Deadlocks

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Chapter 6: Roadmap

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Part II

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Principles

- 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();
}
```

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();
}
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 → 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

```c
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

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

  ![Diagram of chains of waits](image-url)
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

Elegant semaphore solution, but slow

- $T=0$: kernel-mode semaphore kills performance
- $T=100ms$: 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]);
  }
}
```

$\begin{array}{l}
T=0 \\
2M/sec N = 5 \\
T=100ms \\
254/sec N = 500
\end{array}$
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);
}
```

\[ T=0 \]
\[ 1.9M/sec \]
\[ N = 5 \]

\[ T=100ms \]
\[ 2400/sec \]
\[ N = 500 \]
Q: Find problems with this program:

- 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