Part II
Process Management
Chapter 7: Deadlocks

System Model

- **System resources are utilized in the following way:**
  - **Request: If a process makes a request to use a system resource which cannot be granted immediately, then the requesting process blocks until it can acquire the resource.**
  - **Use:The process can operate on the resource.**
  - **Release: The process releases the resource.**
- ***Deadlock*: A set of processes is in a deadlock state when every process in the set is waiting for an event that can only be caused by another process in the set.**

Deadlock: Necessary Conditions

- ***For a deadlock to occur, each of the following four conditions must hold.***
  - **Mutual Exclusion: At least one resource must be held in a non-sharable way.**
  - **Hold and Wait: A process must be holding a resource and waiting for another.**
  - **No Preemption: Resource cannot be preempted.**
  - **Circular Wait: A waits for B, B waits for C, C waits for A.**

Handling Deadlocks

- **Deadlock Prevention and Avoidance: Make sure deadlock will never happen.**
  - **Prevention: Ensure one of the four conditions fails.**
  - **Avoidance: The OS needs more information so that it can determine if the current request can be satisfied or delayed.**
- **Deadlock : Allow a system to enter a deadlock situation, detect it, and recover.**
- **Ignore Deadlock: Pretend deadlocks never occur in the system.**

Deadlock Prevention: 1/4
Mutual Exclusion

- **By ensuring that at least one of the four conditions cannot hold, we can prevent the occurrence of a deadlock.**
- **Mutual Exclusion: Some sharable resources must be accessed exclusively (*e.g.*, printer), which means we cannot deny the mutual exclusion condition.**

Deadlock Prevention: 2/4
Hold and Wait

- **No process can hold some resources and then request for other resources.**
- **Two strategies are possible:**
  - **A process must acquire *all* resources before it runs.**
  - **When a process requests for resources, it must hold none (*i.e.*, returning resources before requesting for more).**
- **Resource utilization may be low, since many resources will be held and unused for a long time.**
- **Starvation is possible. A process that needs some popular resources my have to wait indefinitely.**

Deadlock Prevention: 3/4
No Preemption

- **Resources that are being held by the requesting process are preempted. There are two strategies:**
  - **If a process is holding some resources and requesting for some others that are being held by other processes, the resources of the requesting process are preempted. The preempted resources become available.**
  - **If the requested resources are not available:**
    - **If they are being held by processes that are waiting for additional resources, these resources are preempted and given to the requesting process.**
    - **Otherwise, the requesting process waits until the requested resources become available. While it is waiting, its resources may be preempted.**
    - **This works only if the state of the process and resources can be saved and restored easily (*e.g.*, CPU & memory).**

Deadlock Prevention: 4/4
Circular Waiting

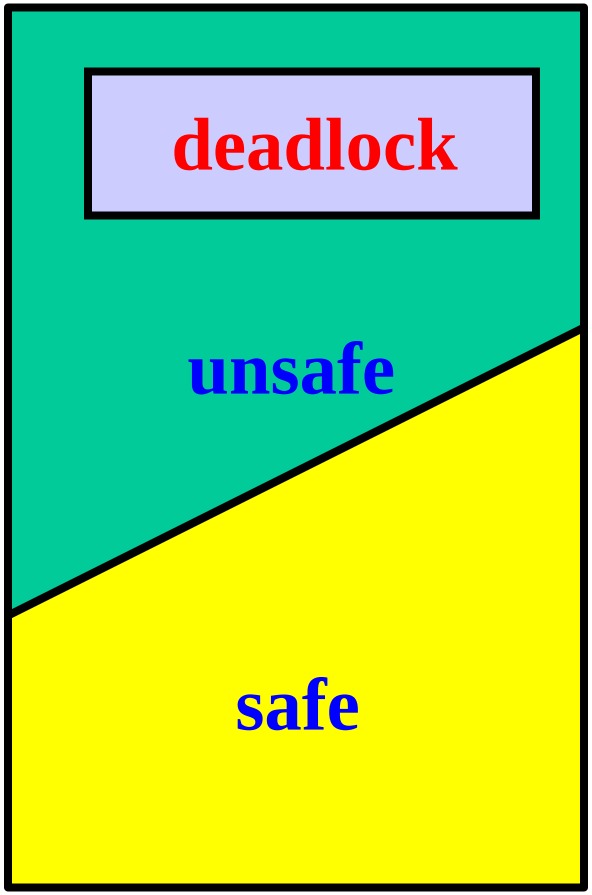
- **To break the circular waiting condition, we can order all resource types (*e.g.*, tapes, printers).**
- **A process can only request resources higher than the resource types it holds.**
- **Suppose the ordering of tapes, disks, and printers are 1, 4, and 8. If a process holds a disk (4), it can only ask a printer (8) and cannot request a tape (1).**
- **A process must release some lower order resources to request a lower order resource. To get tapes (1), a process must release its disk (4).**
- **In this way, no deadlock is possible. Why?**

