Threads and Shared Variables in C++11 and elsewhere

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Credits:

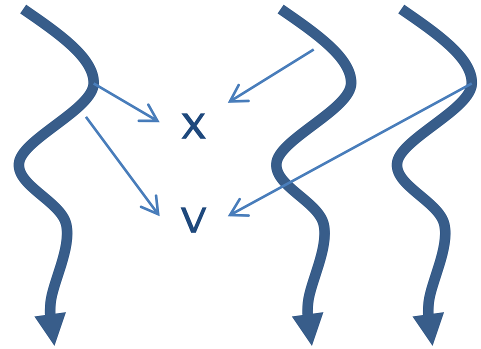
- This describes work done by many people, mostly as part of the ISO C++ standards committee. Other major contributors include: Lawrence Crowl (Sun/Google), Clark Nelson(Intel), Herb Sutter(Microsoft), Paul McKenney(IBM).
- Some of it is heavily based on earlier academic research, notably by Sarita Adve
- … and that doesn’t include the many people who worked on other parts of the language, such as the threads API itself.

Outline

- Overview
- C++11 Threads API (very briefly)
- C++11/C11 Memory model
- Understanding data races
- Atomic objects
- A word about Java
- Conclusions

What are threads?

- Multiple instruction streams (programs) that share memory.
- Static variables, and everything they point to, are shared between them.
- Each thread has its own stack and thread-local variables.



Why threads?

- Controversial:
  - "Threads are evil" gets around 20K Google hits, but
- Threads are a convenient way to process multiple event streams, and
- The dominant way to take advantage of multiple cores for a single application.

Naive threads programming model (Sequential Consistency)

- Threads behave as though their operations were simply interleaved. (Sequential consistency)

Thread 1

```
x = 1;
z = 3;
```

Thread 2

```
y = 2;
r1 = x;
```

  – might be executed as

```
x = 1; y = 2; r1 = x; z = 3;
```

Pre-C++11/C11 Threads in C & C++

- Single-threaded language + Threads API
  - e.g. Posix, Windows
- Exact meaning of shared variables unclear:

```
char x, y;  // Class members
```

Thread 1	*Thread 2*
`x = 1;`	`y = 1;`

Are `x` and `y` set to 1 when both finish?

- Posix: Implementation defined. Windows: ???

- + Much more complicated ways for things to go wrong (very rarely)
- No consistent story to teach programmers.

Threads in C++11

- Threads are finally part of the language! (C11, too)
- Threads API
  - Thread creation, synchronization, …
  - Evolved from `Boost.Thread`.
- Memory model
  - Carefully defines shared variable behavior.
    - Still not quite the naïve sequential consistency model.
- Atomic operations
- Condition variables, `call_once`, `thread_local` variables, parallel constructor execution, thread-safe function-local statics

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Thread creation example:

```
int fib(int n) {
  if (n <= 1) return n;
  int fib1, fib2;
  thread t([=, &fib1]{fib1 = fib(n-1);});
  fib2 = fib(n-2);
  t.join();
  return fib1 + fib2;
}
```

Disclaimers:

- `fib(n-2)` throws ➔ no join ➔ bad things happen
- Don’t really do this! It creates too many threads.
- Easier to use `async()`, which returns a `future` .
- Runs in exponential time. There is an O(log(n)) algorithm.
  - Except that they all overflow for interesting inputs.

Thread creation rules

- Always call `join()`!
  - Language provides `detach()`, `quick_exit()`, but …
- Destroying an unjoined thread invokes `terminate()`.
  - Makes exceptions in parent much safer.
- Program terminates when main thread returns.

Mutual Exclusion

- Real multi-threaded programs usually need to access shared data from multiple threads.
- For example, incrementing a counter in multiple threads:

```
x = x + 1;
```

- Unsafe if run from multiple threads:

```
tmp = x; // 17
                            tmp = x;   // 17
x = tmp + 1; // 18
                            x = tmp + 1; // 18
```

Mutual Exclusion (contd)

- Standard solution:
  - Limit shared variable access to one thread at a time, using locks.
  - Only one thread can be holding lock at a time.

Mutexes restrict interleavings

Thread 1

```
m.lock();
r1 = x;
x = r1+1;
m.unlock();
```

Thread 2

```
m.lock();
r2 = x;
x = r2+1;
m.unlock();
```

– can only be executed as

```
m.lock(); r1 = x; x = r1+1; m.unlock();
m.lock(); r2 = x; x = r2+1; m.unlock();
```

or

```
m.lock(); r2 = x; x = r2+1; m.unlock();
m.lock(); r1 = x; x = r1+1; m.unlock();
```

since second `m.lock()` must follow first `m.unlock()`

Counter with C++11 `mutex`

```
mutex m;

void increment() {
   m.lock();
   x = x + 1;
   m.unlock();
}
```

- Lock not released if critical section throws.

