并发进阶
Advanced Concurrency

现代C++基础
Modern C++ Basics

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- **Memory Order Basics**
- **Atomic Variable Details**
- **Advanced Memory Order**
- **Coroutine**

Initially, I think that most of the committee members underestimated the problem. We knew that Java had a good memory model [Pugh 2004] and hoped to adopt that. I was highly amused to find that representatives from Intel and IBM effectively vetoed that idea by pointing out that by adopting the Java memory model for C++ we would slow down all JVMs by a factor of at least two. Consequently, to preserve the performance of Java, we had to adopt a far more complex model for C++. Ironically and predictably, C++ was then criticized for having a more complicated memory model than Java.

最开始，我想大多数委员都小瞧了这个问题。我们知道 Java 有一个很好的内存模型 [Pugh 2004]，并曾希望采用它。令我感到好笑的是，来自英特尔和 IBM 的代表坚定地否决了这一想法，他们指出，如果在 C++ 中采用 Java 的内存模型，那么我们将使所有 Java 虚拟机的速度减慢至少一半。因此，为了保持 Java 的性能，我们不得不为 C++ 采用一个复杂得多的模型。可以想见而且讽刺的是，C++ 此后因为有一个比 Java 更复杂的内存模型而受到批评。

Advanced Concurrency

Memory Order Basics

"Even with C++11 support, I consider lock-free programming expert-level work."
-- Bjarne Stroustrup, HoPL4, P33

Advanced Concurrency

- Memory Order Basics
  - Overview
  - Sequentially consistent model
  - Acquire-release model
  - Relaxed model

  - There also exists consume-release model, but since it's very difficult for users to annotate and for compilers to analyze better optimizations, all compilers strengthen consume-release model to acquire-release model.
    - C++20: [*Note 1*: Prefer `memory_order::acquire`, which provides stronger guarantees than `memory_order::consume`. Implementations have found it infeasible to provide performance better than that of `memory_order::acquire`. Specification revisions are under consideration. — *end note*]
    - C++26: consume operations are deprecated.

Defang and deprecate memory_order::consume

Doc. No: P3475R1
Contact: Hans Boehm (hboehm@google.com)
Audience: LEWG, CWG, LWG
Date: Jan 11, 2025
Target: C++26

Memory order

- Current programming world stands on the foundation of sequential execution…
  - Compiler / JIT may do aggressive optimization…
    - Here we will "cache" global variables to registers, and eliminate redundant expressions (i.e. `b = addend + 1`).

```
int a, b, addend;

void test()
{
    b = addend + 1;
    a = b - 5;
    b = addend + 3;
```

```
void test(int addend)
{
    int tempb = addend;     // mov esi, DWORD PTR addend[rip]
    int tempa = tempb - 4; // lea edi, [rsi - 4]
    tempb += 4;             // add esi, 4

    a = tempa;              // mov DWORD PTR a[rip], edi
    b = tempb;              // mov DWORD PTR b[rip], esi
```

  - Processors may do out-of-order execution and speculative computation…
  - Each processor may have its own L1/L2 cache…

Memory order

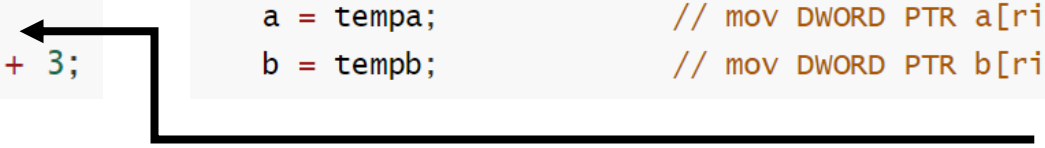
- These optimizations are smart and correct in sequential world, but when it comes to parallelism, some assumptions are not that intuitive…

```
int a, b, addend;

void test()
{
    b = addend + 1;
    a = b - 5;
    b = addend + 3;
```

```
void test(int addend)
{
    int tempb = addend;     // mov esi, DWORD PTR addend[rip]
    int tempa = tempb - 4; // lea edi, [rsi - 4]
    tempb += 4;             // add esi, 4

    a = tempa;              // mov DWORD PTR a[rip], edi
    b = tempb;              // mov DWORD PTR b[rip], esi
```



  - What if there is another thread that modifies `addend` here?
    - `b` can be something other than `tempb + 4`, but compiler optimizations make it impossible.

Memory order

- Among so many compiler optimizations, processor ISA regulations, cache coherence protocols…
  - We need to find a way to unify "as-if" behaviors by abstraction!
- That is what *memory order* for in C++.
  - Three types of memory order:
    - Sequentially consistent model (`seq_cst`)
    - Acquire-release model (`acq_rel`)
    - Relaxed model (`relaxed`)
  - BTW, Rust has completely same regulations as C++.

> Rust pretty blatantly just inherits the memory model for atomics from C++20. This is not due to this model being particularly excellent or easy to understand. Indeed, this model is quite complex and known to have several flaws. Rather, it is a pragmatic concession to the fact that *everyone* is pretty bad at modeling atomics. At very least, we can benefit from existing tooling and research around the
>
> Atomics - The Rustonomicon

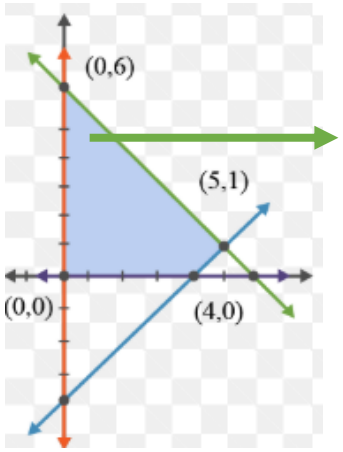
Memory order

[1]: A Concurrency Semantics for Relaxed Atomics that Permits Optimisation and Avoids Thin-air Executions | POPL'16, Jean & Peter from Univ. of Cambridge
POPL is Top Academic Conference in Programming Language Design.

- But, how to describe memory order is still **an unsolved problem** even in academia (even `seq_cst` model has bug fix in C++20).
  - And C++ is pioneer in this field, so the standard has been revised nearly in every version.
  - But normally this is defect in theoretical model; real-world behaviors are not severely affected.
- The key problem is that memory order is *axiomatic*[1], which is rather weak and cannot exactly describe what we want.
  - Memory order gives constraints, and every outcome that can fulfill the constraint is a valid solution.
    - While some solutions are not really valid…we'll see them later.

What memory order regulates:

$$\textit{constraints:} \begin{cases} x + y \geq 6 \\ x - y \geq 4 \\ x \geq 0 \\ y \geq 0 \end{cases}$$



Results that memory order allows

Memory order

Formally, this is regulated by RR/RW/WR/WW coherence in standard; we rephrase it here.

- There are some intuitive basic regulations in memory model.

1. Modification order: for a **single *atomic*** variable, all threads see the same operation sequences.
   - So can `r1 == 1 && r2 == 2 && r3 == 2 && r4 == 1`?
   - No!
   - Reason: r4 cannot read value newer than r3, and r2 cannot read value newer than r1.
     - `r1 == 1 && r2 == 2`: 2 is newer than 1;
     - `r3 == 2 && r4 == 1`: 1 is newer than 2; Conflict!
     - Compilers are not allowed to reorder.
   - But, operations for different atomic variables may have different orders in different threads.

```
-- Initially --
std::atomic<int> x{0};

-- Thread 1 --
x.store(1);

-- Thread 2 --
x.store(2);

-- Thread 3 --
int r1 = x.load();
int r2 = x.load();

-- Thread 4 --
int r3 = x.load();
int r4 = x.load();
```

Memory order

2. Sequenced before: we've covered evaluation order previously…

Expression

- Then, it's order of expression evaluation that computes the whole tree.
  - It is only determined that before the evaluation of root, the left child and the right child will be evaluated first; the order is **unspecified**.
  - e.g. `f1() +1 f2() +2 f3()`, it's `root(+2) -> lChild(f1() + f2()) -> rChild(f3())`, while `lChild` is `root(+1) -> lChild(f1()) -> rChild(f2())`;
    - We can know before `+1` is evaluated, lChild and rChild is first evaluated.
    - However, you can evaluate in the sequence of:
      - `lChild` evaluates `f1()`
      - `rChild` evaluates `f3()`, gets the value.
      - `lChild` evaluates `f2()`, gets the value.
      - This still obeys our rules, e.g. `f1()` and `f2()` evaluated before `lChild`.
    - So if we output `a` in `f1()`, `b` in `f2()`, `c` in `f3()`, any permutation of `abc` is possible!
  - To sum up, evaluation order is hugely determined by how compiler computes the tree.

Memory order

- So if an evaluation `A` definitely computes before another one `B`, then we say `A` is ***sequenced before*** `B`.
  - For example, for different statements.

```
a += 1; // #1 happens before #2
b += 2; // #2
```

  - In the same statement:

```
a += 1, b += 2; // a += 1 is evaluated first
                // then it's sequenced before 'b += 2'
// Yet another smelly example.
a += b++; // b++ is evaluated first since C++17,
          // so here 'b++' sequenced before 'a +='.
```

  - And function parameters are *indeterminately sequenced* since C++17, so there is some order but it's unspecified;
  - And some evaluations are not regulated at all, which means they're *unsequenced* (e.g. `a = b++ + b` is UB, since `b++` and `b` are unsequenced while `b++` has side effect).
- Again, such order is in the sequential view…

Memory order

Data races occur when non-atomic operations on the same memory location do NOT have some certain happens-before relationship.

3. Happens before: in parallel world, which evaluation is executed first is regulated by ***happens-before***.
   - If A is sequenced before B, then A happens before B (single-thread case);
   - If A ***synchronizes with*** B, then A happens before B (inter-thread case);
   - Or A happens before B & B happens before C, then A happens before C.

   - For non-atomic variables, only when A happens before B will effects of A be visible to B.
     - So compilers can do aggressive optimizations, as long as they aren't visible.
   - For atomic variables, HB order is part of MO; if two operations have no HB relationship, then their order in MO is also random.
     - Namely, if B doesn't happen before A, then effects of A may be visible to B.
   - Memory order mainly regulates such "synchronize-with" relationship.

Note: actually, what we teach here is happens-before since C++26; before that (since C++20) this is called simply-happens-before, but it's equivalent to happens-before (since C++11) when no consume operation is involved (and again, we've said that consume operations are never implemented).

Advanced Concurrency

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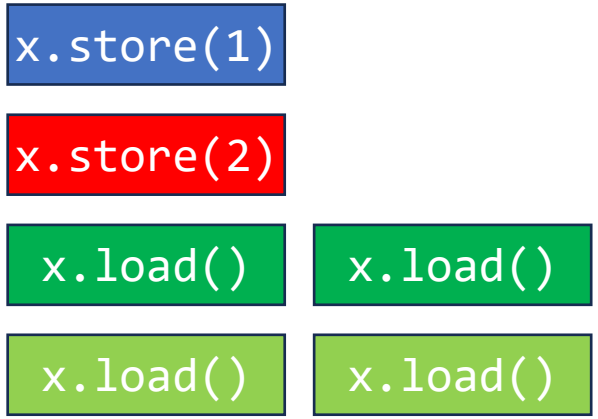
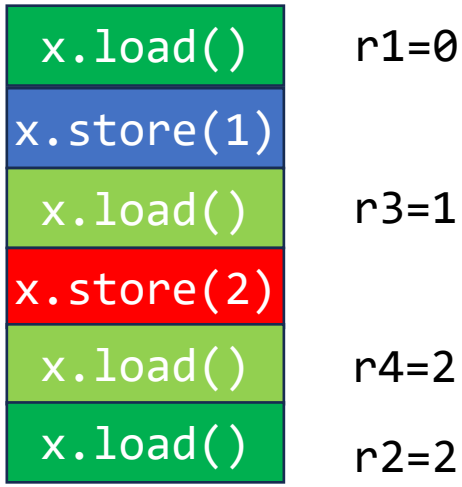
Sequential Consistency

- In real world, all events are sequenced in some way, and all observers will see the same sequence.
- Similarly, we may think operations to have some total order, and all threads observe the same order.
  - This is the core of sequentially consistent model!
  - Back to our example:





r1=0

r3=1

r4=2

r2=2

Interleaving them randomly, we get a total order.

```
-- Initially --
std::atomic<int> x{0};

-- Thread 1 --
x.store(1);

-- Thread 2 --
x.store(2);

-- Thread 3 --
int r1 = x.load();
int r2 = x.load();

-- Thread 4 --
int r3 = x.load();
int r4 = x.load();
```

Sequential Consistency

- Formally, when an atomic load operation B loads a value that's stored by an atomic store operation A, then A synchronizes with B.
  - Then all previous outcomes are visible since B.
- For example:

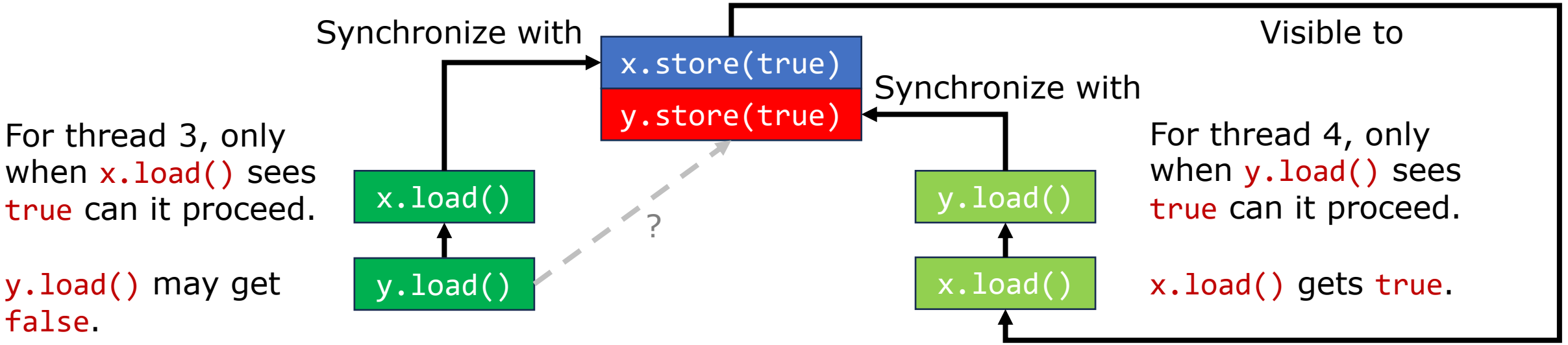
```
std::atomic<bool> x{false}, y{false};
std::atomic<int> z{0};

void write_x() { x.store(true); }
void write_y() { y.store(true); }
void read_x_then_y()
{
    while (!x.load());
    if (y.load())
        ++z;
}
void read_y_then_x()
{
    while (!y.load());
    if (x.load())
        ++z;
}
```

```
int main()
{
    { // 等四个线程全部结束。
        std::jthread a{ write_x }, b{ write_y }, c{ read_x_then_y },
                     d{ read_y_then_x };
    }
    assert(z.load() != 0);
}
```

Can this `assert` fire?

- No, `z.load()` is always non-zero.
- Reason: there is a total order, so either `x.store(true)` or `y.store(true)` occurs first.
  - Let's assume `x.store(true)` happens first since it's completely symmetric.



- Synchronization is implicitly established through reading value.
- Note: `x.store(true)` and `y.store(true)` **do NOT have happens-before relationship**; the order is imposed by total order.

seq_cst model actually uses strongly-happens-before relationship but here they're equivalent; we'll cover it in the next section.

Sequential Consistency

- Note 2: start of threads & joining threads will also establish synchronize-with relationship with function start & return.
  - So here thread joining happens before `z.load()`, and function return happens before thread joining, and `++z` happens before function return. Thus `z.load()` can get 1 or 2 correctly.
- Note 3: operations on atomic variables are indivisible (and thus prevent data races), which is not affected by memory order.
  - Called *atomicity*.
  - Our example in the last lecture:
    - If `a` is atomic variable, then lock protection is not needed.

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Acquire-release Model

- In many architectures like RISC-V, ARM and Power, such total-order assumption is quite expensive, while they support weaker model better.
  - Acquire-release is a commonly supported order!

- So what does acquire-release model guarantee?
  - Only read operations can be “acquire”, and only write operations can be “release”.
  - For an acquire operation `B`, if it reads the value from a release operation `A`, **then `A` synchronizes with `B`** (and thus `A` happens before B).
  - **There is no total order**.

Acquire-release Model

- For example:

Sequenced before store, thus happens before store.

Only when `ptr` loads some value will the program proceed, then store synchronizes with load (and thus happens before load).

Sequenced after load, thus load happens before asserts.

```
std::atomic<std::string*> ptr;
int data;

void producer()
{
    std::string* p = new std::string("Hello");
    data = 42;
    ptr.store(p, std::memory_order_release);
}

void consumer()
{
    std::string* p2;
    while (!(p2 = ptr.load(std::memory_order_acquire)))
        ;
    assert(*p2 == "Hello"); // never fires
    assert(data == 42); // never fires
}

int main()
{
    std::thread t1(producer);
    std::thread t2(consumer);
    t1.join(); t2.join();
}
```

Through three happens-before, we know that `data` is always 42.

