Deadlock

Introduction to Operating Systems
Modeling Resource Contention

• System consists of resources

• 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 (exclusive)
  
  • Release
Conditions for 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**: a process is holding onto a resource (R) while it is waiting for some other resource that can only be released after R is released
The Circular Wait Problem

A set \( \{P_0, P_1, \ldots, P_n\} \) of waiting processes:

- \( P_0 \) 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 \( P_0 \).
The Circular Wait Problem

Dining Philosophers problem:
• All philosophers have picked up one chopstick
• Each is waiting for their 2\textsuperscript{nd} chopstick
• But none can be released until one of the philosophers can pick up that 2\textsuperscript{nd} chopstick…
Resource Allocation Graph

• Vertices are of 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: Notation

- Process

- Resource Type with 4 instances

- $P_i$ requests instance of $R_j$

- $P_i$ is holding an instance of $R_j$
Example: Resource Allocation Graph

• State:
  • P1 has R2 and is waiting for R1
  • P2 has R2 and is waiting for R3
  • P3 has R3

• Assuming no other allocation requests, can all of the processes complete execution?
  • Yes!
Example 2: Resource Allocation Graph

• State:
  • P1 has R2 and is waiting for R1
  • P2 has R2 and is waiting for R3
  • P3 has R3 and is waiting for R2

• Assuming no other allocation requests, can all of the processes complete execution?

• No! Everyone is waiting on somebody else
Example 3: Resource Allocation Graph

- **State:**
  - P1 has R2 and is waiting for R1
  - P2 has R1
  - P3 has R1 and is waiting for R2
  - P4 has R2

- Assuming no other allocation requests, can all of the processes complete execution?
  - Yes!
Deadlock

How do we know if we have a deadlock?

• 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
Dealing with 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, including UNIX
Deadlock Prevention

Approach: we don’t allow one of the four necessary conditions to hold

• Mutual Exclusion
• Hold and Wait
• No preemption
• Circular wait
Deadlock Prevention

Mutual Exclusion

• Do not lock sharable resources (e.g., read-only files)
• But, this does not address non-sharable resources
Deadlock Prevention

Hold and Wait

• Guarantee that whenever a process requests a resource, it does not hold any other resources

• One approach: process must request all resources up front, as a single unit

• Another approach: only allow a process to request resources only when the process has none allocated to it

• Problems: Low resource utilization; starvation possible
Deadlock Prevention

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.
Deadlock Prevention

Circular Wait

• Impose a total ordering of all resource types
• Require that each process requests resources in an increasing order of enumeration

• Two processes cannot both block while waiting for resources that are held by the opposite process
Deadlock Example

Prevention:
• Could force total ordering on the locks
• Could force one thread to give up locks when preempted

/* thread one runs in this function */
void *do_work_one(void *param)
{
    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);
}

/* thread two runs in this function */
void *do_work_two(void *param)
{
    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);
}
Deadlock Example

Two different transactions execute concurrently:

• Transaction 1 transfers $25 from account A to account B, and

• Transaction 2 transfers $50 from account B to account A

Prevention:

• Could have a total ordering of accounts

• Could require all resources to be allocated simultaneously

```c
void transaction(Account from,
                 Account to,
                 double amount)
{
    mutex lock1, lock2;
    lock1 = get_lock(from);
    lock2 = get_lock(to);
    acquire(lock1);
    acquire(lock2);
    withdraw(from, amount);
    deposit(to, amount);
    release(lock2);
    release(lock1);
}
```
Deadlock Prevention

• Kernel can take preventative steps
  • Resource utilization could be poor

• Or the application programmer can take explicit steps
  • E.g., ordering of lock operations
  • Dealing with preemption

• This approach relies on programmers doing the right thing
  • Generally, this is a bad idea…
Deadlock Avoidance

• Deadlock prevention techniques place a lot of restrictions on what can be done
  • In particular: allocation decisions are made using uniformly applied rules
• Next approach (avoidance): dynamically make allocation decisions on a case-by-case basis
  • Only allow an allocation to proceed if there is no opportunity in the current system for deadlock
Deadlock Avoidance

Process Model:

