Deadlocks
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Chapter 6: Roadmap

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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:

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

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

```c
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
• 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

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

ThreadQ () {
    mutexB.Lock();
    mutexA.Lock();
    // critical section
    mutexB.Unlock();
    mutexA.Unlock();
}
```
• 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 → threads) and “wants” (threads → 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

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

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

• Basic approach DPH v1.0:

```java
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)
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 \([N/2]\), 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:

\[ P_i \text{(eat)} \quad P_{i+1} \text{(wait)} \quad P_{i+2} \text{(wait)} \quad \ldots \quad P_{i+k} \text{(wait)} \]
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/sec), or max semaphore = \( \frac{N}{2} \) (1900/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]);
    }
}
```
Prevention

- **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</th>
<th>2400/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>N = 5</td>
<td>2400/sec</td>
</tr>
<tr>
<td>N = 500</td>
<td>2400/sec</td>
</tr>
</tbody>
</table>

DPH v1.4
Q: Find problems with this program:

```
class X {
    char *buf;
    int size;
    X() { buf = new char [100]; size = 100; }
    ~X() { delete buf; }
};
```

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:

```c
main () {
    X x;
}

Func (x);

X temp;

temp = x;

Func(temp);
```

**object x**
- buf = 3340
- size = 100

**object temp**
- buf = 3490
- size = 100

**object temp**
- buf = 3340
- size = 100

100 bytes of RAM at address 3340
100 bytes of RAM at address 3490

- calls temp’s constructor
- copies fields from x to temp
- calls Func with temp on the stack
• Next, on return from Func(x)

  • 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