Acquire-release Model

- On the other hand, since it doesn't have total order:

```
void write_x() { x.store(true, std::memory_order_release); }
void write_y() { y.store(true, std::memory_order_release); }
void read_x_then_y()
{
    while (!x.load(std::memory_order_acquire));
    if (y.load(std::memory_order_acquire))
        ++z;
}
void read_y_then_x()
{
    while (!y.load(std::memory_order_acquire));
    if (x.load(std::memory_order_acquire))
        ++z;
}
```

Store of x and y have no happens-before relationship.

Here we only know that x is true (synchronize-with), while `y.load` and `y.store` don't necessarily have happens-before relationship.

Similarly, `x.load` and `x.store` don't necessarily have happens-before relationship.

Thus, `z.load()` can be 0 here.

Acquire-release Model

- Another example for transitivity:
  - SB(#0, #1)
  - SW(#1, #2)
    - As only when #2 reads `true` can `thread_2` proceed.
  - SB(#2, #3)
  - SW(#3, #4)
  - SB(#4, #5)
- Thus we know HB(#0, #5).

Obviously, acquire-release model can be used to implement spinlock.

```
int data = 0;
std::atomic<bool> sync1{ false },sync2{ false };

void thread_1()
{
    data = 442;                                          // #0
    sync1.store(true,std::memory_order_release);         // #1
}

void thread_2()
{
    while(!sync1.load(std::memory_order_acquire)); // #2
    sync2.store(true,std::memory_order_release);         // #3
}

void thread_3()
{
    while(!sync2.load(std::memory_order_acquire)); // #4
    assert(data == 442);                                 // #5
}
```

Acquire-release Model

- By happens-before relationship, acquire-release model implicitly disables compiler reorder optimization.
  - An acquire operation `B` may happen after another release operation `A`…
    - If a compiler reorders statements `S1` after `B` to before `B`;
    - Or if a compiler reorders statements `S2` before `A` to after `A`;
    - Then `S1` may fail to observe results in `S2`.
  - Thus, acquire & release offers a **one-way instruction barrier** implicitly.
    - All operations that will cause side effects (that may be used by another threads) cannot go below beyond a release operation;
    - All operations that may rely on side effects cannot go above beyond an acquire operation.
  - Intuitively, acquire-release forms some critical section; you cannot move out code in between.

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Relaxed Model

- Sometimes we may want even weaker order…
  - That is, we only need to maintain atomicity; no synchronize-with relationship is needed.
  - This is relaxed model.
- For example:

```
std::atomic<int> x{0}, y{0};

void read_y_then_write_x(int& r1)
{
    r1 = y.load(std::memory_order_acquire); // #1
    x.store(r1, std::memory_order_release); // #2
}

void read_x_then_write_y(int& r2)
{
    r2 = x.load(std::memory_order_acquire); // #3
    y.store(42, std::memory_order_release); // #4
}
```

```
int main()
{
    int r1 = 0, r2 = 0;
    std::jthread{ read_y_then_write_x, std::ref(r1) },
                 { read_x_then_write_y, std::ref(r2) };
    assert(!(r1 == 42 && r2 == 42));
}
```

Exercise: Can this assert fire?

Relaxed Model

```
std::atomic<int> x{0}, y{0};

void read_y_then_write_x(int& r1)
{
    r1 = y.load(std::memory_order_acquire); // #1
    x.store(r1, std::memory_order_release); // #2
}

void read_x_then_write_y(int& r2)
{
    r2 = x.load(std::memory_order_acquire); // #3
    y.store(42, std::memory_order_release); // #4
}
```

- No!
- Assuming that `r1 == 42`,
  - Then #1 reads value from #4, and acquire-release model makes SW(#4, #1).
  - And SB(#3, #4), SB(#1, #2), thus we know HB(#3, #2).
  - Thus, effects of #2 are not visible to #3, and r2 is definitely 0.
- Then what about relaxed model?
  - This assertion may fire…
  - That is, `r1 == 42 && r2 == 42` may be `true`.

```
void read_y_then_write_x(int& r1)
{
    r1 = y.load(std::memory_order_relaxed); // #1
    x.store(r1, std::memory_order_relaxed); // #2
}

void read_x_then_write_y(int& r2)
{
    r2 = x.load(std::memory_order_relaxed); // #3
    y.store(42, std::memory_order_relaxed); // #4
}
```

Relaxed Model

```
void read_y_then_write_x(int& r1)
{
    r1 = y.load(std::memory_order_relaxed); // #1
    x.store(r1, std::memory_order_relaxed); // #2
}

void read_x_then_write_y(int& r2)
{
    r2 = x.load(std::memory_order_relaxed); // #3
    y.store(42, std::memory_order_relaxed); // #4
}
```

- Since relaxed model doesn't establish any synchronize-with relationship…
- Remember our effect rules?

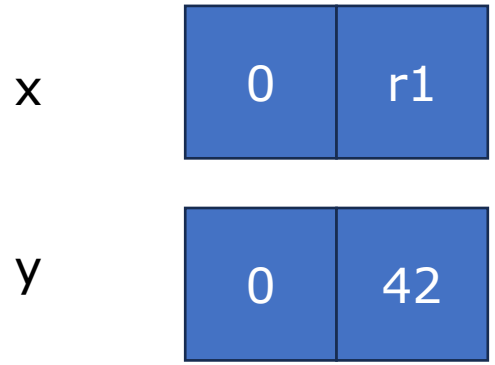
> - For atomic variables, HB order is part of MO; if two operations have no HB relationship, then their order in MO is also random.
>   - Namely, if B doesn't happen before A, then effects of A may be visible to B.

  - So here #1 doesn't happen before #4, then effects of #4 can be read by #1 so `r1 == 42` can be true.
    - And #1 happens before #2, so x can store 42.
  - And #3 doesn't happen before #2, then effects of #2 can be read by #3 so `r2 == 42` can be true.
- Thus, `r1 == 42 && r2 == 42` can be true.

Relaxed Model

- Note 1: again, we emphasize that there is no total order.
  - If there is, then in thread 2 SB(#3, #4) prevents any possible order to make `r2 == 42`.
  - In practice, compilers are allowed to reorder #3 and #4, since destroying such HB doesn't affect any visible effects.
- Note 2: this outcome doesn't violate modification order constraint of a single atomic variable.

All threads see this same modification order.



#3 can read r1, so it can be 42.

#1 can read 42, so r1 can be 42.

Notice that here it's ***can*** instead of ***must***; #1 and #3 can read older values.

Relaxed Model

- Another complex example:

```cpp
std::atomic<int> x{0}, y{0}, z{0};
std::atomic<bool> start{false};

constexpr unsigned int loop_num = 10;
struct ValueStatus { int x, y, z; };

using ValueContainer = std::array<ValueStatus, loop_num>;
```

```cpp
void increment(std::atomic<int>* var, ValueContainer* values)
{
    start.wait(false);
    for (unsigned int i = 0; i < loop_num; i++)
    {
        values[i].x = x.load(std::memory_order_relaxed);
        values[i].y = y.load(std::memory_order_relaxed);
        values[i].z = z.load(std::memory_order_relaxed);

        var->store(i + 1, std::memory_order_relaxed);
    }
}

void read_status(ValueContainer* values)
{
    start.wait(false);
    for (unsigned int i = 0; i < loop_num; i++)
    {
        values[i].x = x.load(std::memory_order_relaxed);
        values[i].y = y.load(std::memory_order_relaxed);
        values[i].z = z.load(std::memory_order_relaxed);
    }
}
```

Like a spinlock, covered later.

```cpp
int main()
{
    std::array<ValueContainer, 5> values;
    {
        std::jthread a{ increment, &x, &values[0] }, b{ increment, &y,
&values[1] }, c{ increment, &z, &values[2] };
        std::jthread d{ read_status, &values[3] }, e{ read_status, &values[4] };

        start.store(true);
        start.notify_all();
    }

    for (const auto& cont: values)
    {
        std::print("[");
        for (auto val : cont)
            std::print("({}, {}, {}) ", val.x, val.y, val.z);
        std::println("]");
    }
}
```

All threads start now.

Relaxed Model

- So what it does is:
  - Three threads, with each one only modifying one of the atomic variables, and reading all of them;
  - Two threads that only read all atomic variables.
- It can only guarantee that:
  - The thread that modifies the variable will see it increases one by one, constrained by happens-before relationship.
    - For example, `values[0]` will have `(0, …, …), (1, …, …), …, (9, …, …)`.
  - And constrained by single-atomic modification order, other variables that are not modified by itself will have non-decreasing values.
    - That is, once a value is read (not necessarily the newest), values older than it cannot be read.

15 [*Note 16*: The four preceding coherence requirements effectively disallow compiler reordering of atomic operations to a single object, even if both operations are relaxed loads. This effectively makes the cache coherence guarantee provided by most hardware available to C++ atomic operations. — *end note*]

Relaxed Model

- Courtesy of *C++ Concurrency in Action, 2nd ed.* by Anthony Williams.

One possible output from this program is as follows:

```
(0,0,0),(1,0,0),(2,0,0),(3,0,0),(4,0,0),(5,7,0),(6,7,8),(7,9,8),(8,9,8),
(9,9,10)
(0,0,0),(0,1,0),(0,2,0),(1,3,5),(8,4,5),(8,5,5),(8,6,6),(8,7,9),(10,8,9),
(10,9,10)
(0,0,0),(0,0,1),(0,0,2),(0,0,3),(0,0,4),(0,0,5),(0,0,6),(0,0,7),(0,0,8),
(0,0,9)
(1,3,0),(2,3,0),(2,4,1),(3,6,4),(3,9,5),(5,10,6),(5,10,8),(5,10,10),
(9,10,10),(10,10,10)
(0,0,0),(0,0,0),(0,0,0),(6,3,7),(6,5,7),(7,7,7),(7,8,7),(8,8,7),(8,8,9),
(8,8,9)
```

Relaxed Model

- Relaxed model may cause very astonishing results, so it needs to be used with extreme caution…
  - Usually it either cooperates with other sync operations (like acquire-release model)…
  - Or it’s used to do very simple job that only needs atomicity.
    - For example, `std::shared_ptr` has a counter to count its copies; when all copies are destructed, the memory is finally freed.
    - We can check the shared count by `.use_count()`, which is normally a relaxed load since it doesn’t need to participate in synchronization.

Advanced Concurrency

Atomic Variables

Advanced Concurrency

- Atomic variables
  - Basic operations
    - atomic_flag
  - Specializations
    - atomic_ref

Basic Operations

- We can divide atomic operations into three categories:
  - Read operations;
  - Write operations;
  - Read-Modify-Write (RMW) operations.
- And for the most general atomic types `std::atomic<T>`:
  - Read operations are `.load(memory_order=std::memory_order_seq_cst)`;
    - And an `operator T`, which can only use seq_cst as order.
  - Write operations are `.store(T newObj, memory_order=std::memory_order_seq_cst)`; Not `T&` or `std::atomic<T>&`!
    - And `operator=(T)`, which can only use seq_cst as order and returns `T newObj`.
    - Notice that atomic types are neither copyable nor moveable.

For methods of atomic operations, if it accepts memory order, then the default parameter is `std::memory_order_seq_cst`; if it doesn't accept memory order, then it just uses `std::memory_order_seq_cst`. We'll not repeat them in the following slides.

Read-Modify-Write

- And we also need atomic RMW operations…
  - This is not same as atomic read + atomic write, since two atomic operations are divisible.
  - RMW operations are indivisible as a whole.
  - For example: `a++`;
    - Read: `temp = a`; Modify: `temp++`; Write: `a = temp`.
    - If it's divisible, two threads running `Inc` may still get value other than `200000`.

```
void Inc(std::atomic<int>& a)
{
    for (int i = 0; i < 100000; i++)
    {
        a++;
    }
}
```

- And RMW operations are:
  - `.exchange(T desired, memory_order) -> T`: read the original value and write `desired`; then return the original value.
    - Actually no modification, but read & write are atomic as a whole.

Read-Modify-Write

- And a composite operation:
  - `.compare_exchange_strong(T& expected, T desired, memory_order success, memory_order failure) -> bool`:
    - Read op: read the value `v`, compare it with `expected`;
    - Modify op: no modification;
    - Write op: if equal (or called *success*), write back `desired`; otherwise (*failure*) write back nothing (but assign `expected = v`).
    - Return value means success or not.
  - So bit of strangely, its operation type depends on its read op:
    - If failure, then it's just a load operation;
    - If success, then it's RMW operation (and the whole operation is atomic).
  - And thus, you can assign two memory order.

BTW such operations are generally called CAS operations (compare-and-swap / compare-and-set).
CAS is the basic operation for *lock-free data structures*.

Read-Modify-Write

- Since RMW operations involve both read and write, the memory order will constrain both of them.
  - `seq_cst`: both read and write use sequential consistent model.
  - `relaxed`: both read and write use relaxed model.
  - But for acquire-release model, acquire and release are separate…
    - So you can use `std::memory_order::acq_rel`!
  - `acq_rel`: use acquire-release model, where read is acquire operation and write is release operation.
  - `acquire`: read is acquire operation while write is relaxed.
  - `release`: write is release operation while read is relaxed.
- And RMW ensures that it reads the newest value in MO, and writes the consequent result as the newest value in MO.

Read-Modify-Write

- There also exists a one-memory-order overload:
  - `.compare_exchange_strong(T& expected, T desired, memory_order success) -> bool;`
    - Failure takes order from success, since RMW order includes read order.

Overloads	Memory model for	
	read-modify-write operation	load operation
(1,2,5,6)	`success`	`failure`
(3,4,7,8)	`order`	• `std::memory_order_acquire` if `order` is `std::memory_order_acq_rel` • `std::memory_order_relaxed` if `order` is `std::memory_order_release` • otherwise `order`

  - Notice that failure is not seq_cst by default.

Read-Modify-Write

- Take our previous example:

```
int data = 0;
std::atomic<bool> sync1{ false },sync2{ false };

void thread_1()
{
    data = 442;                                          // #0
    sync1.store(true,std::memory_order_release);         // #1
}

void thread_2()
{
    while(!sync1.load(std::memory_order_acquire)); // #2
    sync2.store(true,std::memory_order_release);         // #3
}

void thread_3()
{
    while(!sync2.load(std::memory_order_acquire)); // #4
    assert(data == 442);                                 // #5
}
```

Can be rewritten as:

But we notice that it's normally a bad idea to use RMW operation to do spinlock, since write is special in cache coherence protocol (like MESI) and harms efficiency. Here it's just an example.

```
int data = 0;
std::atomic<int> sync{0};

void thread_1()
{
    data = 442;                                          // #0
    sync.store(1, std::memory_order_release);            // #1
}

void thread_2()
{
    int expected = 1;
    while(!sync.compare_exchange_strong(expected, 2,  // #2
                                        std::memory_order_acq_rel))
        expected = 1; // Restore expected to compare again.
}

void thread_3()
{
    while(sync.load(std::memory_order_acquire) != 2); // #4
    assert(data == 442);                                 // #5
}
```

Atomic Operations

- Note 1: atomic variables are **bitwise-compared** and **bitwise-written**.
  1. A customized `operator==` doesn't affect CAS operation;
  2. Particularly, for floating points, bitwise-comparison is very misleading.
     - For example, -0.0 and 0.0 are not bitwise-equal.

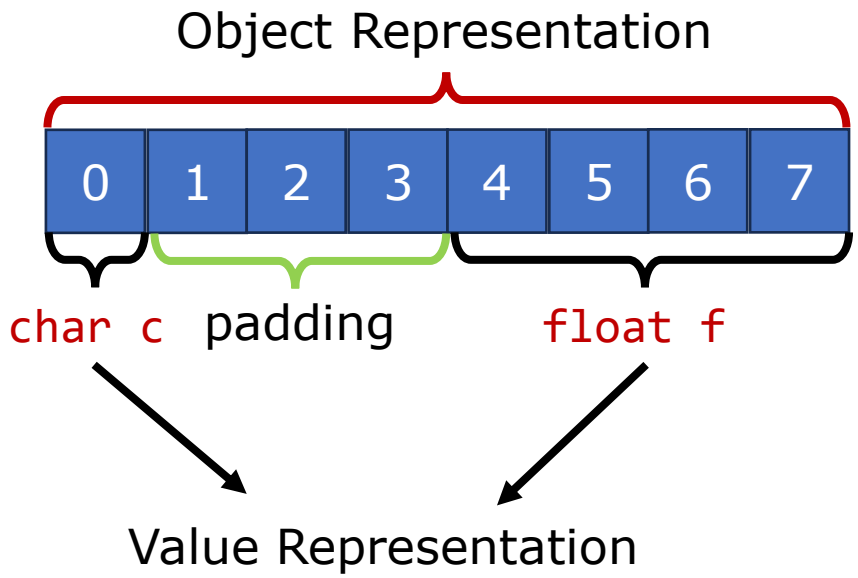
```
std::atomic<float> f{ 0.0 };
float expected = -0.0;
f.compare_exchange_strong(expected, 1.0);
```

     - When expected is -0.0, this CAS returns false; when it's 0.0, it's true.
  3. To make bitwise-written reasonable, `std::atomic<T>` has constraint on `T` – `T` should be trivially copyable.

