Processes Synchronization - Part II

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Deadlocks

Motivation

- Multiprogramming environment: several processes compete for a finite number of resources.
- A process requests resources: if the resources are not available at that time, the process enters a waiting state.
- What if the requests resources are held by other waiting processes?
- This situation is called a deadlock.

Deadlock System Model

- System consists of m resources: $R_1, R_2, \cdots, R_m$
- Resource types: 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 (1/3)

- Deadlock can arise if four conditions hold simultaneously:
  - Mutual exclusion
  - Hold and wait
  - No preemption
  - Circular wait

Deadlock Characterization (2/3)

- 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.

Deadlock Characterization (3/3)

- No preemption
  - A resource can be released only voluntarily by the process holding it, after that process has completed its task.
- Circular wait
  - A set processes: $\{P_0, P_1, \cdots, P_n\}$
  - 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 is waiting for a resource that is held by P_0

Deadlock Example (1/2)

```
/* Create and initialize the mutex locks */
pthread_mutex_t first_mutex;
pthread_mutex_t second_mutex;

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

Deadlock Example (2/2)

```c
void *thread_one(void *args) {
  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);
}
```

```c
void *thread_two(void *args) {
  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);
}
```

Resource-Allocation Graph

Resource-Allocation Graph (1/2)

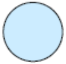
- A set of vertices V and a set of edges E.

- Vertices
  - All the processes in the system: $P = P_1, P_2, \cdots, P_n$
  - All resource types in the system: $R = R_1, R_2, \cdots, R_m$

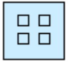
- Edges
  - Request edge: directed edge $P_i \rightarrow R_j$
  - Assignment edge: directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph (2/2)

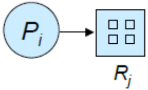
- Process (vertices)



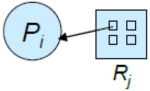
- Resource type with 4 instances (vertices)



- P_i requests instance of R_j (edge)

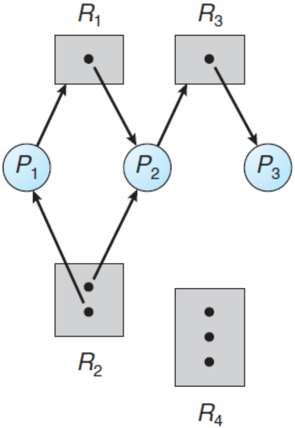


- P_i is holding an instance of R_j (edge)



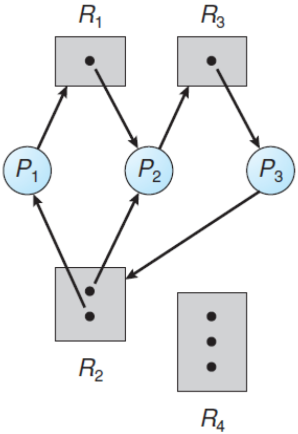
Resource-Allocation Graph Example (1/3)

- Example of a resource allocation graph.



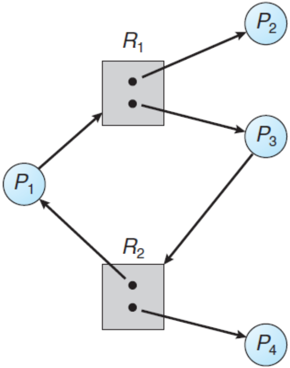
Resource-Allocation Graph Example (2/3)

- Resource allocation graph with a deadlock.



Resource-Allocation Graph Example (3/3)

- Resource allocation graph with a cycle but no deadlock.



Basic Facts

- 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, possibility of deadlock.

Methods for Handling Deadlocks

- Ensure that the system will never enter a deadlock state:
    - Deadlock prevention
    - Deadlock avoidance
- 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.

Deadlock Prevention

Deadlock Prevention (1/3)

- Deadlock can arise if four conditions hold simultaneously:
  - Mutual exclusion
  - Hold and wait
  - No preemption
  - Circular wait

