Chapter 7: Deadlocks
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- The Deadlock Problem
- System Model
- Deadlock Characterization
- Methods for Handling Deadlocks
- Deadlock Prevention
- Deadlock Avoidance
- Deadlock Detection
- Recovery from Deadlock
Chapter Objectives

- To develop a description of deadlocks, which prevent sets of concurrent processes from completing their tasks.
- To present a number of different methods for preventing or avoiding deadlocks in a computer system.
The Deadlock Problem

- 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
    
    \[
    \begin{array}{c c}
    P_0 & P_1 \\
    \text{acquire}(A); & \text{acquire}(B) \\
    \text{acquire}(B); & \text{acquire}(A)
    \end{array}
    \]
Bridge Crossing Example

- 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
- Note – Most OSes do not prevent or deal with deadlocks
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 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 that is held by \( P_1 \), \( P_1 \) is waiting for a resource that is held by \( P_2 \), \ldots, \( P_{n-1} \) is waiting for a resource that is held by \( P_n \), and \( P_n \) is waiting for a resource that is held by \( P_0 \).
A set of vertices $V$ and a set of edges $E$.

- $V$ is partitioned into two types:
  - $P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system

- **request edge** – directed edge $P_i \rightarrow R_j$
- **assignment edge** – directed edge $R_j \rightarrow P_i$
Resource-Allocation Graph (Cont.)

- Process

- Resource Type with 4 instances

- \( P_i \) requests instance of \( R_j \)

- \( P_i \) is holding an instance of \( R_j \)
Example of a Resource Allocation Graph

\[ P = \{P_1, P_2, P_3\} \]
\[ R = \{R_1, R_2, R_3, R_4\} \]
\[ E = \{P_1 \rightarrow R_1, P_2 \rightarrow R_3, R_1 \rightarrow P_2, \]
\[ R_2 \rightarrow P_2, R_2 \rightarrow P_1, R_3 \rightarrow P_3\} \]

Resource instances:
• One instance of resource type R1,
• Two instances of resource type R2,
• One instance of resource type R3,
• Two instances of resource type R4

Process states
• P1 is holding an instance of R2 and waiting for an R1
• P2 is holding an R1 and an R2 and is waiting for an R3
• P3 is holding an R3
Suppose P3 requests an instance of resource type R2.
Two cycles exist in the system:
P1 -> R1 -> P2 -> R3 -> P3 -> R2 -> P1
P2 -> R3 -> P3 -> R2 -> P2

Processes P1, P2, P3 are deadlocked.
We have a cycle but no deadlock.

Process P4 may release its instance of resource type R2. R2 can then be allocated to P3, breaking the cycle.
Basic Facts

- If graph contains no cycles $\Rightarrow$ no deadlock

- If graph contains a cycle $\Rightarrow$
  - 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

- 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, including UNIX
Deadlock Prevention

Restrain the ways request can be made

- **Mutual Exclusion** – not required for sharable resources (i.e. a printer); must hold for nonsharable resources (i.e. read-only files)

- **Hold and Wait** – must guarantee that whenever a process requests a resource, it does not hold any other resources
  
  - Require process to request and **be allocated all its resources** before it begins execution, or allow process to request resources **only when the process has none**
  
  - Low resource utilization; starvation possible
Deadlock Prevention (Cont.)

- **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

Requires that the system has some additional on how resources are to be requested.

- Simplest and most useful model requires that each process declare the \textit{maximum number} of resources of each type that it may need.
- The deadlock-avoidance algorithm \textit{dynamically} examines the resource-allocation state to ensure that there can never be a circular-wait condition.
- Resource-allocation \textit{state} is defined by the number of available and allocated resources, and the \textit{maximum demands} of the processes.
Safe State

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

- System is in safe state if there exists a sequence \(<P_1, P_2, ..., P_n>\) of ALL the processes in the system such that for each \(P_i\), the resources that \(P_i\) can still request can be satisfied by currently available resources + resources held by all the \(P_j\), with \(j < i\).

- That is:
  - 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.
Basic Facts

- If a system is in safe state $\Rightarrow$ no deadlocks
- If a system is in unsafe state $\Rightarrow$ possibility of deadlock
- Avoidance $\Rightarrow$ ensure that a system will never enter an unsafe state.
Safe, Unsafe, Deadlock State

- safe
- unsafe
- deadlock
Avoidance algorithms

- **Single instance** of a resource type
  - Use a resource-allocation graph

- **Multiple instances** of a resource type
  - Use the banker’s algorithm
Claim edge $P_i \rightarrow R_j$ indicated that process $P_j$ 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.
Suppose that P2 requests R2. although R2 is currently free, we can not allocate it to P2, since this action may create a cycle if P1 requests R2 as well.
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

- Multiple instances
- Each process must a priori claim 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 the Banker’s Algorithm

Let $n =$ number of processes, and $m =$ number of resources types.

- **Available**: # of available resources of each type. Vector of length $m$. If available [j] = k, there are $k$ instances of resource type $R_j$ available.

- **Max**: maximum demand of each process. $n \times m$ matrix. If Max [i,j] = k, then process $P_i$ may request at most $k$ instances of resource type $R_j$.

- **Allocation**: # of resources of each type currently allocated to each process. $n \times m$ matrix. If Allocation[i,j] = k then $P_i$ is currently allocated $k$ instances of $R_j$.

