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:

```java
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
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();
}
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
Progress 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

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

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

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

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

- Basic approach DPH v1.0:

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

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

```
CRITICAL_SECTION cs[N];  // one mutex for each fork
HANDLE sema = CreateSemaphore (... , N-1, N-1, ...);

GrabForks (int i) {
    WaitForSingleObject (sema, INFINITE);
    EnterCriticalSection (&cs[i]);
    EnterCriticalSection (&cs[(i+1)\%N]);
}
```

- 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 $1/T = 10$ per second
  - Improves if think delays are random ($1700$/sec), or max semaphore = $N/2$ ($1900$/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]);
    }
}
```

$T=0$

2M/sec $N = 5$

$T=100\text{ms}$

254/sec $N = 500$
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);
}
```

T=0
1.9M/sec
N = 5

T=100ms
2400/sec
N = 500

DPH v1.4
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:

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

Func (x);

X temp;

temp = x;

Func(temp);`
• 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