- Restrain the ways requests can be made.

Deadlock Prevention (2/3)

- Mutual exclusion
  - Not required for sharable resources, e.g., read-only files.
  - Must hold for non-sharable resources.
- Hold and wait
  - Must guarantee that whenever a process requests a resource, it does not hold any other resources.
  - Solution 1: require a process to request and be allocated all its resources before it begins execution.
  - Solution 2: allows a process to request resources only when it has none.
  - Low resource utilization
  - Starvation possible

Deadlock Prevention (3/3)

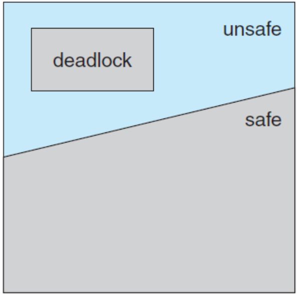
- No preemption
  - If a process that is holding some resources, requests another resource that cannot be immediately allocated to it, then all resources currently being held are released.
  - Preempted resources are added to the list of resources for which the process is waiting.
  - Process will be restarted only when it can regain its old resources, as well as the new ones that it is requesting.

- Circular wait
  - Impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration.

Deadlock Avoidance

Basic Facts

- If a system is in the safe state
  - No deadlock
- If a system is in the unsafe state
  - Possibility of deadlock



- Avoidance
  - Ensure that a system will never enter an unsafe state.

Safe State (1/2)

- When a process requests an available resource, system must decide if immediate allocation leaves the system in a safe state.

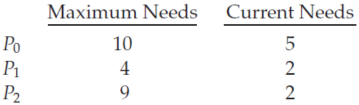
- Safe state: there exists a sequence $\langle P_1, P_2, \cdots, P_n \rangle$ of all the processes in the systems such that for each P_i, the resources that P_i can still request be satisfied by:
  currently available resources + resources held by all the P_j, with $j < i$.

Safe State (2/2)

- If P_i resource needs are not immediately available, then P_i can wait until all P_j have finished.
- When P_j is finished, P_i can obtain needed resources, execute, return allocated resources, and terminate.
- When P_i terminates, P_{i+1} can obtain its needed resources, and so on.

Safe Mode Example (1/2)

- 3 processes: P_0 through P_2
- 1 resource type:
  - A (12 instances)
- Snapshot at time T_0

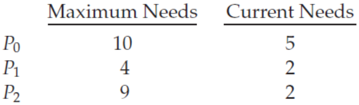


	Maximum Needs	Current Needs
P_0	10	5
P_1	4	2
P_2	9	2

- Safe mode sequence? $\langle P_1, P_0, P_2 \rangle$

Safe Mode Example (2/2)

- 3 processes: P_0 through P_2
- 1 resource type:
  - A (12 instances)
- Snapshot at time T_0



	Maximum Needs	Current Needs
P_0	10	5
P_1	4	2
P_2	9	2

- Suppose that, at time T_1, process P_2 requests and is allocated one more resource.
- Safe mode sequence? Not safe

Avoidance Algorithms

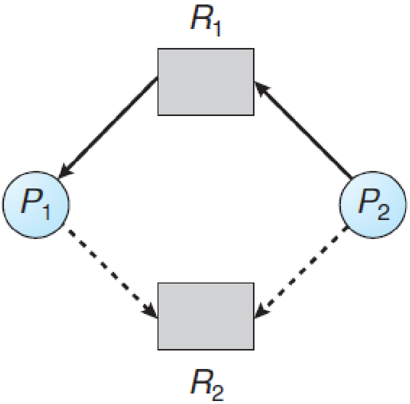
- Single instance of a resource type
    - Use a resource-allocation graph
- Multiple instances of a resource type
    - Use the banker's algorithm

Resource-Allocation Graph Algorithm

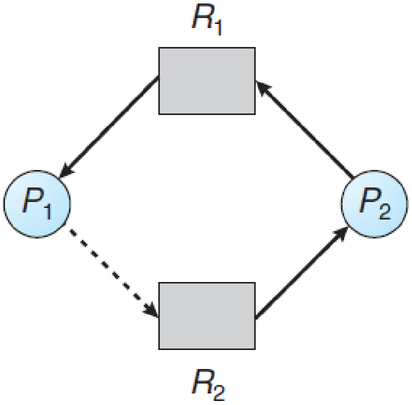
Resource-Allocation Graph Scheme

- Claim edge $P_i \rightarrow R_j$: indicates that process P_i may request resource R_j; represented by a dashed line
- 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.

Resource-Allocation Graph



