The C++ Execution Model

Bryce Adelstein Lelbach

CppCon 2018

NVIDIA

Caveats

~~std::memory_order_consume~~

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Caveats

C++17 and beyond

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The As-If Rule

“Certain other operations are described in this document as undefined. [Note: This document imposes no requirements on the behavior of programs that contain undefined behavior. — end note]”

[intro.abstract] p4

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The Abstract Machine

The C++ abstract machine is a portable abstraction of your operating system, kernel and hardware.

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The Abstract Machine

The C++ abstract machine is a portable abstraction of your operating system, kernel and hardware.

The abstract machine is the intermediary between your C++ program and the system that it is run on.

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The Abstract Machine

```
int main()
{
  std::thread t(f);

  // ...
}
```

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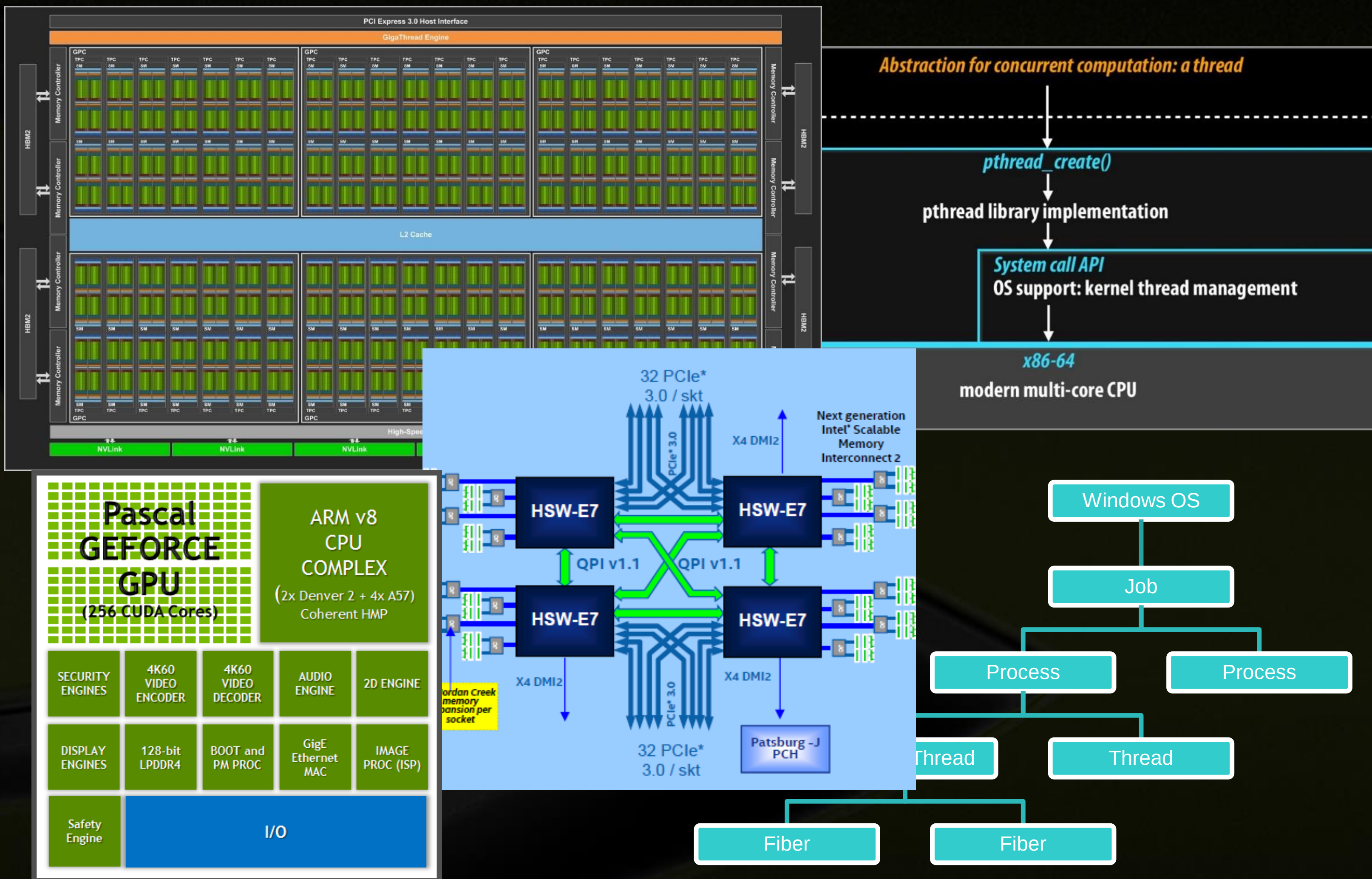
The Abstract Machine



