Lecture 20—Memory Models, Ordering, and Other Atomic Operations

ECE 459: Programming for Performance

February 25, 2015

Part I

Memory Models

Memory Models

Sequential program: statements execute in order.
Your expectation for concurrency: sequential consistency.

> *"... the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program." — Leslie Lamport*

In brief:

1. for each thread: in-order execution;
2. interleave the threads' executions.

No one has it: too expensive.
Recall the worked example for **flush** last time.

Memory Models: Sequential Consistency

Another view of sequential consistency:

- each thread induces an *execution trace*.
- always: program has executed some prefix of each thread's trace.

Reordering

Compilers and processors may reorder non-interfering memory operations.

$$T1 : x = 1; r1 = y;$$

If two statements are independent:

- OK to execute them in either order.
- (equivalently: publish their results to other threads).

Reordering is a major compiler tactic to produce speedup.

Memory Consistency Models

Sequential consistency:

- No reordering of loads/stores.

Sequential consistency for datarace-free programs:

- If your program has no data races, then sequential consistency.

Relaxed consistency (only some types of reorderings):

- Loads can be reordered after loads/stores; and
- Stores can be reordered after loads/stores.

Weak consistency:

- Any reordering is possible.

Still, **reorderings** only allowed if they look safe in current context (i.e. independent; different memory addresses).

2011 Final Exam Question

```
                        x = y = 0

/* thread 1 */                      /* thread 2 */
x = 1;                              y = x;
r1 = y;                             r2 = x;
```

Assume architecture not sequentially consistent
(weak consistency).

Show me all possible (intermediate and final) memory values and how they arise.

2011 Final Exam Question: Solution

must include every permutation of lines
(since they can be in any order);
then iterate over all the values.

Probably actually too long, but shows how memory reorderings complicate things.

The Compiler Reorders Memory Accesses

When it can prove safety, the **compiler** may reorder instructions (not just the hardware).

Example: want thread 1 to print value set in thread 2.

```
                                f = 0

/* thread 1 */                                  /* thread 2 */
while (f == 0) /* spin */;                      x = 42;
printf("%d", x);                                f = 1;
```

- If thread 2 reorders its instructions, will we get our intended result?

  No.

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- If thread 2 reorders its instructions, will we get our intended result?

  No.

Preventing Memory Reordering

A **memory fence** prevents memory operations from crossing the fence (also known as a **memory barrier**).

```
                                f = 0

/* thread 1 */                          /* thread 2 */
while (f == 0) /* spin */;              x = 42;
// memory fence                         // memory fence
printf("%d", x);                        f = 1;
```

- Now prevents reordering; get expected result.

Preventing Memory Reordering in Programs

Step 1: Don't use volatile on variables [1].

Syntax depends on the compiler.

- Microsoft Visual Studio C++ Compiler:

```
_ReadWriteBarrier()
```

- Intel Compiler:

```
    __memory_barrier()
```

- GNU Compiler:

```
__asm__ __volatile__ ("" ::: "memory");
```

The compiler also shouldn't reorder
across e.g. Pthreads mutex calls.

[1] http://stackoverflow.com/questions/78172/using-c-pthreads-do-shared-variables-need-to-be-volatile.

Aside: gcc Inline Assembly

Just as an aside, here's gcc's inline assembly format

```
__asm__ ( assembler template
        : output operands                    /* optional */
        : input operands                     /* optional */
        : list of clobbered registers        /* optional */
        );
```

Last slide used **__volatile__** with __asm__. This isn't the same as the normal C volatile. It means:

- The compiler may not reorder this assembly code and put it somewhere else in the program

Memory Fences: Preventing Hardware Memory Reordering

Memory barrier: no access after the barrier becomes visible to the system (i.e. takes effect) until after all accesses before the barrier become visible.

Note: these are all x86 `asm` instructions.

`mfence`:

- All loads and stores before the fence finish before any more loads or stores execute.

`sfence`:

- All stores before the fence finish before any more stores execute.

`lfence`:

- All loads before the fence finish before any more loads execute.

Preventing Hardware Memory Reordering (Option 2)

Some compilers also support preventing hardware reordering:

- Microsoft Visual Studio C++ Compiler:

```
MemoryBarrier();
```

- Solaris Studio (Oracle) Compiler:

```
__machine_r_barrier();
__machine_w_barrier();
__machine_rw_barrier();
```

- GNU Compiler:

```
__sync_synchronize();
```

Memory Barriers and OpenMP

Fortunately, an OpenMP **flush** (or, better yet, mutexes) also preserve the order of variable accesses.

Stops reordering from both the compiler and hardware.

For GNU, flush is implemented as `__sync_synchronize();`

Note: proper use of memory fences makes `volatile` not very useful (again, `volatile` is not meant to help with threading, and will have a different behaviour for threading on different compilers/hardware).

Part II

Atomic Operations

Atomic Operations

We saw the **atomic** directive in OpenMP.

Most OpenMP atomic expressions map to atomic hardware instructions.

Other atomic instructions exist.

Compare and Swap

Also called **compare and exchange** (`cmpxchg` instruction).

```
int compare_and_swap (int* reg, int oldval, int newval)
{
  int old_reg_val = *reg;
  if (old_reg_val == oldval)
     *reg = newval;
  return old_reg_val;
}
```

- Afterwards, you can check if it returned `oldval`.
- If it did, you know you changed it.

Implementing a Spinlock

Use compare-and-swap to implement spinlock:

```
void spinlock_init(int* l) { *l = 0; }

void spinlock_lock(int* l) {
    while(compare_and_swap(l, 0, 1) != 0) {}
    __asm__ ("mfence");
}

void spinlock_unlock(int* int) {
    __asm__ ("mfence");
    *l = 0;
}
```

You'll see **cmpxchg** quite frequently in the Linux kernel code.

ABA Problem

Sometimes you'll read a location twice.

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ABA Problem

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If the value is the same, nothing has changed, right?
No. This is an **ABA problem**.

You can combat this by "tagging": modify value with nonce upon each write.

Can keep value separately from nonce; double compare and swap atomically swaps both value and nonce.

Just something to be aware of. "Not on exam".

Part III

C++11 Memory Model

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);
```

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```

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[2]:

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

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

[2] 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!)

Part IV

Good C++ Practice

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.

Summary

Memory ordering:

- Sequential consistency;
- Relaxed consistency;
- Weak consistency.

How to prevent memory reordering with fences.
Other atomic operations.
C++11 memory model.
Good increment practice.