CS-453 (project)

Memory ordering

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Order?

A single thread

```
// Single thread

int a = 0;
int b = 0;
print(a, b); // a = 0, b = 0

a = 1;
print(a, b); // a = ·, b = ·

b = 1;
print(a, b); // a = ·, b = ·
```

Order?

A single thread

```
// Single thread

int a = 0;
int b = 0;
print(a, b); // a = 0, b = 0

a = 1;
print(a, b); // a = 1, b = 0

b = 1;
print(a, b); // a = ·, b = ·
```

Order?

A single thread

```
// Single thread

int a = 0;
int b = 0;
print(a, b); // a = 0, b = 0

a = 1;
print(a, b); // a = 1, b = 0

b = 1;
print(a, b); // a = 1, b = 1
```

Order?

Two threads

```
// Global var.

int a = 0;
int b = 0;

// Thread A

a = 1; // write
b = 1; // write
```

```
// Thread B

auto v = b; // read
if (v == 1) {
     print(a, v); // read
     // a = 1, v = 1   □
     // a = 1, v = 0
     // a = 0, v = 1
     // a = 0, v = 0
}
```

Order?

Two threads

```
// Global var.

int a = 0;
int b = 0;

// Thread A

a = 1; // write
b = 1; // write
```

```
// Thread B

auto v = b; // read
if (v == 1) {
     print(a, v); // read
     // a = 1, v = 1   ☑
     // a = 1, v = 0
     // a = 0, v = 1
     // a = 0, v = 0
}
```

Order?

Two threads

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// Global var.

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int b = 0;

// Thread A

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b = 1; // write
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```
// Thread B

auto v = b; // read
if (v == 1) {
     print(a, v); // read
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     // a = 1, v = 0   ☐
     // a = 0, v = 1
     // a = 0, v = 0
}
```

Order?

Two threads

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     // a = 0, v = 1
     // a = 0, v = 0
}
```

Order?

Two threads

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     // a = 0, v = 1   ☐
     // a = 0, v = 0
}
```

Order?

Two threads

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// Thread B

auto v = b; // read
if (v == 1) {
     print(a, v); // read
     // a = 1, v = 1   ☑
     // a = 1, v = 0   ☐
     // a = 0, v = 1   ☑
     // a = 0, v = 0
}
```

Order?

Two threads

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```

Order?

Two threads

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a = 1; // write
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// Thread B

auto v = b; // read
if (v == 1) {
     print(a, v); // read
     // a = 1, v = 1   ☑
     // a = 1, v = 0   ☐
     // a = 0, v = 1   ☑
     // a = 0, v = 0   ☐
}
```

But why complicated? ☹

But why complicated? ☹

Compiler/hardware reordering

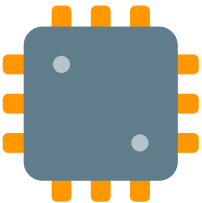
```
a = 1;
b = 1;
```

⇕

```
b = 1;
a = 1;
```

Memory consistency model?

Unrelated R/W (& R/R, W/W) could be carried out-of-order.



(More of that in other courses, e.g., CS-471.)

But why complicated? ☹

It even gets a bit worse...

```
// Global var.

int a = 0;
int b = 0;

// Thread A

a = 1; // write
b = 1; // write
```

```
// Thread B

auto v = b; // read
if (v == 1) {
    print(a, v); // read
    // a = 1, v = 1   ☑
    // a = 1, v = 0   ☐
    // a = 0, v = 1   ☑
    // a = 0, v = 0   ☐
}
```

U.B.!!

But why complicated? ☹

Main takeaway

C11/C++11 do **not** ensure "by default"

that reads/writes

are carried/observed

in program order

by different threads

C11/C++11's solutions ☺

C11/C++11's solutions ☺

Atomic variables

```
#include <atomic>

std::atomic<T> foo = T{};
```

With `T` being:

- Trivially copyable
- Copy and move constructible
- Copy and move assignable

C11/C++11's solutions ☺

Thread fences

Specifies constraints
on the ordering
of memory accesses

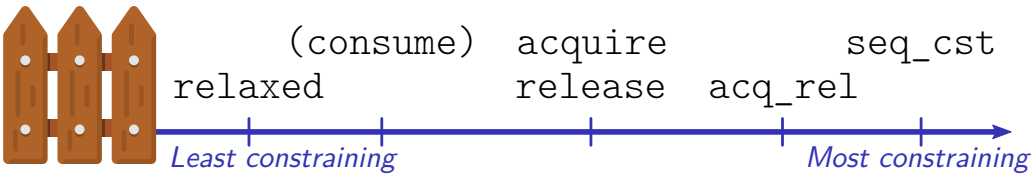
```
#include <atomic>

std::atomic_thread_fence(std::memory_order_/*...*/);