Counter with a `lock_guard`

```
mutex m;

void increment() {
   lock_guard<mutex> _(m);
   x = x + 1;
}
```

- Lock is released in destructor.
- `unique_lock<>` is a generalization of `lock_guard<>`.

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Let’s look back more carefully at shared variables

- So far threads are executed as though thread steps were just interleaved.
  - *Sequential consistency*
- But this provides expensive guarantees that reasonable code can’t take advantage of.

Limits reordering and other hardware/compiler transformations

- "Dekker's" example (everything initially zero) should allow `r1` = `r2` = 0:

Thread 1	*Thread 2*
`x = 1;`	`y = 1;`
`r1 = y;`	`r2 = x;`

- Compilers like to perform loads early.
- Hardware likes to buffer stores.

Sensitive to memory access granularity

Thread 1

```
x = 300;
```

Thread 2

```
x = 100;
```

- If memory is accessed a byte at a time, this may be executed as:

```
x_high = 0;
x_high = 1;    // x = 256
x_low =  44;   // x = 300;
x_low = 100;   // x = 356;
```

And this is at too low a level …

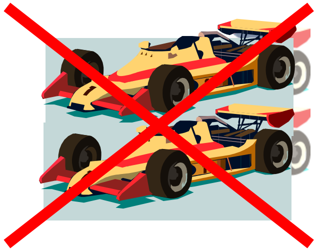
- Taking advantage of sequential consistency involves reasoning about memory access interleaving:
  - Much too hard.
  - Want to reason about larger “atomic” code regions
    - which can’t be visibly interleaved.

Real threads programming model
(1) Data race definition

- Two memory accesses conflict if they
  - access the same scalar object*, e.g. variable.
  - at least one access is a store.
  - E.g. `x = 1;` and `r2 = x;` conflict
- Two ordinary memory accesses participate in a data race if they
  - conflict, and
  - can occur simultaneously
    - i.e. appear as adjacent operations by different threads in interleaving.
- A program is data-race-free (on a particular input) if no sequentially consistent execution results in a data race.

* or contiguous sequence of bit-fields

Real threads programming model (2) A useful restriction



- Sequential consistency only for data-race-free programs!
- Catch-fire semantics for data races!

- Data races are prevented by
  - mutexes (or atomic sections) to restrict interleaving
  - declaring `atomic` (synchronization) variables
    - (wait a few slides…)
- In C++11, there are ways to explicitly relax the sequential consistency guarantee.

Dekker's example, again:

- (everything initially zero):

Thread 1	*Thread 2*
`x = 1;`	`y = 1;`
`r1 = y; //` reads 0	`r2 = x;  //` reads 0

- This has a data race:
  - `x` and `y` can be simultaneously read and updated.
- Has undefined behavior.
- Unless `x` and `y` are declared to have `atomic` type.
  - In which case the compiler has to do what it takes to preclude this outcome.

Data races ➔ undefined behavior: Very strange things may happen

```
unsigned x;

If (x < 3) {
   … // async x change
   switch(x) {
      case 0: …
      case 1: …
      case 2: …
   }
}
```

- Assume switch statement compiled as branch table.
- May assume x is in range.
- Asynchronous change to x causes wild branch.
  - Not just wrong value.

SC for DRF programming model advantages over SC

- Supports important hardware & compiler optimizations.
- DRF restriction ➔ Synchronization-free code sections appear to execute atomically, i.e. without visible interleaving.
  - If one didn't:

Thread 1 (not atomic):

```
a = 1;

b = 1;
```

race!

Thread 2(observer):

```
if (a == 1 && b == 0) {
    …
}
```

Basic Implementation model

- Very restricted reordering of memory operations around synchronization operations:
  - Compiler either understands these, or treats them as opaque(potentially updating any location).
  - Synchronization operations include instructions to limit or prevent hardware reordering (“memory fences”).
- Other reordering is invisible:
  - Only racy programs can tell.

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Understanding data races

- To show that a program behaves correctly:
  1. Demonstrate there are no data races
     - assuming sequential consistency
  2. Demonstrate that it behaves correctly
     - Assuming sequential consistency, and
     - Assuming synchronization-free-regions are indivisible

- Some examples:

- Assume x and done are initially 0/false.
- Consider:

Thread 1

```
x = 42;
done = true;
```

Thread 2

```
while (!done) {}
assert(x == 42);
```

Data race on done.

Frequently breaks repeatably in practice.

Lazy initialization and DCL

- Assume `x` and `initd` are initially 0/false.
- Consider:

Thread 1

```
if (!initd) {
  lock_guard<mutex> _(m);
  x = 42;
  initd = true;
}
read x;
```

Thread 2

```
if (!initd) {
  lock_guard<mutex> _(m);
  x = 42;
  initd = true;
}
read x;
```

Data race on `initd`.

