resource, it doesn't hold any other resources
    - require process to request ***all*** its resources before it begins execution
    - allow process to request resources only when the process has none
  - low resource utilization; starvation possible

Deadlock Prevention

- How to handle **no preemption**
  - if a process requests a resource not available
    - release all resources currently being held
    - preempted resources are added to the list of resources it waits for
    - process will be restarted only when it can get all waiting resources
- How to handle **circular wait**
  - **impose a total ordering of all resource types**
  - require that each process requests resources in an increasing order
  - **Many operating systems adopt this strategy for some locks.**

Circular Wait

- Invalidating the circular wait condition is most common.
- Simply assign each resource (i.e. mutex locks) a unique number.
- Resources must be acquired in order.

first_mutex = 1
second_mutex = 1

code for thread_two could not be written as follows:

```
/* 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);
}

/* 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);
}
```

For dynamic acquired lock

```
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);
}
```

```
transaction(checking_account, savings_account, 25.0)

transaction(savings_account, checking_account, 50.0)
```

Deadlock Avoidance

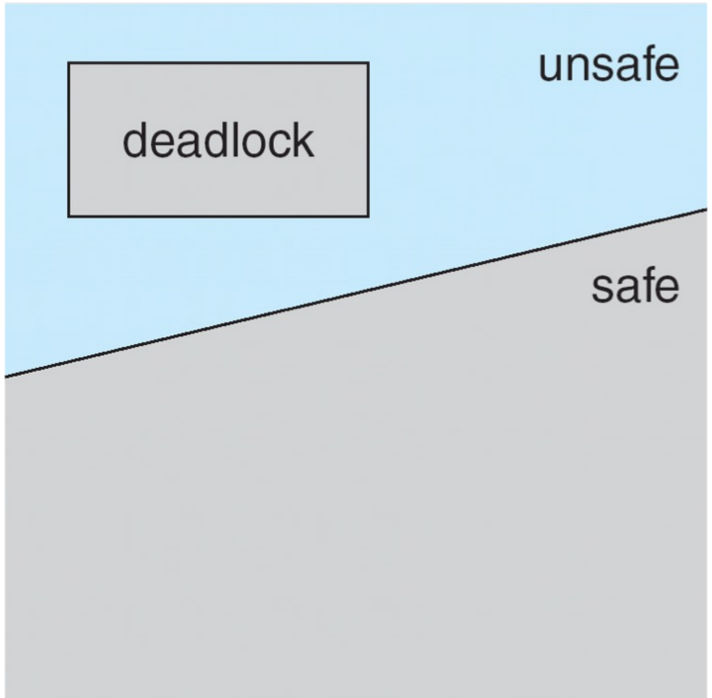
- Deadlock avoidance: require **extra information** about how resources are to be requested
  - **Is this requirement practical**?
- Each process declares a **max** number of resources it may need
- Deadlock-avoidance algorithm ensure there can **never** be a **circular-wait** condition
- Resource-allocation state:
  - the number of **available** and **allocated** resources
  - 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**:
    - there exists a **sequence <P_1, P_2, …, P_n>** of all processes in the system
    - for each P_i, resources that P_i can still request can be satisfied by currently **available resources + resources held by all the P_j**
- **Safe state can guarantee no deadlock**
    - if P_i's resource needs are not immediately available:
        - wait until all P_j have finished
        - when P_j has finished, P_i can obtain needed resources,
    - when P_i terminates, P_{i+1} can obtain its needed resources, and so on

Basic Facts

- If a system is in **safe state** ➠ **no deadlocks**
- If a system is in **unsafe state** ➠ **possibility of deadlock**
- **Deadlock avoidance** ➠ ensure a system **never enters an unsafe state**



Example

- Resources: 12
  - Available is 3

	Max need	Current have	Extra need
P0	10	5	5
P1	4	2	2
P2	9	2	7

- Safe sequences: P1 P0 P2
  - P1 gets and return (5 in total)
  - and then P0 gets all and returns (10 in total)
  - and then P2

