Deadlocks
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March 9, 2023
Chapter 6: Roadmap

6.1 Principles
6.6 Dining philosophers
6.2 Prevention
6.3 Avoidance
6.4 Detection
6.5 Integrated strategies
6.7 Unix
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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
- Important problem in the field of synchronization

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();
}
```
**Principles**

- 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

Mutexes place L-shaped obstacles/barriers on the progress diagram that cannot be crossed
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
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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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 ≤ i ≤ N-1)
- Forks are labeled 0 to N-1 as well

Philosopher (int i) {
    while (true) {
        Think ();
        GrabForks (i);
        Eat ();
        DropForks (i);
    }
}

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

```
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 \( \lceil N/2 \rceil \), why allow all N to grab forks?
- How many should be allowed to use forks?
  - To achieve max concurrency, N-1, but …
  - Algorithm is 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

**Elegant semaphore solution, but slow**
- $T=0$: kernel-mode semaphore kills performance
- $T=100$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]);
    } else {
        // special case, a leftie
        EnterCriticalSection (&cs[0]);
        EnterCriticalSection (&cs[N-1]);
    }
}
```

$T=0$

<table>
<thead>
<tr>
<th>2M/sec N = 5</th>
</tr>
</thead>
</table>

$T=100$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);
}
```

<table>
<thead>
<tr>
<th>N</th>
<th>T=0</th>
<th>1.9M/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>100ms</td>
<td>2400/sec</td>
</tr>
<tr>
<td>500</td>
<td>T=0</td>
<td></td>
</tr>
</tbody>
</table>

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

```cpp
class X {
    char *buf;
    int size;
    X() { buf = new char [100]; size = 100; }
    ~X() { delete buf; }
};
main () {
    X x;
    Func (x);
}
void Func (X x) {
    return;
}
```

• 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
  - Located at address 3340

- **Object temp**
  - buf = 3490
  - size = 100
  - Located at address 3490

- **Object temp**
  - buf = 3340
  - size = 100
  - Copies fields from x to temp

- Calls temp's constructor

- Calls `Func(temp)` 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)

  - passes 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