Deadlock Avoidance: 1/5

- **Each process provides the maximum number of resources of each type it needs.**
- **With these information, there are algorithms that can ensure the system will never enter a deadlock state. This is *deadlock avoidance*.**
- **A sequence of processes <P_1, P_2, …, P_n> is a *safe sequence* if for each process P_i in the sequence, its resource requests can be satisfied by the remaining resources and the sum of all resources that are being held by P_1, P_2, …, P_{i-1}. This means we can suspend P_i and run P_1, P_2, …, P_{i-1} until they complete. Then, P_i will have all resources to run.**

Deadlock Avoidance: 2/5

- **A state is *safe* if the system can allocate resources to each process (up to its maximum, of course) in some order and still avoid a deadlock.**
- **In other word, a state is *safe* if there is a safe sequence. Otherwise, if no safe sequence exists, the system state is *unsafe*.**
- **An unsafe state is not necessarily a deadlock state. On the other hand, a deadlock state is an unsafe state.**



Deadlock Avoidance: 3/5

- A system has 12 tapes and three processes ***A***, ***B***, ***C***. At time t_0, we have:

3 free tapes

	Max needs	Current holding	Will need
A	10	5	5
B	4	2	2
C	9	2	7

- Then, <***B***, ***A***, ***C***> is a safe sequence (safe state).
- The system has 12-(5+2+2)=3 free tapes.
- Since ***B*** needs 2 tapes, it can take 2, run, and return 4. After ***B*** completes, the system has (3-2)+4=5 tapes. ***A*** now can take all 5 tapes and run. Finally, ***A*** returns 10 tapes for ***C*** to take 7 of them.

Deadlock Avoidance: 4/5

- A system has 12 tapes and three processes ***A***, ***B***, ***C***. At time t_1, ***C*** has one more tape:

	Max needs	Current holding	Will need
A	10	5	5
B	4	2	2
C	9	3	6

- The system has 12-(5+2+3)=2 free tapes.
- At this point, only ***B*** can take these 2 and run. It returns 4, making 4 free tapes available.
- But, none of ***A*** and ***C*** can run, and a deadlock occurs.
- The problem is due to granting ***C*** one more tape.

Deadlock Avoidance: 5/5

- **A *deadlock avoidance algorithm* ensures that the system is always in a safe state. Therefore, no deadlock can occur.**
- **Resource requests are granted only if in doing so the system is still in a safe state.**
- **Consequently, resource utilization may be *lower* than those systems without using a deadlock avoidance algorithm.**

Banker's Algorithm: 1/2

- **The system has *m* resource types and *n* processes.**
- **Each process must declare its maximum needs.**
- **The following arrays are used:**
  - ***Available*[1..*m*]: one entry for each resource. *Available*[*i*]=*k* means resource type *i* has *k* units available.**
  - ***Max*[1..*n*,1..*m*]: maximum demand of each process. *Max*[*i,j*]=*k* means process *i* needs *k* units of resource *j*.**
  - ***Allocation*[1..*n*,1..*m*]: resources allocated to each process. *Allocation*[*i,j*]=*k* means process *i* is currently allocated *k* units of resource *j*.**
  - ***Need*[1..*n*,1..*m*]: the remaining resource need of each process. *Need*[*i,j*]=*k* means process *i* needs *k* more units of resource *j*.**

Banker's Algorithm: 2/2

- **We will use $A[i,*]$ to indicate the i-th row of matrix A.**
- **Given two arrays $A[1..m]$ and $B[1..m]$, $A \le B$ if $A[i] \le B[i]$ for all i. Given two matrices $A[1..n,1..m]$ and $B[1..n,1..m]$, $A[i,*] \le B[i,*]$ if $A[i,j] \le B[i,j]$ for all j.**
- **When a resource request is made by process i, this algorithm calls the Resource-Request algorithm to determine if the request can be granted. The Resource-Request algorithm calls the Safety Algorithm to determine if a state is safe.**

Safety Algorithm

1. **Let *Work*[1..*m*] and *Finish*[1..*n*] be two working arrays.**
2. ***Work := Available* and *Finish*[*i*]=*FALSE* for all *i***
3. **Find an *i* such that both**
   - ***Finish*[*i*] = *FALSE*   // process *i* is not yet done**
   - ***Need*[*i*,*] ≤ *Work*   // its need can be satisfied**