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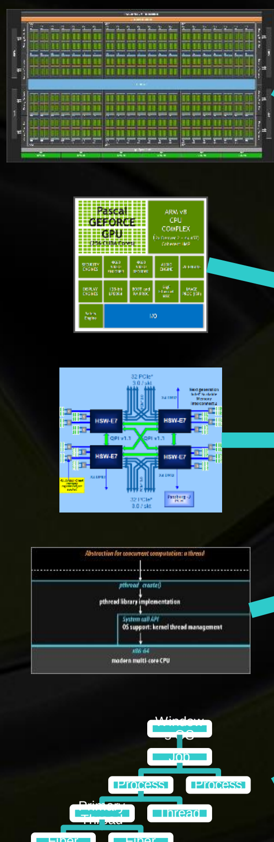
Source: anandtech.com, intel.com, cs.cmu.edu, slideshare.net

The Abstract Machine

Concrete Systems | **Abstract Machine** | **Portable Code**



Threads

Storage

```
int main()
{
  std::thread t(f);

  // ...
}
```

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The Abstract Machine

C++ programs describe operations that are performed on the abstract machine.

C++ implementations define the characteristics of the abstract machine and translate operations on the abstract machine into operations on the system.

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Storage Model

Storage is flat; no notion hierarchy (caches, etc).

Objects reside in storage at a single memory location.

[intro.object] p9

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Storage Model

Some objects may not have a unique memory location.

- **Eligible empty base classes.**
- **Objects marked `[[no_unique_address]]`.**

[intro.object] p7

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Storage Model

Under as-if, an implementation is allowed to store two objects at the same machine address or not store an object at all.

[basic.memobj] footnote 32

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Storage Model

An object cannot have more than one memory location.

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Storage Model

```
struct A {
  X x;

  X& X::operator=(X const& rhs)
  {
    if (&rhs == this) return *this;
    auto newx = new X(*rhs.x);
    delete x;
    x = newx;
    return *this;
  }
};
```

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Accessibility

Every thread in a program can potentially access every object and function in a program.

[intro.multithread] p1 s2

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Threads of Execution

A ***thread of execution*** is a single flow of control in a program which evaluates a function call; threads may run concurrently.

[intro.multithread] p1 s1

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Threads of Execution

A ***thread of execution*** **is a single flow of control in a program which evaluates a function call; threads may run concurrently.**

[intro.multithread] p1 s1

Main Thread of Execution

Evaluate `main()`

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Threads of Execution

A *thread of execution* is a single flow of control in a program which evaluates a function call; threads may run concurrently.

[intro.multithread] p1 s1

Main Thread of Execution

`std::thread t(f);`

Evaluate `main()`

Evaluate `f()`

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Threads of Execution

Variables with static storage duration are initialized as a consequence of program initiation. Variables with thread storage duration are initialized as a consequence of thread execution.

[basic.start.static] p1

Main Thread of Execution

Static storage initialization
Thread storage initialization
Evaluate `main()`
Thread storage destruction
Static storage destruction

`std::thread t(f);`

Thread storage initialization
Evaluate `f()`
Thread storage destruction

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Threads of Execution

Okay, so threads **evaluate** a function call.

What does it mean to **evaluate** a function call?

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Expressions

An ***expression*** is a sequence of operators and operands that specifies a computation.