- **Need**: the remaining resource need of each process. $n \times m$ matrix. If Need[i,j] = k, then $P_i$ may need $k$ more instances of $R_j$ to complete its task.

$$\text{Need [i,j]} = \text{Max[i,j]} - \text{Allocation [i,j]}$$
Safety Algorithm

1. Let $Work$ and $Finish$ be vectors of length $m$ and $n$, respectively. Initialize:

   $Work = Available$

   $Finish[i] = false$ for $i = 0, 1, ..., n-1$

2. Find an index $i$ 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
Resource-Request Algorithm for Process $P_i$

$Request = \text{request vector for process } P_i$. 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 $P_i$
   - If unsafe $\Rightarrow$ $P_i$ must wait, and the old resource-allocation state is restored
Example of Banker’s Algorithm

- 5 processes $P_0$ through $P_4$;
- 3 resource types:
  - $A$ (10 instances), $B$ (5 instances), and $C$ (7 instances)

Snapshot at time $T_0$:

<table>
<thead>
<tr>
<th></th>
<th>Allocation</th>
<th>Max</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A  B  C</td>
<td>A  B  C</td>
<td>A  B  C</td>
</tr>
<tr>
<td>$P_0$</td>
<td>0  1  0</td>
<td>7  5  3</td>
<td>3  3  2</td>
</tr>
<tr>
<td>$P_1$</td>
<td>2  0  0</td>
<td>3  2  2</td>
<td></td>
</tr>
<tr>
<td>$P_2$</td>
<td>3  0  2</td>
<td>9  0  2</td>
<td></td>
</tr>
<tr>
<td>$P_3$</td>
<td>2  1  1</td>
<td>2  2  2</td>
<td></td>
</tr>
<tr>
<td>$P_4$</td>
<td>0  0  2</td>
<td>4  3  3</td>
<td></td>
</tr>
</tbody>
</table>
Example (Cont.)

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

$Need$

\[
\begin{array}{ccc}
A & B & C \\
P_0 & 7 & 4 & 3 \\
P_1 & 1 & 2 & 2 \\
P_2 & 6 & 0 & 0 \\
P_3 & 0 & 1 & 1 \\
P_4 & 4 & 3 & 1 \\
\end{array}
\]

- The system is in a safe state since the sequence $< P_1, P_3, P_4, P_2, P_0 >$ satisfies safety criteria
Example: $P_1$ Request (1,0,2)

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

<table>
<thead>
<tr>
<th>Allocation</th>
<th>Need</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>A B C</td>
<td>A B C</td>
<td>A B C</td>
</tr>
<tr>
<td>$P_0$</td>
<td>0 1 0</td>
<td>7 4 3</td>
</tr>
<tr>
<td>$P_1$</td>
<td>3 0 2</td>
<td>0 2 0</td>
</tr>
<tr>
<td>$P_2$</td>
<td>3 0 1</td>
<td>6 0 0</td>
</tr>
<tr>
<td>$P_3$</td>
<td>2 1 1</td>
<td>0 1 1</td>
</tr>
<tr>
<td>$P_4$</td>
<td>0 0 2</td>
<td>4 3 1</td>
</tr>
</tbody>
</table>

- Executing safety algorithm shows that sequence $<P_1, P_3, P_4, P_0, P_2>$ 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

- 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 order of $n^2$ 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
Several Instances of a Resource Type

- **Available**: A vector of length \( m \) indicates the number of available resources of each type.

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

- **Request**: An \( n \times m \) matrix indicates the current request of each process. If \( \text{Request} \left[ i, j \right] = k \), then process \( P_i \) is requesting \( k \) more instances of resource type \( R_j \).
Detection Algorithm

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. \( \text{Work} = \text{Work} + \text{Allocation}_i \)
   \( \text{Finish}[i] = \text{true} \)
   go to step 2

4. If \( \text{Finish}[i] == \text{false} \), for some \( i \), \( 1 \leq i \leq n \), then the system is in deadlock state. Moreover, if \( \text{Finish}[i] == \text{false} \), 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
Example of Detection Algorithm

- Five processes $P_0$ through $P_4$; three resource types A (7 instances), B (2 instances), and C (6 instances)
- Snapshot at time $T_0$:

<table>
<thead>
<tr>
<th>Allocation</th>
<th>Request</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>A B C</td>
<td>A B C</td>
<td>A B C</td>
</tr>
</tbody>
</table>

$P_0$ 0 1 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

- Sequence $<P_0, P_2, P_3, P_1, P_4>$ will result in $Finish[i] = true$ for all $i$
Example (Cont.)

- \( P_2 \) requests an additional instance of type \( C \)

\[
\begin{array}{c|ccc}
\text{Request} & A & B & C \\
\hline
P_0 & 0 & 0 & 0 \\
P_1 & 2 & 0 & 1 \\
P_2 & 0 & 0 & 1 \\
P_3 & 1 & 0 & 0 \\
P_4 & 0 & 0 & 2 \\
\end{array}
\]

- State of system?
  - \(<P_0, P_2, P_3, P_1, P_4>\>
  - Can reclaim resources held by process \( P_0 \), but still insufficient resources to fulfill other processes’ requests
  - Deadlock exists, consisting of processes \( P_1, P_2, P_3, \) and \( P_4 \)
Detection-Algorithm Usage

- When, and how often, to invoke depends on:
  - How often a deadlock is likely to occur?
  - How many processes will be affected by deadlock when it happens?

- If deadlocks occur frequently, then the detection algorithm should be invoked frequently.

- Resources allocated to the deadlocked processes will be idle until the deadlock can be broken.
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?
Recovery from Deadlock: 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
End of Chapter 7