What is Deadlock?

- Two or more entities need a resource to make progress, but will never get that resource.

- **Examples from everyday life:**
  - Gridlock of cars in a city
  - Class scheduling: Two students want to swap sections of a course, but each section is currently full.

- **Examples from Operating Systems:**
  - Two processes spool output to disk before either finishes, and all free disk space is exhausted
  - Two processes consume all memory buffers before either finishes
A set of processes is in a DEADLOCK state when every process is waiting for an event initiated by another process in the set.

- **Process A**
  - Request X
  - Request Y
  - Release X
  - Release Y

- **Process B**
  - Request Y
  - Request X
  - Release Y
  - Release X
Deadlock Illustration

- A requests & receives X
- B requests & receives Y
- A requests Y and blocks
- B requests X and blocks

The “Deadly Embrace”
Terminology

- Preemptible vs. Non-preemptible

- Shared vs. Exclusive resource
  - Example of Shared resource: File
  - Example of Exclusive resource: Printer
Terminology ...

- Indefinite postponement
  - Job is continually denied resources needed to make progress

Example: High priority processes keep CPU busy 100% of time, thereby denying CPU to low priority processes
Three Solutions to Deadlock

#1: Mr./Ms. Conservative  (Prevention)

“We had better not allocate if it could ever cause deadlock”

Process waits until all needed resource free
Resources underutilized
Three Solutions to Deadlock …

#2: Mr./Ms. Prudent (Avoidance)

“If resource is free and with its allocation we can still guarantee that everyone will finish, use it.”

Better resource utilization
Process still waits
Three Solutions to Deadlock...

#3: Mr./Ms. Liberal *(Detection/Recovery)*

“If it’s free, use it -- why wait?”

Good resource utilization, minimal process wait time
Until deadlock occurs....
Names for Three Methods on Last Slide

1) **Deadlock Prevention**
   - Design system so that possibility of deadlock is avoided *a priori*

2) **Deadlock Avoidance**
   - Design system so that if a resource request is made that *could* lead to deadlock, then block requesting process.
   - Requires knowledge of future requests by processes for resources.

3) **Deadlock Detection and Recovery**
   - Algorithm to detect deadlock
   - Recovery scheme
4 Necessary Conditions for Deadlock

- **Mutual Exclusion**
  - Non-sharable resources

- **Hold and Wait**
  - A process must be holding resources and waiting for others

- **No pre-emption**
  - Resources are released voluntarily

- **Circular Wait**
Deadlock Prevention

Deny one or more of the necessary conditions

- Prevent "Mutual Exclusion"
  - Use only sharable resources

=> Impossible for practical systems
Deadlock Prevention ...

- Prevent “Hold and Wait”

  (a) Preallocation - process must request and be allocated all of its required resources before it can start execution

  (b) Process must release all of its currently held resources and re-request them along with request for new resources

=> Very inefficient

=> Can cause "indefinite postponement": jobs needing lots of resources may never run
Deadlock Prevention ...

- Allow “Resource Preemption”
  - Allowing one process to acquire exclusive rights to a resource currently being used by a second process

  => Some resources can not be preempted without detrimental implications (e.g., printers, tape drives)

  => May require jobs to restart
Deadlock Prevention ...

- Prevent Circular Wait
  - Order resources and
  - Allow requests to be made only in an increasing order
# Preventing Circular Wait

**Process:**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Request:**

<table>
<thead>
<tr>
<th></th>
<th>W</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Z</th>
<th>W</th>
<th>Y</th>
<th>X</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th></th>
<th>A / W</th>
<th>B / X</th>
<th>C / Y</th>
</tr>
</thead>
</table>

**Impose an ordering on Resources:**

1. W
2. X
3. Y
4. Z

**After first 4 requests:**

A / W
D / Z
B / X
C / Y

**Process D cannot request resource W without voluntarily releasing Z first**
Problems with Linear Ordering Approach

(1) Adding a new resource that upsets ordering requires all code ever written for system to be modified!

(2) Resource numbering affects efficiency

=> A process may have to request a resource well before it needs it, just because of the requirement that it must request resources in ascending sequence
Deadlock Avoidance

- OS never allocates resources in a way that could lead to deadlock

=> Processes must tell OS in advance how many resources they will request
Banker’s Algorithm

- Banker's Algorithm runs each time:
  - a process requests resource - *Is it Safe?*
  - a process terminates - *Can I allocate released resources to a suspended process waiting for them?*

- A new state is *safe* if and only if every process can complete after allocation is made

=> Make allocation, then check system state and de-allocate if safe/unsafe
Definition: Safe State

- State of a system
  - An enumeration of which processes hold, are waiting for, or might request which resources

- Safe state
  - No process is deadlocked, and there exists no possible sequence of future requests in which deadlock could occur.
  - No process is deadlocked, and the current state will not lead to a deadlocked state
## Deadlock Avoidance

### Safe State:

<table>
<thead>
<tr>
<th>Process</th>
<th>Current Loan</th>
<th>Max Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process 1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Process 2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Process 3</td>
<td>5</td>
<td>8</td>
</tr>
</tbody>
</table>