• Each process must declare up front the maximum number of resources of each type that it may need to complete execution

• Then, during execution, the process may request those resources as they are actually needed
  • Must respect the declared needs at the start
Three possible situations:

• **Deadlock**: a circular wait has happened

• **Safe**: given the current allocations and the potential allocation of the remaining needs, all processes can complete without deadlock occurring

• **Unsafe**: deadlock has not occurred, but if the right set of needs are requested, then deadlock will happen
Safe State

- System is in **safe state** if there exists a sequence \(<P_1, P_2, \ldots, P_n>\) of ALL the executing processes such that:
  - \(P_1\) can allocate its remaining needs from the available resources, use them, and then free all of its resources
  - Each \(P_i\) can allocate its remaining needs from the available resources **plus** those that would be released by processes \(P_1 \ldots P_{i-1}\)
  - That is:
    - If \(P_i\) resource needs are not immediately available, then \(P_i\) can wait until all \(P_j\) have finished (where \(j < i\))
    - \(P_i\) can then obtain the needed resources, execute, return allocated resources, and terminate
    - When \(P_i\) terminates, \(P_{i+1}\) is guaranteed to be able to obtain its needed resources, etc.
System State

Three possible situations:

• **Deadlock**: a circular wait has happened

• **Safe**: all processes can complete without deadlock occurring

• **Unsafe**: deadlock has not occurred, but if the right set of needs are requested, then deadlock will happen
System Allocation Algorithm

• Goal: always stay in a safe state

• When a new request is made by a process:
  • Kernel tests whether the new state will be safe or not
  • If safe, then allocation is allowed
  • If unsafe, then the process is placed in a waiting queue until a safe state can be achieved
Avoidance Algorithms

• All resources are single-instance:
  • We can just look at the resource allocation graph to determine whether a cycle can happen

• Multiple instances of some resources:
  • Use the **Banker’s Algorithm** to determine safe vs unsafe
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: $P_i \rightarrow R_j$ **solid line**

• Request edge converted to an assignment edge when the resource is allocated to the process
  • Assignment edge: $R_j \rightarrow P_i$ **solid line**

• When a resource is released by a process, assignment edge reconverts back to a claim edge

• All resources must be claimed before any allocation requests are made
Resource Allocation Graph

• P1:
  • Claimed: R2
  • Assigned R1
• P2:
  • Claimed: R2
  • Requested: R1

Two independent questions:
• If P1 requests R2, is it safe to assign it?
• If P2 requests R2, is it safe to assign it?
Resource-Allocation Graph

Hypothetical: Assign R2 to P2:
- Now in an unsafe state!
- If P1 then requests R2, we will have deadlock

Conclusion: we should not assign R2 to P2 right now
Resource Allocation Graph

• P1:
  • Claimed: R2
  • Assigned R1

• P2:
  • Claimed: R2
  • Requested: R1

Two independent questions:
• If P1 requests R2, is it safe to assign it?
• If P2 requests R2, is it safe to assign it?
Assign R2 to P1:

- We do not have a cycle

Conclusion: we can safely perform this assignment
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.
- If a cycle would result, then the process is placed into a waiting queue.

This works great if there is only one instance per resource type.
Banker’s Algorithm

• Multiple instances of each resource
  • These are interchangeable instances

• Each process must claim the maximum use of resources before any requests can be made

• When a process requests a resource it may have to wait

• When a process gets all its resources it must return them and terminate 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**: Vector of length $m$. If $\text{available}[j] == k$, there are $k$ instances of resource type $R_j$ available to be allocated.

• **Max**: $n \times m$ matrix. If $\text{Max}[i,j] == k$, then process $P_i$ may request at most $k$ instances of resource type $R_j$.

• **Allocation**: $n \times m$ matrix. If $\text{Allocation}[i,j] == k$ then $P_i$ is currently allocated $k$ instances of $R_j$.