[expr.pre] p1 s2

```
f();
f(a, b);

a + b;
// `operator+(a, b)` call.

T a = 2;
T a(2);
// `T::T(int)` call.
```

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Expressions

Subexpressions **are a part of a larger expression.**

[intro.execution] p3, p4

```
T a = (*f)(a + b, c);
```

```
T::T call
```

```
(*f)(a + b, c);
```

```
(*f)          a + b          c
```

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Expressions

Full expressions **are not subexpressions.**

[intro.execution] p5

```
if (a == T()) { … }
// Full expression includes:
// lvalue-to-rvalue conversion
// T-to-bool conversion
// operator==(T, T) call
```

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Expressions

Full expressions **are not subexpressions.**

[intro.execution] p5

```
if (a == T()) { … }
// Full expression includes:
// lvalue-to-rvalue conversion
// T-to-bool conversion
// operator==(T, T) call

{
  T b;
} // Full expression: T::~T
```

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Expressions

Full expressions **may include subexpressions that are not lexically part of the expression.**

[intro.execution] p6

```
void foo(T a = g());

foo();
// Full expression includes:
// g call
// T::T call
// f call
```

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Evaluations

Evaluation **of an expression includes value computations and the initiation of side effects.**

[intro.execution] p7 s2

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Evaluations

Side effects **change the environment:**

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Evaluations

Side effects **change the environment:**

- **Reading a `volatile` object or modifying any object.**

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Evaluations

Side effects **change the environment:**

- **Reading a `volatile` object or modifying any object.**
- **Calling a library I/O function.**

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Evaluations

Side effects **change the environment:**

- **Reading a `volatile` object or modifying any object.**
- **Calling a library I/O function.**
- **Calling a function that does any of the above.**

[intro.execution] p7 s1

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Evaluations

Value computations **are pure and have no observable effect.**

[intro.execution] p7 s2

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Evaluations

Completion of the execution of an evaluation does not imply completion of its side effects.

[intro.execution] p7 s3

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Evaluations

```
int a;
int b;
a = a + b;

cout << a * a;

foo(a + b);
```

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Sequenced Before

Given any two evaluations A and B within the same thread of execution, if A is ***sequenced before*** B, then the execution of A shall precede the execution of B.

[intro.execution] p8 s2

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Sequenced Before

The sequenced before relationship is…

- Asymmetric: A is sequenced before B does not imply that B is sequenced before A.

  [intro.execution] p8 s1

- Transitive: If A is sequenced before B and B is sequenced before C, then A is sequenced before C.

  [intro.execution] p8 s1

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Sequenced Before

Each full expression is sequenced before the next full expression in program order.

[intro.execution] p9

```
a;
b;
// a sequenced before b
```

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Sequenced Before

If A and B are *indeterminately sequenced*, then either A is sequenced before B or B is sequenced before A, but it is unspecified which. E.g. A and B are not interleaved.

[intro.execution] p8 s4

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Sequenced Before

If A and B are ***unsequenced***, then A is not ***sequenced before*** B and B is not ***sequenced before*** A. E.g. A and B may be **interleaved**.

[intro.execution] p8 s3

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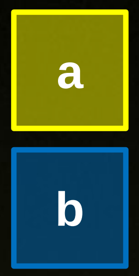
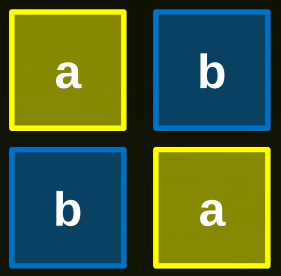
Sequenced Before

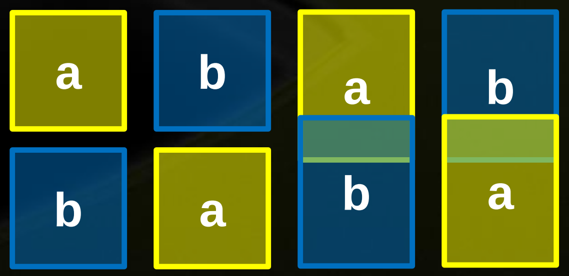
A is ***sequenced before*** B



A and B are
indeterminately sequenced



A and B are
unsequenced



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Sequenced Before

```
constexpr float a = // ...
std::vector<float> x = // ...
std::vector<float> y = // ...

std::for_loop(
  std::execution::seq,
  0, x.size(),
  [&] (int i) {
    y[i] += a * x[i];
  }
);
```

load y[i]
load x[i]
fma a * x[i] + y[i]
store y[i]
load y[i+1]
load x[i+1]
fma a * x[i+1] + y[i+1]
store y[i+1]
load y[i+2]
load x[i+2]
fma a * x[i+2] + y[i+2]
store y[i+2]
load y[i+3]
load x[i+3]
fma a * x[i+3] + y[i+2]
store y[i+3]

