CSC 539: Operating Systems Structure and Design

Spring 2006

Process deadlock

- deadlock prevention
- deadlock avoidance
- deadlock detection
- recovery from deadlock

1

Process deadlock

in general, can partition system resources into equivalence types or classes

e.g, CPUs, RAM, files, printers, tape drives, …

when a process requests a resource from a particular resource class, any available resource in the class is allocated to the process

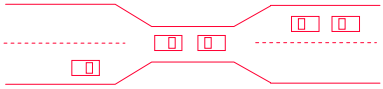
- generally, resources go through the sequence:
  1. request
  2. use
  3. release

deadlock occurs when a set of processes is waiting for resources that are held by other processes in the set

2

Deadlock examples

real-world example: single-lane bridge



- 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 & rollback)
- several cars may have to be backed up if a deadlock occurs
- starvation is possible

system example: 2 tape drives

- P_1 and P_2 each hold one tape drive and each needs another one

system example: semaphores A and B, initialized to 1

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

3

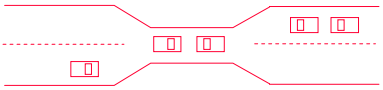
Deadlock characterization

deadlock can arise if 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 held by P_1
  P_1 is waiting for a resource held by P_2
  …
  P_n is waiting for a resource held by P_0

consider single-lane bridge example:

- 4 necessary conditions?

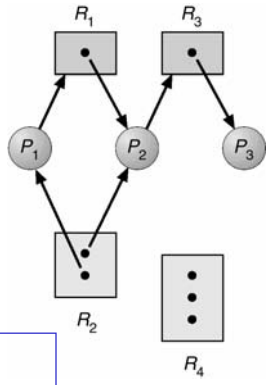


4

System resource allocation graph

we can use a directed graph to represent the state of the system as it allocates resources and deals with requests for resources

- nodes of graph represent processes or resources
  - – process nodes will have circles around them
  - – resource nodes will have rectangles around them
- edges of graph represent allocations or requests
  - – process to resource edge is a request
  - – resource to process edge is an allocation



in this example:

P_1 has R_2, has requested R_1

P_2 has R_1 & R_2, has requested R_3

P_3 has R_3

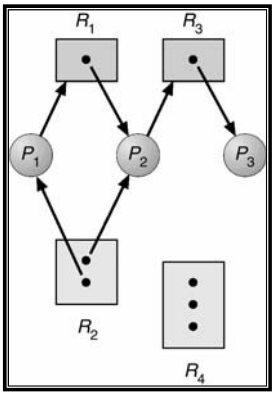
5

cycle = deadlock?

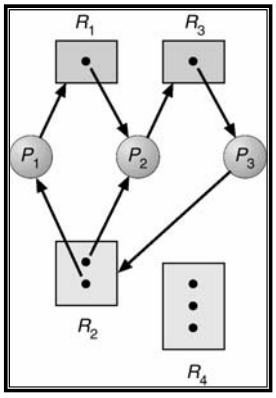
If graph contains no cycles → no deadlock

If graph contains a cycle →

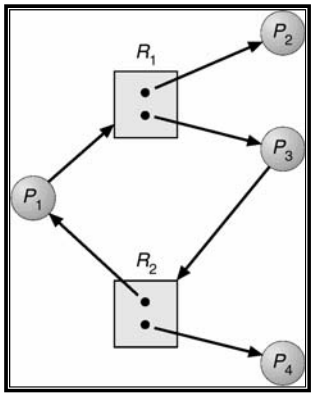
- if only one instance per resource type, then deadlock.
- if several instances per resource type, deadlock is *possible*



no deadlock



deadlock



no deadlock

6

Methods for dealing with deadlock

Prevention or *Avoidance*: ensure system never enters a deadlocked state

- deadlock prevention scheme
  ensure that at least one of the necessary conditions cannot hold
- deadlock avoidance scheme
  require the OS to know the resource usage requirements of all processes
  for each request, the OS decides if it could lead to a deadlock before granting

Detection & Recovery:

- allow deadlocks to occur
- system implements an algorithm for deadlock detection, if so then recover

Ignorance:

- assume/pretend deadlocks never occur in the system
- used by most operating systems, including UNIX & Windows

7

Deadlock prevention

to prevent deadlock, must eliminate one of the four necessary conditions

- **Mutual Exclusion:** can't eliminate since some resources are not shareable
- **Hold and Wait:** options exist, but wasteful and may lead to starvation
  1. grant all resources when process starts, or
  2. allocate and deallocate resources in complete groups
- **No Preemption:** options exist, but taking away resources can be tricky
- **Circular Wait:** most likely candidate
  impose an ordering on resources [R_0, R_1, …, R_n], and require that each process requests resources in increasing order

  e.g., P_0 wants R_0, R_1, and R_2
  P_1 wants R_1, R_2, and R_3

  informal proof that resource ordering ensures no circular wait?

