The C/C++ Memory Model: Overview and Formalization

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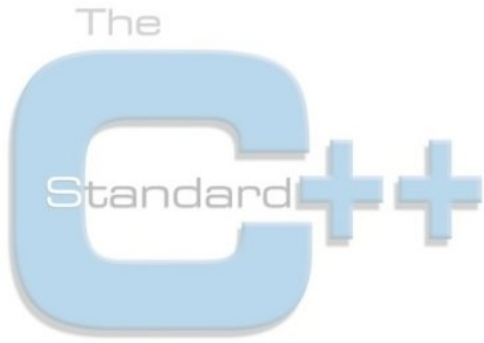
Verification of Concurrent C Programs

C11 / C++11

In 2011, new versions of the ISO standards for C and C++, informally known as C11 and C++11, were ratified.

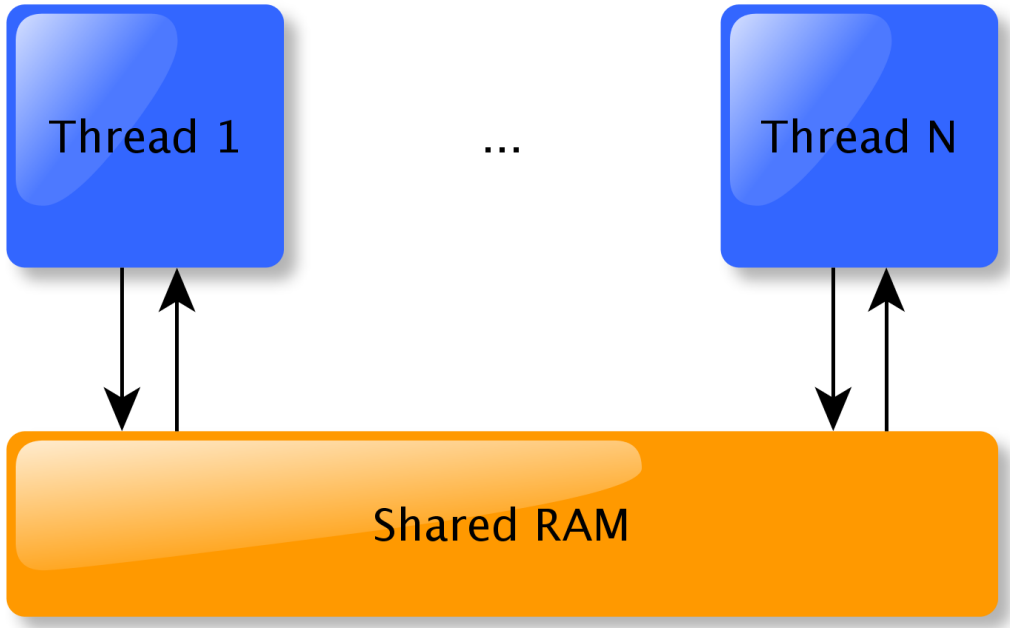
These standards define a memory model for C/C++.

Support for this model has recently become available in popular compilers (GCC 4.4, Intel C++ 13.0, MSVC 11.0, Clang 3.1).



Memory Models

A memory model describes the interaction of threads through shared data.



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."

Example (Dekker's algorithm)