   If no such *i* exists, go to Step 5
4. ***Work* = *Work* + *Allocation*[*i*,*] // run it and reclaim**

   ***Finish*[*i*] = *TRUE*   // process *i* completes**

   go to Step 3
5. **If *Finish*[*i*] = *TRUE* for all *i*, the system is in a safe state.**

Resource-Request Algorithm

1. Let *Request*[1..*n*,*1*..*m*] be the request matrix. *Request*[*i*,*j*]=*k* means process *i* requests *k* units of resource *j*.
2. If *Request*[*i*,*]≤*Need*[*i*,*], go to Step 3. Otherwise, it is an error.
3. If *Request*[*i*,*]≤*Available*, go to Step 4. Otherwise, process *i* waits.
4. Do the following:

   Available = *Available* – *Request*[*i*,*]

   Allocation[*i*,*] = *Allocation*[*i*,*]+*Request*[*i*,*]

   Need[*i*,*] = *Need*[*i*,*] – *Request*[*i*,*]

   If the result is a safe state (Safety Algorithm), the request is granted. Otherwise, process *i* waits and the resource-allocation tables are restored back to the original.

Example: 1/4

- Consider a system of 5 processes *A*, *B*, *C*, *D* and *E*, and 3 resource types (*X*=10, *Y*=5, *Z*=7). At time t_0, we have

	Allocation			*Max*			*Need=Max-Alloc*			*Available*		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
A	0	1	0	7	5	3	7	4	3	3	3	2
B	2	0	0	3	2	2	1	2	2			
C	3	0	2	9	0	2	6	0	0			
D	2	1	1	2	2	2	0	1	1			
E	0	0	2	4	3	3	4	3	1			

- A safe sequence is <*B*,*D*,*E*,*C*,*A*>. Since *B*'s [1,2,2]≤ *Avail*'s [3,3,2], *B* runs. Then, *Avail*=[2,0,0]+[3,3,2]=[5,3,2]. *D* runs next. After this, *Avail*=[5,3,2]+[2,1,1]=[7,4,3]. *E* runs next.
- *Avail*=[7,4,3]+[0,0,2]=[7,4,5]. Since *C*'s [6,0,0]≤*Avail*=[7,4,5], *C* runs. After this, *Avail*=[7,4,5]+[3,0,2]=[10,4,7] and *A* runs.
- There are other safe sequences: <*D*,*E*,*B*,*A*,*C*>, <*D*,*B*,*A*,*E*,*C*>, …

Example: 2/4

- Now suppose process ***B*** asks for 1 ***X*** and 2 ***Z***s. More precisely, ***Request***$_B$ = [1,0,2]. ***Is the system still in a safe state if this request is granted?***
- Since ***Request***$_B$ = [1,0,2] ≤ ***Available*** = [3,3,2], this request may be granted as long as the system is safe.
- If this request is actually granted, we have the following:

	Allocation			*Max*			*Need=Max-Alloc*			*Available*		
	X	***Y***	***Z***	***X***	***Y***	***Z***	***X***	***Y***	***Z***	***X***	***Y***	***Z***
A	0	1	0	7	5	3	7	4	3	2	3	0
B	3	0	2	3	2	2	0	2	0			
C	3	0	2	9	0	2	6	0	0			
D	2	1	1	2	2	2	0	1	1			
E	0	0	2	4	3	3	4	3	1			

[3,0,2]=[2,0,0]+[1,0,2]   **[0,2,0]=[1,2,2]-[1,0,2]**   **[2,3,0]=[3,3,2]-[1,0,2]**

Example: 3/4

	Allocation			*Max*			*Need=Max-Alloc*			*Available*		
	X	***Y***	***Z***	***X***	***Y***	***Z***	***X***	***Y***	***Z***	***X***	***Y***	***Z***
A	0	1	0	7	5	3	7	4	3	2	3	0
B	3	0	2	3	2	2	0	2	0			
C	3	0	2	9	0	2	6	0	0			
D	2	1	1	2	2	2	0	1	1			
E	0	0	2	4	3	3	4	3	1			

- ***Is the system in a safe state after this allocation?***
- **Yes, because the safety algorithm will provide a safe sequence <*B*,*D*,*E*,*A*,*C*>. Verify it by yourself.**
- **Therefore, *B*'s request of [1,0,2] can safely be made.**

Example: 4/4

	Allocation			*Max*			*Need=Max-Alloc*			*Available*		
	X	***Y***	***Z***	***X***	***Y***	***Z***	***X***	***Y***	***Z***	***X***	***Y***	***Z***
A	0	1	0	7	5	3	7	4	3	2	3	0
B	3	0	2	3	2	2	0	2	0			
C	3	0	2	9	0	2	6	0	0			
D	2	1	1	2	2	2	0	1	1			
E	0	0	2	4	3	3	4	3	1			