Often works in practice, but not reliable.

- *Assume* `x` *and* `y` *are initially zero.*
- Consider:

Thread 1

```
if (x)
  y = 1;
```

Thread 2

```
if (y)
  x = 1;
```

No data race.

But that was unclear before C++11.

- `struct { char a; char b; } x;`

- Consider:

Thread 1	*Thread 2*
`x.a = 1;`	`x.b = 1;`

No data race in C++11 or C11.

But there may be one under older Posix rules.

- `struct { int a:8; int b:8; } x;`

- Consider:

Thread 1	*Thread 2*
`x.a = 1;`	`x.b = 1;`

Data race!

- `struct { char a; int b:11; } x;`
- Consider:

Thread 1	*Thread 2*
`x.a = 1;`	`x.b = 1;`

No data race.

But existing compilers commonly introduce a data race.

- `list<int> x;`

- Consider:

Thread 1	*Thread 2*
`x.push_front(1);`	`x.pop_front();`

Data Race.

Data races are defined for scalar accesses.

Default rule for libraries:

Race on scalars ↔ Race on object

- `list<int> x;   mutex m;`

- Consider:

Main Thread

occasionally

```
{ lock_guard<mutex> _(m);
  x.push_front(1);
}
```

Thread 2

```
for(;;) {
  lock_guard<mutex> _(m);
  if(!x.empty()) …
}
```

Data Race.

Thread 2 races with `x`*'s destructor.*

(That's why `thread::detach()` is discouraged.)

- Consider:

Thread 1

```
for (;;) {}
x = 1;
```

Thread 2

```
x = 2;
```

No data race

but undefined behavior anyway.

Infinite loops that perform neither IO nor synchronization have undefined behavior!

- `int x; mutex m;`

- Consider:

Thread 1

```
x = 42;
m.lock();
```

Thread 2

```
while(m.try_lock())
  m.unlock();
assert(x == 42);
```

Data Race.

`try_lock()` may fail spuriously.

(Reality is complicated. This simple rule works.)

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Atomic objects

- Pthreads programs
  - Should not have data races
  - Frequently have intentional data races
- Problem:
  - Lock-based synchronization often perceived as too heavy weight.
- C++11/C11 solution: atomic objects
  - Allow concurrent access
    - Do not participate in data races.
  - By default preserve simple sequentially consistent behavior

A note on naming

- Roughly similar (synchronization variables):
  - C++11 `atomic<t>, atomic_??`
  - C11 `_Atomic(t), atomic_??`
  - Java `volatile` (or `j.u.c.atomic`)
- Related, but profoundly different:
  - C# `volatile`
  - OpenMP 3.1 `atomic`
- Unrelated (at least officially):
  - C & C++ `volatile`

C++0x atomics

```
template< T > struct atomic {
  // GREATLY simplified
  constexpr atomic( T ) noexcept;
  atomic( const atomic& ) = delete;
  atomic& operator =( const atomic& ) = delete;
  void store( T ) noexcept;
  T load( ) noexcept;
  T operator =( T ) noexcept;   // similar to store()
  T operator T () noexcept;   // equivalent to load()
  T exchange( T ) noexcept;
  bool compare_exchange_weak( T&, T) noexcept;
  bool compare_exchange_strong( T&, T) noexcept;
  bool is_lock_free() const noexcept;
};
```

C++0x atomics, contd

- Integral, pointer specializations add atomic increment operators.
- Atomic to atomic assignment intentionally not supported.
  - But it is in C11!

Counter with atomic object

```
atomic<int> x;

void increment() {
  x++;  // not x = x + 1
}
```

Dekker's example, version 2

`atomic<int> x,y;` // initially zero

Thread 1	*Thread 2*
`x = 1;`	`y = 1;`
`r1 = y;`	`r2 = x;`

- No data races.
- ***Disallows*** `r1` = `r2` = 0.
- Compiler and hardware do whatever it takes.

Done flag, version 2

```
int x;                    // initially zero
atomic<bool> done;        // initially false
```

Thread 1

```
x = 42;
done = true;
```

Thread 2

```
while (!done) {}
assert(x == 42);
```

- No data races. Works.
- Compiler and hardware do whatever it takes.

Lazy initialization version 2

```
atomic<bool> initd; // initially false.
int x;
```

Thread 1

```
if (!initd) {
  lock_guard<mutex> _(m);
  x = 42;
  initd = true;
}
read x;
```

Thread 2

```
if (!initd) {
  lock_guard<mutex> _(m);
  x = 42;
  initd = true;
}
read x;
```

No data race.