Atomic Operations

```
struct S
{
    char c;  // 1 byte value
             // 3 bytes of padding bits (assuming alignof(float) == 4)
    float f; // 4 bytes value (assuming sizeof(float) == 4)
};
```

- Note 2: padding bits are **NOT** compared **since C++20**.
  - Before C++20, they're compared.
  - Formally, object representation v.s. value representation.



We'll talk about memory layout in detail in *Memory Management*.

Atomic Operations

- Reason: padding comparison may lead to astonishing false. If you really want to compare padding, you can manually pad as members.

- But, if it's atomic union, when different types have different value representations (i.e. padding positions are not same), only shared padding parts will be omitted.

- NOTICE:
  1. libc++ hasn't implemented it; libstdc++ currently implements it as DR (i.e. since gcc13, no matter what standard you specify, only value representation is compared).
  2. For union, no matter whether types have shared padding positions, MS-STL will only compare object representation (as of 2025/7). A simple test.

Atomic Operations

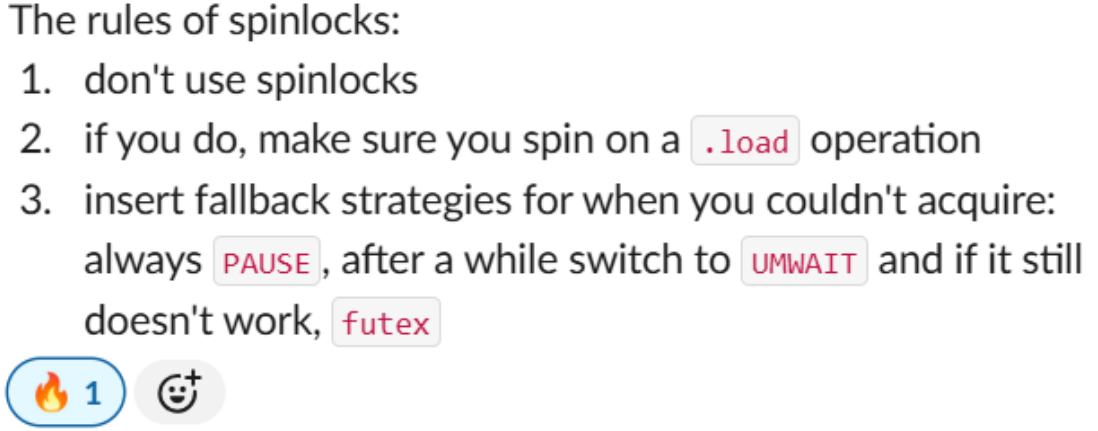
- Note 3: there also exists `.compare_exchange_weak(…)`, with completely same parameters as `.compare_exchange_strong`.
  - The effects are also same, except that `weak` may fail spuriously.
    - That is, it may report failure when it's in fact equal; but when it reports success, then it's definitely equal.
    - So that in some platforms, it may be cheaper to use `weak` than `strong`.
  - Normally we don't want that spurious failure, so `weak` is usually used in a loop.

```
expected = current.load();
do {
  desired = function(expected);
} while (!current.compare_exchange_weak(expected, desired));
```

    - So when the loop body is relatively cheap, `weak` can be beneficial to performance.
    - But if you don't use in loop or loop is very expensive, `strong` is expected.

spinlock

- Though we can implement spinlock by acq_rel, it's very inefficient.



  - Normally we should rely on platform-dependent features.
    - Like in x86, there are lots of idle instructions (PAUSE, UMWAIT, etc.) to reduce busy-wait overhead.
    - And in OS layer, we can use lots of native utilities like futex on Linux, `WaitOnAddress` on Windows, etc.
- To maximize efficiency, C++20 introduces `.wait()` for atomics.

A brief but good article about idle instructions: 漫话Linux之"躺平": IDLE 子系统

- `.wait(T old, memory_order)`: block when `.load(memory_order)` is equal to `old`.
  - Similar to condition variables:
  1. You need to call `.notify_one()` and `.notify_all()` after modification to waken up waiting side;
     - And pay attention to possible ABA problem.
  2. It may spuriously wake up and do comparison, even if not notified.
- For example, again:

```
int data = 0;
std::atomic<bool> sync1{ false },sync2{ false };

void thread_1()
{
    data = 442;                                     // #0
    sync1.store(true,std::memory_order_release);    // #1
}

void thread_2()
{
    while(!sync1.load(std::memory_order_acquire)); // #2
    sync2.store(true,std::memory_order_release);    // #3
}

void thread_3()
{
    while(!sync2.load(std::memory_order_acquire)); // #4
    assert(data == 442);                            // #5
}
```

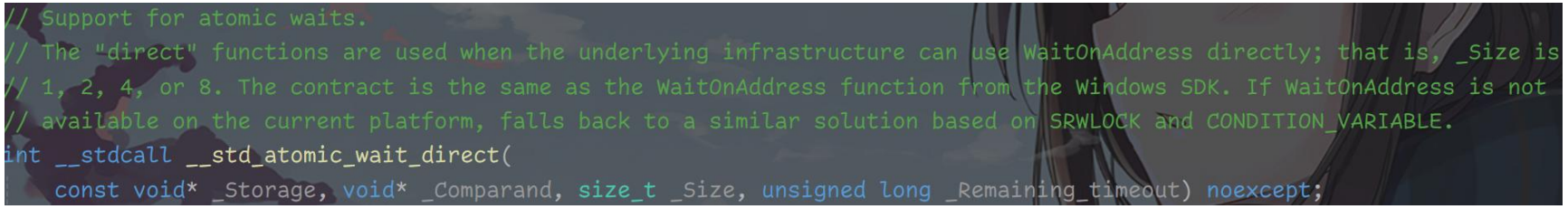
```
int data = 0;
std::atomic<bool> sync1{ false },sync2{ false };

void thread_1()
{
    data = 442;                                     // #0
    sync1.store(true, std::memory_order_release);   // #1
    sync1.notify_one();
}

void thread_2()
{
    sync1.wait(false, std::memory_order_acquire);   // #2
    sync2.store(true, std::memory_order_release);   // #3
    sync2.notify_one();
}

void thread_3()
{
    sync2.wait(false, std::memory_order_acquire);   // #4
    assert(data == 442);                            // #5
}
```

spinlock*



```
// Support for atomic waits.
// The "direct" functions are used when the underlying infrastructure can use WaitOnAddress directly; that is, _Size is
// 1, 2, 4, or 8. The contract is the same as the WaitOnAddress function from the Windows SDK. If WaitOnAddress is not
// available on the current platform, falls back to a similar solution based on SRWLOCK and CONDITION_VARIABLE.
int __stdcall __std_atomic_wait_direct(
    const void* _Storage, void* _Comparand, size_t _Size, unsigned long _Remaining_timeout) noexcept;
```

- About how `.wait()` is implemented, FYI.
  - Windows & MS-STL: by `WaitOnAddress` if supported in Windows SDK; otherwise by e.g. condition variable.
  - Linux & libstdc++:

```
#if __glibcxx_atomic_wait // C++ >= 20 && (linux_futex || gthread)
    _GLIBCXX_ALWAYS_INLINE void
    wait(bool __old,
        memory_order __m = memory_order_seq_cst) const noexcept
    {
      const __atomic_flag_data_type __v
        = __old ? __GCC_ATOMIC_TEST_AND_SET_TRUEVAL : 0;

      std::__atomic_wait_address_v(&_M_i, __v,
          [__m, this] { return __atomic_load_n(&_M_i, int(__m)); });
    }
```

```
template<typename _Tp, typename _ValFn>
  void
  __atomic_wait_address_v(const _Tp* __addr, _Tp __old,
                          _ValFn __vfn) noexcept
  {
    __detail::__enters_wait __w(__addr);
    __w._M_do_wait_v(__old, __vfn);
  }
```

Memory order is contained in `__vfn`.

```
template<typename _Tp, typename _ValFn>
  void
  _M_do_wait_v(_Tp __old, _ValFn __vfn)
  {
    do
      {
        __platform_wait_t __val;
        if (__base_type::_M_do_spin_v(__old, __vfn, __val))
          return;
        __base_type::_M_w._M_do_wait(__base_type::_M_addr, __val);
      }
    while (__detail::__atomic_compare(__old, __vfn()));
  }
```

For article to introduce it, see [Implementing C++20 atomic waiting in libstdc++ | Red Hat Developer](#).

```
template<typename _Up, typename _ValFn,
         typename _Spin = __default_spin_policy>
  bool
  _M_do_spin_v(const _Up& __old, _ValFn __vfn,
               __platform_wait_t& __val,
               _Spin __spin = _Spin{ })
  { return _S_do_spin_v(_M_addr, __old, __vfn, __val, __spin); }
```

```
struct __default_spin_policy
{
  bool
  operator()() const noexcept
  { return false; }
};
```

```
template<typename _Up, typename _ValFn,
         typename _Spin = __default_spin_policy>
  static bool
  _S_do_spin_v(__platform_wait_t* __addr,
               const _Up& __old, _ValFn __vfn,
               __platform_wait_t& __val,
               _Spin __spin = _Spin{ })
{
  auto const __pred = [=]
    { return !__detail::__atomic_compare(__old, __vfn()); };

  if constexpr (__platform_wait_uses_type<_Up>)
    {
      __builtin_memcpy(&__val, &__old, sizeof(__val));
    }
  else
    {
      __atomic_load(__addr, &__val, __ATOMIC_ACQUIRE);
    }
  return __atomic_spin(__pred, __spin);
}
```

```
  template<typename _Pred,
           typename _Spin = __default_spin_policy>
    bool
    __atomic_spin(_Pred& __pred, _Spin __spin = _Spin{ }) noexcept
    {
      for (auto __i = 0; __i < __atomic_spin_count; ++__i)
        {
          if (__pred())
            return true;

          if (__i < __atomic_spin_count_relax)
            __detail::__thread_relax();
          else
            __detail::__thread_yield();
        }

      while (__spin())
        {
          if (__pred())
            return true;
        }

      return false;
    }
```

Spin for `__atomic_spin_count` times

"Relax" first

`false` directly, so this part is jumped.

```
inline constexpr auto __atomic_spin_count_relax = 12;
inline constexpr auto __atomic_spin_count = 16;
```

```
    inline void
    __thread_yield() noexcept
    {
#if defined _GLIBCXX_HAS_GTHREADS && defined _GLIBCXX_USE_SCHED_YIELD
     __gthread_yield();
#endif
    }

    inline void
    __thread_relax() noexcept
    {
#if defined __i386__ || defined __x86_64__
      __builtin_ia32_pause();
#else
      __thread_yield();
#endif
    }
```

By e.g. PAUSE instruction.

By futex

```
    struct __waiter_pool : __waiter_pool_base
    {
      void
      _M_do_wait(const __platform_wait_t* __addr, __platform_wait_t __old) noexcept
      {
#ifdef _GLIBCXX_HAVE_PLATFORM_WAIT
        __platform_wait(__addr, __old);
#else
        __platform_wait_t __val;
        __atomic_load(__addr, &__val, __ATOMIC_SEQ_CST);
        if (__val == __old)
          {
            lock_guard<mutex> __l(_M_mtx);
            __atomic_load(__addr, &__val, __ATOMIC_RELAXED);
            if (__val == __old)
              _M_cv.wait(_M_mtx);
          }
#endif // __GLIBCXX_HAVE_PLATFORM_WAIT
      }
    };


  template<typename _Tp>
    void
    __platform_wait(const _Tp* __addr, __platform_wait_t __val) noexcept
    {
      auto __e = syscall (SYS_futex, static_cast<const void*>(__addr),
                          static_cast<int>(__futex_wait_flags::__wait_private),
                          __val, nullptr);
      if (!__e || errno == EAGAIN)
        return;
      if (errno != EINTR)
        __throw_system_error(errno);
    }
```

Lock-free?

- Finally, usually the reason we use atomic variables instead of lock is that they’re more efficient.
  - But are atomic variables really lock-free?
- No, not necessary…
  - C++ does **NOT** regulate that atomic variables should be lock-free.
  - Common platforms will support small types like integers to be lock-free by atomic instructions in ISA;
    - But if you use a very large struct, then no atomic instruction can do that!
    - Or if your platform only supports very weak ISA, then even not all atomic integers are lock-free…
- Instead, C++ provides interface to check whether it’s lock-free.

For non-lock-free atomic types, you may need to link additional libraries; like in gcc and clang you need `-latomic`.

Lock-free?

- A `constexpr static` boolean: `std::atomic<T>::is_always_lock_free`; only when on the current platform `std::atomic<T>` is definitely lock-free will it be `true`.
- A normal function: `.is_lock_free()`; some lock-free types may be only determined in runtime (e.g. when its address are over-aligned).

- C++20 adds some aliases that are guaranteed to be lock-free:

Aliases for special-purpose types

`atomic_signed_lock_free` (C++20)	a signed integral atomic type that is lock-free and for which waiting/notifying is most efficient (typedef)
`atomic_unsigned_lock_free` (C++20)	an unsigned integral atomic type that is lock-free and for which waiting/notifying is most efficient (typedef)

Note: `std::atomic_int`*N*`_t`, `std::atomic_uint`*N*`_t`, `std::atomic_intptr_t`, and `std::atomic_uintptr_t` are defined if and only if `std::int`*N*`_t`, `std::uint`*N*`_t`, `std::intptr_t`, and `std::uintptr_t` are defined, respectively.

`std::atomic_signed_lock_free` and `std::atomic_unsigned_lock_free` are optional in freestanding implementations. (since C++20)

1. ↑ Support for always lock-free integral atomic types and presence of type aliases `std::atomic_signed_lock_free` and `std::atomic_unsigned_lock_free` are implementation-defined in a freestanding implementation.(since C++20)

atomic_flag

- Besides, C++ standard regulates a special type to be definitely lock-free: `std::atomic_flag`.
  - It's similar to `std::atomic<bool>`, but the latter is not regulated to be lock-free.
  - And since its value is either `true` or `false`, methods are renamed directly.
  - Read op:
    - `.test(memory_order)`, since C++20.
  - Write op:
    - `.clear(memory_order)`: set to `false`.
  - RMW op:
    - `.test_and_set(memory_order)`: set to `true` and return the previous test result.
  - Spinlock:
    - `.wait(bool old, memory_order)`, `.notify_one()`, `.notify_all()`, since C++20.

atomic_flag

- And for ctor:

std::atomic_flag::atomic_flag

Defined in header <atomic>

`atomic_flag() noexcept = default;`	(1)	(since C++11) (until C++20)
`constexpr atomic_flag() noexcept;`		(since C++20)
`atomic_flag( const atomic_flag& ) = delete;`	(2)	(since C++11)

Constructs a new `std::atomic_flag`.

1) Trivial default constructor, initializes `std::atomic_flag` to unspecified state. (until C++20)

1) Initializes `std::atomic_flag` to clear state. (since C++20)

2) The copy constructor is deleted; `std::atomic_flag` is not copyable.

Before C++20

In addition, `std::atomic_flag` can be value-initialized to clear state with the expression `ATOMIC_FLAG_INIT`. For an `atomic_flag` with static storage duration, this guarantees static initialization: the flag can be used in constructors of static objects.

ATOMIC_FLAG_INIT

Defined in header <atomic>

```
#define ATOMIC_FLAG_INIT /* implementation-defined */
```
(since C++11)

Defines the initializer which can be used to initialize `std::atomic_flag` to clear (false) state in the form `std::atomic_flag v = ATOMIC_FLAG_INIT;`. It is unspecified if it can be used with other initialization contexts.

If the flag has is a complete object with static storage duration, this initialization is static.

This is the only way to initialize `std::atomic_flag` to a definite value: the value held after any other initialization is unspecified.	(until C++20)
This macro is no longer needed since default constructor of `std::atomic_flag` initializes it to clear state. It is kept for the compatibility with C.	(since C++20)

Advanced Concurrency

- Atomic variables
  - Basic operations
    - atomic_flag
  - Specializations
    - atomic_ref

Specializations

- Some atomic types are specialized to provide more convenient methods; we list them here.
  - Integers:
    - The character types `char`, `char8_t`(since C++20), `char16_t`, `char32_t`, and `wchar_t`;
    - The standard signed integer types: `signed char`, `short`, `int`, `long`, and `long long`;
    - The standard unsigned integer types: `unsigned char`, `unsigned short`, `unsigned int`, `unsigned long`, and `unsigned long long`;
    - Any additional integral types needed by the typedefs in the header `<cstdint>`.
  - Floating points (since C++20):

    When instantiated with one of the cv-unqualified floating-point types (`float`, `double`, `long double` and cv-unqualified extended floating-point types(since C++23)), `std::atomic` provides additional atomic operations
  - And raw pointers.

Member types

Type	Definition
`value_type`	T (regardless of whether specialized or not)
`difference_type`[1]	`value_type` (only for `atomic<`*Integral*`>` and `atomic<`*Floating*`>`(since C++20) specializations)
	`std::ptrdiff_t` (only for `std::atomic<U*>` specializations)

Specializations

- They just add common RMW operators and corresponding function overloads (to provide memory order).
  - Operators: `+=, -=, ++, --, &=, |=, ^=`;
    - But they do NOT return `*this`; except for postfix `++`, they return the **new** value (i.e. the stored value).
  - Functions: `fetch_xxx`, i.e. `fetch_add/sub/and/or/xor(T, memory_order)`.
    - And they return the **original** value.
  - And another two functions since C++26: `fetch_max/min(T, mo)`, which writes maximum/minimum value back.
- Floating points only provide `+=, -=, add, sub`;
- Pointers only provide `+=, -=, ++, --, add, sub, max, min`;

Specializations

- Note 1: since C++20, there also exist specializations for `std::shared_ptr` and `std::weak_ptr`, and we'll talk about them in *Memory Management*.