Unsafe State In Resource-Allocation Graph



Resource-Allocation Graph Algorithm

- 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 in the resource allocation graph.

Banker’s Algorithm

Banker's Algorithm

- Multiple instances
- Each process must a priori claim of the maximum use.
- When a process requests a resource it may have to wait.
- 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, 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*: $n \times m$ matrix.
  - If $Max[i,j] = k$, then process P_i may request at most k instances of resource type R_j.
- *Allocation*: $n \times m$ matrix.
  - If $Allocation[i,j] = k$ then P_i is currently allocated k instances of R_j.
- *Need*: $n \times m$ matrix.
  - If $Need[i,j] = k$, then P_i may need k more instances of R_j to complete its task $Need[i,j] = Max[i,j] - Allocation[i,j]$

Safety Algorithm

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

2. Find an i such that both:
   1. $Finish[i] = false$
   2. $Need_i \leq Work$

   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.

Resource-Request Algorithm for Process P_i (1/2)

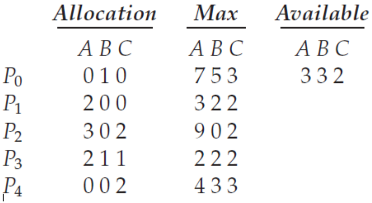
- $Request_i$ = request vector for process P_i. If $Request_i[j] = k$, then process P_i wants k instances of resource type R_j.
- 1. If $Request_i \leq Need_i$, go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim.
- 2. If $Request_i \leq Available$, go to step 3. Otherwise P_i must wait, since resources are not available.

Resource-Request Algorithm for Process P_i (2/2)

- 3. Pretend to allocate requested resources to P_i by modifying the state as follows:
  $Available = Available - Request_i$
  $Allocation_i = Allocation_i + Request_i$
  $Need_i = Need_i - Request_i$
  - If safe: the resources are allocated to P_i
  - If unsafe: P_i must wait, and the old resource-allocation state is restored

Banker's Algorithm Example (1/3)

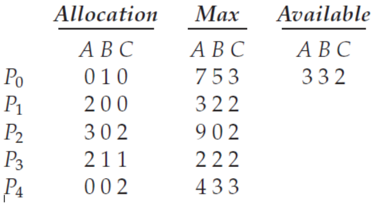
- 5 processes: P_0 through P_4
- 3 resource types:
  - A (10 instances), B (5 instances), and C (7 instances)
- Snapshot at time T_0



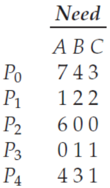
	Allocation	*Max*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 1 0	7 5 3	3 3 2
P_1	2 0 0	3 2 2	
P_2	3 0 2	9 0 2	
P_3	2 1 1	2 2 2	
P_4	0 0 2	4 3 3	

Banker's Algorithm Example (2/3)

- The content of the matrix *Need* is defined to be *Max* − *Allocation*



	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	

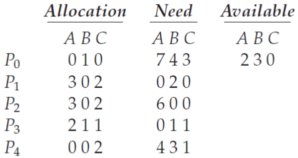


	Need
	A B C
P_0	7 4 3
P_1	1 2 2
P_2	6 0 0
P_3	0 1 1
P_4	4 3 1

- Is the system safe? $\langle P_1, P_3, P_4, P_2, P_0 \rangle$ satisfies safety criteria.

Banker's Algorithm Example (3/3)

- P_1 Request $(1, 0, 2)$
- Check that *Request* $\leq$ *Available*: $(1, 0, 2) \leq (3, 3, 2) \Rightarrow$ *true*



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

- Executing safety algorithm shows that sequence $\langle P_1, P_3, P_4, P_0, P_2 \rangle$ satisfies safety requirement.
- Can request for $(3, 3, 0)$ by P_4 be granted?
- Can request for $(0, 2, 0)$ by P_0 be granted?

Deadlock Detection

Deadlock Detection

- Allow system to enter deadlock state
- Detection algorithm
- Recovery scheme

