Last Class: Synchronization Problems

- **Reader Writer**
  - Multiple readers, single writer
  - In practice, use read-write locks

- **Dining Philosophers**
  - Need to hold multiple resources to perform task

Real-world Examples

- **Producer-consumer**
  - Audio-Video player: network and display threads; shared buffer
  - Web servers: master thread and slave thread
- **Reader-writer**
  - Banking system: read account balances versus update
- **Dining Philosophers**
  - Cooperating processes that need to share limited resources
    - Set of processes that need to lock multiple resources
      - Disk and tape (backup),
    - Travel reservation: hotel, airline, car rental databases
Today: Deadlocks

- What are deadlocks?
- Conditions for deadlocks
- Deadlock prevention
- Deadlock detection

Deadlocks

**Deadlock:** A condition where two or more threads are waiting for an event that can only be generated by these same threads.

- Example:
  
  Process A:
  
  printer.Wait();
  disk.Wait();
  // copy from disk
  // to printer
  printer.Signal();
  disk.Signal();

  Process B:
  
  disk.Wait();
  printer.Wait();
  // copy from disk
  // to printer
  printer.Signal();
  disk.Signal();
Deadlocks: Terminology

- **Deadlock** can occur when several threads compete for a finite number of resources simultaneously.
- **Deadlock prevention** algorithms check resource requests and possibly availability to prevent deadlock.
- **Deadlock detection** finds instances of deadlock when threads stop making progress and tries to recover.
- **Starvation** occurs when a thread waits indefinitely for some resource, but other threads are actually using it (making progress).
  => Starvation is a different condition from deadlock.

Necessary Conditions for Deadlock

Deadlock can happen if all the following conditions hold.

- **Mutual Exclusion**: at least one thread must hold a resource in non-sharable mode, i.e., the resource may only be used by one thread at a time.
- **Hold and Wait**: at least one thread holds a resource and is waiting for other resource(s) to become available. A different thread holds the resource(s).
- **No Preemption**: A thread can only release a resource voluntarily; another thread or the OS cannot force the thread to release the resource.
- **Circular wait**: A set of waiting threads \( \{t_1, ..., t_n\} \) where \( t_i \) is waiting on \( t_{i+1} \) (\( i = 1 \) to \( n \)) and \( t_n \) is waiting on \( t_1 \).
Deadlock Detection Using a Resource Allocation Graph

- We define a graph with vertices that represent both resources \( \{r_1, \ldots, r_m\} \) and threads \( \{t_1, \ldots, t_n\} \).
  - A directed edge from a thread to a resource, \( t_i \rightarrow r_j \) indicates that \( t_i \) has requested that resource, but has not yet acquired it (Request Edge).
  - A directed edge from a resource to a thread \( r_j \rightarrow t_i \) indicates that the OS has allocated \( r_j \) to \( t_i \) (Assignment Edge).
- If the graph has no cycles, no deadlock exists.
- If the graph has a cycle, deadlock might exist.

What if there are multiple interchangeable instances of a resource?
  - Then a cycle indicates only that deadlock might exist.
  - If any instance of a resource involved in the cycle is held by a thread not in the cycle, then we can make progress when that resource is released.
Detect Deadlock and Then Correct It

- Scan the resource allocation graph for cycles, and then break the cycles.
- Different ways of breaking a cycle:
  - Kill all threads in the cycle.
  - Kill the threads one at a time, forcing them to give up resources.
  - Preempt resources one at a time rolling back the state of the thread holding the resource to the state it was in prior to getting the resource. This technique is common in database transactions.
- Detecting cycles takes $O(n^2)$ time, where $n$ is $|T| + |R|$. When should we execute this algorithm?
  - Just before granting a resource, check if granting it would lead to a cycle? (Each request is then $O(n^2)$.)
  - Whenever a resource request can't be filled? (Each failed request is $O(n^2)$.)
  - On a regular schedule (hourly or ...)? (May take a long time to detect deadlock)
  - When CPU utilization drops below some threshold? (May take a long time to detect deadlock)
- What do current OS do?
  - Leave it to the programmer/application.

