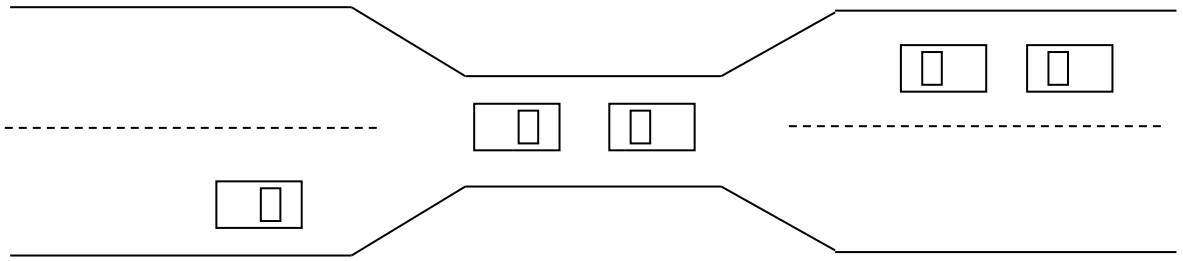
Deadlocks

The Deadlock Problem (1)

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

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

The Deadlock Problem (2)



- 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 be backed up if a deadlock occurs
- Starvation is possible

System Model

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

  CPU cycles, memory space, I/O devices

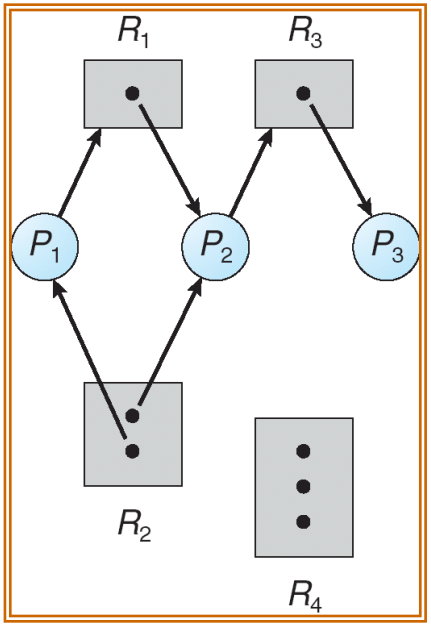
- Each resource type R_i has W_i instances.
- Each process utilizes a resource as follows:
  - request
  - use
  - release

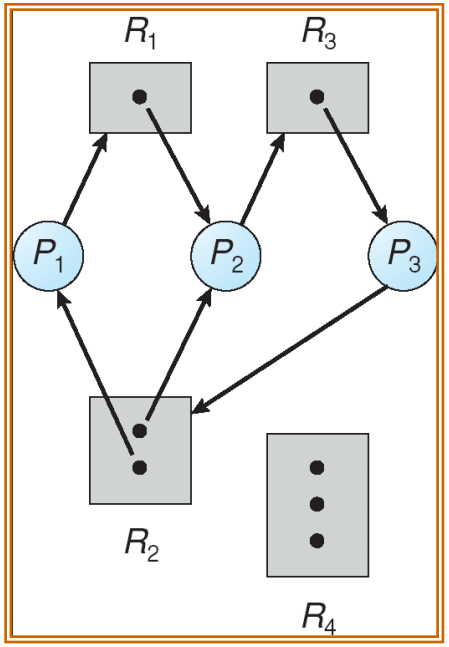
Deadlock Characterization (1)

