Deadlocks
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March 19, 2019
Chapter 6: Roadmap

6.1 Principles
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6.2 Prevention
6.3 Avoidance
6.4 Detection
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Part II
Chapter 3: Processes
Chapter 4: Threads
Chapter 5: Concurrency
Chapter 6: Deadlocks
Deadlock is a permanent (infinite) wait for resources
- Requires at least two mutexes or one semaphore

Typical example with threads P and Q:
- Two mutexes locked in different order
- Common source of deadlocks in more general cases

Another example:

ThreadP() {
    mutexA.Lock();
    mutexB.Lock();
    // critical section
    mutexA.Unlock();
    mutexB.Unlock();
}

ThreadQ() {
    mutexB.Lock();
    mutexA.Lock();
    // critical section
    mutexB.Unlock();
    mutexA.Unlock();
}

CarNorth() {
    mutexA.Lock();
    mutexC.Lock();
    // drive
    mutexA.Unlock();
    mutexC.Unlock();
}

CarWest() {
    mutexC.Lock();
    mutexD.Lock();
    // drive
    mutexC.Unlock();
    mutexD.Unlock();
}
Example (cont’d): deadlock possible in general and...
- Certain when each grabs their first mutex:

Conditions for a deadlock to be possible
- 1) Mutual exclusion (no sharing)
- 2) Hold and wait (allowed to hold one resource and wait for another, i.e., acquisition of multiple mutexes is not atomic)
- 3) No preemption (held resources not released until critical section has been successfully completed)

Conditions for it to be certain
- 1)-3) plus 4) circular wait
Progress Diagram

- Assume two threads P and Q in parallel execution
  - Denote by t the absolute time
  - Progress diagram is a 2D parametric curve \((x(t), y(t))\) where \(x(t)\) is the number of instructions executed by Q and \(y(t)\) by P

Curves must be monotonically non-decreasing in both axes
Back to our example with P and Q

Mutex places L-shaped obstacles/barriers on the progress diagram that cannot be crossed.

ThreadP () {
    mutexA.Lock();
    mutexB.Lock();
    // critical section
    mutexA.Unlock();
    mutexB.Unlock();
}

ThreadQ () {
    mutexB.Lock();
    mutexA.Lock();
    // critical section
    mutexB.Unlock();
    mutexA.Unlock();
}

Progress Diagram
• In three quadrants near the origin, deadlock possible
  – In one, it is certain
• All other sections are safe
  – Except impossible states behind barriers
• Static or dynamic analysis to detect deadlocks
• What happens with N threads?
  – N-dimensional diagram
• How about these diagrams?
• In what order are mutexes acquired?
  – Write pseudo code for P/Q
To visualize deadlocks, often a graph is drawn between all threads and resources

- Edges of this bipartite graph are labeled with “held by” (resources $\rightarrow$ threads) and “wants” (threads $\rightarrow$ resources)

If this directed graph has a cycle, there is a deadlock

- Car labels (N, E, W, S) map to North/East/West/South position
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Dining Philosophers

• Yet another famous synchronization problem
  - Proposed by Dijkstra in 1965

• N philosophers are sitting at a round table with N forks between them
  - Usually $N = 5$ and the food is spaghetti, but this is not essential

• Each thinks for a random period of time until becoming hungry, then attempts to eat
  - Food requires usage of both adjacent forks
Dining Philosophers

- Operation of a philosopher (each is a separate thread 0 \leq i \leq N-1)
- Forks are labeled 0 to N-1 as well

```c
Mutex mutexFork[N]; // one for each fork

DropForks (int i) {
    mutexFork[i].Unlock();
    mutexFork[(i+1)%N].Unlock();
}
```

- Basic approach DPH v1.0:

```c
Mutex mutexFork[N]; // one for each fork

GrabForks (int i) {
    mutexFork[i].Lock(); // right fork
    mutexFork[(i+1)%N].Lock(); // left fork
}
```

- When all are hungry, deadlock is possible
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In deadlock prevention, the algorithm is modified by programmer to make one of the 4 conditions leading to deadlock impossible

- **Condition #1: mutual exclusion**
  - Typically cannot be safely eliminated (e.g., cars cannot drive on top of each other thru intersection)

- **Condition #2: hold and wait**
  - Can be overcome with WaitAll, DPH v1.1

    ```
    Mutex mutexFork[N];  // one mutex for each fork
    GrabForks (int i) {
        WaitAll (mutexFork[i], mutexFork[(i+1)%N]); // both forks
    }
    ```