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Sequenced Before

```
constexpr float a = // ...
std::vector<float> x = // ...
std::vector<float> y = // ...

std::for_loop(
  std::execution::unseq,
  0, x.size(),
  [&] (int i) {
    y[i] += a * x[i];
  }
);
```

load y[i]
load y[i+1]
load y[i+2]
load y[i+3]
load x[i]
load x[i+1]
load x[i+2]
load x[i+3]
fma a * x[i] + y[i]
fma a * x[i+1] + y[i+1]
fma a * x[i+2] + y[i+2]
fma a * x[i+3] + y[i+2]
store y[i]
store y[i+1]
store y[i+2]
store y[i+3]

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Statements

Statements **are compositions of full expressions.**

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Statements

Statements **are compositions of full expressions.**

```
{
  statement0;
  statement1;
  // `statement0` is
  // sequenced before
  // `statement1`.
}
```

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Statements

Statements **are compositions of full expressions.**

```
{
  statement0;
  statement1;
  // `statement0` is
  // sequenced before
  // `statement1`.
}
```

```
if (condition)
  body;
// `condition` is
// sequenced before
// `body`.
```

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Statements

Statements **are compositions of full expressions.**

```
{
  statement0;
  statement1;
  // `statement0` is
  // sequenced before
  // `statement1`.
}
```

```
if (condition)
  body;
// `condition` is
// sequenced before
// `body`.
```

```
while (condition)
  body;
// Each evaluation of `condition`
// is sequenced before each
// evaluation of `body`.
```

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Function Evaluation

When calling a function…

1. Every evaluation within the function and every evaluation not within the function are indeterminately sequenced.

[intro.execution] p11 s2

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Function Evaluation

When calling a function…

1. Every evaluation within the function and every evaluation not within the function are indeterminately sequenced.

   [intro.execution] p11 s2

2. The expression designating the function is sequenced before the argument expressions.

   [expr.call] p8 s1

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Function Evaluation

When calling a function…

1. Every evaluation within the function and every evaluation not within the function are indeterminately sequenced.

   [intro.execution] p11 s2

2. The expression designating the function is sequenced before the argument expressions.

   [expr.call] p8 s1

3. Each argument expression is indeterminately sequenced with all other argument expressions.

   [expr.call] p8 s2

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Function Evaluation

When calling a function…

1. Every evaluation within the function and every evaluation not within the function are indeterminately sequenced.

   [intro.execution] p11 s2

2. The expression designating the function is sequenced before the argument expressions.

   [expr.call] p8 s1

3. Each argument expression is indeterminately sequenced with all other argument expressions.

   [expr.call] p8 s2

4. Every expression in the body of the function is sequenced after the expression designating the function and every argument expression of the function .

   [intro.execution] p11 s1

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Function Evaluation

```
void b(…) { e; }

g(a, (b)(c, d), f);
```

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Function Evaluation

```
void b(…) { e; }

g(a, (b)(c, d), f);
```

a and e are indeterminately sequenced (Rule 1)
f and e are indeterminately sequenced (Rule 1)

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Function Evaluation

```
void b(…) { e; }

g(a, (b)(c, d), f);
```

a and e are indeterminately sequenced (Rule 1)
f and e are indeterminately sequenced (Rule 1)
(b) is sequenced before c and d (Rule 2)

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Function Evaluation

```
void b(…) { e; }

g(a, (b)(c, d), f);
```

a and e are indeterminately sequenced (Rule 1)
f and e are indeterminately sequenced (Rule 1)
(b) is sequenced before c and d (Rule 2)
c and d are indeterminately sequenced (Rule 3)