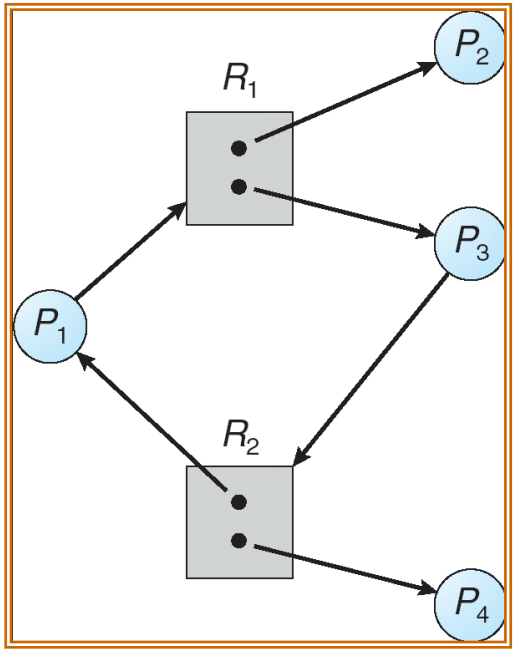
- Necessary and sufficient conditions for a deadlock
  - Mutual exclusion: only one process at a time can use a resource
  - Hold and wait: a process holding at least one resource is waiting to acquire additional resources held by other processes
  - No preemption: a resource can be released only voluntarily by the process holding it, after that process has completed its task
  - Circular wait: there exists a set {P0, P1, …, Pn} of waiting processes such that P0 is waiting for a resource that is held by P1, P1 is waiting for a resource that is held by P2, …, Pn–1 is waiting for a resource that is held by Pn, and P0 is waiting for a resource that is held by P0

Deadlock Characterization (2)

- Resource-allocation graph







If no cycle exists then there is no deadlock
(necessary condition)
If a cycle exists then there may be a deadlock
(a cycle is a necessary and sufficient condition for deadlock when resources involved have a single instance)

Deadlock Characterization (3)

```
class A implements Runnable
{
   private Lock first, second;

   public A(Lock first, Lock second) {
      this.first = first;
      this.second = second;
   }

   public void run() {
      try {
         first.lock();
         // do something
            second.lock();
            // do something else
      }
      finally {
         first.unlock();
         second.unlock();
      }
   }
}
```

```
class B implements Runnable
{
   private Lock first, second;

   public A(Lock first, Lock second) {
      this.first = first;
      this.second = second;
   }

   public void run() {
      try {
         second.lock();
         // do something
            first.lock();
            // do something else
      }
      finally {
         second.unlock();
         first.unlock();
      }
   }
}
```

Methods for Handling Deadlocks (1)

- Use a protocol that prevents or avoids deadlocks
  - Deadlock prevention: ensure that one of the necessary conditions cannot hold
  - Deadlock avoidance: keep track of available and allocated resources and future requests and releases to decide whether the current request should be satisfied or not
- Allow deadlocks to occur but detect them and recover
- Ignore the problem
  - Most popular approach (deadlocks tend to be rare)
    - Unix, Windows, Java
  - Manual restart to recover (mechanism may be useful in other situations too)
- Different approaches may be preferable for different resources

Methods for Handling Deadlocks (2)

- Handling deadlocks in Java
  - `suspend(), resume(), stop()`

```
public class ClockApplet extends Applet implements Runnable
{
    private Thread clockThread;
    private boolean ok = false;
    private Object mutex = new Object();

    public void run() {
       while (true) {
          try {
             // sleep for 1 second
             Thread.sleep(1000);

             // repaint the date and time
             repaint();

             // see if we need to suspend ourself
             synchronized (mutex) {
                while (ok == false)
                   mutex.wait();
             }
          }
          catch (InterruptedException e) { }
       }
    }

    public void start() {
       // Figure 7.7
    }

    public void stop() {
       // Figure 7.7
    }

    public void paint(Graphics g) {
      g.drawString(new java.util.Date().toString(),10,30);
    }
}
```

```
// this method is called when the applet is
// started or we return to the applet
public void start() {
    ok = true;

    if (clockThread == null) {
       clockThread = new Thread(this);
       clockThread.start();
    }
    else {
       synchronized(mutex) {
          mutex.notify();
       }
    }
}

// this method is called when we
// leave the page the applet is on
public void stop() {
    synchronized(mutex) {
       ok = false;
    }
}
```