- Note 2: atomic pointers do NOT mean you access underlying objects atomically; they mean pointer themselves are atomic.
  - And that's why there are no `operator*` and `operator->` for atomic pointers.
  - Since C++20, `std::atomic_ref` is introduced for that atomic access.

atomic_ref

- An example adjusted from C++20 the Complete Guide by *Nicolai. M. Josuttis*.

- Most of methods in `std::atomic_ref<T>` are same as `std::atomic<T>` as if operating on it directly.
  - So not listed again.

```
// create and initialize an array of integers with the value 100:
std::array<int, 1000> values;
std::fill_n(values.begin(), values.size(), 100);

// initialize a common stop token for all threads:
std::stop_source allStopSource;
std::stop_token allStopToken{ allStopSource.get_token() };

// start multiple threads concurrently decrementing the value:
std::vector<std::jthread> threads;
for (int i = 0; i < 9; ++i)
{
    threads.push_back(std::jthread{
        [&values](std::stop_token st) {
            while (!st.stop_requested())
            {
                std::size_t idx = GetRandomIndex(values.size());
                std::atomic_ref val{ values[idx] };
                auto newVal = --val;
                if (newVal <= 0)
                    std::println("index {} is zero", idx);
            }
        },
        allStopToken // pass the common stop token
    });
}

allStopSource.request_stop();
```

atomic_ref

1. To denote const reference, you can use `std::atomic_ref<const T>`; then write operations will be disabled.
   - `const std::atomic_ref<T>` is shallow const; as reference itself is already `const`, this shallow const does nothing.
2. When an object is accessed by `std::atomic_ref`, you shouldn't access it by normal reference and pointers to avoid data races.
   - And of course, you need to ensure the lifetime of referenced object doesn't end (i.e. not dangling reference).
   - And different `std::atomic_ref` shouldn't overlap. Formally:

> through those `atomic_ref` instances. No subobject of the object referenced by `atomic_ref` shall be concurrently referenced by any other `atomic_ref` object.

atomic_ref

3. And some unique members:
   - Data members:
     - `static constexpr std::size_t required_alignment`, the referenced object should align with `required_alignment`; otherwise UB.
   - Methods:
     - `.address()`: since C++26, returning pointer to the referenced object.
     - copy ctor: reference the same object as another `std::atomic_ref`.
       - But it's not copy assignable.
4. Even if `std::atomic<T>` is lock free, `std::atomic_ref<T>` may not be lock free; their implementations are different.

Advanced Concurrency

Advanced Memory Order

Advanced Concurrency

- Advanced Memory Order
  - Release Sequence
  - Out-of-thin-air Problem
  - Memory Model Conflict
  - Fence

Release Sequence

- Observe code below:

```
std::vector<int> items;
std::atomic<int> readySize{0};

void Producer()
{
    int size = 10;
    for (int i = 0; i < size; i++)
        items.push_back(i); // #0
    readySize.store(10, std::memory_order_release); // #1
}
```

```
void Consumer()
{
    while (true)
    {
        int idx = readySize.fetch_sub(1, std::memory_order_acquire); // #2
        if (idx <= 0) {
            wait_for_random_time();
            continue;
        }
        else {
            int item = items[idx - 1]; // #3
            Process(item);
        }
    }
}
```

Release Sequence

- Assuming that there is only one producer and one consumer, then it's definitely correct.
  - If producer is not ready, then consumer will wait;
  - The first time `idx > 0`, it means that #2 read value from #1 and thus SW(#1, #2).
    - And SB(#0, #1), SB(#2, #3), thus HB(#0, #3).
    - That is, when the consumer extracts a value, it's guaranteed that the producer has already stored it, which ensures correctness.
  - And for following `fetch_sub`, since they're performed in the same thread, SB makes it still correct.

- But, what about one producer + two consumers?

Release Sequence

```
void Consumer()
{
    while (true)
    {
        int idx = readySize.fetch_sub(1, std::memory_order_acquire); // #2
        if (idx <= 0) {
            wait_for_random_time();
            continue;
        }
        else {
            int item = items[idx - 1]; // #3
            Process(item);
        }
    }
}
```

- For the consumer that first sees `idx > 0`, it's still correct (as we analyzed before).
- But for the second consumer, $\#2_2$ reads value from write in $\#2_1$.
  - But write in $\#2_1$ is relaxed, so there is no SW($\#2_1$, $\#2_2$);
  - Thus, we cannot conclude HB(#0, $\#3_2$)…
  - That is, when the second consumer extracts a value, it's **NOT** guaranteed that the producer has already stored it.
- To solve it, we can use `acq_rel` instead of `acquire`;
  - But we've said that `acquire` only introduces one-way barrier, while `acq_rel` will introduce two-way barrier, which harms optimization.

Release Sequence

- To overcome this counter-intuitive result, C++ introduces ***release sequence***.

> 5 A *release sequence* headed by a release operation *A* on an atomic object *M* is a maximal contiguous sub-sequence of side effects in the modification order of *M*, where the first operation is *A*, and every subsequent operation is an atomic read-modify-write operation. [intro.multithread]

> 2 An atomic operation *A* that performs a release operation on an atomic object *M* synchronizes with an atomic operation *B* that performs an acquire operation on *M* and takes its value from any side effect in the release sequence headed by *A*. [atomics]

  - In other words, the release operation can be maintained through a continuous bunch of RMW operations (no matter what memory order they have), as long as there are no other new modifications kick in.
- In our example, this means SW(#1, $\#2_2$) is thus guaranteed.

Release Sequence

- This is slightly weaker than `acq_rel`.
  - If we use `acq_rel`, we can conclude SW(#2_1, #2_2) and thus infer HB(#1, #2_2).
  - But by release sequence, we can only conclude SW(#1, #2_2); there is no HB relationship between #2_1 and #2_2.
- Take our previous example, again:

```
int data = 0;
std::atomic<int> sync{0};

void thread_1()
{
    data = 442;                                          // #0
    sync.store(1, std::memory_order_release);            // #1
}
```

```
void thread_2()
{
    int expected = 1;
    while(!sync.compare_exchange_strong(expected, 2,  // #2
                                        std::memory_order_acq_rel))
        expected = 1; // Restore expected to compare again.
}

void thread_3()
{
    while(sync.load(std::memory_order_acquire) != 2); // #4
    assert(data == 442);                              // #5
}
```

Can we weaken this order to `relaxed`?

Release Sequence

```
int data = 0;
std::atomic<int> sync{0};

void thread_1()
{
    data = 442;                                          // #0
    sync.store(1, std::memory_order_release);            // #1
}
```

- Yes, #1 + #2 is a release sequence, and thus SW(#1, #4).
  - With SB(#0, #1) and SB(#4, #5), we thus know HB(#0, #5), which means `assert` never fire.
- But code right is incorrect:
  - Since there is no SW(#1, #2), thus we don't know HB(#1, #6), and thus no HB(#0, #6).
  - And we say that two non-atomic operations that have no HB relationship will cause *data races*.
  - Thus, #6 is UB.
- If we use `acq_rel` here, then from SW(#1, #2) we know HB(#0, #6), then it's correct.

```
void thread_2()
{
    int expected = 1;
    while(!sync.compare_exchange_strong(expected, 2,  // #2
                                        std::memory_order_relaxed))
        expected = 1; // Restore expected to compare again.
    assert(data == 442); // #6
}
```

Release Sequence before C++20*

- This part is **optional**.
- Actually before C++20, release sequence can have more components:

Release sequence

After a *release operation* A is performed on an atomic object M, the longest continuous subsequence of the modification order of M that consists of:

1) Writes performed by the same thread that performed A. (until C++20)

2) Atomic read-modify-write operations made to M by any thread.

Is known as *release sequence headed by A*.

  - And C++20 weakens release sequence; but why do C++11 introduce it while C++20 delete it?
- Consider code right:

```
int y = 0;
std::atomic<int> x{0};

void thread_1()
{
    y = 1;                                          // #1
    x.store(1, std::memory_order_release);          // #2
    x.store(3, std::memory_order_relaxed);          // #3
}
```

```
void thread_2()
{
    if (x.load(std::memory_order_acquire) == 3) // #4
        assert(y == 1);                         // #5
}
```

Release S

```
int y = 0;
std::atomic<int> x{0};

void thread_1()
{
    y = 1;                                  // #1
    x.store(1, std::memory_order_release); // #2
    x.store(3, std::memory_order_relaxed); // #3
}
```

```
void thread_2()
{
    if (x.load(std::memory_order_acquire) == 3) // #4
        assert(y == 1);                         // #5
}
```

- We know that to execute #5, #4 needs to be true, which means that #4 needs to load value from #3.
  - But #3 is a relaxed store, thus there is no SW relationship, and thus we cannot infer HB(#1, #5).
  - So here #5 has data races with #1.
- But intuitively, since SB(#2, #3) and #2 is release operation, it's "natural" to think SW(#2, #4).
  - Thus, C++11 regulates that following writes in the same thread are also part of release sequence.
- However, this is not natural at all[1, 2]...

[1]: Common Compiler Optimisations are Invalid in the C11 Memory Model and what we can do about it | POPL'15, Viktor et.al.
[2]: P0982R1: Weaken release sequences

Release Sequence before C++20*

- We may introduce a new thread:
  - If #6 kicks in between #2 and #3 in modification order of x…
  - Then this release sequence is destroyed and suddenly #5 has data races with #1 again.
- This is counter-intuitive again and will make program buggy.
  - That is, the relaxed order, which should not be engaged in any SW relationship, weirdly corrupts other HB relationship.

```
int y = 0;
std::atomic<int> x{0};

void thread_1()
{
    y = 1;                                  // #1
    x.store(1, std::memory_order_release); // #2
    x.store(3, std::memory_order_relaxed); // #3
}

void thread_2()
{
    if (x.load(std::memory_order_acquire) == 3) // #4
        assert(y == 1);                         // #5
}

void thread_3()
{
    x.store(2, std::memory_order_relaxed); // #6
}
```

Release Sequence before C++20*

- Two ways to solve that:
  - [1], as an academic paper, proposes a very complex way to strengthen the memory model to make release sequence still valid;
  - [2], as a C++ proposal, proposes to minimize changes and thus weaken release sequence by cancelling the first rule.

Release sequence

After a *release operation* A is performed on an atomic object M, the longest continuous subsequence of the modification order of M that consists of:

1) Writes performed by the same thread that performed A. (until C++20)

2) Atomic read-modify-write operations made to M by any thread.

Is known as *release sequence headed by A*.

  - This means even if there is no thread 3, code has data races (as we reason before that HB(#1, #5) doesn't hold water).

[1]: Common Compiler Optimisations are Invalid in the C11 Memory Model and what we can do about it | POPL'15, Viktor et.al.
[2]: P0982R1: Weaken release sequences

Advanced Concurrency

- Advanced Memory Order
  - Release Sequence
  - Out-of-thin-air Problem
  - Memory Model Conflict
  - Fence

Out-of-thin-air Problem

- We've said relaxed model can cause astonishing results:
  - Here `r1 == 42 && r2 == 42` is possible.
- Then what about code below?

```
// Thread 1:
r1 = y.load(std::memory_order_relaxed);
if (r1 == 42)
    x.store(r1, std::memory_order_relaxed);
// Thread 2:
r2 = x.load(std::memory_order_relaxed);
if (r2 == 42)
    y.store(42, std::memory_order_relaxed);
```

```
void read_y_then_write_x(int& r1)
{
    r1 = y.load(std::memory_order_relaxed); // #1
    x.store(r1, std::memory_order_relaxed); // #2
}

void read_x_then_write_y(int& r2)
{
    r2 = x.load(std::memory_order_relaxed); // #3
    y.store(42, std::memory_order_relaxed); // #4
}
```

- We only add two if without any new atomic operations, which should not affect any HB order, and theoretically `r1 == 42 && r2 == 42` is still a valid solution.

Out-of-thin-air Problem

- Reasoning process is same as we point out before:

  - Remember our effect rules?
    - For atomic variables, if B doesn't happen before A, then effects of A may be visible to B (as long as there are no effects after A take place).
    - So here #1 doesn't happen before #4, then effects of #4 can be read by #1 so `r1 == 42` can be true.
      - And #1 happens before #2, so x can store 42.
    - And #3 doesn't happen before #2, then effects of #2 can be read by #3 so `r2 == 42` can be true.

- However, this outcome is contradictory with logical causality（因果律）.

Out-of-thin-air Problem

```
// Thread 1:
r1 = y.load(std::memory_order_relaxed);
if (r1 == 42)
    x.store(r1, std::memory_order_relaxed);
// Thread 2:
r2 = x.load(std::memory_order_relaxed);
if (r2 == 42)
    y.store(42, std::memory_order_relaxed);
```

- The logical preconditions are as follows (→ means "requires"):
  - #2 store happens → r1 == 42 → #1 loads 42 → #4 store happens → r2 == 42 → #3 loads 42 → #2 store happens.
  - So the precondition to make #2 happen, is that #2 has already happened.
  - This is logical fallacy, i.e. begging the question（循环论证，即通过假设结果正确，推出结果正确。）
- Compared with our normal example:
  - #2 store happen have **NO** precondition.

```
// Thread 1:
r1 = y.load(std::memory_order_relaxed);
x.store(r1, std::memory_order_relaxed);
// Thread 2:
r2 = x.load(std::memory_order_relaxed);
y.store(42, std::memory_order_relaxed);
```

- Such logical fallacy is called "out-of–thin-air problem" in relaxed order; `r1 == 42 && r2 == 42` comes from nowhere but it's allowed by theoretical model.

Out-of-thin-air Problem

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

- If we allow it to happen, a scary example will be right too:
  - Initially `x == 0 && y == 0`, we can still get `r1 == 42 && r2 == 42`.
  - Because we can "assume" that r1 loads 42, and then we find that `x == 42 && y == 42 && r1 == 42 && r2 == 42` is a valid and consistent solution.
    - Again, we beg the question…
- However, these problems are still under investigation in academy:
  1. How can we describe out-of-thin-air problem in current model?
  2. How can compilers detect out-of-thin-air problem?
     - Currently we can only describe it by data dependency, which is almost not trackable in complex program.
  3. How can we avoid out-of-thin-air problem in the most efficient way?

An Initial Study of Two Approaches to Eliminating Out-of-Thin-Air Results is a good academic survey for this.

- Of course, lots of academic work tries to solve them with different approaches…
  - And before a widely-accepted model & description is proposed, C++ standard chooses the most conservative way to state it:

[8] Implementations should ensure that no "out-of-thin-air" values are computed that circularly depend on their own computation.

[*Note 5*: For example, with x and y initially zero,

```
// Thread 1:
r1 = y.load(memory_order::relaxed);
x.store(r1, memory_order::relaxed);
// Thread 2:
r2 = x.load(memory_order::relaxed);
y.store(r2, memory_order::relaxed);
```

this recommendation discourages producing `r1 == r2 == 42`, since the store of 42 to y is only possible if the store to x stores 42, which circularly depends on the store to y storing 42. Note that without this restriction, such an execution is possible. — *end note*]

And since out-of-thin-air problem is not well-defined now, we only assert that no processor will do operations that violate causality.

[9] [*Note 6*: The recommendation similarly disallows `r1 == r2 == 42` in the following example, with x and y again initially zero:

```
// Thread 1:
r1 = x.load(memory_order::relaxed);
if (r1 == 42) y.store(42, memory_order::relaxed);
// Thread 2:
r2 = y.load(memory_order::relaxed);
if (r2 == 42) x.store(42, memory_order::relaxed);
```

— *end note*]

Advanced Concurrency

- Advanced Memory Order
  - Release Sequence
  - Out-of-thin-air Problem
  - Memory Model Conflict
  - Fence

Memory Model Conflict

- We've said that sequential consistent model ensures total order, while acquire-release & relaxed model doesn't.
  - What if we mix their operations?
  - For example[1, 2]:

```
// Thread 1:
x.store(1, std::memory_order_seq_cst); // A
y.store(1, std::memory_order_release); // B
// Thread 2:
r1 = y.fetch_add(1, std::memory_order_seq_cst); // C
r2 = y.load(std::memory_order_relaxed); // D
// Thread 3:
y.store(3, std::memory_order_seq_cst); // E
r3 = x.load(std::memory_order_seq_cst); // F
```

  - Initial value of x and y are both 0, can `r1 == 1 && r2 == 3 && r3 == 0`?