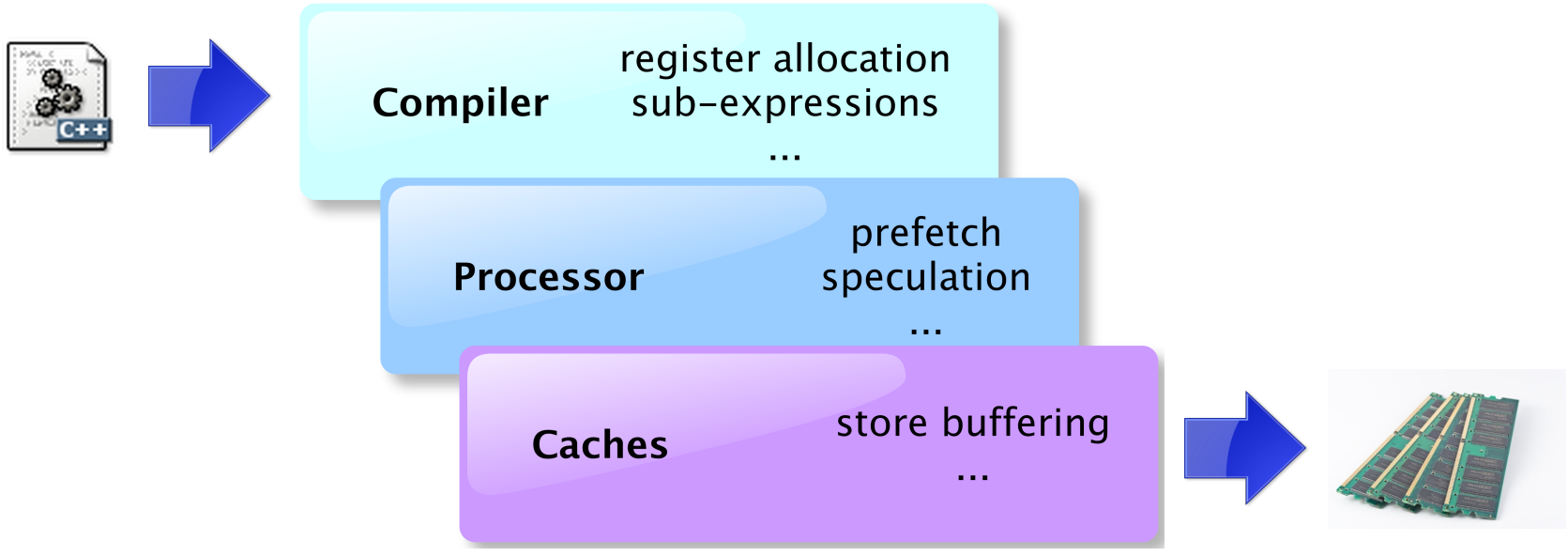
$$x = 0;\ y = 0;$$

$$\begin{array}{l} x = 1; \\ r1 = y; \end{array} \quad \Big\| \quad \begin{array}{l} y = 1; \\ r2 = x; \end{array}$$

$$\text{assert}\,(r1 == 1 \,||\, r2 == 1);$$

Real Hardware

Real hardware doesn't run the code that you wrote.



Concurrency in C/C++

- Pthreads 
- Hardware model 

- C11/C++11 

C11/C++11 Concurrency

Simple concurrency:

- Sequential consistency for data-race free code ($\rightarrow$ locks).
- Data races cause undefined behavior.

Expert concurrency:

- Atomic memory locations

Data Races

- Two (or more) threads concurrently[1] access the same memory location.
- At least one of the threads writes.

Example (Dekker's algorithm)

```
int x(0); int y(0);

x = 1;   ||   y = 1;
r1 = y;  ||   r2 = x;
```

[1] I.e., not ordered by happens-before.

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std :: atomic<T>

Operations:

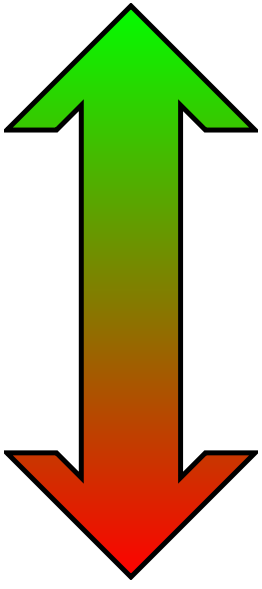
- x.load(memory_order)
- x.store(T, memory_order)

Concurrent accesses on atomic locations do not race.[1]

The memory_order argument specifies ordering constraints between atomic and non-atomic memory accesses in different threads.

[1] Except during initialization.

std :: memory_order



seq_cst — total order (SC for DRF code)

release / acquire
release / consume
} message passing

relaxed — no synchronization

std :: memory_order_seq_cst

There is a total order over all seq_cst operations. This order contributes to inter-thread ordering constraints.[1]

Example (Dekker's algorithm)

```
atomic_int x(0); atomic_int y(0);

x.store(1, seq_cst);          ||  y.store(1, seq_cst);
int r1 = y.load(seq_cst);     ||  int r2 = x.load(seq_cst);

assert(r1 == 1 || r2 == 1);
```

[1] Similar to memory_order_{release | acquire}.

std :: memory_order_release/acquire

An acquire load makes prior writes to other memory locations made by the thread that did the release visible in the loading thread.

Example (message passing)

```
int data(0); atomic_bool flag(false);

// sender                          || // receiver
data = 42;                         || while (!flag.load(acquire))
flag.store(true, release);         ||       {};
                                   || assert(data == 42);
```

std :: memory_order_consume

A consume load makes prior writes to data-dependent memory locations made by the thread that did the release visible in the loading thread.