8

Deadlock avoidance

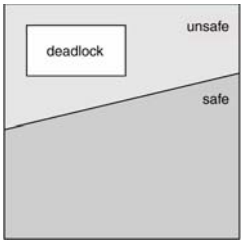
if have some knowledge of future resource demands (e.g., max number of resources needed per process), can avoid deadlock situations

- **safe state:** a state is safe if the system can allocate resources to each process (up to its maximum need) in some sequence and still avoid a deadlock
- **safe sequence:** a sequence of processes $\{P_0, P_1, \ldots, P_n\}$ is safe for the current allocation state if, for each P_i, the resources that P_i can still request are either free or else held by $\{P_0, P_1, \ldots, P_{i-1}\}$

  →a safe sequence implies that each process need only wait for lower numbered processes to finish before it can finish

Note: unsafe ≠ deadlock

- a safe state is guaranteed no deadlock
- an unsafe state *may* lead to deadlock



9

Example: safe or unsafe?

suppose there are 12 instances of a given resource (e.g., tape drives)

in the current state, resources are allocated to 3 processes

Process P:	max need = 10,	currently allocated = 5
Process Q:	max need = 4,	currently allocated = 2
Process R:	max need = 9,	currently allocated = 2

is this a safe state?

if so, identify a safe sequence.

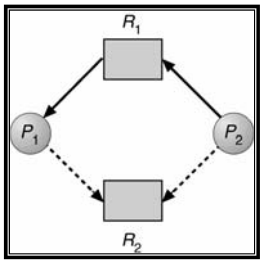
10

Resource allocation graph algorithm

if there is only one instance of each resource class, then unsafe states can be avoided by considering a generalized resource allocation graph

- allocation edge $R_i \rightarrow P_j$ if R_i is currently held by P_j (as before)
- request edge $P_i \rightarrow R_j$ if P_i has requested R_j (as before)
- claim edge $P_i \dashrightarrow R_j$ if P_i may eventually request R_j

unsafe avoidance: do not allocate resource if it creates a cycle



allocate R_2 to P_1: OK

allocate R_2 to P_2: NOT ALLOWED

- leads to cycle in graph (unsafe state)

Banker's algorithm

the banker's algorithm can avoid deadlocks even with multiple instances

- looks at each request for resources and tests if the request moves the system into an unsafe state
- if the system is still safe, then the request is granted
- if the system would become unsafe, then the request is denied

utilizes the following data structures:

- Available[m] number of resources of R_m that are unallocated
- Max[n][m] max demand of P_n for R_m
- Allocation[n][m] number of R_m that are allocated to P_n
- Need[n][m] number of R_m that may be needed by P_n

  Note: Need[n, m] = Max[n, m] – Allocation[n, m]

as in C++, will treat a matrix as a vector of vectors (Max[i] is max resources demand for P_i)

for vectors X & Y, $X \leq Y$ if and only if $X[i] \leq Y[i]$ for all i

Example: banker's algorithm

suppose have: 3 types of resources (6 of type A, 2 of type B, 2 of type C)
3 processes (P, Q, and R)

	Max	Allocation	Available	Need
	A B C	A B C	A B C	A B C
P	2 1 0	0 1 0	1 1 0	2 0 0
Q	3 1 1	2 0 0		1 1 1
R	5 1 2	3 0 2		2 1 0

is the system in a safe state?

13

Banker's: safety algorithm

to find out whether a system is in a safe state:

1. define vector: Finish[k] = false (for all k ≤ n)
2. find an i such that (Finish[i] == false && Need[i] ≤ Available)
   if no such i, then go to STEP 4
3. update: Available = Available + 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
   otherwise, the system is in an unsafe state

	Max	**Allocation**	**Available**	**Need**
	A B C	A B C	A B C	A B C
P	2 1 0	0 1 0	2 1 1	2 0 0
Q	3 1 1	2 0 0		1 1 1
R	5 1 2	2 0 1		3 1 1

is this state safe?

14

Banker's: resource request algorithm

let Request[i] be the request vector from P_i

1. if Request[i] > Need[i], then ERROR (asked for too many resources) & EXIT
2. if Request[i] > Available[i], then deny request and P_i must wait
   (the requested resources are not currently available)
3. otherwise, pretend to allocate the resources
   Available = Available – Request[i]
   Allocation[i] = Allocation[i] + Request[i]
   Need[i] = Need[i] – Request[i]
4. call the Safety algorithm, if safe then allocation is OK
   otherwise, the request is denied and the pretended allocation is undone

	Max	Allocation	Available	Need
	A B C	A B C	A B C	A B C
P	2 1 0	0 1 0	2 1 1	2 0 0
Q	3 1 1	2 0 0		1 1 1
R	5 1 2	2 0 1		3 1 1

what if R asks for [1 0 1] ?