Deadlock Prevention

**Prevent deadlock:** ensure that at least one of the necessary conditions doesn't hold.

1. **Mutual Exclusion:** make resources sharable (but not all resources can be shared)
2. **Hold and Wait:**
   - Guarantee that a thread cannot hold one resource when it requests another
   - Make threads request all the resources they need at once and make the thread release all resources before requesting a new set.
3. **No Preemption:**
   - If a thread requests a resource that cannot be immediately allocated to it, then the OS preempts (releases) all the resources that the thread is currently holding.
   - Only when all of the resources are available, will the OS restart the thread.
   - *Problem:* not all resources can be easily preempted, like printers.
4. **Circular wait:** impose an ordering (numbering) on the resources and request them in order.
Deadlock Prevention with Resource Reservation

- Threads provide advance information about the maximum resources they may need during execution.
- Define a sequence of threads \{t_1, ..., t_n\} as safe if for each \(t_i\), the resources that \(t_i\) can still request can be satisfied by the currently available resources plus the resources held by all \(t_j, j < i\).
- A safe state is a state in which there is a safe sequence for the threads.
- An unsafe state is not equivalent to deadlock, it just may lead to deadlock, since some threads might not actually use the maximum resources they have declared.
- Grant a resource to a thread is the new state is safe
- If the new state is unsafe, the thread must wait even if the resource is currently available.
- This algorithm ensures no circular-wait condition exists.

Example

- Threads \(t_1\), \(t_2\), and \(t_3\) are competing for 12 tape drives.
- Currently, 11 drives are allocated to the threads, leaving 1 available.
- The current state is safe (there exists a safe sequence, \{t_1, t_2, t_3\} where all threads may obtain their maximum number of resources without waiting)
  - \(t_1\) can complete with the current resource allocation
  - \(t_2\) can complete with its current resources, plus all of \(t_1\)'s resources, and the unallocated tape drive.
- \(t_3\) can complete with all its current resources, all of \(t_1\) and \(t_2\)'s resources, and the unallocated tape drive.

<table>
<thead>
<tr>
<th></th>
<th>max need</th>
<th>in use</th>
<th>could want</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t_1)</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>(t_2)</td>
<td>8</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>(t_3)</td>
<td>12</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>
Example (contd)

• If $t_3$ requests one more drive, then it must wait because allocating the drive would lead to an unsafe state.
• There are now 0 available drives, but each thread might need at least one more drive.

<table>
<thead>
<tr>
<th></th>
<th>max need</th>
<th>in use</th>
<th>could want</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$t_2$</td>
<td>8</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$t_3$</td>
<td>12</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

Deadlock Avoidance using Resource Allocation Graph

• Claim edges: an edge from a thread to a resource that may be requested in the future
• Satisfying a request results in converting a claim edge to an allocation edge and changing its direction.
• A cycle in this extended resource allocation graph indicates an unsafe state.
• If the allocation would result in an unsafe state, the allocation is denied even if the resource is available.
  – The claim edge is converted to a request edge and the thread waits.
• This solution does not work for multiple instances of the same resource.
Banker's Algorithm

- This algorithm handles multiple instances of the same resource.
- Force threads to provide advance information about what resources they may need for the duration of the execution.
- The resources requested may not exceed the total available in the system.
- The algorithm allocates resources to a requesting thread if the allocation leaves the system in a safe state.
- Otherwise, the thread must wait.

Preventing Deadlock with Banker's Algorithm

```java
class ResourceManager {
    int n;       // # threads
    int m;      // # resources
    int avail[m], // # of available resources of each type
               max[n,m],  // # of each resource that each thread may want
               alloc[n,m], // # of each resource that each thread is using
               need[n,m],  // # of resources that each thread might still request
```
Banker's Algorithm: Resource Allocation

```java
public void synchronized allocate (int request[], int i) {
    // request contains the resources being requested
    // i is the thread making the request

    if (request > need[i]) // vector comparison
        error(); // Can't request more than you declared
    else while (request[i] > avail)
        wait(); // Insufficient resources available

    // enough resources exist to satisfy the requests
    // See if the request would lead to an unsafe state
    avail = avail - request; // vector additions
    alloc[i] = alloc[i] + request;
    need[i] = need[i] - request;

    while (!safeState ()) {
        // if this is an unsafe state, undo the allocation and wait
        <undo the changes to avail, alloc[i], and need[i]>
        wait ();
        <redo the changes to avail, alloc[i], and need[i]>
    }
}
```