Example

- Safe sequences: P1 P0 P2
  - Available is 3

	Max need	Current have	Extra need
P0	10	5	5
P1	4	2	2
P2	9	2	7

Example

- Safe sequences: P1 P0 P2
  - Available is 3 -> give 2 to P1

	Max need	Current have	Extra need
P0	10	5	5
P1	4	2	2
P2	9	2	7

Example

- Safe sequences: P1 P0 P2
  - Available is 1 -> give 2 to P1

	Max need	Current have	Extra need
P0	10	5	5
P1	4	4	0
P2	9	2	7

  - P1 gets and return -> Available is 5

	Max need	Current have	Extra need
P0	10	5	5
P1	0	0	0
P2	9	2	7

Example

- Safe sequences: P1 P0 P2
  - Available is 3

	Max need	Current have	Extra need
P0	10	5	5
P1	4	2	2
P2	9	2	7

  - P1 gets and return (5 in total) -> Available is 5

	Max need	Current have	Extra need
P0	10	5	5
P1	0	0	0
P2	9	2	7

Example

- Safe sequences: P1 P0 P2
  - P1 gets and return (available = 5),
  - and then P0 gets all needs and returns (available = 10),
  - and then P2

Example

- Resources: 12
  - Available is 3

	Max need	Current have	Extra need
P0	10	5	5
P1	4	2	2
P2	9	2	7

- What if we allocate 1 more for P2?
  - Available is 2

	Max need	Current have	Extra need
P0	10	5	5
P1	4	2	2
P2	9	3	6

Example

- Resources: 12
    - Available is 2

	Max need	Current have	Extra need
P0	10	5	5
P1	4	2	2
P2	9	3	6

    - P1 gets and returns, available = 4, cannot fulfil the needs of P0 or P2

Deadlock Avoidance Algorithms

- Single instance of each resource type ➠ use **resource-allocation graph**
- Multiple instances of a resource type ➠ use the **banker's algorithm**

