Deadlocks

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**Updates**

- Memory heaps
  - Normal new/delete ops go to the **process heap**
  - Internal mutex, slow delete
- Private heap doesn’t need to mutex
  - Benchmark with 12 threads on a 6-core system

```c
#define ITER   1e7
DWORD __stdcall HeapThread (...) {
    HANDLE heap = HeapCreate
      (HEAP_NO_SERIALIZE,
       4 * 1024 * sizeof(DWORD), 0);

    DWORD **arr = new (DWORD *) [ITER];
    for (int i = 0; i < ITER; i++)
        arr[i] = (DWORD*) HeapAlloc
          (heap, HEAP_NO_SERIALIZE,
           sizeof(DWORD));

    for (int i=0; i < ITER; i++)
        delete arr[i];
    HeapDestroy (heap);
}
```

**3.3M/s**

```c
#define ITER   1e7
DWORD __stdcall HeapThread (...) {
    HANDLE heap = HeapCreate
      (HEAP_NO_SERIALIZE,
       4 * 1024 * sizeof(DWORD), 0);

    DWORD **arr = new (DWORD *) [ITER];
    for (int i = 0; i < ITER; i++)
        arr[i] = new DWORD [1];

    for (int i = 0; i < ITER; i++)
        HeapFree (heap,
           HEAP_NO_SERIALIZE, arr[i]);
}
```

**36M/s**

```c
#define ITER   1e7
DWORD __stdcall HeapThread (...) {
    HANDLE heap = HeapCreate
      (HEAP_NO_SERIALIZE,
       4 * 1024 * sizeof(DWORD), 0);

    DWORD **arr = new (DWORD *) [ITER];
    for (int i = 0; i < ITER; i++)
        arr[i] = (DWORD*) HeapAlloc
          (heap, HEAP_NO_SERIALIZE,
           sizeof(DWORD));

    for (int i=0; i < ITER; i++)
        HeapDestroy (heap);
}
```

**12M/s**
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
6.8 Linux
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Part II

Chapter 3: Processes
Chapter 4: Threads
Chapter 5: Concurrency
Chapter 6: Deadlocks
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:

```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();
}
```

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

CarWest () {
    mutexC.Lock();
    mutexD.Lock();
    // drive
    mutexC.Unlock();
    mutexD.Unlock();
}
```

```
A

B

C

D
```
• 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 certain L-shaped obstacles/barriers on the progress diagram that cannot be crossed.

```c
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

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

```c
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=100ms  
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:** How does this program crash:

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

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

```cpp
void Func (X x) {
    return;
}
```

**A:** Deletion of invalid block from the heap
- 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
There is also a memory leak in the above scenario

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

100 bytes of RAM at address 3490

100 bytes of RAM at address 3340

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

X temp; calls temp's constructor
copies fields from x to temp
calls Func with temp in the stack
• Next, on return from Func(x)

  - saves a lot of headache with copying stuff over, also faster

• Lesson: pass class pointers whenever feasible

  - If a call-by-value is needed, use copy constructors

  - See http://en.wikipedia.org/wiki/Copy_constructor