[1]: Repairing sequential consistency in C/C++11 | PLDI'17, Lahav et.al.
[2]: P0668R5: Revising the C++ memory model

Memory Model Co

```
// Thread 1:
x.store(1, std::memory_order_seq_cst); // A
y.store(1, std::memory_order_release); // B
// Thread 2:
r1 = y.fetch_add(1, std::memory_order_seq_cst); // C
r2 = y.load(std::memory_order_relaxed); // D
// Thread 3:
y.store(3, std::memory_order_seq_cst); // E
r3 = x.load(std::memory_order_seq_cst); // F
```

- In seq_cst total order:
  - To make `r1 == 1 && r2 == 3`, C needs to read `y == 1` but D needs to read `y == 3` and thus in total order C → E.
    - If E → C, then D can never get 3.
    - B is not `seq_cst` operation so B → C is not among total order.
  - To make `r3 == 0`, F needs to read `x == 0` and thus in total order F → A.
  - And we know that SB restricts total order E → F.
  - So in `seq_cst` model, such result just needs total order C → E → F → A.

- While in HB relationship…
  - We first note that in SW relationship, `seq_cst` is equivalent to `acq_rel`.

Memory Model Co

```
// Thread 1:
x.store(1, std::memory_order_seq_cst); // A
y.store(1, std::memory_order_release); // B
// Thread 2:
r1 = y.fetch_add(1, std::memory_order_seq_cst); // C
r2 = y.load(std::memory_order_relaxed); // D
// Thread 3:
y.store(3, std::memory_order_seq_cst); // E
r3 = x.load(std::memory_order_seq_cst); // F
```

- We only know:
  - SW(Init_x, F), SB(A, B), SB(C, D), SB(E, F).
- To make `r1 == 1`, C reads value from B and thus SW(B, C).
  - Thus HB(A, B, C, D).
- To make `r2 == 3`, as long as HB(D, E) is not true.
  - And there is no way to deduce it's true, and thus it's Okay.

- So in different angles of views, we seem to get contradictory results:
  - In total order, C → E → F → A;
  - In HB order, HB(A, B, C, D).
- Before C++20, it's regulated HB order should be consistent with total order, i.e. `r1 == 1 && r2 == 3 && r3 == 0` is impossible.

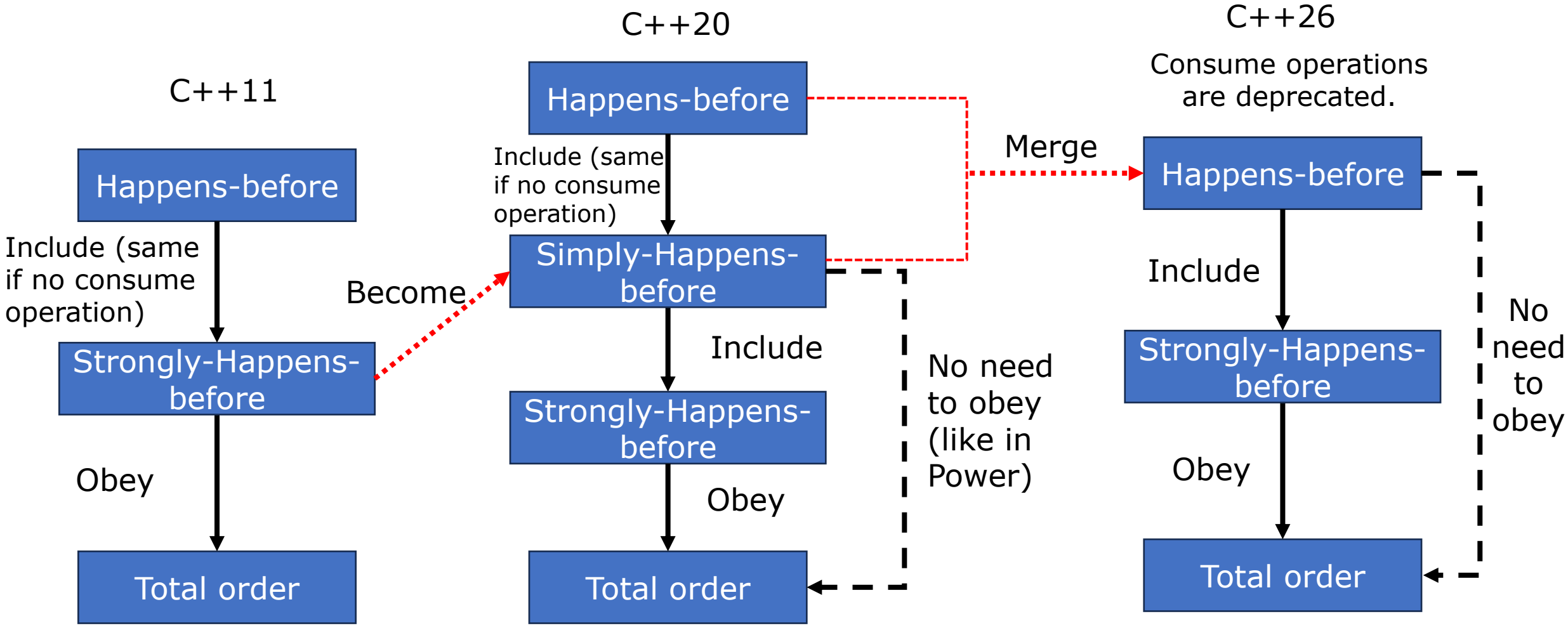
Memory Model Conflict

- However, Power and ARM allow it (especially Power)…
  - To maximize optimization, instead of fixing compilers, the C++20 standard is thus revised to allow such contradiction.
- Formally, only ***strongly-happens-before*** relationship should obey total order.

  1) A is *sequenced-before* B.
  2) A *synchronizes with* B, and both A and B are sequentially consistent atomic operations.
  3) A is *sequenced-before* X, X *simply*(until C++26) *happens-before* Y, and Y is *sequenced-before* B.
  4) A *strongly happens-before* X, and X *strongly happens-before* B.

  - In our example, SW(B, C) are not all seq_cst atomic operations, and thus SHB(A, B, C, D) is not true.
    - We can only assert SHB(A, D), since SB(A, B) && HB(B, C) && SB(C, D); but since D is not seq_cst, SHB(A, D) is still not involved in total order.

Happens-before Revision*



What we teach is based on C++26; and since consume operations are never implemented, it can also be seen as based on C++20.

Advanced Concurrency

- Advanced Memory Order
  - Release Sequence
  - Out-of-thin-air Problem
  - Memory Model Conflict
  - Fence

Fence

- Sometimes we want to synchronize without an explicit atomic variable…
  - And fence, as a global barrier, is for that!
  - `std::atomic_thread_fence(memory_order)`.
- It somehow imposes memory order globally:
  - For a release fence, as if adding release order for following atomic writes.
    - BUT the relationship is just SW **from fence**.
  - For an acquire fence, as if adding acquire order for previous atomic reads.
    - BUT the relationship is just SW **from fence**.
- Specifically:

Depending on the value of the `order` parameter, the effects of this call are:

- When `order == std::memory_order_relaxed`, there are no effects.
- When `order == std::memory_order_acquire` or `order == std::memory_order_consume`, is an acquire fence.
- When `order == std::memory_order_release`, is a release fence.
- When `order == std::memory_order_acq_rel`, is both a release fence and an acquire fence.
- When `order == std::memory_order_seq_cst`, is a sequentially-consistent ordering acquire fence and release fence.

Fence

- For example:
  - When #3 is true, it reads value from #2;
  - And we say #3 is “as if” an acquire operation since it’s atomic read before acquire fence…
    - So then SW relationship is established.
  - And SW starts from fence…
    - Thus it’s SW(#2, **#4**), not SW(#2, #3).
    - So HB(#1, #5), then it’s safe for this read.

```
constexpr int num_mailboxes = 32;
std::atomic<bool> mailbox_receiver[num_mailboxes]{};
std::string mailbox_data[num_mailboxes];

void Writer(int i)
{
    mailbox_data[i] = compute(i);                                    // #1
    mailbox_receiver[i].store(true, std::memory_order_release);      // #2
}

void Reader()
{
    for (int i = 0; i < num_mailboxes; ++i)
    {
        if (std::mailbox_receiver[i].load(std::memory_order_relaxed)) // #3
        {
            std::atomic_thread_fence(std::memory_order_acquire);     // #4
            do_work(mailbox_data[i]);                                // #5
        }
    }
}

int main()
{
    std::jthread writer_threads[num_mailboxes];
    for (int i = 0; i < num_mailboxes; i++)
    {
        writer_threads[i] = std::jthread{ Writer, i };
    }
    std::jthread reader_thread{ Reader };
    return 0;
}
```

Fence

```
void Reader()
{
    for (int i = 0; i < num_mailboxes; ++i)
    {
        if (std::mailbox_receiver[i].load(std::memory_order_relaxed)) // #3
        {
            do_work(mailbox_data[i]);                                 // #5
            std::atomic_thread_fence(std::memory_order_acquire);      // #4
        }
    }
}
```

- Is it still correct if we swap #4 and #5?
  - No, since SW(#2, **#4**) doesn't imply HB(#1, #5) then.
- So we can see that fence strengthens atomic operations globally, which also incurs higher overhead.
- Formally:

[2] A release fence *A* synchronizes with an acquire fence *B* if there exist atomic operations *X* and *Y*, both operating on some atomic object *M*, such that *A* is sequenced before *X*, *X* modifies *M*, *Y* is sequenced before *B*, and *Y* reads the value written by *X* or a value written by any side effect in the hypothetical release sequence *X* would head if it were a release operation.

[3] A release fence *A* synchronizes with an atomic operation *B* that performs an acquire operation on an atomic object *M* if there exists an atomic operation *X* such that *A* is sequenced before *X*, *X* modifies *M*, and *B* reads the value written by *X* or a value written by any side effect in the hypothetical release sequence *X* would head if it were a release operation.

[4] An atomic operation *A* that is a release operation on an atomic object *M* synchronizes with an acquire fence *B* if there exists some atomic operation *X* on *M* such that *X* is sequenced before *B* and reads the value written by *A* or a value written by any side effect in the release sequence headed by *A*.

Fence

- Another example:
  - If #6 is true, then #4 reads value from #3;
  - And #4 is atomic read before acquire fence, #3 is atomic write after release fence.
    - So “as if” #3 is release operation, #4 is acquire operation.
    - Thus SW relationship from fence is established.
  - Then SW(**#2**, **#5**), and thus HB(#1, #7), so #7 is safe to read.

```
std::atomic<int> arr[3] = {-1, -1, -1};
std::string data[1000]; //non-atomic data

// Thread A, compute 3 values.
void ThreadA(int v0, int v1, int v2)
{
//  assert(0 <= v0, v1, v2 < 1000);
    data[v0] = computation(v0);                                          #1
    data[v1] = computation(v1);
    data[v2] = computation(v2);
    std::atomic_thread_fence(std::memory_order_release);                 #2
    std::atomic_store_explicit(&arr[0], v0, std::memory_order_relaxed);  #3
    std::atomic_store_explicit(&arr[1], v1, std::memory_order_relaxed);
    std::atomic_store_explicit(&arr[2], v2, std::memory_order_relaxed);
}

// Thread B, prints between 0 and 3 values already computed.
void ThreadB()
{
    int v0 = std::atomic_load_explicit(&arr[0], std::memory_order_relaxed); #4
    int v1 = std::atomic_load_explicit(&arr[1], std::memory_order_relaxed);
    int v2 = std::atomic_load_explicit(&arr[2], std::memory_order_relaxed);
    std::atomic_thread_fence(std::memory_order_acquire);                 #5
//  v0, v1, v2 might turn out to be -1, some or all of them.
//  Otherwise it is safe to read the non-atomic data because of the fences:
    if (v0 != -1)                                                        #6
        print(data[v0]);                                                 #7
    if (v1 != -1)
        print(data[v1]);
    if (v2 != -1)
        print(data[v2]);
}
```

Advanced Concurrency

Coroutine

Advanced Concurrency

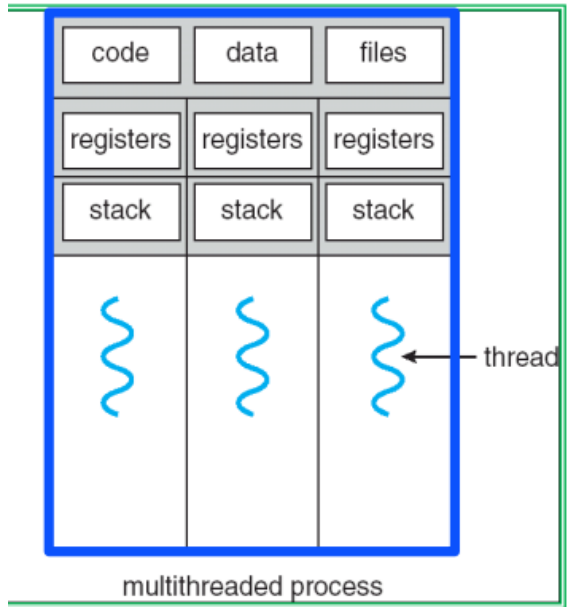
- Coroutine
  - Overview
  - Basics
  - Awaiter
  - `std::generator` in Detail

Coroutine

- We know that threads are **competitive** execution context.
  - They won’t suspend until schedulers force them by interruption.

- But sometimes, instruction streams **cooperate** with each other.
  - That is, they suspend and switch to other streams voluntarily.
  - This is coroutine (**co**operative **routine**).
- Coroutines define a set of **suspension points**;
  - When execution streams reach a suspension point, they will **transfer** rights to other coroutines;
  - Execution will be restored when other coroutines transfer rights back.
  - Just like a state machine!

Coroutine category



- And there are two ways to implement coroutine…
- Stackful coroutines, or fiber*（有栈协程 / 纤程）.
  - Recap: thread model.
    - Each thread has its own registers and stack; context switch saves old registers and loads new registers in kernel space.
  - Similarly, stackful coroutines have their own registers and stack.
    - And suspension point just saves & loads registers voluntarily in user space.
- Stackless coroutine（无栈协程）.
  - The state is explicitly allocated in some space;
    - Thus registers don’t represent its state and there is no need to save them.
  - They will just occupy stack of current thread, instead of allocating a new stack.

*: Sometimes fiber refers to user-space threads, which is still competitive instead of cooperative.

Coroutine

```
int MyCoroutine(int arg)
{
    yield arg + 1; // suspends
    yield arg + 2; // suspends
}
```

```
void Test()
{
    auto coro = GenerateMyCoroutine(1);
    auto m0 = coro(); // 2
    auto m1 = coro(); // 3
}
```

- A very naïve example (pseudocode).

- For stackful coroutine:
  - `coro` is just `Context`;
  - Resume: restore ins. pointer, restore stack pointer, restore registers.
  - Suspend: set result, save ins. pointer, save stack pointer, save registers.

```
void MyCoroutineImpl(Context& context)
{
    int temp = arg + 1;
    *context.result = temp;
    return; // jump back by return
    int temp2 = arg + 2;
    *context.result = temp2;
    return;
}
```

```
struct Context
{
    std::byte* stackBase = new std::byte[STACK_SIZE];
    std::byte* stackPtr = stackBase + STACK_SIZE;
    void* instructionPtr = &MyCoroutineImpl;
    uint64_t registers[16];
    int* result = new int;

    void operator()() {
        /* 1. Set jump-back address; */
        /* 2. Resume registers... */
        // 3. Resume context
        __asm__ __volatile__(
            "movq %%rsp, %0\n\t" "movq %%rbp, %1\n\t" "movq %%rip, %2\n\t"
            : "=m"(stackPtr), "=m"(stackBase), "=m"(instructionPtr)
        );
        // ---------- Resumption ends ----------
        // --- Processor just runs normally by %rip, and jumps back... ---
        // ---------- Suspension begins ----------
        /* 4. Save registers... */
        // 5. Save contexts (assuming %rax stores next resume address).
        __asm__ __volatile__(
            "movq %0, %%rsp\n\t" "movq %1, %%rbp\n\t" "movq %2, %%rax\n\t"
            : "=m"(stackPtr), "=m"(stackBase), "=m"(instructionPtr)
        );

        return result;
    }
};
```

Coroutine

- For stackless coroutine, we can rewrite without any assembly.
  - Any variable with lifetime that spans over suspension point will be saved in `context`.
  - It's just like a normal function call, so it uses stack of caller.

- C++ adopts stackless coroutine for zero-overhead abstraction.
  - But there also exists P0876 for fiber.

```
struct Context
{
    int arg; // internal variables.
    int label = 0;
};

void MyCoroutineImpl(Context& context)
{
    switch(context.label)
    {
        case 0: goto label0;
        case 1: goto label1;
        case 2: { throw std::runtime_error{ "..." }; }
    }
label0:
    context.label = 1;
    return context.arg + 1;
label1:
    context.label = 2;
    return context.arg + 2;
}
```

Advanced Concurrency

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Coroutine

Coroutine interface

Suspension point

```
Task MyCoroutine(int max)
{
    std::println("CORO {} start", max);
    for (int val = 1; val <= max; ++val) {
        std::println("CORO {} / {}", val, max);
        co_await std::suspend_always{};
    }
    std::println("CORO {} end", max);
    co_return;
}
```

`co_return;` can be omitted here.

- To use coroutine in C++, we need to define a function with `co_await`, `co_yield` or `co_return`.