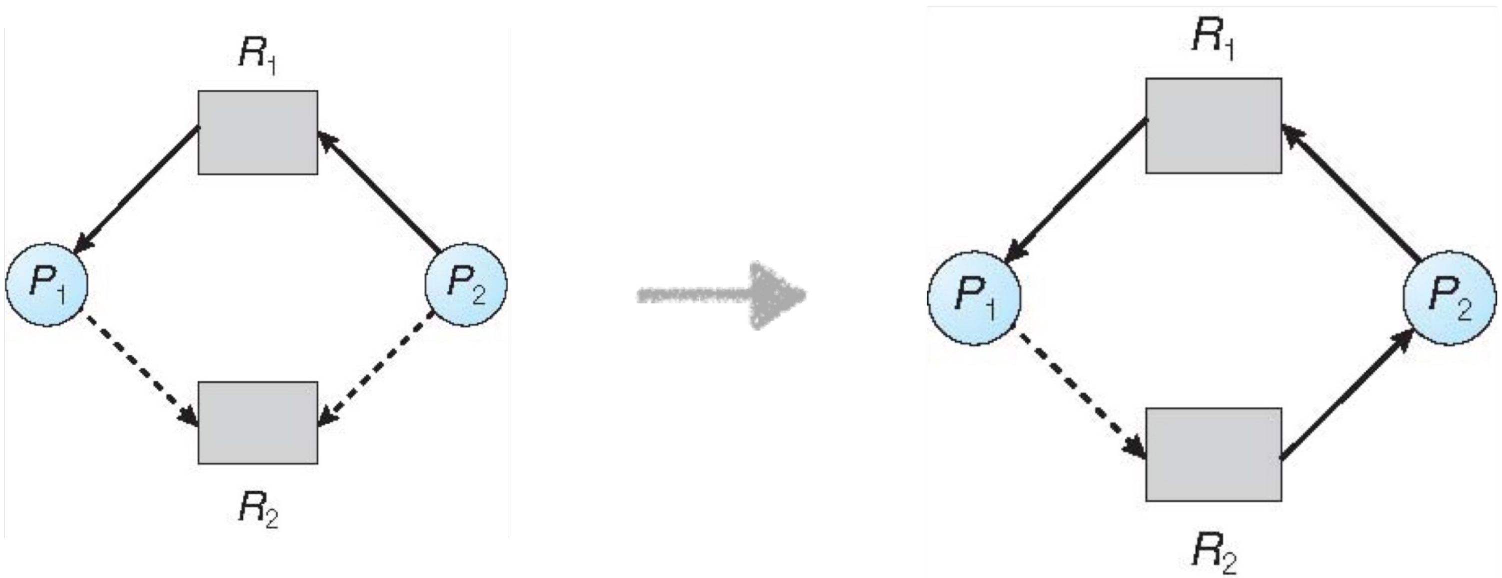
Single-instance Deadlock Avoidance

- Resource-allocation graph can be used for **single instance resource** deadlock avoidance
  - one new type of edge: **claim edge**
    - claim edge $P_i \rightarrow R_j$ indicates that process P_i ***may*** request resource R_j
    - claim edge is represented by a **dashed** line
  - **resources must be claimed a priori in the system**

- Transitions in between edges
  - ***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
  - ***assignment edge*** reconverts to a ***claim edge*** when a resource is released by a process

Single-instance Deadlock Avoidance

- 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 the formation of a **cycle**
  - **no cycle ➠ safe state**



Banker’s Algorithm

- Banker’s algorithm is for **multiple-instance resource deadlock avoidance**
  - each process must claim **maximum** use of each resource type **in advance**
  - when a process requests a resource it may have to wait
  - when a process gets all its resources it must release them in a finite amount of time

Data Structures for the Banker's Algorithm

- **n** processes, **m** types of resources
  - **available**: an array of length ***m***, instances of available resource
    - available[j] = k: k instances of resource type R_j available
  - **max**: a ***n x m*** matrix
    - max [i,j] = k: process P_i may request at most k instances of resource R_j
  - **allocation**: ***n x m*** matrix
    - allocation[i,j] = k: P_i is currently allocated k instances of R_j
  - **need**: ***n x m*** matrix
    - need[i,j] = k: 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: Example

- System state:
  - **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	

Banker's Algorithm: Safe State

- Data structure to compute whether the system is in a safe state
  - use **work** (a vector of length *m*) to track **allocable resources**
    - **current available resources**
    - **unallocated + released by finished processes**
  - use **finish** (a vector of length n) to track whether process has finished
  - initialize: **work = available**, **finish[i] = false** for i = 0, 1, …, n- 1
- Algorithm:
  - find an i such that **finish[i] = false && need[i] ≤ work** if no such i exists, go to step 3
  - **work = work + allocation[i]**, **finish[i] = true**, go to step 1
  - if finish[i] == true for all i, then the system is in a safe state

Bank's Algorithm: Resource Allocation

- Data structure: request vector for process P_i
  - **request**[j] = k then process P_i wants k instances of resource type R_j
- Algorithm:

1. if request[i]≤ need[i] go to step 2; otherwise, raise error condition (the process has exceeded its maximum claim)
2. if request[i] ≤ available, go to step 3; otherwise P_i must wait (not all resources are not available)
3. pretend to allocate requested resources to P_i by modifying the state:

   available = available – request[i]

   allocation[i] = allocation[i] + request[i]

   need[i] = need[i] – request[i]
4. use **previous algorithm** to test if it is a safe state, if so ➠ allocate the resources to P_i
5. if unsafe ➠ P_i must wait, and the old resource-allocation state is restored