Single Instance of Each Resource Type

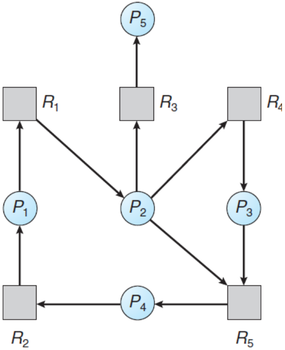
- Maintain wait-for graph.
  - Nodes are processes.
  - $P_i \rightarrow P_j$ if P_i is waiting for P_j.

- Periodically invoke an algorithm that searches for a cycle in the graph.

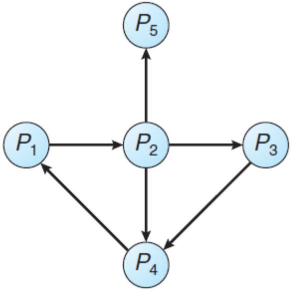
- If there is a cycle, there exists a deadlock.

- An algorithm to detect a cycle in a graph requires an $O(n^2)$ operations, where n is the number of vertices in the graph.

Resource-Allocation Graph and Wait-for Graph



Resource-allocation graph



Corresponding Wait-for graph

Data Structures for Deadlock Detection

- *Available*: vector of length m, indicates the number of available resources of each type.

- *Allocation*: $n \times m$ matrix, defines the number of resources of each type currently allocated to each process.

- *Request*: $n \times m$ matrix, indicates the current request of each process.
  - If $Request[i, j] = k$, then P_i requesting k more instances of resource type R_j.

Detection Algorithm (1/2)

- 1. Let *Work* and *Finish* be vectors of length m and n, respectively.
  Initialize:
  a. $Work = Available$
  b. For $i = 1, 2, \cdots, n$, if $Allocationi \neq 0$, 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

Detection Algorithm (2/2)

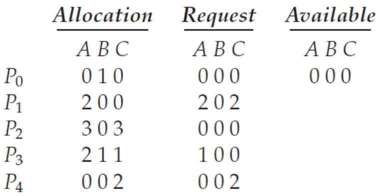
- 3. $Work = Work + Allocation_i$
  $Finish[i] = true$
  go to step 2

- 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.

- Algorithm requires an order of $O(m \times n^2)$ operations to detect whether the system is in deadlocked state.

Detection Algorithm Example (1/2)

- 5 processes: P_0 through P_4
- 3 resource types:
    - A (7 instances), B (2 instances), and C (6 instances)
- Snapshot at time T_0

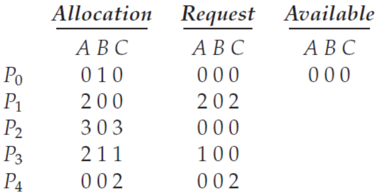


	Allocation	*Request*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 1 0	0 0 0	0 0 0
P_1	2 0 0	2 0 2	
P_2	3 0 3	0 0 0	
P_3	2 1 1	1 0 0	
P_4	0 0 2	0 0 2	

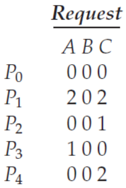
- Deadlock? Sequence $\langle P_0, P_2, P_3, P_1, P_4 \rangle$ will result in $Finish[i] = true$ for all i

Detection Algorithm Example (2/2)

- 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 0	
P_3	2 1 1	1 0 0	
P_4	0 0 2	0 0 2	



	Request
	A B C
P_0	0 0 0
P_1	2 0 2
P_2	0 0 1
P_3	1 0 0
P_4	0 0 2

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

Recovery From Deadlock

Recovery from Deadlock

- Process termination
- Resource preemption

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?
    1. Priority of the process.
    2. How long process has computed, and how much longer to completion.
    3. Resources the process has used.
    4. Resources process needs to complete.
    5. How many processes will need to be terminated.

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.

Summary

Summary

- Deadlock
- Four simultaneous conditions: mutual exclusion, hold and wait, no preemption, circular wait
- Deadlock prevention
- Deadlock avoidance: resource-allocation algorithm, banker's algorithm
- Deadlock detection: Wait-for graph
- Deadlock recovery: process termination, resource preemption

Questions?

Acknowledgements

Some slides were derived from Avi Silberschatz slides.