Last Class: Monitors

- Monitor wraps operations with a mutex
- Condition variables release mutex temporarily
- C++ does not provide a monitor construct, but monitors can be implemented by following the monitor rules for acquiring and releasing locks
- It is possible to implement monitors with semaphores

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 \( \{r_1, ..., r_m\} \) and threads \( \{t_1, ..., t_n\} \).
  - 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)

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 \( \{t_1, \ldots, t_n\} \) 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>
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<th></th>
<th>max need</th>
<th>in use</th>
<th>could want</th>
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<tr>
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<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>
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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.

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<td>5</td>
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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!!)