15

Example: banker's algorithm

suppose 5 processes: P_0 through P_4
3 resource types: *A* (10), *B* (5), and *C* (7)

snapshot at time T_0:

	Max	Allocation	Available	Need
	A B C	A B C	A B C	A B C
P_0	7 5 3	0 1 0	3 3 2	7 4 3
P_1	3 2 2	2 0 0		1 2 2
P_2	9 0 2	3 0 2		6 0 0
P_3	2 2 2	2 1 1		0 1 1
P_4	4 3 3	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 the safety criteria

16

Example: banker's algorithm (cont.)

	Max	Allocation	Available	Need
	A B C	A B C	A B C	A B C
P_0	7 5 3	0 1 0	3 3 2	7 4 3
P_1	3 2 2	2 0 0		1 2 2
P_2	9 0 2	3 0 2		6 0 0
P_3	2 2 2	2 1 1		0 1 1
P_4	4 3 3	0 0 2		4 3 1

P_1 requests [1 0 2]

1. Request[i] ≤ Need[i]: [1 0 2] ≤ [1 2 2], so no ERROR
2. Request[i] ≤ Available[i]: [1 0 2] ≤ [3 3 2], so resources are available
3. pretend to allocate the resources

	Max	Allocation	Available	Need
	A B C	A B C	A B C	A B C
P_0	7 5 3	0 1 0	2 1 0	7 4 3
P_1	3 2 2	3 2 2		0 0 0
P_2	9 0 2	3 0 2		6 0 0
P_3	2 2 2	2 1 1		0 1 1
P_4	4 3 3	0 0 2		4 3 1

the sequence P1, P3, P4, P0, P2 satisfies the safety requirement

17

Example: banker's algorithm (cont.)

	Max	Allocation	Available	Need
	A B C	A B C	A B C	A B C
P_0	7 5 3	0 1 0	3 3 2	7 4 3
P_1	3 2 2	2 0 0		1 2 2
P_2	9 0 2	3 0 2		6 0 0
P_3	2 2 2	2 1 1		0 1 1
P_4	4 3 3	0 0 2		4 3 1

P_4 requests [3 3 0] ?

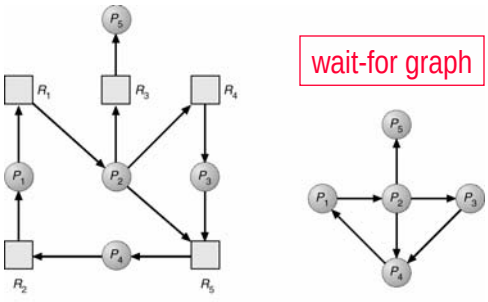
P_0 requests [0 2 0] ?

18

Deadlock detection

if there is only a single instance of each resource, can construct a wait-for graph out of the resource allocation graph

- remove all resource nodes and collapse the edges



a deadlock has occurred if and only if there is a cycle in the wait-for graph

- to detect deadlock, need to periodically check for cycles
  can be accomplished in $O(n^2)$ operations, where n is number of processes

19

Deadlock detection algorithm

if multiple instances of resources, need test similar to safety algorithm

1. define vector: Finish[k] = (Allocation[k] == 0)
2. find an i such that (Finish[i] == false && Request[i] ≤ Available)
   if no such i, then go to STEP 4
3. update: Available = Available + Allocation[i], Finish[i] = true
   go to STEP 2
4. if (Finish[i] == false) for any i, then P_i is deadlocked
   otherwise, no deadlock

	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_4	2 1 1	1 0 0	
P_5	0 0 2	0 0 2	

not deadlocked

P0, P2, P3, P1, P4 results in Finish[i] == true for all i

20

Deadlock detection algorithm (cont.)

1. define vector: Finish[k] = (Allocation[k] == 0)
2. find an i such that (Finish[i] == false && Request[i] ≤ Available)
   if no such i, then go to STEP 4
3. update: Available = Available + Allocation[i], Finish[i] = true
   go to STEP 2
4. if (Finish[i] == false) for any i, then P_i is deadlocked
   otherwise, no deadlock

	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_4	2 1 1	1 0 0	
P_5	0 0 2	0 0 2	

deadlock!

can reclaim P_0's resources, but not enough to meet requests of other processes

21

When to detect deadlock?

checking for deadlock is time consuming

- given n processes, m resource types, deadlock detection is $O(m*n^2)$

testing at every resource request would greatly slow down all requests

if deadlocks are rare or only affect a small number of processes, then may resort to testing periodically (e.g., once a day, when CPU use < 40%)

- note that if testing is sporadic, there may be many cycles in the resource graph
- will not be able to tell which of the deadlocked processes "caused" the deadlock

22

Deadlock recovery

to recover from deadlock, must eliminate one of the necessary conditions

- this involves preempting a resource or aborting a deadlocked process

preempting a resource

How do you select a victim?
When preempt a resource, how do you roll back the process?
How do you prevent starvation?

aborting a process

Do you abort all deadlocked processes or one at a time?

Note: it is possible to combine the three basic approaches

prevention + avoidance + detection

allowing the use of the optimal approach for each class of resources

23