- For caller, it gets coroutine interface from a coroutine.
  - Coroutine interface needs to encapsulate underlying details, and provides APIs to manipulate coroutine.

```
int main()
{
    Task task = MyCoroutine(3);
    std::println("coro() started");
    while (task.Resume()) {
        std::println("coro() suspended");
    }
    std::println("coro() done");
}
```

```
coro() started
CORO 3 start
CORO 1 / 3
coro() suspended
CORO 2 / 3
coro() suspended
CORO 3 / 3
coro() suspended
CORO 3 end
coro() done
```

Coroutine

```
class Task
{
public:
    struct promise_type;
private:
    using CoroHandle = std::coroutine_handle<promise_type>;
    CoroHandle coroHandle_;

public:
    Task(CoroHandle handle) : coroHandle_{ handle } {}
```

Declare first to use in template parameter.

- So how is a coroutine interface defined?
  - It should have a `std::coroutine_handle` (defined in `<coroutine>`) as data member, which already represents high-level abstraction of a coroutine.
  - Then it needs to define `promise_type`, which customizes the behavior of a coroutine.
- Roughly speaking, a coroutine will be translated to:

```
// Contains:
// 1. promise; 2. variables that span lifetime over
// suspension points, including parameters.
struct coroutine_frame { ... };

T some_coroutine(Params... params)
{
    auto f = new coroutine_frame{std::forward<Params>(params)...};
    auto returnObject = f->promise.get_return_object();
    /* Resume the coroutine, omitted temporarily. */
    return returnObject;
}
```

Copy coroutine params to coroutine frame first.

```
struct promise_type
{
    Task get_return_object()
    {
        return Task{ CoroHandle::from_promise(*this) };
    }
    std::suspend_always initial_suspend() { return {}; }
    void return_void() {}
    void unhandled_exception() { std::terminate(); }
    std::suspend_always final_suspend() noexcept { return {}; }
};
```

Coroutine

- `std::coroutine_handle` exposes several operations:

Observers	
`done`	checks if the coroutine has completed (public member function)
`operator bool`	checks if the handle represents a coroutine (public member function)
Control	
`operator()` `resume`	resumes execution of the coroutine (public member function)
`destroy`	destroys a coroutine (public member function)
Promise Access	
`promise`	access the promise of a coroutine (public member function)
`from_promise` [static]	creates a `coroutine_handle` from the promise object of a coroutine (public static member function)

Promise on the coroutine frame can be used to get the handle, and vice versa.

```
/* Resume the coroutine, omitted temporarily. */
return returnObject;
```

Equiv. to

```
using HandleType = std::coroutine_handle<decltype(f->promise)>;
HandleType::from_promise(f->promise).resume();
return returnObject;
```

Coroutine

- And then, the function body of the coroutine is treated as below:

```
Task MyCoroutine(int max)
{
    std::println("CORO {} start", max);
    for (int val = 1; val <= max; ++val) {
        std::println("CORO {} / {}", val, max);
        co_await std::suspend_always{};
    }
    std::println("CORO {} end", max);
    co_return;
}
```

```
{
    promise-type promise promise-constructor-arguments ;
    try {
        co_await promise.initial_suspend() ;
        function-body
    } catch ( ... ) {
        if (!initial-await-resume-called)
            throw ;
        promise.unhandled_exception() ;
    }
final-suspend :
    co_await promise.final_suspend() ;
}
```

Let’s see what happens step by step…

Coroutine

```
coro() started
CORO 3 start
CORO 1 / 3
coro() suspended
CORO 2 / 3
coro() suspended
CORO 3 / 3
coro() suspended
CORO 3 end
coro() done
```

```
T some_coroutine(Params... params)
{
    auto f = new coroutine_frame{std::forward<Params>(params)...};
    auto returnObject = f->promise.get_return_object();
    using HandleType = std::coroutine_handle<decltype(f->promise)>;
    HandleType::from_promise(f->promise).resume();
    return returnObject;
}
```

1. Here the coroutine will stop immediately, before execution of user-defined code.
2. If user-defined code throws, `.unhandled_exception()` will be called.
3. Execute when user-defined code `co_return`, here the coroutine will suspend at final point.
   - Must be `noexcept`.
4. `co_return;` doesn't return anything, thus promise needs to define `return_void`.

```
{
    promise-type promise promise-constructor-arguments ;
    try {
        co_await promise.initial_suspend() ;
        function-body
    } catch ( ... ) {
        if (!initial-await-resume-called)
            throw ;
        promise.unhandled_exception() ;
    }
final-suspend :
    co_await promise.final_suspend() ;
}
```

```
    std::suspend_always initial_suspend() { return {}; }
    void return_void() {}
    void unhandled_exception() { std::terminate(); }
    std::suspend_always final_suspend() noexcept { return {}; }
};
```

Coroutine

- And finally, we need to expose APIs of handle in coroutine interface:

```
public:
    Task(CoroHandle handle) : coroHandle_{ handle } {}
    bool Resume()
    {
        coroHandle_.resume();
        return !coroHandle_.done();
    }

    ~Task()
    {
        if (coroHandle_)
            coroHandle_.destroy();
    }
```

Coroutine

1. Besides `std::suspend_always`, `std::suspend_never` is also sometimes used.
   - `co_await std::suspend_never{}` means “do not suspend, continue to execute”;
   - For example:

```
std::suspend_never initial_suspend() { return {}; }
```

```
coro() started
CORO 3 start
CORO 1 / 3
coro() suspended
CORO 2 / 3
coro() suspended
CORO 3 / 3
coro() suspended
CORO 3 end
coro() done
```

`suspend_always`

```
CORO 3 start
CORO 1 / 3
coro() started
CORO 2 / 3
coro() suspended
CORO 3 / 3
coro() suspended
CORO 3 end
coro() done
```

`suspend_never`

```
int main()
{
    Task task = MyCoroutine(3);
    std::println("coro() started");
    while (task.Resume()) {
        std::println("coro() suspended");
    }
    std::println("coro() done");
}
```

Immediate resume when creating the coroutine.

Coroutine

2. `.final_suspend()` should almost always suspend, and thus `std::suspend_never` is seldom used here.
   - If `final_suspend` doesn't suspend, then coroutine frame will be destroyed automatically and return to caller; thus it's not due to memory leak.
   - Reason 1: `coroutine_handle` and promise will be illegal after deallocation of coroutine frame…
     - Thus, it's UB to use `.done()` to check whether coroutine can be resumed after that, and UB to access data member of the promise.
     - Also, it's UB to `.destroy()` due to double free, making it hard to wrap in coroutine interface.
     - Just like a dangling pointer.
   - Reason 2: if lifetime of a coroutine is nested within caller, then **h**eap **a**llocation e**l**ision **o**ptimization (HALO) may be performed by compiler.
     - And suspension at final point makes it much easier for compiler to judge HALO.

Coroutine

3. Even if you suspend at `.final_suspend()`, it's UB to call `.resume()` again.
   - And `resume` or `destroy` a non-suspended coroutine (like call `.resume()` in another thread) is also UB.
4. If you want to `co_return` some value, you can define `void return_value`.

```
std::println("CORO {} end", max);
co_return max + 1;
```

```
struct promise_type
{
    int value;
    void return_value(int retVal) { value = retVal; }
auto GetReturnValue() const noexcept {
    assert(coroHandle_.done());
    return coroHandle_.promise().value;
}
```

Coroutine interface

Return type of `return_void` and `return_value` must be `void`.

Coroutine

- Note 1: you can define overloads for `return_value`, or even make it template, so that you can `co_return` different types.
  - For example:

```
struct promise_type
{
    std::string value;
    void return_value(int retVal) {
        value = std::to_string(retVal);
    }
    template<std::convertible_to<std::string> T>
    void return_value(T&& retVal) {
        value = std::string{ std::forward<T>(retVal) };
    }
```

```
co_return max + 1;
co_return "123";
```

- Note 2: you cannot define both `return_void` and `return_value`.
  - And `co_return;` is only interpreted as `p.return_void()`, so defining `return_value` without accepting parameters is also useless.
- Note 3: you cannot use `return` in coroutine.

[dcl.fct.def.coroutine], [stmt.return.coroutine].

Coroutine

```
try {
    co_await promise.initial_suspend() ;
    function-body
} catch ( ... ) {
    if (!initial-await-resume-called)
        throw ;
    promise.unhandled_exception() ;
}
```

5. Common practices to implement `.unhandled_exception()`:
   - Ignore the exception;
   - Process the exception locally; for example:

```
void unhandled_exception()
{
    try { throw; }  rethrow the exception in catch block.
    catch (const std::exception& ex) { std::println("{}", ex.what()); }
    catch (...) { std::println("UNKNOWN EXCEPTION"); }
}
```

   - End or abort the program (e.g., by `std::terminate()`);
   - Storing the exception for later use with `std::current_exception()`.

```
std::exception_ptr ex;
void unhandled_exception() {
    ex = std::current_exception();
}
```

```
bool Resume() {
    if (auto ex = coroHandle_.promise().ex)
        std::rethrow_exception(ex);
```

Coroutine

```
Task MyCoroutine(int max)
{
    std::println("CORO {} start", max);
```

6. The `promise_type` is actually looked up by `std::coroutine_traits<R, Args…>`.
   - Like in our example, it's found by `std::coroutine_traits<Task, int>`.
   - By default, it just uses `R::promise_type`, and thus we need to define `promise_type` inside `Task`.
7. Besides default initialization, promise can also be constructed with parameters of coroutine.
   - Like in our example,

```
struct promise_type
{
    promise_type(int paramMax) { /*...*/ }
```

   - This may be useful for allocator parameter (covered in the future).

In a rare case, you can specialize `std::coroutine_traits` to e.g. pass coroutine interface by parameter and define `promise_type` elsewhere. Still, you need to keep return type of `.get_return_object()` to be convertible to return type of coroutine. We don't cover it here since it's not very useful.

Coroutine

8. If you don’t want to throw exception when failing to allocate coroutine frame, you can define `static CoroutineInterface get_return_object_on_allocation_failure()` additionally;
   - Then `new` will use `std::nothrow_t`…

```
auto* state = ::new (std::nothrow) __g_state(static_cast<int&&>(x));
if (state == nullptr) {
    return __g_promise_t::get_return_object_on_allocation_failure();
}
```

   - For example:

```
struct promise_type
{
    static auto get_return_object_on_allocation_failure() {
        return Task{ nullptr };
    } // Return an empty Task.
```

Coroutine

9. Finally details about `std::coroutine_handle`…
   - It’s very similar to a raw pointer to the coroutine frame.
   - Default ctor / ctor by `nullptr`: the handle doesn’t represent a coroutine;
   - Copy & Move ctor / assignment: shallow copy; copies refer to the same coroutine;
   - Address-related:

Export/Import	
`address`	exports the underlying address, i.e. the pointer backing the coroutine (public member function)
`from_address` [static]	imports a coroutine from a pointer (public static member function)

   - Comparable and hashable.
   - And finally, `std::coroutine_handle<void>` is specialized to represent any coroutine frame.

Conversion	
`operator coroutine_handle<>`	obtains a type-erased `coroutine_handle` (public member function)

     - As it erases promise type, `.promise()` and `.from_promise()` are not defined.
     - It’s useful for general execution, since `.resume()` exists.

Coroutine

```cpp
int MyCoroutine(int arg)
{
    yield arg + 1; // suspends
    yield arg + 2; // suspends
}
```

- But we only implement suspension now...
  - How to implement the pseudocode example at the beginning?
- To yield a value, you need:
  - `co_yield xxx;` in coroutine;
  - `Awaiter yield_value(Type xxx)` in `promise_type`.
    - And a common `Awaiter` is just `std::suspend_always`, which means `co_yield` will always suspend the coroutine.
    - Similar to `.return_value()`, you can overload / make it template.
  - And interface:

```cpp
struct promise_type
{
    int value;
    std::suspend_always yield_value(int val)
    {
        value = val;
        return {};
    }
```

```cpp
auto GetYieldValue() const noexcept {
    return coroHandle_.promise().value;
}
```

```cpp
Task MyCoroutine(int arg)
{
    co_yield arg + 1;
    co_yield arg + 2;
}
```

```cpp
int main()
{
    Task task = MyCoroutine(3);
    while (task.Resume()) {
        std::println(
            "{}", task.GetYieldValue());
    }
```

Coroutine

- To conclude, `promise_type` needs five mandatory operations:
  - `.get_return_object() -> CoroutineInterface`;
  - `.initial_suspend() -> Awaiter`, to specify initial behavior before executing user code;
  - `.final_suspend() -> Awaiter`, to specify final behavior after executing user code;
  - `.return_void/return_value() -> void`, to support `co_return`;
  - `.unhandled_exception() -> void`, to handle exceptions thrown in coroutine;
- And some optional operations:
  - `.yield_value()`, to support `co_yield`;
  - `static get_return_object_on_allocation_failure()-> CoroutineInterface`, to provide default coroutine interface object instead of throwing exception when coroutine frame allocation fails.

Minimal example of a coroutine interface.

```cpp
class [[nodiscard]] Task
{
public:
    struct promise_type;
private:
    using CoroHandle = std::coroutine_handle<promise_type>;
    CoroHandle coroHandle_;

    void Destroy_() { if (coroHandle_) coroHandle_.destroy(); }

public:
    Task(CoroHandle handle) : coroHandle_{ handle } {}
    Task(const Task&) = delete;
    Task& operator=(const Task&) = delete;
    ~Task() { Destroy_(); }
    Task(Task&& another) noexcept : coroHandle_{
        std::exchange(another.coroHandle_, nullptr)
    } {}
    Task& operator=(Task&& another) noexcept {
        Destroy_();
        coroHandle_ = std::exchange(another.coroHandle_, nullptr);
        return *this;
    }
    bool Resume() const {
        if (!coroHandle_ || coroHandle_.done())
            return false;
        coroHandle_.resume();
        return !coroHandle_.done();
    }

    struct promise_type
    {
        Task get_return_object() {
            return Task{ CoroHandle::from_promise(*this) };
        }
        std::suspend_always initial_suspend() { return {}; }
        void return_void() {}
        void unhandled_exception() { std::terminate(); }
        std::suspend_always final_suspend() noexcept { return {}; }
    };
};
```

You can also add e.g. `.yield_value()`, and add APIs in coroutine interface
(after definition of `promise_type`, since using its members needs complete definition).

Coroutine

- Exercise: implement a very simple `std::generator`.
  - We've briefly taught `std::generator` in Lecture 4 *Ranges & Algorithms*…
  - So just add `.yield_value()` and iterator!
    - As end iterator cannot be determined, just use `std::default_sentinel_t`.
      - For example:

```cpp
std::generator<int> func(int end)
{
    std::cout << "Ahh..";
    for (int begin = 0; begin < end; begin++)
        co_yield begin;
    co_return;
}
```

```cpp
auto generator = func(3);
```

      - When you call `generator.begin()`, the generator function will pause at `co_yield begin`.
        - When you dereference the iterator, you will get the `begin` (i.e. 0) now.

```cpp
for (auto it = generator.begin(); it != generator.end(); it++)
    std::cout << *it;
// or
for (auto& num : generator)
    std::cout << num;
```

Trivial parts…

```cpp
template<typename T>
class [[nodiscard]] Generator
{
public:
    struct promise_type;
private:
    using CoroHandle = std::coroutine_handle<promise_type>;
    CoroHandle coroHandle_;

    Generator(CoroHandle handle) : coroHandle_{ handle } {}

public:
    Generator(const Generator&) = delete;
    Generator& operator=(const Generator&) = delete;
    Generator(Generator&& another) noexcept : coroHandle_{
        std::exchange(another.coroHandle_, nullptr)
    } { }
    Generator& operator=(Generator&& another) noexcept {
        std::swap(coroHandle_, another.coroHandle_);
        return *this;
    }
    ~Generator() { if (coroHandle_) coroHandle_.destroy(); }
```

```cpp
struct promise_type
{
    T val;
    std::suspend_always yield_value(auto&& initVal) {
        val = std::forward<decltype(initVal)>(initVal);
        return {};
    }

    Generator get_return_object() {
        return Generator{ CoroHandle::from_promise(*this) };
    }
    std::suspend_always initial_suspend() const noexcept { return {}; }
    void return_void() const noexcept {}
    void unhandled_exception() { std::terminate(); }
    std::suspend_always final_suspend() noexcept { return {}; }
};
```

```cpp
class iterator
{
    friend class Generator;
    CoroHandle handle_;

    iterator(CoroHandle handle) : handle_{ handle } {}
    auto ExchangeEmpty_() { return std::exchange(handle_, nullptr); }

public:
    iterator(iterator&& another) noexcept : handle_{ another.ExchangeEmpty_()} {}
    iterator& operator=(iterator&& another) noexcept {
        handle_ = another.ExchangeEmpty_();
        return *this;
    }

    auto& operator*() const noexcept { return handle_.promise().val; }
    iterator& operator++() { handle_.resume(); return *this; }
    void operator++(int) { ++(*this); }

    friend bool operator==(const iterator& it, std::default_sentinel_t) {
        return it.handle_.done();
    }
};
```

```cpp
iterator begin() {
    coroHandle_.resume();
    return iterator{ coroHandle_ };
}

auto end() const noexcept { return std::default_sentinel; }
```

Here we:

1. Store the value inside promise and do forward assignment in `.yield_value()`;
2. Return reference to it in `operator*`;

The actual specification and implementation of `std::generator` is more complex and will be covered later.