Available = 2
## Deadlock Avoidance

### Unsafe State:

<table>
<thead>
<tr>
<th>Process</th>
<th>Current Loan</th>
<th>Max Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process 1</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Process 2</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Process 3</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Available = 1
Safe to Unsafe Transition

Current state being safe does not necessarily imply future states are safe

Current Safe State:

<table>
<thead>
<tr>
<th></th>
<th>Current Loan</th>
<th>Maximum Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process 1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Process 2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Process 3</td>
<td>5</td>
<td>8</td>
</tr>
</tbody>
</table>

Available = 2

Suppose Process 3 requests and gets one more resource

<table>
<thead>
<tr>
<th></th>
<th>Current Loan</th>
<th>Maximum Need</th>
</tr>
</thead>
<tbody>
<tr>
<td>User1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>User2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>User3</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

Available = 1
Basic Facts

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

deadlock

unsafe

safe
Banker’s Algorithm

- Multiple instances of resources.
- 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:** 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:
   \[ \text{Work} = \text{Available} \]
   \[ \text{Finish}[i] = false \text{ for } i = 1, 2, 3, ..., n. \]

2. Find an $i$ such that both:
   (a) $\text{Finish}[i] = false$
   (b) $\text{Need}_i \leq \text{Work}$
   If no such $i$ exists, go to step 4.

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

4. If $\text{Finish}[i] == true$ for all $i$, then the system is in a safe state.
Safety Algorithm

1. Let Work and Finish be vectors of length $m$ and $n$, respectively. Initialize:
   \[ Work = Available \]
   \[ Finish[i] = \text{false for } i = 1,2,3, \ldots, n. \]

   \[ i=1; \]
   while ($i \leq n$) Do {
       if (!Finish[i] && Need$_i \leq Work$) {
           Finish[i] = True;
           Work = Work + Allocation$_i$;
           i = 1;
       } else i++;
   }

   if (Finish[i] == true for all $i$) return (SAFE)
   else return (UNSAFE);
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:

   $Available = Available - Request_i$;
   $Allocation_i = Allocation_i + Request_i$;
   $Need_i = Need_i - Request_i$;

- 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*.

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

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

- 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 A B C A B C</td>
<td></td>
<td></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 $<P_1, P_3, P_0, P_2, P_4>$ 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?
Banker's Algorithm: Summary

(+) PRO's:

😊 Deadlock never occurs.

😊 More flexible & more efficient than deadlock prevention. (Why?)

(-) CON's:

😢 Must know max use of each resource when job starts.

   => No truly dynamic allocation

😢 Process might block even though deadlock would never occur
Deadlock Detection

Allow deadlock to occur, then recognize that it exists

- Run deadlock detection algorithm whenever locked resource is requested
- Could also run detector in background
Resource Graphs

Graphical model of deadlock

Nodes:

1) Processes
   - \( \text{Pi} \)

2) Resources
   - \( \text{Rj} \)

Edges:

1) Request
   - \( \text{Pi} \rightarrow \text{Rj} \)

2) Allocate
   - \( \text{Pi} \leftarrow \text{Rj} \)
Resource Graphs: Example

P1 holds 2 units of R1
P1 holds 1 unit of R2
R1 has a total inventory of 4 units
P2 holds 1 unit of R1
P2 requests 1 unit of R2 (and is blocked)
Operations on Resource Graphs: An Overview

1) Process requests resources: **Add arc(s)**

2) Process acquires resources: **Reverse arc(s)**

3) Process releases resources: **Delete arc(s)**
Graph Reductions

- A graph is **reduced** by performing operations 2 and 3 (reverse, delete arc)

- A graph is **completely reducible** if there exists a sequence of reductions that reduce the graph to a set of isolated nodes

- A process P is **not** deadlocked if and only if there exists a sequence of reductions that leave P unblocked

- If a graph is completely reducible, then the system state it represents is not deadlocked
Operations on Resource Graphs: Details

1) P requests resources (Add arc)
   
   Precondition:
   - P must have no outstanding requests
   - P can request any number of resources of any type
   
   Operation:
   - Add one edge (P, Rj) for each resource copy Rj requested

2) P acquires resources (Reverse arc)
   
   Precondition:
   - Must be available units to grant all requests
   - P acquires all requested resources

   Operation:
   - Reverse all request edges directed from P toward resources
3) P releases resources (Delete arc)

Precondition:
- P must have no outstanding requests
- P can release any subset of resources that it holds

Operation:
- Delete one arc directed away from resource for each released resource
Resource Graphs

NO....One sequence of reductions:

1) P1 acquires 1 unit of R1
2) P1 releases all resources (finishes)
3) P2 acquires 2 units of R2
4) P2 releases all resources (finishes)
NO.... One sequence of Reductions:

1) P2 acquires 2 units of R2
2) P2 releases all resources (finishes)
3) P1 acquires 2 units of R1
4) P1 releases all resources (finishes)
Resource Graphs...

What if there was only 2 available unit of R2?

Can deadlock occur with multiple copies of just one resource?
Recovering from Deadlock

Once deadlock has been detected, the system must be restored to a non-deadlocked state

1) Kill one or more processes
   - Might consider priority, time left, etc. to determine order of elimination

2) Preempt resources
   - Preempted processes must rollback
   - Must keep ongoing information about running processes