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Function Evaluation

```
void b(…) { e; }

g(a, (b)(c, d), f);
```

a and e are indeterminately sequenced (Rule 1)
f and e are indeterminately sequenced (Rule 1)
(b) is sequenced before c and d (Rule 2)
c and d are indeterminately sequenced (Rule 3)
c and d are sequenced before e (Rule 4)

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Function Evaluation

```
void b(…) { e; }

g(a, (b)(c, d), f);
```

a and e are indeterminately sequenced (Rule 1)
f and e are indeterminately sequenced (Rule 1)
(b) is sequenced before c and d (Rule 2)
c and d are indeterminately sequenced (Rule 3)
c and d are sequenced before e (Rule 4)
a – f are sequenced before the body of g (Rule 2)

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Function Evaluation

```
struct A {
  A(int i) { cout << i; }
};


tuple t0 ( A(0), A(1) ) ;
// GCC 8:  "10"


tuple t1 { A(0), A(1) } ;
// GCC 8:  "01"
```

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Function Evaluation

```
struct A {
  A(int i) { cout << i; }
};


tuple t0 ( A(0), A(1) ) ;
// GCC 8:  “10”


tuple t1 { A(0), A(1) } ;
// GCC 8:  “01”
```

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Function Evaluation

```
struct A {
  A(int i) { cout << i; }
};


tuple t0 ( A(0), A(1) ) ;
// GCC 8:  “10”
// LLVM 7: “01”

tuple t1 { A(0), A(1) } ;
// GCC 8:  “01”
// LLVM 7: “01”
```

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Operator Evaluation

The value computations (but not the side effects) of an operator are sequenced before the value computations (but not the side effects) of its operands.

[intro.execution] p10 s2

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Operator Evaluation

The operand expressions to the following operators are sequenced left to right:

- `E1 && E2` [expr.log.and] p2 s2
- `E1 || E2` [expr.log.or] p2 s2
- `E1 << E2` and `E1 >> E2` [expr.shift] p4
- `E1, E2` [expr.comma] p1 s3
- `E1[E2]` [expr.sub] p1 s6
- `E1.*E2` and `E1->*E2` [expr.mptr.oper] p3 s3

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Operator Evaluation

The operands **expressions** to the following operators operators are **sequenced** right to left:

- `E2 = E1` and `E2 @= E1` [expr.ass] p1 s5

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Synchronizes With

Two library operations A and B may be related by the *synchronizes with* relation.

[intro.races] p6

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Synchronizes With

Asymmetric: A synchronizes with B does not imply that B synchronizes with A.

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Synchronizes With

Ways to achieve synchronizes with:

- Atomic acquire/release.
- Mutex lock/unlock.
- Thread create/join.
- Future/promise.
- Parallel algorithm fork/join.

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Synchronizes With

```
T data = // ...
atomic<bool> r(false);
```

```
data = ...
r.store(1, memory_order_release);
```

Synchronizes with

```
if (r.load(memory_order_acquire)) {
  T tmp = data;
  // ...
}
```

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Synchronizes With

```
T data = // ...
atomic<bool> r(false);
```

```
data = ...
r.store(1, memory_order_release);
```

Synchronizes with

```
if (r.load(memory_order_acquire)) {
  T tmp = data;
  // ...
}
```

No
synchronizes with

```
if (r.load(memory_order_acquire)) {
  T tmp = data;
  // ...
}
```

```
data = ...
r.store(1, memory_order_release);
```

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Synchronizes With

```
T data = // ...
std::mutex mtx;
```

Synchronizes with

```
{ std::lock_guard l(mtx); // Lock
  T tmp = data;
  // ...
}                         // Unlock

{ std::lock_guard l(mtx); // Lock
  T tmp = data;
  // ...
}                         // Unlock

{ std::lock_guard l(mtx); // Lock
  T tmp = data;
  // ...
}                         // Unlock
```

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Happens Before

Given any two evaluations A and B…

If A *happens before* B:

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Happens Before

Given any two evaluations A and B…

If A *happens before* B:

- A is sequenced before B, or

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Happens Before

Given any two evaluations A and B…

If A *happens before* B:

- **A is sequenced before B, or**
- **A synchronizes with B, or**

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Happens Before

Given any two evaluations A and B…

If A ***happens before*** B:

- A is sequenced before B, or
- A synchronizes with B, or
- For some evaluation X, A happens before X and X happens before B.