Banker's Algorithm: Safety Check

```java
private boolean safeState () {
    boolean work[m] = avail[m]; // accommodate all resources
    boolean finish[n] = false; // none finished yet

    // find a process that can complete its work now
    while (find i such that finish[i] == false
        and need[i] <= work) { // vector operations
        work = work + alloc[i]
        finish[i] = true;
    }

    if (finish[i] == true for all i)
        return true;
    else
        return false;
}
```

- Worst case: requires $O(mn^2)$ operations to determine if the system is safe.
Example using Banker's Algorithm

System snapshot:

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Allocation</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  B  C</td>
<td>A  B  C</td>
<td>A  B  C</td>
<td></td>
</tr>
<tr>
<td>P0</td>
<td>0 0 1</td>
<td>0 0 1</td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>1 7 5</td>
<td>1 0 0</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>2 3 5</td>
<td>1 3 5</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>0 6 5</td>
<td>0 6 3</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2 9 9</td>
<td>1 5 2</td>
<td></td>
</tr>
</tbody>
</table>

Example (contd)

• How many resources are there of type (A,B,C)?

• What is the contents of the Need matrix?

<table>
<thead>
<tr>
<th></th>
<th>A  B  C</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0</td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td></td>
</tr>
</tbody>
</table>

• Is the system in a safe state? Why?
Example: solutions

• How many resources of type (A,B,C)? (3,14,11)
  resources = total + avail
• What is the contents of the need matrix?
  Need = Max - Allocation.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P_1</td>
<td>0</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>P_2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P_3</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

• Is the system in a safe state? Why?
  Yes, because the processes can be executed in the sequence P_0, P_2, P_1, P_3, even if each
  process asks for its maximum number of resources when it executes.

Example (contd)

• If a request from process P_1 arrives for additional resources of (0,5,2), can the
  Banker's algorithm grant the request immediately?
• What would be the new system state after the allocation?

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Allocation</th>
<th>Need</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>P_0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>P_1</td>
<td>1</td>
<td>7</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>P_2</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>P_3</td>
<td>0</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• What is a sequence of process execution that satisfies the safety constraint?
Example: solutions

If a request from process $P_1$ arrives for additional resources of $(0,5,2)$, can the Banker's algorithm grant the request immediately? Show the system state, and other criteria.

Yes. Since
1. $(0,5,2) \leq (1,5,2)$, the Available resources, and
2. $(0,5,2) + (1,0,0) = (1,5,2) \leq (1,7,5)$, the maximum number $P_1$ can request.
3. The new system state after the allocation is:

<table>
<thead>
<tr>
<th>Allocation</th>
<th>Max</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>P₀</td>
<td>0 0 1</td>
<td>0 0 1</td>
</tr>
<tr>
<td>P₁</td>
<td>1 5 2</td>
<td>1 7 5</td>
</tr>
<tr>
<td>P₂</td>
<td>1 3 5</td>
<td>2 3 5</td>
</tr>
<tr>
<td>P₃</td>
<td>0 6 3</td>
<td>0 6 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 0 0</td>
</tr>
</tbody>
</table>

and the sequence $P₀, P₂, P₁, P₃$ satisfies the safety constraint.

Summary

• Deadlock: situation in which a set of threads/processes cannot proceed because each requires resources held by another member of the set.
• Detection and recovery: recognize deadlock after it has occurred and break it.
• Avoidance: don't allocate a resource if it would introduce a cycle.
• Prevention: design resource allocation strategies that guarantee that one of the necessary conditions never holds.
• Code concurrent programs very carefully. This only helps prevent deadlock over resources managed by the program, not OS resources.
• Ignore the possibility! (Most OSes use this option!!)