C++11 explicitly ordered (low-level) atomics

- Problem:
  - “Do whatever it takes” (ensuring SC) can be expensive.
    - At least on some current hardware.
    - Though less so on modern x86 hardware.
    - And the cost appears to be decreasing.
- “Solution”:
  - Allow programmers to explicit relax sequential consistency.
  - Programs no longer behave as though threads were simply interleaved.
  - Much more complicated & bug-prone.
    - Complexity is hard to localize.
  - Sometimes significantly faster on current hardware.

done flag, version 3?

```
atomic<bool> done;
int x;
```

Thread 1:

```
x = 42;
done.store(true, memory_order_release);
```

Thread 2:

```
while (!done.load(memory_order_acquire)) {}
assert (x == 42);
```

Details not covered here.

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Data Races in Java

- C++0x leaves data race semantics undefined.
  - “catch fire” semantics
- Java supports sand-boxed code.
- Don’t know how to prevent data-races in sand-boxed, malicious code.
- Java must provide some guarantees in the presence of data races.

This is hard!

- Want
  - Constrained race semantics for essential security properties.
  - Unconstrained race semantics to support compiler and hardware optimizations.
  - Simplicity.
- No known good solution.

Java 2005 “Solution”

See

http://docs.oracle.com/javase/specs/jls/se7/html/jls-17.html#jls-17.4.8

- The good news:
  - Sequential consistency for data-race-free programs.
- The bad news:
  - Data race semantics are broken.
    - Main theorem about compiler optimizations is wrong. (Aspinall&Sevcik 2007)
    - Other issues.
    - Too complicated …
  - We don’t really know how to fix it.
- Avoid data races!
  - Also in Java.

Conclusions

- C++11 and C11 are (finally!) multithreaded languages.
- Shared variables are (finally!) well-defined.
  - No matter which API you use!
- Atomics make it easier to write data-race-free programs.
- C++ “Catch fire” data-races are a useful compromise:
  - Programs should be data-race-free anyway.
  - We don’t know how to define data race semantics.
  - Unlike Java, we have (mostly) sound shared-variable semantics.
  - But behavior of buggy programs is completely unconstrained.
    - Unhelpful for debugging
    - Like C arrays and bounds checking …
- Java data races aren’t really defined either.
- Data races are evil!

Questions?

- For more information:

Easily understandable

  - Boehm, Adve, You Don't Know Jack About Shared Variables or Memory Models , Communications of the ACM, Feb 2012.
  - Boehm, “Threads Basics”, HPL TR 2009-259.
  - Adve, Boehm, “Memory Models: A Case for Rethinking Parallel Languages and Hardware, Communications of the ACM, August 2010.
  - Boehm, Adve, “Foundations of the C++ Concurrency Memory Model”, PLDI 08.
  - Mark Batty, Scott Owens, Susmit Sarkar, Peter Sewell, and Tjark Weber, “Mathematizing C++ Concurrency”, POPL 2011.

C++ specific

Mathematically rigorous

A safer way to write parallel `fib()`

```
int fib(int n) {
  if (n <= 1) return n;
  int fib2;
  auto fib1 =
     async([=]{return fib(n-1);});
  fib2 = fib(n-2);
  return fib1.get() + fib2;
}
```

New compiler restrictions

- Single thread compilers currently may add data races: (PLDI 05)

```
struct {char a; char b} x;
```

```
x.a = 'z';
```

→

```
tmp = x;
tmp.a = 'z';
x = tmp;
```

  - `x.a = 1` in parallel with `x.b = 1` may fail to update x.b.
- Still broken in gcc in subtle cases involving bit-fields.

Some restrictions are a bit more annoying:

- Compiler may not introduce "speculative" stores:

```
int count;   // global, possibly shared
…
for (p = q; p != 0; p = p -> next)
   if (p -> data > 0) ++count;
```

```
int count;   // global, possibly shared
…
reg = count;
for (p = q; p != 0; p = p -> next)
   if (p -> data > 0) ++reg;
count = reg; // may spuriously assign to count
```

Also some hardware restrictions

- Multiprocessors need fast byte stores.
- Should be able to implement sequential consistency without locks, e.g. by adding fences.
  - You might have thought this was obvious …
  - Took years to confirm for X86, PowerPC!

Safe uses for low-level atomics

- Use `memory_order_relaxed` if no concurrent access to an atomic is possible.
- Use `memory_order_relaxed` to atomically update variables (e.g. increment counters) that are only read with synchronization.
- Use `memory_order_release` / `memory_order_acquire`, when it's OK to ignore the update, at least for some time (?)

C++0x fine-tuned double-checked locking

```
atomic<bool> x_init;

if (!x_init.load(memory_order_acquire) {
   l.lock();
   if (!x_init.load(memory_order_relaxed) {
      initialize x;
      x_init.store(true, memory_order_release);
   }
   l.unlock();
}
use x;
```