• **Need**: $n \times m$ matrix. If $\text{Need}[i,j] == k$, then $P_i$ may need $k$ more instances of $R_j$ to complete its task.

\[
\text{Need } [i,j] = \text{Max}[i,j] - \text{Allocation } [i,j]
\]
Banker’s Algorithm: Determining Safety

Let \textbf{Work} and \textbf{Finish} be vectors of length \( m \) and \( n \), respectively. Initialize:

\[
\text{Work} = \text{Available} \\
\text{Finish}[i] = \text{false} \text{ for } i = 0, 1, \ldots, n-1
\]

2. Find an \( i \) such that both:
   
   (a) \( \text{Finish}[i] = \text{false} \)
   
   (b) \( \text{Need}_i \leq \text{Work} \) \hspace{1cm} // \text{NOTE: all resource needs of process } i \text{ must be fulfillable}

   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 \( \text{Finish}[i] == \text{true} \) for all \( i \), then the system is in a safe state
   
   Otherwise, it is unsafe
• Examples
Using the Banker’s Algorithm

\textit{Request}_i = \text{request vector for process } P_i. \text{ If } Request_i[j] = k \text{ then process } P_i \text{ wants } k \text{ instances of resource type } R_j. \text{ Three cases:}

1. \text{ If } Request_i > Need_i \text{ raise error condition, since process has exceeded its maximum claim}
2. \text{ If } Request_i > Available, P_i \text{ must wait, since the resources are not available}
3. \text{ Pretend} to allocate requested resources to \textit{P}_i \text{ by modifying the state as follows:}

\begin{align*}
\text{Available} & = \text{Available} - \text{Request}_i; \\
\text{Allocation}_i & = \text{Allocation}_i + \text{Request}_i; \\
\text{Need}_i & = \text{Need}_i - \text{Request}_i;
\end{align*}

\begin{itemize}
\item If safe \(\Rightarrow\) the resources are allocated to \textit{P}_i
\item If unsafe \(\Rightarrow\) \textit{P}_i \text{ must wait, and the old resource-allocation state is restored}
\end{itemize}
### Banker’s Example III

<table>
<thead>
<tr>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0$</td>
</tr>
<tr>
<td>$P_1$</td>
</tr>
<tr>
<td>$P_2$</td>
</tr>
<tr>
<td>$P_3$</td>
</tr>
<tr>
<td>$P_4$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Allocation</th>
<th>Max</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
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<td>A B C</td>
<td>A B C</td>
</tr>
<tr>
<td>0 1 0</td>
<td>7 5 3</td>
<td>3 3 2</td>
</tr>
<tr>
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<td>3 2 2</td>
<td></td>
</tr>
<tr>
<td>3 0 2</td>
<td>9 0 2</td>
<td></td>
</tr>
<tr>
<td>2 1 1</td>
<td>2 2 2</td>
<td></td>
</tr>
<tr>
<td>0 0 2</td>
<td>4 3 3</td>
<td></td>
</tr>
</tbody>
</table>
Banker’s Example IV

New request by Process 1: 1,0,2
• Will we be in a safe state?

<table>
<thead>
<tr>
<th>Process</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>P₀</td>
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<tr>
<td>P₁</td>
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<td>3 2 2</td>
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</tr>
<tr>
<td>P₂</td>
<td>3 0 2</td>
<td>9 0 2</td>
<td></td>
</tr>
<tr>
<td>P₃</td>
<td>2 1 1</td>
<td>2 2 2</td>
<td></td>
</tr>
<tr>
<td>P₄</td>
<td>0 0 2</td>
<td>4 3 3</td>
<td></td>
</tr>
</tbody>
</table>
Deadlock Summary

Necessary and sufficient conditions for deadlock (all must be true):

• Mutual Exclusion
• Hold and Wait
• No preemption
• Circular wait
Deadlock Summary

Deadlock Prevention:
• Fixed set of rules that apply to all situations
• Remove one of the necessary conditions
• Simple
• But: can be overly conservative and may not give us good use of the available resources
Deadlock Summary

Deadlock Avoidance:

• Make context-specific decisions on the fly as to whether an allocation request should be granted

• Single instance per resource type:
  • Use allocation graph
  • If an allocation results in a cycle, then do not grant it

• Multiple instances per resource type:
  • Banker’s Algorithm
  • If an allocation results in an unsafe state, then do not grant it