Banker's Algorithm: Example

- System state:
  - **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
	A B C	A B C
P_0	0 1 0	7 5 3
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

available
A B C
3 3 2

Banker's Algorithm: Example

- System state:
  - **5 processes** P_0 through P_4
  - **3 resource types**: A (10 instances), B (5 instances), and C (7 instances)
- need = max – allocation

	allocation	max	need
	A B C	A B C	A B C
P_0	0 1 0	7 5 3	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

available
A B C
3 3 2

Banker's Algorithm: Example

- System state:
  - **5 processes** P_0 through P_4
  - **3 resource types**: A (10 instances), B (5 instances), and C (7 instances)
- need = max – allocation

	allocation	max	need
	A B C	A B C	A B C
P_0	0 1 0	7 5 3	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

available
A B C
3 3 2

- First one can be either P1 or P3

Banker's Algorithm: Example

- What's the safe sequence

	allocation	max	need
	A B C	A B C	A B C
P_0	0 1 0	7 5 3	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

available
A B C
3 3 2

- finish[1] = true, needed[1] < work -> work = work + allocation = [5 3 2]
- finish[3] = true, needed[3]< work -> work = work + allocation = [7 4 3]
- finish[4] = true, needed[4] < work -> work = work + allocation = [7 4 5]
- finish[2] = true, needed[2] < work -> work = work + allocation = [10 4 7]
- finish[0] = true, needed[0] < work -> work = work + allocation = [10 5 7]

Banker’s Algorithm: Example

- P1 requires and gets allocated 1 0 2 more

	allocation	max	need
	A B C	A B C	A B C
P_0	0 1 0	7 5 3	7 4 3
P_1	3 0 2	4 2 4	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

available
A B C
2 3 0

- Check whether it is in safe state?
  - We cannot find a process that the need[i] < work[i]