Deadlock Prevention

- Mutual exclusion
  - Sharable and non-sharable resources
  - For non-sharable resources this is not an option
- Hold and wait
  - Request all resources at the beginning
  - Request resource only when you hold none
  - - poor resource utilisation
  - - starvation is possible
- No preemption
  - Preempt all currently held resources when a request cannot be immediately granted
  - Preempt resource currently held by a waiting process
  - Only applicable to resources whose state can be easily saved and restored
- Circular wait
  - Impose total ordering on resources, acquire resources in ascending order (all instances at the same time)
    - Follow the normal order of usage
  - Works only if developers follow the protocol!
    - Witness: lock order verifier

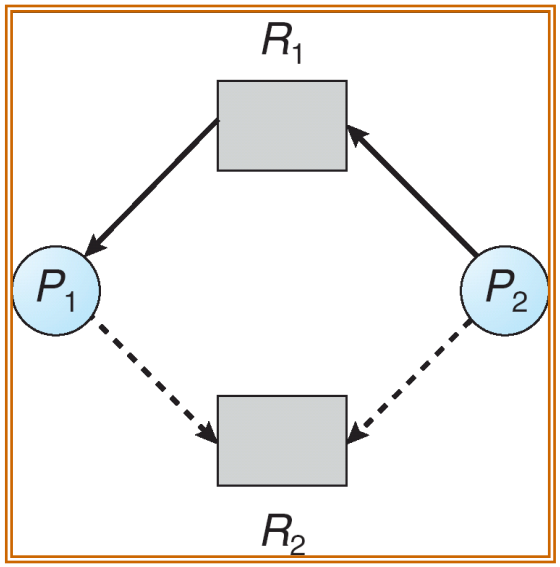
Deadlock Avoidance (1)

- 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
  - If there exists a sequence <P1, P2, …, Pn> of ALL the processes in the systems such that 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
    - An unsafe state may lead to a deadlock
    - As long as the state is safe, the OS can avoid unsafe states (and deadlocks)
  - - resource utilisation may be low

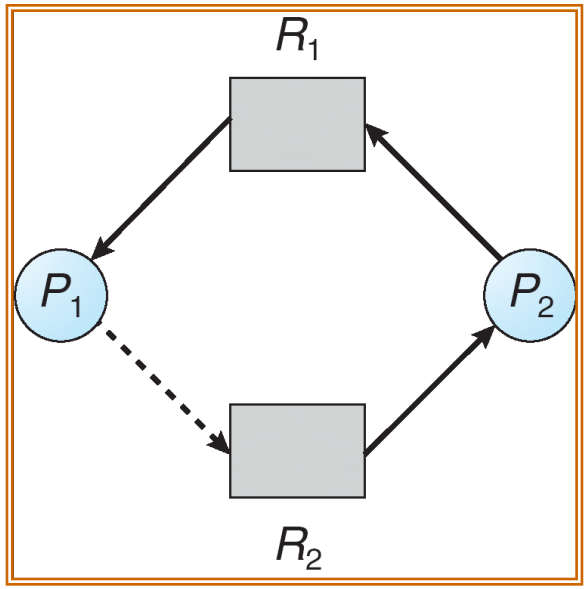
Deadlock Avoidance (2)

- Resource allocation graph
  - System with only one instance of each resource
  - Claim edges: dashed line, the process may request the resource in the future
    - Claim edge converts to request edge when a process requests a resource
    - Request edge converted to an assignment edge when the resource is allocated to the process
    - When a resource is released by a process, assignment edge reconverts to a claim edge
    - Resources must be claimed a priori in the system
  - Requests can be granted only if converting the request edge to an assignment edge does not result in the formation of a cycle in the resource allocation graph
    - Cycle detection algorithm of order n square in the number of processes

Deadlock Avoidance (3)



P2 request R2



Deadlock Avoidance (4)