- **After this allocation, *E*'s request $Request_E$=[3,3,0] cannot be granted since $Request_E$=[3,3,0] ≤[2,3,0] is false.**
- ***A*'s request $Request_A$=[0,2,0] cannot be granted because the system will be unsafe.**
- **If $Request_A$=[0,2,0] is granted, *Available*=[2,1,0].**
- **None of the five processes can finish and the system is unsafe.**

Deadlock Detection

- If a system does not use a deadlock prevention or a deadlock avoidance algorithm, then a deadlock situation may occur. Thus, we need
  - An algorithm that can examine the system state to determine if a deadlock has occurred. This is a *deadlock detection* algorithm.
  - An algorithm that can help recover from a deadlock. This is a *recovery* algorithm.
- A deadlock detection algorithm does not have to know the maximum need *Max* and the current need *Need*. It uses only *Available*, *Allocation* and *Request*.

Deadlock Detection Algorithm

1. Let *Work*[1..*m*] and *Finish*[1..*n*] be two working arrays.
2. *Work := Available* and *Finish*[*i*]=*FALSE* for all *i*
3. Find an *i* such that both
   - *Finish*[*i*] = *FALSE* // process *i* is not yet done
   - *Request*[*i*,*] ≤ *Work* // its request can be satisfied

   If no such *i* exists, go to Step 5
4. *Work* = *Work* + *Allocation*[*i*,*] // run it and reclaim

   Finish[*i*] = *TRUE* // process *i* completes

   go to Step 3
5. If *Finish*[*i*] = *TRUE* for all *i*, the system is in a safe state. If *Finish*[*i*] = *FALSE*, then process P_i is deadlocked.

Use Request here rather than Need in the safety algorithm

Example: 1/2

	Allocation			*Request*			*Available*		
	X	***Y***	***Z***	***X***	***Y***	***Z***	***X***	***Y***	***Z***
A	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
B	**2**	**0**	**0**	**2**	**0**	**2**			
C	**3**	**0**	**3**	**0**	**0**	**0**			
D	**2**	**1**	**1**	**1**	**0**	**0**			
E	**0**	**0**	**2**	**0**	**0**	**2**			

- **Suppose maximum available resource is [7,2,6] and the current state of resource allocation is shown above.**
- ***Is the system deadlocked?*** **No. We can run *A* first, making *Available*=[0,1,0].**
- **Then, we run *C*, making *Available*=[3,1,3]. This is followed by *D*, making *Available*=[5,2,4], and followed by *B* and *E*.**

Example: 2/2

	Allocation			*Request*			*Available*		
	X	***Y***	***Z***	***X***	***Y***	***Z***	***X***	***Y***	***Z***
A	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
B	**2**	**0**	**0**	**2**	**0**	**2**			
C	**3**	**0**	**3**	**0**	**0**	**1**			
D	**2**	**1**	**1**	**1**	**0**	**0**			
E	**0**	**0**	**2**	**0**	**0**	**2**			

- **Suppose *C* requests for one more resource *Z*.**
- **Now, *A* can run, making *Available*=[0,1,0].**
- **However, none of *B*, *C*, *D* and *E* can run. Therefore, *B*, *C*, *D* and *E* are deadlocked!**

The Use of a Detection Algorithm

- **Frequency**
  - **If deadlocks occur frequently, then the detection algorithm should be invoked frequently.**
  - **Once per hour or whenever CPU utilization becomes low (*i.e.*, below 40%). Low CPU utilization means more processes are waiting.**

How to Recover: 1/3

- **When a detection algorithm determines a deadlock has occurred, the algorithm may inform the system administrator to deal with it. Of, allow the system to *recover* from a deadlock.**
- **There are two options.**
  - **Process Termination**
  - **Resource Preemption**
- **These two options are not mutually exclusive.**

Recovery: Process Termination: 2/3

- **Abort all deadlocked processes**
- **Abort one process at a time until the deadlock cycle is eliminated**
- **Problems:**
  - **Aborting a process may not be easy. What if a process is updating or printing a large file? The system must find some way to maintain the state of the file and printer before they can be reused.**
  - **The termination may be determined by the priority/importance of a process.**

Recovery: Resource Preemption: 3/3

- **Selecting a victim: which resources and which processes are to be preempted?**
- **Rollback: If we preempt a resource from a process, what should be done with that process?**
  - **Total Rollback: abort the process and restart it**
  - **Partial Rollback: rollback the process only as far as necessary to break the deadlock.**
- **Starvation: We cannot always pick the same process as a victim. Some limit must be set.**