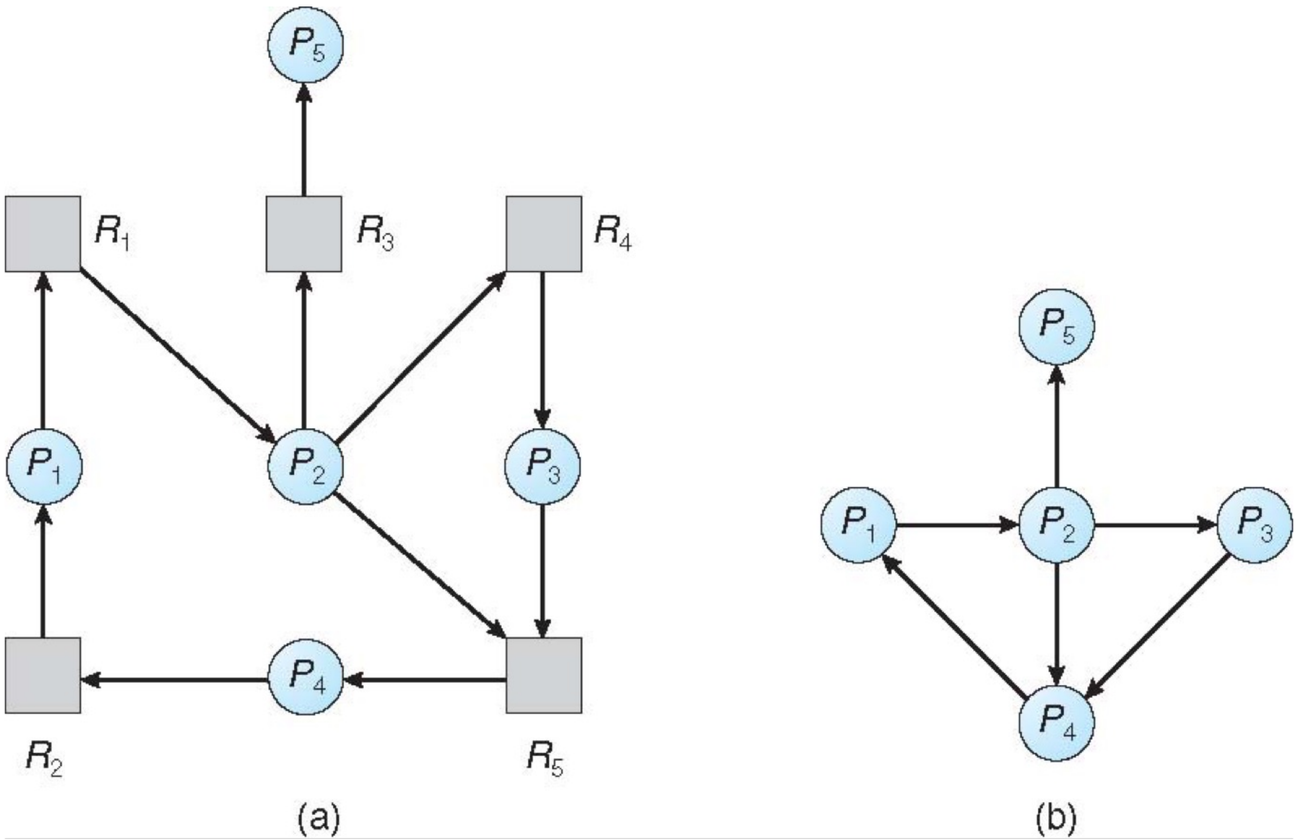
Deadlock Detection

- Allow system to enter deadlock state, but detect and recover from it
- Detection algorithm and recovery scheme

Deadlock Detection: Single Instance Resources

- 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
  - 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

Wait-for Graph Example



Resource-allocation Graph wait-for graph

Deadlock Detection: Multi-instance Resources

- Detection algorithm similar to Banker's algorithm's safety condition
  - to prove it is **not possible** to enter a **safe state**
- Data structure
  - **available**: a vector of length *m,* 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
    - request [i, j] = k: process P_i is requesting k more instances of resource R_j
  - **work**: a vector of *m*, the allocatable instances of resources
  - **finish**: a vector of *m*, whether the process has finished
    - if allocation[i] ≠ 0 ➟ finish[i] = false; otherwise, finish[i] = true

Deadlock Detection: Multi-instance

- Find an process i such that **finish[i] == false && request[i] ≤ work**
  - if no such i exists, go to step 3
- **work = work + allocation[i]**; **finish[i] = true**, go to step 1
- If finish[i] == false, for some i the system is in deadlock state
  - if finish[i] == false, then P_i is deadlocked

Example of Detection Algorithm

- System states:
  - five processes P_0 through P_4
  - three resource types: A (7 instances), B (2 instances), and C (6 instances)
- Snapshot at time T0:

	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	

P0: [0 0 0] -> [0 1 0]
P2: [0 1 0] -> [3 1 3]
P3: [3 1 3] -> [5 2 4]
P1: [5 2 4] -> [7 2 4]
P4: [7 2 4] -> [7 2 6]

- Sequence <P_0, P_2, P_3, P_1, P_4> will result in finish[i] = true for all i

Example (Cont.)

- P2 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	

- State of system?
  - can reclaim resources held by process P_0, but insufficient resources to fulfill other processes; requests
    - P1: [0 0 0] -> [0 1 0]
  - deadlock exists, consisting of processes P_1, P_2, P_3, and P_4

Deadlock Recovery: Option I

- Terminate deadlocked processes. options:
  - 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?

Deadlock Recovery: Option II

- Resource preemption
  - Select a victim
  - Rollback
  - Starvation
    - How could you ensure that the resources do not preempt from the same process?

Takeaway

- Deadlock occurs in which condition?
- Four conditions for deadlock
- Deadlock can be modeled via resource-allocation graph
- Deadlock can be prevented by breaking one of the four conditions
- Deadlock can be avoided by using the banker’s algorithm
- A deadlock detection algorithm
- Deadlock recovery