[intro.races] p7, p8, p9, p10

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Happens Before

Happens before doesn't mean happened before.

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Happens Before

```
int x = 0;

int y = 0;


void foo()
{
  x = y + 1;
  y = 1;
}
```

```
// GCC 8.2 -O3 x86-64

x:
  .zero 4
y:
  .zero 4

foo():
  movl y(%rip), %eax
  movl $1, y(%rip)
  addl $1, %eax
  movl %eax, x(%rip)
  ret
```

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Source: [Preshing on Programming]

Happens Before

Happens before doesn't mean happened before.

Happening before doesn't mean happens before.

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Happens Before

```
std::atomic<bool> ready = false;
int data = 0;

std::thread producer(
  [&] {
    data = 42;
    ready.store(true, memory_order_relaxed);
  });

std::thread consumer(
  [&] {
    if (ready.load(memory_order_relaxed))
      std::cout << data;
  });
```

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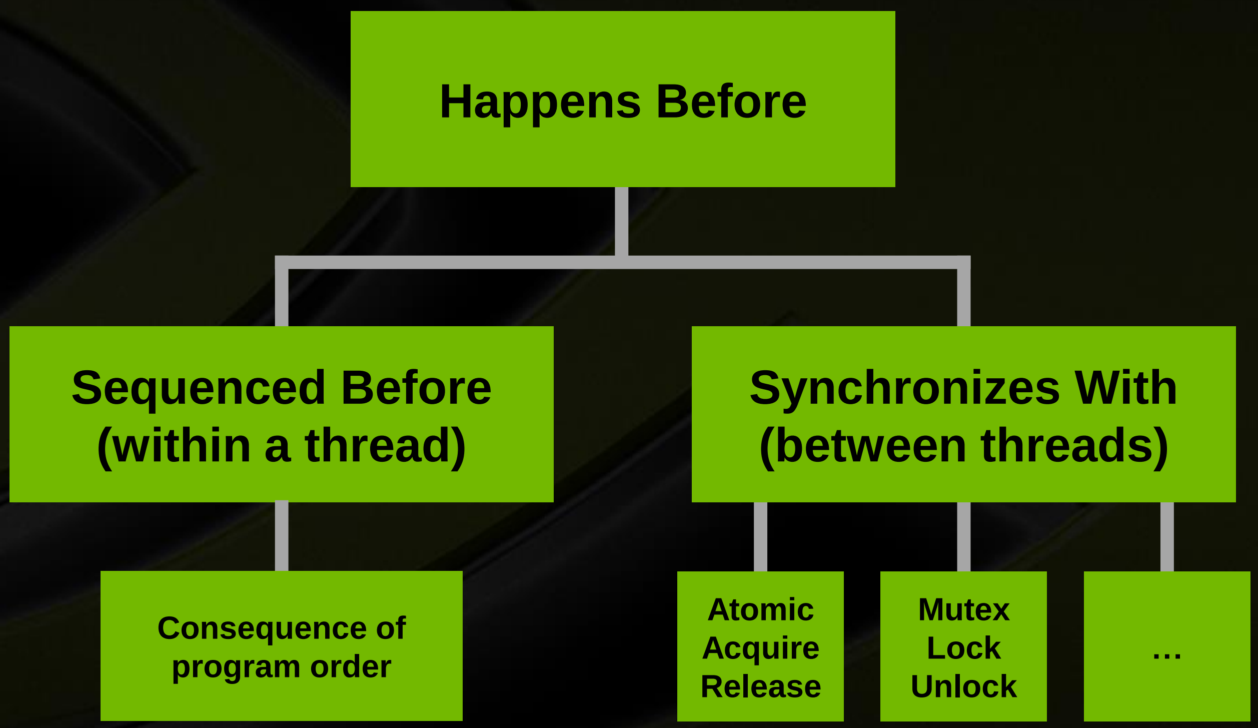
Source: Preshing on Programming

Happens Before

- **Happens before** describes arbitrary concatenations of **sequenced before** and **synchronizes with**.