Coroutine Lifetime Concern

- Finally a very important note: **parameters of coroutine should rarely be reference**.
  - For example:
- For a normal function, when will the temporary bound to `s` destructed?
  - Temporaries are destructed when the statement ends, i.e. after `;`.
- Normally, as use of parameter ends when function returns, passing temporary is completely fine.
- But for coroutine…

```
std::generator<char> explode(const std::string& s) {
    for (char ch : s) {
        co_yield ch;
    }
}

int main() {
    auto coro = explode("hello world"s); // #0
    for (char ch : coro) {
        std::cout << ch << '\n';
    }
}
```

Coroutine Lifetime Concern

- Coroutine in C++ is still a function!
  - Compilers just “transform” your coroutine code to another normal function, like our `switch` + `goto` code.
- So for loop in coroutine, after the first suspension…
  - `s` will be dangling reference and future `.resume()` is wrong.

```
std::generator<char> explode(const std::string& s) {
    for (char ch : s) {
        co_yield ch;
    }
}
```

- This problem is even more subtle for lambda coroutine.
  - Is code below correct?

```
auto task = getCoro()(3);
task.resume();
```

```
auto getCoro()
{
    std::string str{ "CORO" };
    // lambda表达式也可以是协程。
    auto coro = [str](int max) -> Task {
        std::cout << str << max << "start\n";
        for (int val = 1; val <= max; ++val) {
            std::cout << str << val << "\n";
            co_await std::suspend_always{};
            std::cout << str << max << "end\n";
        }
    }
    return coro;
}
```

Coroutine Lifetime Concern

```
auto task = getCoro()(3);
task.resume();
```

- No!
  - We know that lambda captures have same lifetime as lambda itself.
  - And `getCoro()` creates a temporary lambda, and passing 3 generates a coroutine interface `task`.
  - And the temporary lambda is destructed, so captures are invalid and thus coroutine code is also UB.
- The correct way is quite strange:

```
auto taskValidGuard = getCoro();
auto task = taskValidGuard(3);
task.resume();
```

- So to conclude, unless you've considered carefully:
  1. Do NOT use reference type in coroutine parameters;
  2. Do NOT use stateful lambda coroutine, or generally pay special attention to public member coroutine.

Advanced Concurrency

- Coroutine
  - Overview
  - Basics
  - Awaiter
    - Symmetric Transfer
  - `std::generator` in Detail

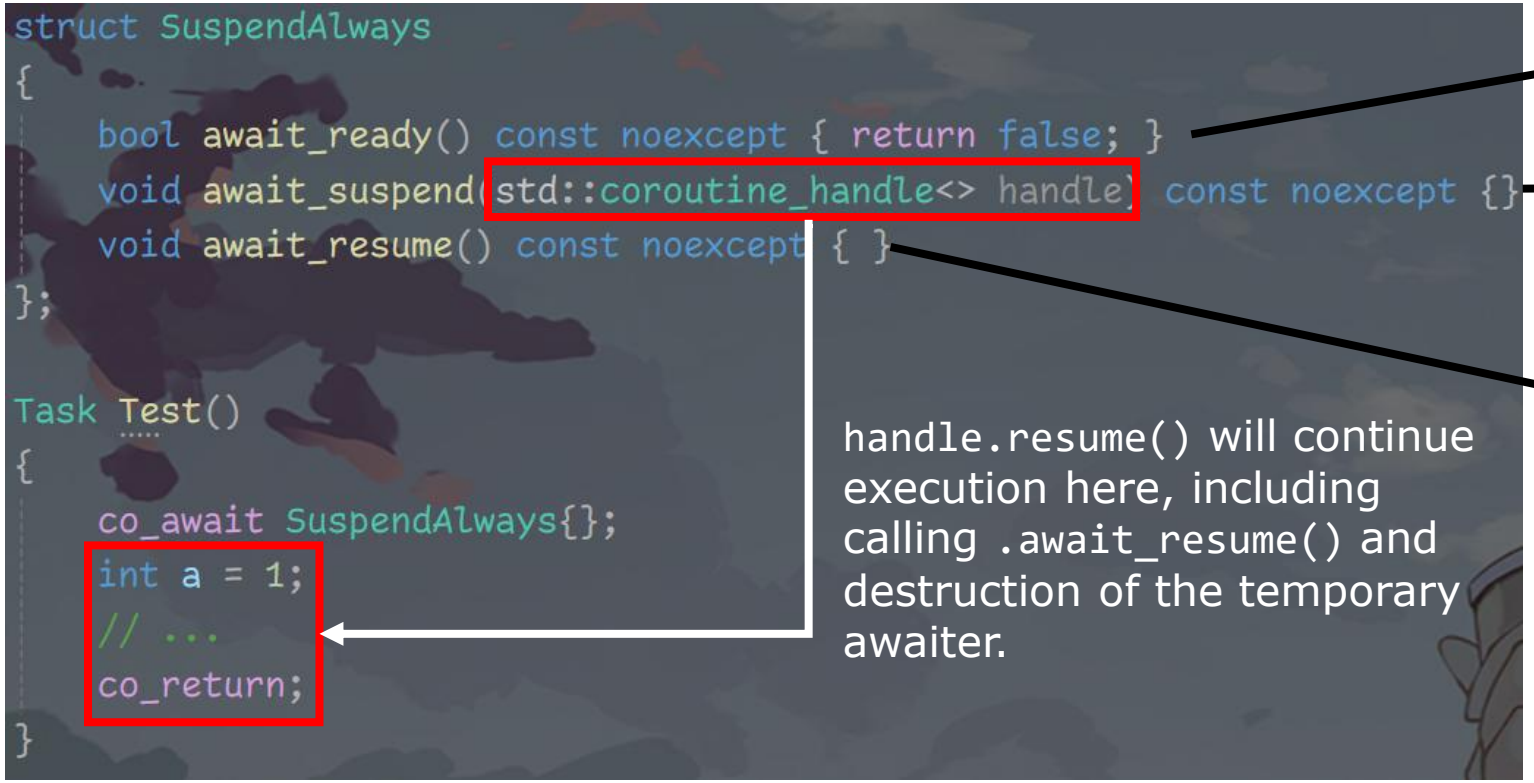
Awaiter

```
Task MyCoroutine(int max)
{
    std::println("CORO {} start", max);
    for (int val = 1; val <= max; ++val) {
        std::println("CORO {} / {}", val, max);
        co_await std::suspend_always{};
    }
    std::println("CORO {} end", max);
    co_return;
}
```

- Previously we just use two predefined types to await, either `std::suspend_always` or `std::suspend_never`.
  - But how can they suspend / continue execution?
- Generally speaking, **awaiter** can be defined to manipulate behaviors of later coroutine.
  - For awaiter, three APIs needs to be defined:
  - `.await_ready() -> bool`: `false` means later execution is not ready, i.e. suspend; `true` means not to suspend;
  - `.await_suspend(CoroutineHandle continuation) -> void`: called when suspended, determine what should be done for later execution;
  - `.await_resume() -> T`: when the current suspension resumes, what should be executed first before later execution. `T` means return value of `co_await`.

Awaiter

- So actually, predefined ones are very easy to implement:



Awaiter

- For example, implement `NaiveTaskCont` that:
  - When we await another task, we want next `.Resume()` to resume the new task.

```
NaiveTaskCont Test2()
{
    std::println("Hello,");
    co_await std::suspend_always{};
    std::println("World!");
}

NaiveTaskCont Test()
{
    std::println("Test: before Test2.");
    co_await Test2();
    std::println("Test: after Test2.");
}
```

```
int main()
{
    auto m = Test();
    while (m.Resume())
    {
        std::println("Back to main.");
    }
    return 0;
}
```

```
Microsoft Visual Studio 调
Test: before Test2.
Back to main.
Hello,
Back to main.
World!
Back to main.
Test: after Test2.
```

The basic parts are completely same.

```cpp
class NaiveTaskCont
{
public:
    struct promise_type;
private:
    using CoroHandle = std::coroutine_handle<promise_type>;
    CoroHandle coroHandle_;

    void Destroy_() noexcept { if (coroHandle_) coroHandle_.destroy(); }

public:
    NaiveTaskCont(CoroHandle handle) : coroHandle_{ handle } {}
    NaiveTaskCont(const NaiveTaskCont&) = delete;
    NaiveTaskCont& operator=(const NaiveTaskCont&) = delete;
    NaiveTaskCont(NaiveTaskCont&& another) noexcept : coroHandle_{
        std::exchange(another.coroHandle_, nullptr)
    } { }
    NaiveTaskCont& operator=(NaiveTaskCont&& another) noexcept {
        Destroy_();
        coroHandle_ = std::exchange(another.coroHandle_, nullptr);
        return *this;
    }
    ~NaiveTaskCont() { Destroy_(); }
```

And we can use linked list to go to the deepest task.

```cpp
struct promise_type
{
    CoroHandle nextLevelHandle_;

    NaiveTaskCont get_return_object() {
        return NaiveTaskCont{ CoroHandle::from_promise(*this) };
    }
    std::suspend_always initial_suspend() { return {}; }
    void return_void() {}
    void unhandled_exception() { std::terminate(); }
    std::suspend_always final_suspend() noexcept { return {}; }
};

bool await_ready() const noexcept { return false; }
void await_suspend(CoroHandle continuation) {
    auto& promise = continuation.promise();
    promise.nextLevelHandle_ = coroHandle_;
}
void await_resume() const noexcept {}
```

In `co_await x;` we call `x.await_suspend()`, and we need to set new task `x` as next level handle of current coroutine.

Each time we call `.Resume()`, we find the deepest task by linked list and resume it.

```cpp
bool Resume() {
    if (!coroHandle_ || coroHandle_.done())
        return false;

    auto resumeHandle = coroHandle_;
    while (true)
    {
        auto& promise = resumeHandle.promise();
        auto nextHandle = promise.nextLevelHandle_;
        if (nextHandle == nullptr)
            break;
        if (nextHandle.done())
        {
            promise.nextLevelHandle_ = nullptr;
            break;
        }
        resumeHandle = nextHandle;
    }

    resumeHandle.resume();
    return !coroHandle_.done();
}
```

```cpp
NaiveTaskCont Test()
{
    std::println("Test: before Test2.");
    co_await Test2();
    std::println("Test: after Test2.");
}
```

```cpp
NaiveTaskCont Test2()
{
    std::println("Hello,");
    co_await std::suspend_always{};
    std::println("World!");
}
```

1. `Test()` is called, coroutine interface `A` is created and suspends at initial point;
2. `Resume()`, execute until `co_await Test2()`;
   - `Test2()` is called, new interface `B` is created and suspends at initial point;
   - `B.await_ready()` returns `false`, meaning `A` needs to suspend;
   - `B.await_suspend(cont)` attaches handle of `B` (`this->coroHandle_`) as next level of handle of `A` (`cont`).
3. `Resume()`, find the deepest task (`B`) and resume it, execute until `suspend_always`.
4. `Resume()`, execute until `B` reaches final point.
5. `Resume()`, execute until `A` reaches final point.
   - `B.await_resume()` is called first;
   - `B` is destructed, as it's a temporary returned by `Test2()`.
   - Later code like `println` is then executed.

Awaiter

- Besides defining awaiter APIs directly, there also exist two other ways to do `co_await`:
  1. By `operator co_await`, which delegates `co_await` to return value.
     - Quite like `operator->`!
     - This can isolate awaiter APIs and make them not exposed to users in coroutine interface.

```
class ContAwaiter
{
    CoroHandle nextLevelHandle_;
    ContAwaiter(CoroHandle handle) : nextLevelHandle_{ handle } {}
    friend NaiveTaskCont;

public:
    bool await_ready() const noexcept { return false; }
    void await_suspend(CoroHandle continuation) {
        auto& promise = continuation.promise();
        promise.nextLevelHandle_ = nextLevelHandle_;
    }
    void await_resume() const noexcept {}
};

ContAwaiter operator co_await() const noexcept { return { coroHandle_ }; }
```

Awaiter

2. By `.await_transform()` in promise, which will intercept almost all `co_await x;` and substitute as `co_await promise.await_transform(x)`.

   - You can also add constraint or overloads;
   - To disable `co_await` in your coroutine, you can use `=delete`.
     - Like in `std::generator`: **`await_transform`** [deleted]

- Order is: for `co_await x`, if `p.await_transform()` fails, then `x.operator co_await`; if `x.operator co_await` fails, then find awaiter APIs of `x`.

Awaiter

```
struct promise_type
{
    T val;
    std::suspend_always yield_value(auto&& initVal) {
        val = std::forward<decltype(initVal)>(initVal);
        return {};
    }
```

- Look back to `co_yield x`…
  - It’s essentially equiv. to `co_await promise.yield_value(x)`.
  - Particularly, initial await, final await and `co_yield` will bypass `.await_transform()`.
- For example, if we want to do a back-and-forth conversion:

```
struct BackAwaiter
{
    std::string& convertedVal;

    bool await_ready() const noexcept { return false; }
    void await_suspend(CoroHandle handle) const noexcept {}
    std::string&& await_resume() noexcept { return std::move(convertedVal); }
};
```

```
struct promise_type
{
    int val;
    std::string convertedVal;

    BackAwaiter yield_value(int init_val) {
        val = init_val;
        convertedVal.clear();
        return BackAwaiter{ convertedVal };
    }
```

Awaiter

- Return value of `.await_resume()` is treated as return value of `co_await`, and thus is also return value of `co_yield`.

- Not that useful, just a naïve example.

```cpp
    int GetInteger() const noexcept { return coroHandle_.promise().val; }
    void SetString(std::string newVal) {
        coroHandle_.promise().convertedVal = std::move(newVal);
    }
};

Task Test()
{
    std::string r1 = co_yield 42;
    std::println("Get string value: {}", r1);
    std::string r2 = co_yield 442;
    std::println("Get string value: {}", r2);
}

int main()
{
    auto task = Test();
    while (task.Resume())
    {
        auto convertedStr = std::to_string(task.GetInteger());
        task.SetString(std::move(convertedStr));
    }
}
```

```
Get string value: 42
Get string value: 442
```

Advanced Concurrency

- Coroutine
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Symmetric Transfer

- All programs before are sequentially executed, though we can suspend and resume them.
  - In many cases, coroutine will cooperate with multithreading, which will then execute different streams in parallel.
- Consider a common case:
  - We have a `ServiceA` and a `ServiceB`, and the result of `ServiceA` will be sent to `ServiceB`.
    - For example, `ServiceA` is network receive, and `ServiceB` is data processing.
  - For synchronous code, we may just write:

```
std::vector<std::byte> DoServiceA() {}
void DoServiceB(std::span<const std::byte>) {}
```

```
auto result = DoServiceA();
DoServiceB(result);
```

Symmetric Transfer

- More generally, we may use callback:

```
void DoServiceAWithCallBack(auto&& callback) {}
DoServiceAWithCallBack(DoServiceB);
```

- So actually, we just treat `DoServiceB` as later execution of `DoServiceA`.
  - Of course, we can use coroutine to do so automatically:

```
struct promise_type
{
    CoroHandle lastLevelHandle;

    Task get_return_object() { return Task{ CoroHandle::from_promise(*this) }; }
    std::suspend_always initial_suspend() const noexcept { return {}; }
    void return_void() const noexcept { }
    void unhandled_exception() const noexcept { std::terminate(); }
    auto final_suspend() noexcept;
};
```

When the current task ends, resume original task automatically.

```
auto Task::promise_type::final_suspend() noexcept
{
    struct FinalAwaiter
    {
        bool await_ready() noexcept { return false; }
        void await_suspend(CoroHandle handle) noexcept
        {
            auto lastLevelHandle = handle.promise().lastLevelHandle;
            if (lastLevelHandle)
                lastLevelHandle.resume();
        }
        void await_resume() noexcept {}
    };

    return FinalAwaiter{};
}
```

```cpp
struct Awaiter
{
    CoroHandle handle;

    bool await_ready() const noexcept { return false; }
    void await_suspend(CoroHandle lastLevelHandle)
    {
        handle.promise().lastLevelHandle = lastLevelHandle;
        handle.resume();
    }
    void await_resume() const noexcept {}
};
Awaiter operator co_await() && noexcept {
    return { coroHandle_ };
}
void Start() { coroHandle_.resume(); }
```

```cpp
Task DoServiceA(std::vector<std::byte>& result) { co_return; }

Task DoServiceB()
{ // Actually we can write Task<ResultType>, but for brievty.
    std::vector<std::byte> result;
    co_await DoServiceA(result);
    // Process result.
}
```

```cpp
auto task = DoServiceB();
task.Start();
```

When a task is awaited, attach the execution stream and resume new task.

A task can only be attached once, and then it will be executed to end. Use rvalue ref qualifier to notice users.

The whole process is like:

1. `DoServiceB()` creates a coroutine interface `B`;
2. `.Start()` resumes it until `co_await`;
3. `DoServiceA()` creates a coroutine interface `A`;
4. `awaiter.await_suspend()` resumes `A`;
5. `A` reaches `co_return`;
6. `final_awaiter.await_suspend()` resumes `B`;
7. `B` reaches `co_return`;
8. `B.resume()` returns ->
   `final_awaiter.await_suspend()` returns ->
   `A.resume()` returns ->
   `awaiter.await_suspend()` returns.
9. `Task.Start()` returns, all instructions are fully executed.