- Banker's algorithm
  - Multiple instances of each resource type
  - Less efficient than the resource allocation graph 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*]

Deadlock Avoidance (5)

- Safety algorithm $m \times n^2$

1. Let ***Work*** and ***Finish*** be vectors of length *m* and *n*, respectively. Initialize:
   Work = *Available*
   Finish [*i*] = *false* for *i* = 0, 1, …, *n*- 1.
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

Deadlock Avoidance (6)

$Request_i$ = 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. Pretend to allocate requested resources to P_i by modifying the state as follows:

$$Available = Available - Request;$$
$$Allocation_i = Allocation_i + Request_i;$$
$$Need_i = Need_i - Request_i;$$

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

Deadlock Avoidance (7)

- Example
  - 5 processes P0 through P4;

    3 resource types: A (10 instances), B (5 instances), and C (7 instances)

Snapshot at time T0:

	Allocation	Max	Available
	A B C	A B C	A B C
P0	0 1 0	7 5 3	3 3 2
P1	2 0 0	3 2 2	
P2	3 0 2	9 0 2	
P3	2 1 1	2 2 2	
P4	0 0 2	4 3 3	

Deadlock Avoidance (8)

The content of the matrix Need is defined to be Max – Allocation

	Need
	A B C
P0	7 4 3
P1	1 2 2
P2	6 0 0
P3	0 1 1
P4	4 3 1

The system is in a safe state since the sequence < P1, P3, P4, P2, P0> satisfies safety criteria

Deadlock Avoidance (9)

P1 Request (1,0,2)

Check that Request ≤ Available (that is, (1,0,2) ≤ (3,3,2) ⇒ true.

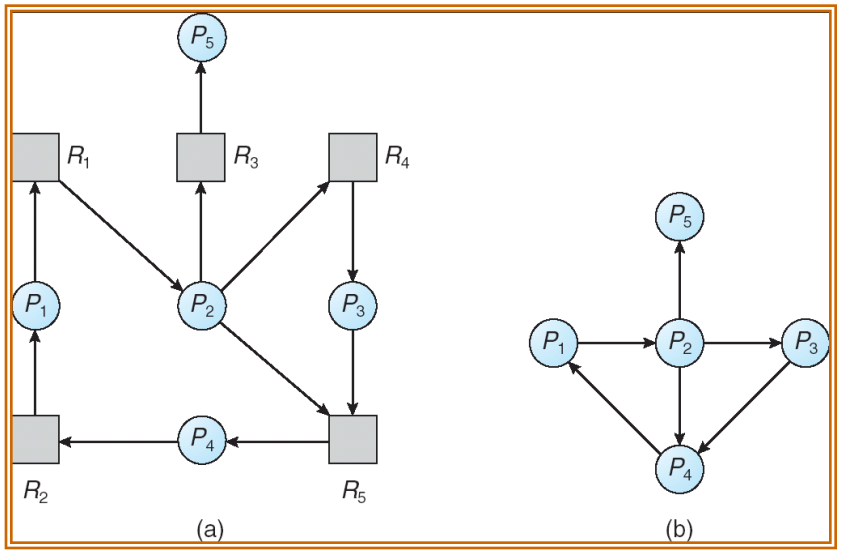
	Allocation	Need	Available
	A B C	A B C	A B C
P0	0 1 0	7 4 3	2 3 0
P1	3 0 2	0 2 0	
P2	3 0 1	6 0 0	
P3	2 1 1	0 1 1	
P4	0 0 2	4 3 1	

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?

Deadlock Detection (1)

- Single instance of each resource type
  - 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



Deadlock Detection (2)

- Several instance of each 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

  - Detection algorithm $m \times n^2$

1. Let *Work* and *Finish* be vectors of length *m* and *n*, respectively Initialize:
   (a) *Work* = *Available*
   (b) For *i* = 1,2, …, *n*, if $Allocation_i \neq 0$, then *Finish*[i] = false;otherwise, *Finish*[i] = *true*.
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.
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 deadlock state. Moreover, if *Finish*[*i*] == *false*, then P_i is deadlocked.