    - Besides speed, main drawback is that all needed mutexes must be known ahead of time and acquired in bulk

WaitAll is either super slow (Windows) or absent (Unix)
**Prevention**

- **Condition #4: circular wait**
  - Design algorithm such that a circular deadlock cannot occur
- **Notice that presence of 3 or fewer cars (4 or fewer philosophers) cannot cause a cyclic wait graph**
  - Use a semaphore to control how many at the table
- **Q: how many can eat concurrently?**
  - If only $\lfloor N/2 \rfloor$, why allow all $N$ to grab forks?
- **How many should be allowed to use forks?**
  - To achieve max concurrency, $N-1$, but …
- **Algorithm prone to persistent chains of waits:**

\[
\begin{align*}
P_i \text{ (eat)} & \quad P_{i+1} \text{ (wait)} & \quad P_{i+2} \text{ (wait)} & \quad \ldots \quad P_{i+k} \text{ (wait)}
\end{align*}
\]
• Suppose $T > 0$ is the eat+think delay in seconds
  - Max theoretical rate of algorithm is $\frac{N}{2} \times \frac{1}{T}$
  - If $T = 0$, then mutex locking/unlocking is the bottleneck

• Elegant semaphore solution, but slow
  - $T=0$: kernel-mode semaphore kills performance
  - $T=100\text{ms}$: prone to sequential chains of waits, in which case performance may deteriorate to $\frac{1}{T} = 10$ per second
  - Improves if think delays are random ($1700/\text{sec}$), or max semaphore $= N/2$ ($1900/\text{sec}$)
Another way to prevent circular wait is to request resources in the same order from all threads.

If thread holds resource \( i \) and wants \( j \), then \( j > i \)

- If all other threads comply with this rule, a loop back to \( i \) in the resource graph is impossible.

DPH v1.3

```c
CRITICAL_SECTION cs[N]; // one mutex for each fork

GrabForks (int i) {
    if (i != N-1) {  // not the last guy
        EnterCriticalSection (&cs[i]);
        EnterCriticalSection (&cs[(i+1)%N]);
    } else {
        // special case, a leftie
        EnterCriticalSection (&cs[0]);
        EnterCriticalSection (&cs[N-1]);
    }
}
```

T=0
2M/sec N = 5

T=100ms
254/sec N = 500
• **Condition #3**: no preemption of held mutexes
  - Let waiter (OS) forcefully remove forks and reassign them
• More realistic version:
  - If unable to make progress, threads can voluntarily release held mutexes, randomly sleep, and start again
• Similar to PC 3.4, which was the fastest in prior tests

```c
CRITICAL_SECTION cs[N]; // one mutex for each fork

GrabForks (int i) {
    EnterCriticalSection (&cs[i]);
    do {
        if (TryEnterCriticalSection ( &cs[ (i+1)%N ] ) != 0)
            break;
        // unable to acquire
        LeaveCriticalSection (&cs[i]);
        Sleep (rand()*DELAY);
        EnterCriticalSection (&cs[i]);
    } while (true);
}
```

<table>
<thead>
<tr>
<th>$T=0$</th>
<th>1.9M/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N = 5$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$T=100\text{ms}$</th>
<th>2400/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N = 500$</td>
<td></td>
</tr>
</tbody>
</table>
Q: Find problems with this program:

A: Deletion of invalid block and a memory leak
   - Thrown when main() exits

Reason is that a copy of x is created to pass to Func
   - This copy gets deleted when Func() returns
   - Which in turn triggers destructor ~X() and deletion of buf

Finally, when main quits, it calls ~X() again
   - Which attempts to delete buf a second time
A walk-thru of what happens:

```cpp
main () {
    X x;
    Func (x);
    X temp;
    temp = x;
    Func(temp);
}
```

1. **object x**
   - buf = 3340 at address 3340
   - size = 100

2. **object temp**
   - buf = 3490 at address 3490
   - size = 100

3. **object temp**
   - buf = 3340 at address 3340
   - size = 100

- Calls `temp`'s constructor
- Copies fields from `x` to `temp`
- Calls `Func` with `temp` on the stack
- 100 bytes of RAM at address 3340
- 100 bytes of RAM at address 3490
• Next, on return from Func(x)
  - Saves a lot of headache with copying stuff over, also faster
• Lesson: pass pointers to classes whenever feasible
  - Saves a lot of headache with copying stuff over, also faster
• If a call-by-value is needed, use copy constructors
  - See http://en.wikipedia.org/wiki/Copy_constructor