std::atomic<T> foo = T{};
foo.load(std::memory_order_/*...*/);
foo.store(T{}, std::memory_order_/*...*/);
```

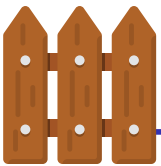
C11/C++11's solutions ☺

Thread fences



C11/C++11's solutions ☺

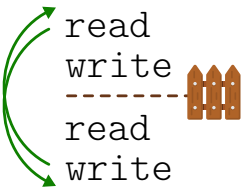
Thread fences



(consume) acquire seq_cst

relaxed release acq_rel

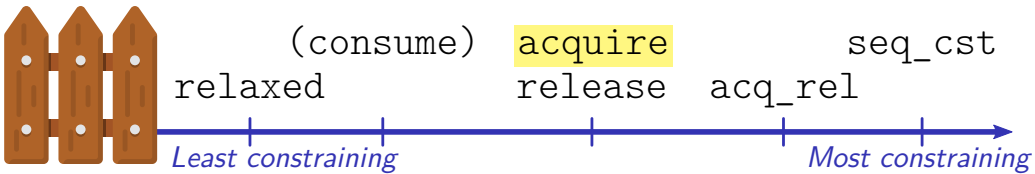
Least constraining *Most constraining*

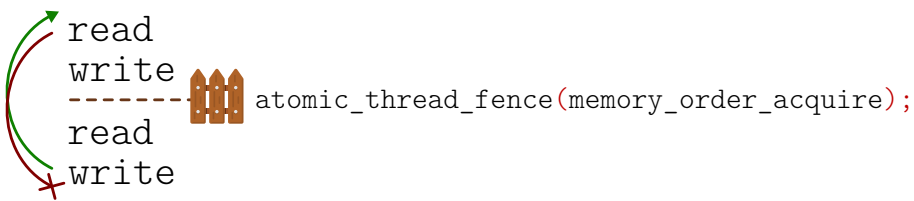



```
atomic_thread_fence(memory_order_relaxed);
```

C11/C++11's solutions ☺

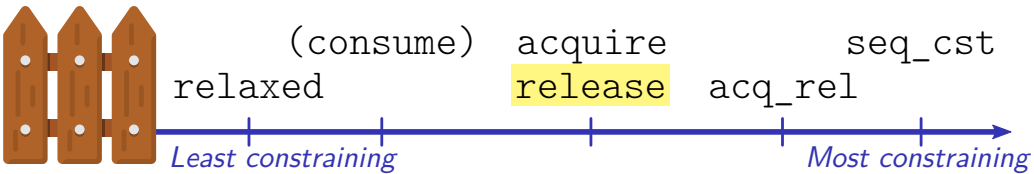
Thread fences

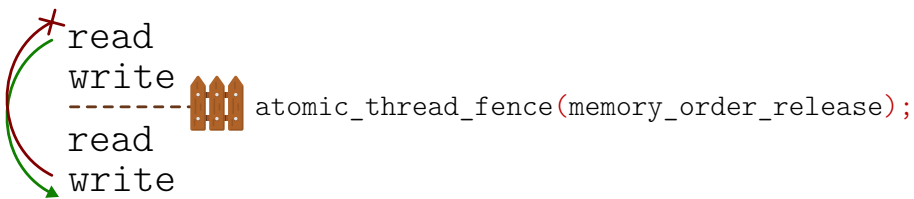




C11/C++11's solutions ☺

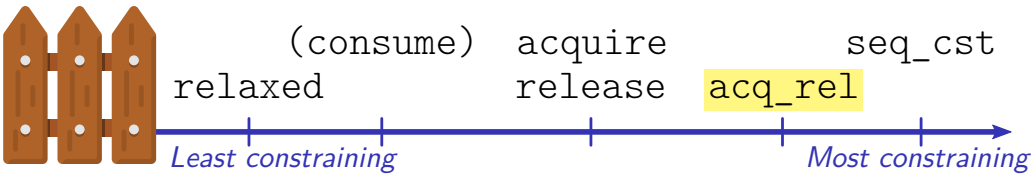
Thread fences

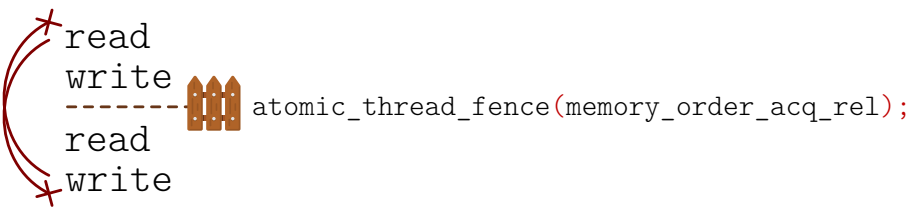




C11/C++11's solutions ☺

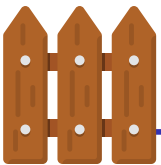
Thread fences





C11/C++11's solutions ☺

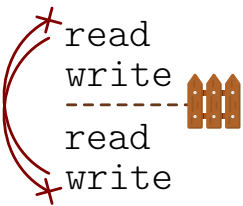
Thread fences



(consume) acquire seq_cst

relaxed release acq_rel

Least constraining *Most constraining*