Symmetric Transfer

- Before we continue, a small discussion:
  - If seems not necessary to use coroutine at all…
  - However, we can use awaiter to transfer execution to another thread easily:

```
class SchedulerAwaiter
{
public: // 其他两个忽略了
    void await_suspend(std::coroutine_handle<> handle) {
        someThread.dispatch(handle); // 在这个线程上调用handle.resume().
        return; // 当前线程向上返回给caller
    }
};
```

```
Task DoServiceAAsync(std::vector<std::byte>& result)
{
    co_await SchedulerAwaiter{ threadPool };
    co_return;
}

Task DoServiceB()
{
    std::vector<std::byte> result;
    co_await DoServiceAAsync(result);
}
```

  - Then all instruction streams since `DoServiceAAsync()` will execute on another thread in the thread pool, and the main thread can go on without waiting.
    - By coroutine, it's very easy to switch executions on different schedulers.

However, you should pay special attention to synchronization problem before & after transfer. Particularly, mutex cannot be locked on thread A and unlocked on thread B (and such code is easy to implement in coroutine!).

Symmetric Transfer

- However, such stream concatenation has a severe problem…
  - Consider another simple code segment:
  - When `count` is large enough, it will cause stack overflow.

```
Task completes_synchronously() { co_return; }

Task loop_synchronously(int count) {
    for (int i = 0; i < count; ++i) {
        co_await completes_synchronously();
    }
}
```

- Let’s analyze the whole process again…
  - For each loop, the stack occupation is like:
  - `completes_synchronously()` creates a new coroutine; coroutine frame generation will occupy stack temporarily.
    - When this function returns, stack will be popped then.

```
T some_coroutine(Params... params)
{
    auto f = new coroutine_frame{std::forward<Params>(params)...};
    auto returnObject = f->promise.get_return_object();
    using HandleType = std::coroutine_handle<decltype(f->promise)>;
    HandleType::from_promise(f->promise).resume();
    return returnObject;
}
```

Symmetric Transfer

- Other parts will occupy stack indeed:
  1. `awaiter.await_suspend()`;
  2. `newTaskHandle.resume()`;
  3. And the new task will execute its own code, until `co_return`. Stackless coroutine will occupy caller's stack, just like a function call.
  4. `final_awaiter.await_suspend()`;
  5. `lastTaskHandle.resume()`;
  6. And the loop continues to execute, which again occupies stack.
- Only when loop reaches its end will all of stack be popped.
  - However, we expect the loop to execute without stack push…
- Core reason: recursive call of `.resume`.

Symmetric Transfer

- To solve this problem, coroutine also supports ***symmetric transfer***.
  - That is, `.await_suspend()` can return a coroutine handle, meaning that continue to execute this handle.
  - Compared with calling `.resume()` inside `.await_suspend()` directly, symmetric transfer will **pop the stack first**.
    - In previous analysis, this means:
      - 2, 3 and 4 will be popped before 5;
      - 5, 6 and next 1 will be popped before next 2.
    - This utilizes *tail-call optimization* elegantly, but we don't dig into that.

```
CoroHandle task::await_suspend(CoroHandle continuation)
{
    coro_.lastLevelHandle = continuation;
    return coro_;
}

CoroHandle task::final_awaiter::await_suspend(CoroHandle handle)
{
    return handle.promise().lastLevelHandle;
}
```

If you're interested, I strongly recommend you to read C++ Coroutines: Understanding Symmetric Transfer by Lewis Baker.

And notice that gcc doesn't implement optimization here (see bugzilla) so symmetric transfer will still cause stack overflow.

Symmetric Transfer

```
void await_suspend(CoroHandle handle) noexcept
{
    auto lastLevelHandle = handle.promise().lastLevelHandle;
    if (lastLevelHandle)
        lastLevelHandle.resume();
}
```

```
CoroHandle task::final_awaiter::await_suspend(CoroHandle handle)
{
    return handle.promise().lastLevelHandle;
}
```

No `if` like code above.

- But still a small bug…
  - When `lastLevelHandle` is `nullptr`, then we are resuming `nullptr` and it's thus UB.
- To return the caller like `void`, we can use `std::noop_coroutine()`:

```
std::coroutine_handle<> await_suspend(CoroHandle handle) noexcept
{
    auto lastLevelHandle = handle.promise().lastLevelHandle;
    if (lastLevelHandle)
        return lastLevelHandle;
    return std::noop_coroutine();
}
```

  - It returns `std::coroutine_handle<std::noop_coroutine_promise>`, another specialized handle that will return to caller directly when resumed.

Symmetric Transfer

- And finally, when `.await_suspend()` has only two options…
  - Either suspends, or continue to execute;
  - Then you can also use `bool`-returning variant; For example:

```
bool await_suspend(std::coroutine_handle<> handle)
{
    if (someCond) // Do suspension
        return true;
    // Some other process
    return false; // Continue to execute handle
}
```

- Note 1: You can rewrite it with handle-returning variant, but since `bool`-returning variant is simpler, compilers are likely to do optimization better.

Symmetric Transfer

- Note 2: compared with in `.await_ready()`, coroutine already suspends in `.await_suspend()`.
  - If you return `true` in `.await_ready()`, `.await_resume()` won't be called;
  - But if you return `false` in `.await_suspend()`, `.await_resume()` will be called.
- Note 3: all awaiter APIs and `promise_type` APIs can be `constexpr`, just like normal methods.
  - However, coroutine cannot be `constexpr` currently.
  - This may be enhanced by P3367R4: constexpr coroutines.

Advanced Concurrency

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Generator

- Let's see what `std::generator` really does after learning coroutine!
  1. The promise type will store **pointer** to yielded value, instead of storing value and doing assignment.
     - First, let's see `T` is value type or rvalue reference.

```cpp
std::generator<std::string> Test()
{
    std::string s{ "442" };
    co_yield std::move(s);
    co_yield "123";
}
```

```cpp
using reference = T&&; // reference collapsing.
using yielded = T&&;

struct promise_type
{
    std::remove_reference_t<yielded>* ptr;
    std::suspend_always yield_value(yielded val) {
        ptr = &val;
        return {};
    }
```

     - We know that it's transformed to:

```cpp
std::string s{ "442" };
co_await promise.yield_value(std::move(s));
co_await promise.yield_value("123");
```

Generator

```
std::string s{ "442" };
co_await promise.yield_value(std::move(s));
co_await promise.yield_value("123");
```

- So it seems that we store pointer to temporary…
  - We know that it's dangerous to do so in normal function.
    - A similar example from homework of Lecture 5 *Lifetime & Type Safety*:

有，在`SomeFunc`调用时构造了一个临时变量，传递给参数`vec`。**在函数调用结束后，临时变量析构，因此`a`变为悬垂引用。**

> 你可能会问，`const&`不是会延长生命周期吗？一定要注意，只有返回临时变量才会延长，返回引用并不会。

```
const std::vector<int>& SomeFunc(const std::vector<int>& vec)
{
    return vec;
}

const auto& a = SomeFunc({1,2,3});
std::cout << a[0];
```

- But here it's safe!
  - All temporaries destruct when the whole statement (i.e. until `;`) ends.
  - So when will `co_await` end?
  - **When coroutine resumes again**, after calling `.await_resume()`!

Generator

- Thus, the temporary persists until next resumption, which makes it safe to store pointer and dereference.
  - Compared with move assignment, this saves one move.
- Then iterator just returns rvalue reference:

```
reference operator*() const noexcept {
    return static_cast<reference>(*(handle_.promise().ptr));
}
```

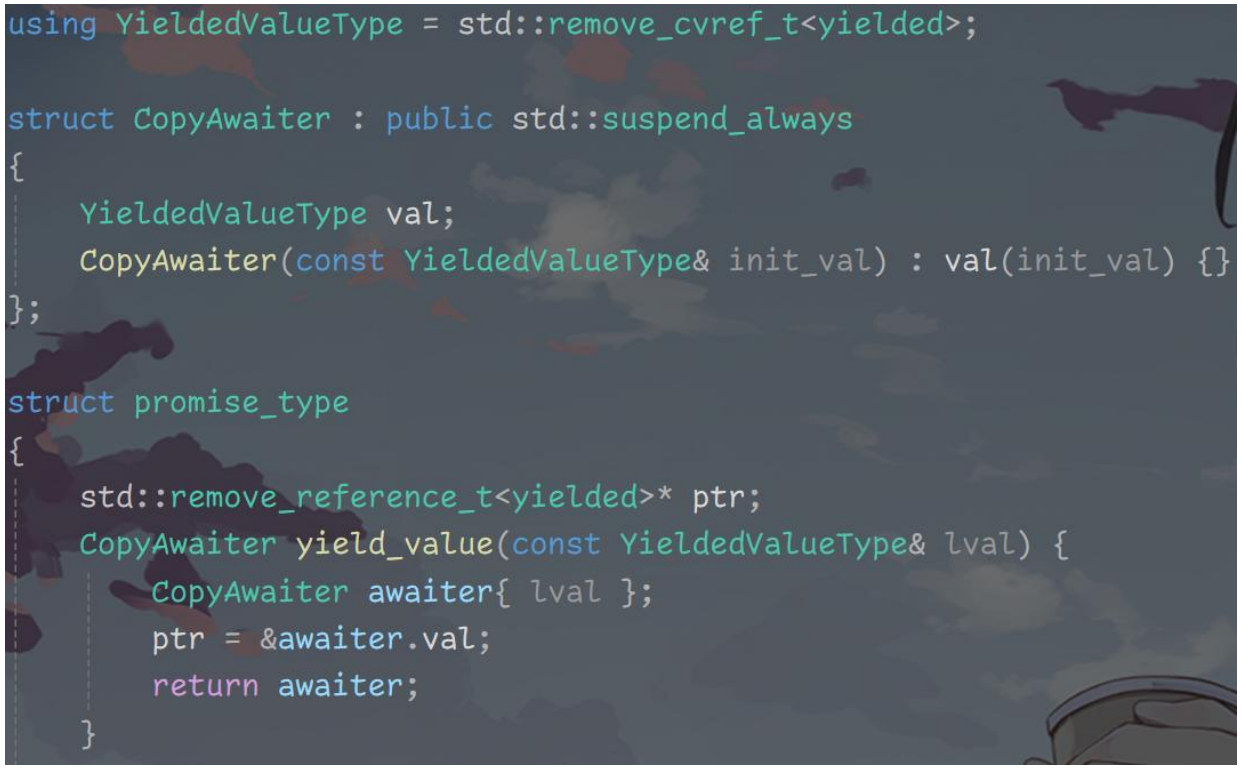
- Wait, what about yielding lvalue?
  - Here we only accept rvalue reference…
  - If user yields lvalue, we should not move it like rvalue in `operator*`.

```
using reference = T&&; // reference collapsing.
using yielded = T&&;

struct promise_type
{
    std::remove_reference_t<yielded>* ptr;
    std::suspend_always yield_value(yielded val) {
        ptr = &val;
        return {};
    }
```

Generator

- `std::generator` adds an overload for `const T&`, which **copies it to awaiter** and then stores pointer.
  - The iterator `operator*` still returns rvalue reference, but refers to the copy.



```
using YieldedValueType = std::remove_cvref_t<yielded>;

struct CopyAwaiter : public std::suspend_always
{
    YieldedValueType val;
    CopyAwaiter(const YieldedValueType& init_val) : val(init_val) {}
};

struct promise_type
{
    std::remove_reference_t<yielded>* ptr;
    CopyAwaiter yield_value(const YieldedValueType& lval) {
        CopyAwaiter awaiter{ lval };
        ptr = &awaiter.val;
        return awaiter;
    }
```

Generator

- For `std::generator<T>`, where `T` is lvalue reference…
  - Then just store pointer and return as corresponding reference.
- So to conclude, `T` just means how to reference the object:

```
std::suspend_always yield_value( yielded val ) noexcept;                    (1)  (since C++23)

auto yield_value( const std::remove_reference_t<yielded>& lval )
    requires std::is_rvalue_reference_v<yielded> &&
             std::constructible_from<std::remove_cvref_t<yielded>,
                 const std::remove_reference_t<yielded>&>;                  (2)  (since C++23)
```

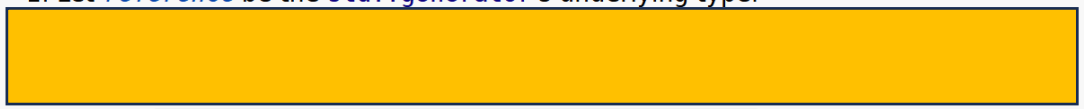
1) Assigns `std::addressof(val)` to *value_*. Returns `{}`.

2) Returns an awaitable object `x` of an unspecified type that stores an object of type `std::remove_cvref_t<yielded>`. `x` is direct-non-list-initialized with `lval`, whose member functions are configured so that *value_* points to that stored object. Then suspends the coroutine.

std::generator::*iterator*::operator*

```
reference operator*() const
    noexcept( std::is_nothrow_copy_constructible_v<reference> );   (since C++23)
```

1. Let *reference* be the `std::generator`'s underlying type.



Equivalent to `return static_cast<reference>(*p.value_);`.

Generator

- Besides, generator also supports to specify value type + reference type by `std::generator<Ref, Value>`.
  - So actually `std::generator<Ref>` just sets `Value` as `void`, and deduces real value type from `Ref`.

Member	Definition
value (private)	`std::conditional_t<std::is_void_v<V>, std::remove_cvref_t<Ref>, V>;` (exposition-only member type*)
reference (private)	`std::conditional_t<std::is_void_v<V>, Ref&&, Ref>;` (exposition-only member type*)

- For example, if you want `operator*` to return value type:
  - But promise still stores pointer, and accepts `const&` in `.yield_value()`.

yielded	`std::conditional_t<std::is_reference_v<reference>, reference, const reference&>`

```cpp
std::generator<int, int> Test(int arg)
{
    co_yield 1;
    co_yield arg;
}

int main()
{
    // Here type of val is int.
    for (decltype(auto) val : Test(2)) {
        std::println("Here {}!", val);
    }
}
```

Generator

- It can also be used for proxy reference type.
  - Like `std::vector<bool>::reference` as a bit proxy.

```cpp
std::generator<std::vector<bool>::reference, bool> Test()
{
    std::vector<bool> vec{ false, true };
    co_yield vec[0];
    co_yield vec[1];
}

int main()
{
    auto rng = Test();
    static_assert(std::same_as<
        std::ranges::range_value_t<decltype(rng)>, bool>);
    // type of val is still vector<bool>::reference
    for (decltype(auto) val : rng) {
        std::println("Here {}!", val);
    }
}
```

But to be honest `std::generator<Ref, Value>` is rarely used.

`std::generator` also accepts allocator as the third type parameter; covered in the next lecture.

Generator

- Finally, `std::generator` also supports recursive yield.
  - That is, it delegates resumption to another `generator`; when delegator finally ends, it continues to execute itself.
  - To distinguish yield and delegation, it needs `stdr::elements_of` as tag.
- For example, to do inorder traversal of a binary tree:

```cpp
template<typename T>
struct Tree
{
    T value;
    Tree *left{}, *right{};

    std::generator<const T&> traverse_inorder() const
    {
        if (left)
            co_yield std::ranges::elements_of(left->traverse_inorder());

        co_yield value;

        if (right)
            co_yield std::ranges::elements_of(right->traverse_inorder());
    }
};
```

Actually you can delegate to any range, which is equivalent to loop and yield its elements. But currently it may have some defeats and will be submitted as DR.

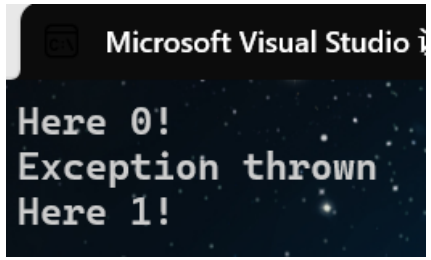
Generator

- Note: `.unhandled_exception()` will propagate exception level by level, so you can catch it at any level.
  - For example:

```
std::generator<int> WillThrow()
{
    co_yield 0;
    throw std::runtime_error{ "Test" };
    co_yield 1;
}

std::generator<int> Foo()
{
    try {
        co_yield std::ranges::elements_of{ WillThrow() };
    }
    catch(const std::exception& ex) {
        std::println("Exception thrown");
    }
    co_yield 1;
}

int main()
{
    for (auto val : Foo()) {
        std::println("Here {}!", val);
    }
}
```



If you don't catch it here, it will propagate to caller.

This is implemented by storing `exception_ptr` and checking in `.await_resume()` returned by delegation.

Summary

- Memory order basics
  - Happens-before, Synchronizes-with
  - Sequential Consistent
  - Acquire-Release
  - Relaxed
- Atomic variables
  - Read, Write, RMW, spinlock
  - Specializations, atomic_flag, atomic_ref
- Advanced memory order
  - Release Sequence
  - Out-of-thin-air problem
  - Strongly-happens-before
  - Fence
- Coroutine
  - Stackful & stackless coroutine;
  - Basics: promise_type;
  - Awaiter and symmetric transfer;
  - std::generator

Next lecture…

- We’ll talk about memory management…
  - Smart pointers;
  - Allocator;
  - PMR;
  - …