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Execution Steps

The evaluations executed by threads are delineated by ***execution steps***.

[intro.progress] p3

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Execution Steps

The evaluations executed by threads are delineated by ***execution steps***.

[intro.progress] p3

An execution step is:

- Termination of the thread.

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Execution Steps

The **evaluations** executed by **threads** are delineated by ***execution steps***.

[intro.progress] p3

An **execution step** is:

- Termination of the thread.
- An access of a `volatile` object.

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Execution Steps

The evaluations executed by threads are delineated by ***execution steps***.

[intro.progress] p3

An execution step is:

- Termination of the thread.
- An access of a `volatile` object.
- Completion of:
  - A library I/O function call.

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Execution Steps

The evaluations executed by threads are delineated by ***execution steps***.

[intro.progress] p3

An execution step is:

- Termination of the thread.
- An access of a `volatile` object.
- Completion of:
  - A library I/O function call.
  - A synchronization operation.

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Execution Steps

The evaluations executed by threads are delineated by ***execution steps***.

[intro.progress] p3

An execution step is:

- Termination of the thread.
- An access of a `volatile` object.
- Completion of:
  - A library I/O function call.
  - A synchronization operation.
  - An atomic operation.

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Forward Progress

Some atomic operations may fail spuriously due to interference from other threads.

Implementations are encouraged, but not required, to prevent spurious failures from indefinitely delaying progress.

[intro.progress] p2.2

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Forward Progress

Block: Wait for a **condition** to be **satisfied** before continuing execution.

[defns.block]

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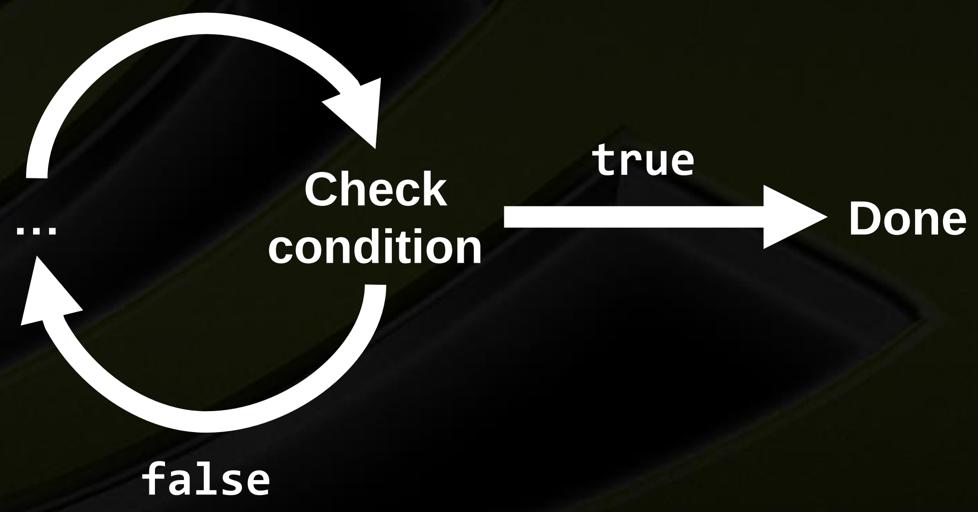
Forward Progress

Blocking library functions **are considered to continuously execute execution steps while waiting for their condition to be satisfied.**

Thus, blocking makes progress.



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Forward Progress

Forward progress guarantees that something observable should eventually happens.

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Execution Steps

Implementations may assume that all threads will eventually perform an execution step.

[intro.progress] p1

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Execution Steps

Implementations may assume that all threads will eventually perform an execution step.

[intro.progress] p1

AKA infinite loops that have no observable effects are undefined behavior.