Example (message passing)

```
int data(0); atomic<int*> p(0);

// sender                          ||  // receiver
data = 42;                         ||  while (p.load(consume) == 0)
p.store(&data, release );          ||        {};
                                   ||  assert(*p == 42);
```

std :: memory_order_relaxed

Relaxed operations impose very weak inter-thread ordering constraints ($\rightarrow$ coherence).

Example (message passing)

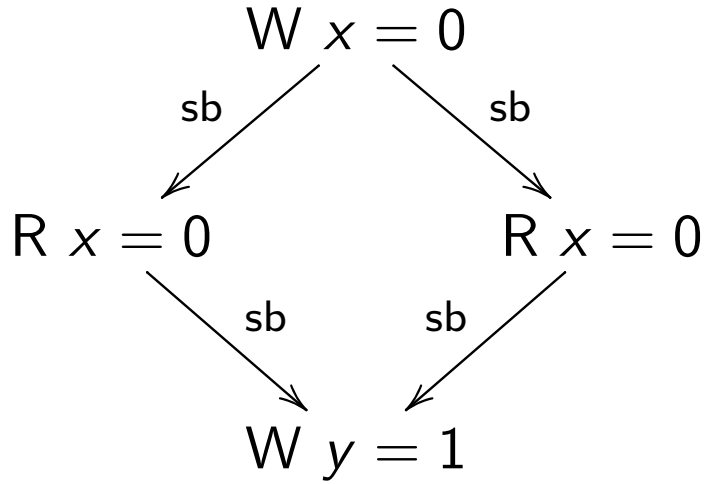
```
int data(0); atomic<int*> p(0);

// sender                          || // receiver
data = 42;                         || while (p.load(consume) == 0)
p.store(&data, release );          ||     while (p.load( relaxed ) == 0) ;
                                   || assert(*p == 42);
```

The Formal Model (1)

Program executions consist of memory actions. The program source determines several relations over these actions.

Example

```
int x = 0;
int y = (x == x);
```



The Formal Model (2)

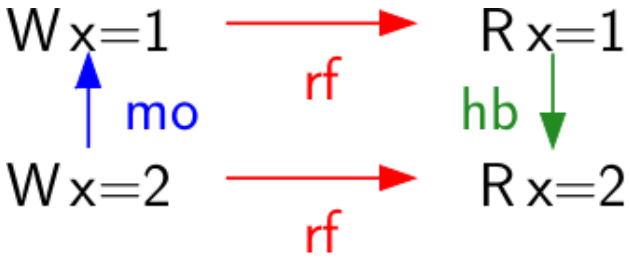
A candidate execution is specified by three relations:

- sc is a total order over all seq_cst actions.
- reads-from (rf) relates write actions to read actions at the same location that read the written value.
- For each atomic location, the modification order (mo) is a total order over all writes at this location.

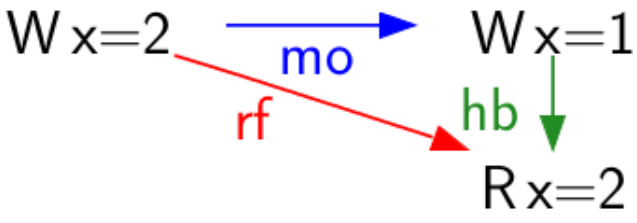
From these, various other relations (e.g., happens-before) are derived. The memory model imposes constraints on these relations.

Coherence

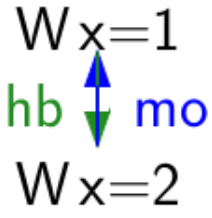
The following are all forbidden.



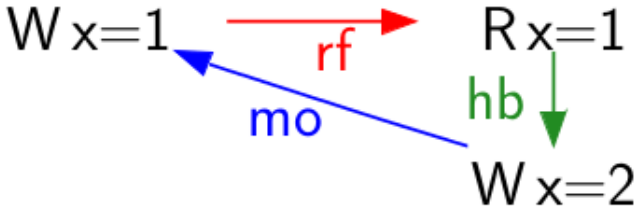
CoRR



CoWR



CoWW



CoRW

Program Semantics

Consider all consistent candidate executions.

If at least one of them has a data race,[2] the program has undefined behavior.

Otherwise, its semantics is the set of consistent candidate executions.

