Lecture 17 — C/C++11 Memory Model

Patrick Lam & Jeff Zarnett
p.lam@ece.uwaterloo.ca, jzarnett@uwaterloo.ca

Department of Electrical and Computer Engineering
University of Waterloo

December 22, 2015

Language Support: Before C/C++11

Before C/C++11:
    no language-level definition of threads.

Not even a well-formed question to ask what this means:

Thread 1:

```
foo = 7;
bar = 42;
```

Thread 2:

```
printf("%d\n", foo);
printf("%d\n", bar);
```

Language Support: Before C/C++11

Before C/C++11:

no language-level definition of threads.

Not even a well-formed question to ask what this means:

Thread 1:

```
foo = 7;
bar = 42;
```

Thread 2:

```
printf("%d\n", foo);
printf("%d\n", bar);
```

pre C/C++11: no such thing as a thread!

Language Support in C++11: Defining the Question

Now[1]:

- a memory model
- primitives: mutexes, atomics, memory barriers.

Previous example has undefined behaviour
per C++11. (why?)

[1] `http://www.quora.com/C++-programming-language/How-are-the-threading-and-memory-models-different-in-C++-as-compared-to-C`

Language Support in C++11: Atomics

We've seen the notion of atomics. Here's the C++11 notation:

```
atomic<int> foo, bar;
```

Thread 1:

```
foo.store(7);
bar.store(42);
```

Thread 2:

```
printf("%d\n", foo.load());
printf("%d\n", bar.load());
```

What are the possible outputs? (good exam question!)

Prefix and Postfix

Lots of people use postfix out of habit, but prefix is better.

In C, this isn't a problem.

In some languages (like C++), it can be.

Why? Overloading

In C++, you can overload the ++ and – operators.

```
class X {
public:
  X& operator++();
  const X operator++(int);
...
};

X x;
++x; // x.operator++();
x++; // x.operator++(0);
```

Common Increment Implementations

Prefix is also known as **increment and fetch**.

```
X& X::operator++()
{
  *this += 1;
  return *this;
}
```

Postfix is also known as **fetch and increment**.

```
const X X::operator++(int)
{
  const X old = *this;
  ++(*this);
  return old;
}
```

Efficiency

If you're the least concerned about efficiency, always use **prefix** increments/decrements instead of defaulting to postfix.

Only use `postfix` when you really mean it, to be on the safe side.

Digression: The Wayside

(Daderot, Wikimedia Commons)

It’s Not Just Software

Nathaniel Hawthorne wrote:

> *I have been equally unsuccessful in my architectural projects; and have transformed a simple and small old farm-house into the absurdest anomaly you ever saw; but I really was not so much to blame here as the ~~programmer~~ village-carpenter, who took the matter into his own hands, and produced an unimaginable sort of thing instead of what I asked for. (January 1864)*

Original budget:	\$500	(\$7540 inflation-adjusted)
Actual cost:	\$2000	(\$30160 inflation-adjusted)

Locking

Locks prevent data races.

- Locks' extents constitute their **granularity**—do you lock large sections of your program with a big lock, or do you divide the locks and protect smaller sections?

Concerns when using locks:

- overhead;
- contention; and
- deadlocks.

Locking: Overhead

Using a lock isn't free. You pay:

- allocated memory for the locks;
- initialization and destruction time; and
- acquisition and release time.

These costs scale with the number of locks that you have.

Locking: Contention

Most locking time is wasted waiting for the lock to become available.

How can we fix this?

- Make the locking regions smaller (more granular);
- Make more locks for independent sections.

The more locks you have, the more you have to worry about deadlocks.

Key condition:
    waiting for a lock held by process X
while holding a lock held by process X'. ($X = X'$ allowed).

Formal Deadlock Definition

The four conditions for deadlock are:

1. **Mutual Exclusion**
2. **Hold-and-Wait**
3. **No Preemption**
4. **Circular-Wait**

Does this look familiar?