```
atomic_thread_fence(memory_order_seq_cst);
```

total order

C11/C++11's solutions ☺

Thread experiment

```
// Global
a = 0;
b = 0;
c = 0;
d = 0;
```

```
// Threads {0,1}
print(a,c);
print(b,d);
b = 1;
a = 1;
```

```
// Threads {2,3}
print(a,c);
print(b,d);
d = 1;
c = 1;
```

C11/C++11's solutions ☺

Thread experiment

```
// Global
a = 0;
b = 0;
c = 0;
d = 0;
```

```
// Threads {0,1}
print(a,c);
print(b,d);
b = 1;
a = 1;
```

relaxed

relaxed

```
// Threads {2,3}
print(a,c);
print(b,d);
d = 1;
c = 1;
```

relaxed

relaxed

Values of (a,b,c,d) that could be read by threads 0 and 2

Thread 0:	1100	1100	1100	1001
Thread 2:	1100	1111	0011	0110

C11/C++11's solutions ☺

Thread experiment

```
// Global
a = 0;
b = 0;
c = 0;
d = 0;
```

```
// Threads {0,1}
print(a,c);
print(b,d);
b = 1;
a = 1;
```

acquire

relaxed

```
// Threads {2,3}
print(a,c);
print(b,d);
d = 1;
c = 1;
```

acquire

relaxed

Values of (a,b,c,d) that could be read by threads 0 and 2

Thread 0:	1100	1100	1100	1001
Thread 2:	1100	1111	0011	0110

C11/C++11's solutions ☺

Thread experiment

```
// Global
a = 0;
b = 0;
c = 0;
d = 0;
```

```
// Threads {0,1}
print(a,c);
print(b,d);
b = 1;
a = 1;
```


```
// Threads {2,3}
print(a,c);
print(b,d);
d = 1;
c = 1;
```

Values of (a,b,c,d) that could be read by threads 0 and 2

Thread 0:	1100	1100	1100	~~1001~~
Thread 2:	1100	1111	0011	~~0110~~

C11/C++11's solutions ☺

Thread experiment

```
// Global
a = 0;
b = 0;
c = 0;
d = 0;
```

```
// Threads {0,1}
print(a,c);
print(b,d);
b = 1;
a = 1;
```

seq_cst

seq_cst

```
// Threads {2,3}
print(a,c);
print(b,d);
d = 1;
c = 1;
```

seq_cst

seq_cst

Values of (a,b,c,d) that could be read by threads 0 and 2

Thread 0:	1100	1100	~~1100~~	~~1001~~
Thread 2:	1100	1111	~~0011~~	~~0110~~

Order!

Original code

```
// Global var.

int a = 0;
int b = 0;

// Thread A

a = 1; // write
b = 1; // write
```

```
// Thread B

auto v = b; // read
if (v == 1) {
     print(a, v); // read
     // a = 1, v = 1   ☑
     // a = 1, v = 0   ☐
     // a = 0, v = 1   ☑
     // a = 0, v = 0   ☐
}
```

Order!

Corrected code

```
// Global var.

#include <atomic>

int a = 0;
std::atomic<int> b = 0;

// Thread A

a = 1; // write
b = 1; // atomic write
```

```
// Thread B

auto v = b; // atomic read
if (v == 1) {
     print(a, v); // read
     // a = 1, v = 1   ☑
     // a = 1, v = 0   ☐
     // a = 0, v = 1   ☐
     // a = 0, v = 0   ☐
}
```

Order!

Corrected code

```
// Global var.

#include <atomic>

int a = 0;
std::atomic<int> b = 0;

// Thread A

a = 1; // write
b.store(1, release);
```

```
// Thread B

auto v = b.load( acquire );
if (v == 1) {
     print(a, v); // read
     // a = 1, v = 1   ☑
     // a = 1, v = 0   ☐
     // a = 0, v = 1   ☐
     // a = 0, v = 0   ☐
}
```

Order!

I want to know more

Here you go

- https://preshing.com/...
  - ... 20120612/an-introduction-to-lock-free-programming
  - ... 20120913/acquire-and-release-semantics
- https://en.cppreference.com/w/{c,cpp}/...
  - ... atomic{,/memory_order}
  - ... language/memory_model
- Memory Barriers: a Hardware View for Software Hackers, Paul E. McKenney

Next time

- *Read–Modify–Write* atomic primitives (e.g. compare & swap)
- Workshop: "Writing my own lock"