Deadlock Detection (3)

- Five processes P0 through P4; 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
P0	0 1 0	0 0 0	0 0 0
P1	2 0 0	2 0 2	
P2	3 0 3	0 0 0	
P3	2 1 1	1 0 0	
P4	0 0 2	0 0 2	

  Sequence <P0, P2, P3, P1, P4> will result in Finish[i] = true for all i.

Deadlock Detection (4)

- P2 requests an additional instance of type C.

	Request
	A B C
P0	0 0 0
P1	2 0 1
P2	0 0 1
P3	1 0 0
P4	0 0 2

State of system?

Can reclaim resources held by process P0, but insufficient resources to fulfill other processes; requests

Deadlock exists, consisting of processes P1, P2, P3, and P4.

Deadlock Detection (5)

- When, and how often, to invoke depends on:
  - How often a deadlock is likely to occur?
  - How many processes will need to be rolled back?
    - one for each disjoint cycle
- 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

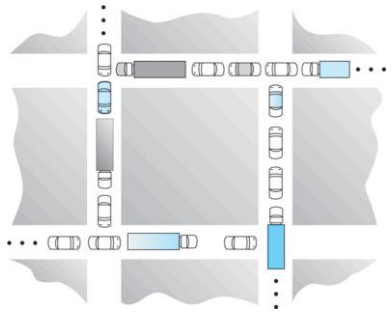
- Process termination
  - Abort all deadlocked processes
  - Abort one process at a time until the deadlock cycle is eliminated
  - In which order should we choose to abort?
    - Priority of the process
    - How long process has computed, and how much longer to completion
    - Resources the process has used
    - Resources process needs to complete
    - How many processes will need to be terminated
    - Is process interactive or batch
- 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 number of rollback in cost factor

For contemplation (1)

- Consider the deadlock situation that could occur in the dining philosophers problem when the philosophers obtain the chopsticks one at a time. Discuss how the four necessary conditions for deadlock indeed hold in this setting. Discuss how deadlocks could be avoided by eliminating any one of the four conditions.
- Compare the circular-wait scheme with the deadlock-avoidance schemes (like the banker's algorithm) with respect to the following issues:
  - Runtime overheads
  - System throughput
- Java's locking mechanism (the synchronized statement) is considered reentrant. That is, if a thread acquires the lock for an object (by invoking a synchronized method or block), it can enter other synchronized methods or blocks for the same object. Explain how deadlock would be possible if Java's locking mechanism were not reentrant.

For contemplation (2)

- Consider the traffic deadlock depicted in the figure.
  - Show that the four necessary conditions for deadlock indeed hold in this example.
  - State a simple rule for avoiding deadlocks in this system.



- Consider the following snapshot of a system:

	Allocation	*Max*	*Available*
	A B C D	*A B C D*	*A B C D*
P0	0 0 1 2	0 0 1 2	1 5 2 0
P1	1 0 0 0	1 7 5 0	
P2	1 3 5 4	2 3 5 6	
P3	0 6 3 2	0 6 5 2	
P4	0 0 1 4	0 6 5 6	

Answer the following questions using the banker's algorithm:

- What is the content of the matrix *Need*?
- Is the system in a safe state?
- If a request from process *P1* arrives for (0,4,2,0), can the request be granted immediately?

For contemplation (3)

- Consider a system consisting of four resources of the same type that are shared by three processes, each of which needs at most two resources. Show that the system is deadlock-free.
- Consider a system consisting of m resources of the same type, being shared by n processes. Resources can be requested and released by processes only one at a time. Show that the system is deadlock free if the following two conditions hold:
  - The maximum need of each process is between 1 and m resources
  - The sum of all maximum needs is less than m + n