Consider two processors trying to get two *locks*:

Thread 1	**Thread 2**
`Get Lock 1`	`Get Lock 2`
`Get Lock 2`	`Get Lock 1`
`Release Lock 2`	`Release Lock 1`
`Release Lock 1`	`Release Lock 2`

Processor 1 gets Lock 1, then Processor 2 gets Lock 2. Oops! They both wait for each other (deadlock).

Key to Preventing Deadlock

Always be careful if
your code **acquires a lock while holding one**.

Here's how to prevent a deadlock:

- Ensure consistent ordering in acquiring locks; or
- Use `trylock`.

Preventing Deadlocks—Ensuring Consistent Ordering

```
void f1() {
    lock(&l1);
    lock(&l2);
    // protected code
    unlock(&l2);
    unlock(&l1);
}

void f2() {
    lock(&l1);
    lock(&l2);
    // protected code
    unlock(&l2);
    unlock(&l1);
}
```

This code will not deadlock: you can only get **l2** if you have **l1**.

Formal Lock Ordering

If the set of all resources in the system is $R = \{R_0, R_1, R_2, ...R_m\}$:

Assign to each resource R_k a unique integer value. Let us define this function as $f(R_i)$, that maps a resource to an integer value.

This integer value is used to compare two resources: if a process has been assigned resource R_i, that process may request R_j only if $f(R_j) > f(R_i)$.

If the process needs more than one of R_i then the request for all of these must be made at once (in a single request).

To get R_i when already in possession of a resource R_j where $f(R_j) > f(R_i)$, the process must release any resources R_k where $f(R_k) \geq f(R_i)$.

If these two protocols are followed, then a circular-wait condition cannot hold.

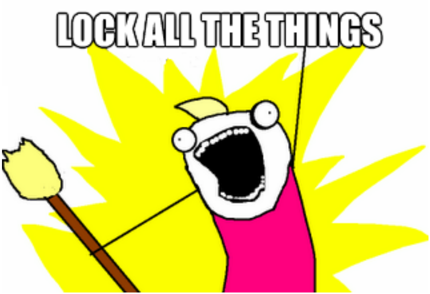
Preventing Deadlocks—Using `trylock`

Recall: Pthreads' `trylock` returns 0 if it gets the lock.

```
void f1() {
    lock(&l1);
    while (trylock(&l2) != 0) {
        unlock(&l1);
        // wait
        lock(&l1);
    }
    // protected code
    unlock(&l2);
    unlock(&l1);
}
```

This code also won't deadlock: it will give up **l1** if it can't get **l2**.

(BTW: trylocks also enable measuring lock contention.)



(with one lock)

Coarse-Grained Locking (2)

Advantages:

- Easier to implement;
- No chance of deadlocking;
- Lowest memory usage / setup time.

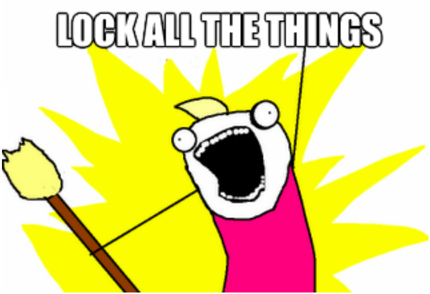
Disadvantages:

- Your parallel program can quickly become sequential.

Coarse-Grained Locking Example—Python GIL

This is the main reason (most) scripting languages have poor parallel performance; Python's just an example.

- Python puts a lock around the whole interpreter
  (global interpreter lock).
- Only performance benefit you'll see from threading is if a thread is waiting for IO.
- Any non-I/O-bound threaded program will be **slower** than the sequential version (plus, it'll slow down your system).



(with all different locks)

Fine-Grained Locking (2)

Advantages:

- Maximizes parallelization in your program.

Disadvantages

- May be mostly wasted memory / setup time.
- Prone to deadlocks.
- Generally more error-prone (be sure you grab the right lock!)

Fine-Grained Locking Examples

The Linux kernel used to have **one big lock**
that essentially made the kernel sequential.

- (worked fine for single-processor systems!)

Now uses finer-grained locks for performance.

Databases may lock fields / records / tables.
(fine-grained $\rightarrow$ coarse-grained).

Can lock individual objects.

Summary

C++11 memory model.
Good increment practice.
Lock granularity.