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Forward Progress

Three classes of *forward progress guarantees*:

- ***Concurrent forward progress*.**
- ***Parallel forward progress*.**
- ***Weakly parallel forward progress*.**

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Forward Progress

Concurrent forward progress: **The thread will make progress, regardless of whether other threads are making progress.**

[intro.progress] p7

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Forward Progress

Concurrent forward progress example:

- **Preemptive OS thread scheduling.**
- **Unbounded thread pool.**

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Source: P0072

Forward Progress

Parallel forward progress: Once the thread has executed its first execution step, the thread will make progress.

[intro.progress] p9

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Forward Progress

Parallel forward progress example:

- **Run-to-completion userspace tasking.**
  - **Bounded thread pool.**
- **Threads on modern NVIDIA GPUs.**

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Forward Progress

Weakly parallel forward progress: The thread is not guaranteed to make progress.

[intro.progress] p11

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Forward Progress

Weakly parallel forward progress example:

- **Non-preemptive OS thread scheduling.**
- **Suspendable userspace tasking.**
  - **Work-stealing task schedulers.**
  - **Fibers.**
- **Threadless asynchrony.**
  - **Lazy execution.**
  - **C++ coroutines.**
- **Threads on legacy GPUs.**

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Source: [P0072]

Forward Progress

Which guarantee does the `main` thread make?

[intro.progress] p8

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Implementation defined.

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Forward Progress

Which guarantee do `std::threads` make?

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Forward Progress

Which guarantee do `std::threads` make?

Implementation defined.

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Boost Blocking

Boost Blocking: **Block on a thread with weaker forward progress while preserving the calling thread's forward progress.**

[intro.progress] p14

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Boost Blocking

When a thread P boost blocks on a set S of other threads, the forward progress guarantees of at least one of the threads in S is temporarily upgraded to P's forward progress guarantee. Repeat until the blocking condition is satisfied.

[intro.progress] p14

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Boost Blocking

Boost blocking ensures your children threads make progress, not your siblings.

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Boost Blocking

```
struct lazy_thread {
  function<void()> f;

  void join() {
    if (f) {
      // Boost block by running the thread in the
      // calling thread.
      f();
      f = function<void()>{};
    } else {
      throw make_error_code(errc::invalid_argument);
    }
  }
};
```

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Boost Blocking

...

```
while (!empty && !done) {
  auto f = pop_next();
  f();
}
```

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Boost Blocking


```
while (!empty && !done) {
  auto f = pop_next();
  f();
}
```

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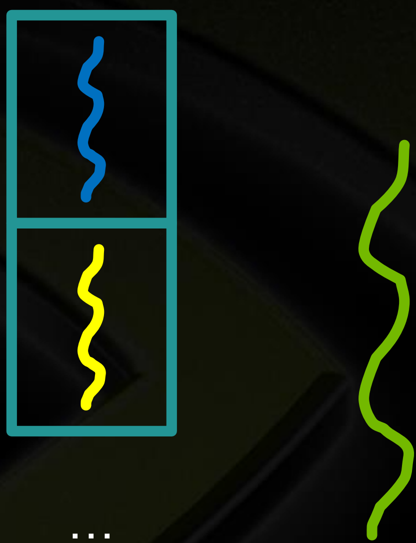
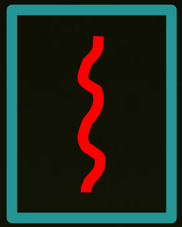
Boost Blocking




```
while (!empty && !done) {
  auto f = pop_next();
  f();
}
```



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Boost Blocking

```
static_thread_pool pool(…);

auto task = pool.execute_async(




);
```

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Boost Blocking

```
static_thread_pool pool(…);

auto task = pool.execute_async(
  [&] {
    auto child0 = pool.execute_async(…);
    auto child1 = pool.execute_async(…);
    …
    child0.join();
    child1.join();
  }
);
```

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Boost Blocking

```
static_thread_pool pool(1);

auto task = pool.execute_async(
  [&] {
    auto child0 = pool.execute_async(…);
    auto child1 = pool.execute_async(…);
    …
    child0.join();
    child1.join();
  }
);
```

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Summary

C++ Execution Model:

- Threads evaluate expressions that access and modify flat storage.
- Evaluation within a thread is driven by sequenced before relations.
- Interactions between threads is driven by synchronizes with relations.
- Forward progress promises eventual termination.

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