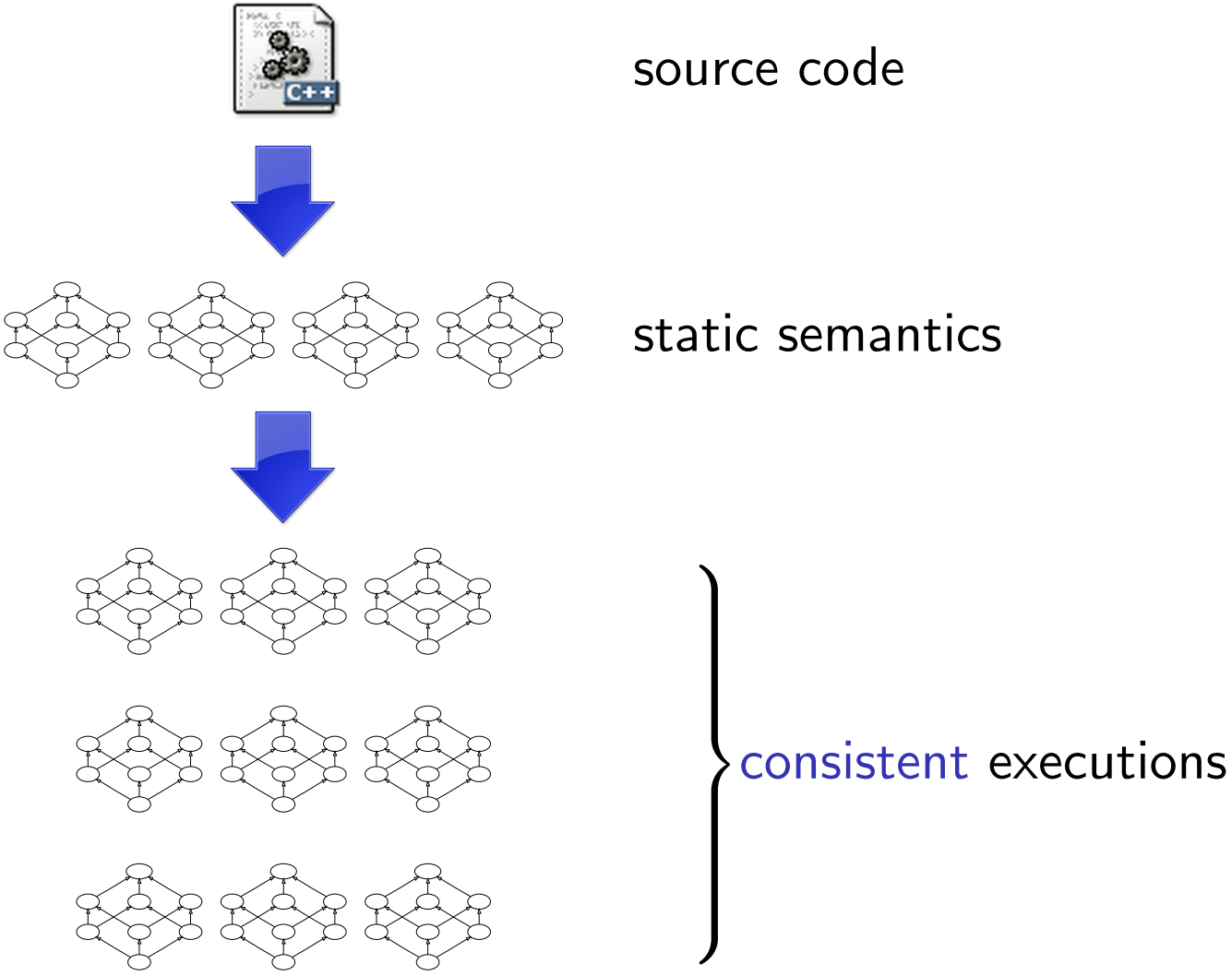
[2] There are actually several kinds.

Fine Points

- Fences
- Self-satisfying conditionals
- DRF in a SC semantics, but not DRF in C(++)11

```
atomic_int x(0);  atomic_int y(0);

if (x.load(seq_cst) == 1)        ||  if (y.load(seq_cst) == 1)
  atomic_init(&y,1);             ||    atomic_init(&x,1);
```

CppMem & Nitpick



Conclusion and Future Challenges

Since 2011, C and C++ have a memory model.

We have a formal (machine-readable, executable) version of this memory model.

- Compiler correctness
- Program transformations
- Static analysis
- Dynamic analysis
- Program logics
- Formal verification
- Equivalent models