Concurrency Improvements in C++20: A Deep Dive

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C++20 - Concurrency

2020

The Big Four

- Concepts
- Modules
- Ranges library
- Coroutines

Core Language

- Three-way comparison operator
- Designated initialization
- `consteval` and `constinit`
- Template improvements
- Lambda improvements
- New attributes

Library

- `std::span`
- Container improvements
- Arithmetic utilities
- Calendar and time zone
- Formatting library

Concurrency

- Atomics
- Semaphores
- Latches and barriers
- Cooperative interruption
- `std::jthread`

Atomics

Atomics are the foundation of the C++ memory model

➡ Atomic operations on atomics define the synchronization and ordering constraints

- Synchronization and ordering constraints hold for atomics and non-atomics
- Synchronization and ordering constraints are used by the high-level threading interface
  - Threads and tasks
  - Mutexe and locks
  - Condition variables
  - ...

Atomics

- The atomic flag `std::atomic_flag`
  - Has a very simple interface (`clear` and `test_and_set`).
  - Is the only data type guaranteed to be lock free.

- `std::atomic`

```
std::atomic<T*>
std::atomic<integral types>
std::atomic<user-defined types>
std::atomic<floating points> (C++20)
std::atomic<smart pointers> (C++20)
```

Atomics

Operation (`std::atomic_flag`)	Description
`test_and_set`	Sets the value and returns the previous value.
`clear`	Clears the value.

Operation (`std::atomic`)	Description
`is_lock_free`	Checks if the atomic object is lock-free.
`load`	Returns the value of the atomic.
`store`	Replaces the value of the atomic with the non-atomic.
`exchange`	Replaces the value with the new value. Returns the old value.
`compare_exchange_weak` `compare_exchange_strong`	`atom.compare_exchange_strong(expect, desir)` ▪ If `atom` is equal to `expect` returns `true`, `atom` becomes `desir`. ▪ If not returns `false`, `expect` is updated with `atom`.
`fetch_add, +=` `fetch_sub, -=`	Adds (substracts) the value and returns the previous value.
`++, --`	Increments or decrements the atomic.

[fetch_mult.cpp]

Atomics (C++20)

- `std::atomic_flag` and `std::atomic`
  - Enable synchronization of threads
    - `atom.notify_one()`: Notifies one waiting operation
    - `atom.notify_all()`: Notifies all waiting operations
    - `atom.wait(val)`: Waiting for a notification and blocks if `atom == val`
  - The default constructor initializes the value.

[atomicWaitAtomicBool.cpp]()

Atomics (C++20)

C++11 has `std::shared_ptr` for shared ownership.

- General rule: use smart pointers
- But:
  - The handling of the control block is thread-safe.
  - Access to the resource is not thread-safe.
- Solution in C++20:
  - `std::atomic<std::shared_ptr>`
  - `std::atomic<std::weak_ptr>`

Atomics

Three reasons for atomic smart pointers.

- Consistency
  - `std::shared_ptr` is the only non-atomic type that supports atomic operations
- Correctness
  - The correct use of the atomic operation weighs on the shoulder of the user

  ⇒ very error-prone

  `std::atomic_store(&sharPtr, localPtr)` **!=** `sharPtr = localPtr`
- Speed
  - `std::shared_ptr` is designed for the general use

Atomics (C++20)

`std::atomic_ref` (C++20) applies atomic operations to the referenced object

- Writing and reading of the referenced object is no data race
- The lifetime of the referenced object must exceed the lifetime of `std::atomic_ref`
- `std::atomic_ref` provides the same interface as `std::atomic`

- `std::atomic_ref`

```
std::atomic_ref<T*>
std::atomic_ref<integral types>
std::atomic_ref<user-defined types>
std::atomic_ref<floating points>
```

[atomicReference.cpp]()

Semaphores (C++20)

Semaphores are synchronization mechanisms to control access to a shared variable.

A semaphore is initialized with a counter greater than 0

- Requesting the semaphore decrements the counter
- Releasing the semaphores increments the counter
- A requesting thread is blocked if the counter is 0

- C++20 support two semaphores.
  - `std::counting_semaphore`
  - `std::binary_semaphore (std::counting_semaphore<1>)`

Semaphores (C++20)

Member Function	Description
`counting_semaphore::max()`	Returns the maximum value of the `counter`.
`sem.release(upd = 1)`	Increases the counter by `upd` and unblocks threads acquiring the semaphore.
`sem.acquire()`	Decrements counter by 1. Blocks if the `counter` is 0.
`sem.try_acquire()`	Tries to decrement the `counter` by 1. Don't block f the `counter` is 0.
`sem.try_acquire_for(relTime)`	Decrement the `counter` by 1. Blocks for at most for the time duration `relTime` if the `counter` is 0.
`sem.try_acquire_until(absTime)`	Decrement the `counter` by 1. Blocks at most until the time point `absTime` if `counter` is 0.

threadSynchronisationSemaphore.cpp

Condition Variables

- The sender sends a notification.

Member Function	Description
`cv.notify_one()`	Notifies one waiting thread
`cv.notify_all()`	Notifies all waiting threads

- The receiver is waiting for the notification while holding the mutex.

Member Function	Description
`cv.wait(lock, ... )`	Waits for the notification
`cv.wait_for(lock, relTime, ... )`	Waits for the notification for a time duration
`cv.wait_until(lock, absTime, ... )`	Waits for the notification until a time point

➡ To protect against spurious wakeup and lost wakeup, the `wait` member function should be used with a predicate.

Condition Variables

Thread 1: Sender

- Prepares the work
- Notifies the receiver

```
// Prepares the work
{
    lock_guard<mutex> lck(mut);
    ready = true;
}
condVar.notify_one();
```

[conditionVariable.cpp]

Thread 2: Receiver

- Waits for its notification while holding the lock
  - Gets the lock
  - Checks and eventually continues to sleep
- Completes the work
- Releases the lock

```
{
    unique_lock<mutex>lck(mut);
    condVar.wait(lck,[]{ return ready; });
    // Completes the work
}   // Releases the look
```

Performance Test: Ping Pong Game

- One thread executes a ping function, and the other a pong function.
- The ping thread waits for the notification of the pong thread and sends the notification back to the pong thread.
- The game stops after 1’000’000 ball changes.

Execution Time	Condition Variables	Atomic Flag	Atomic Bool	Semaphores
Windows	0.7 sec	0.3 sec	0.4 sec	0.4 sec
Linux (virtualized)	21 sec	1.8 sec	2 sec	1.6 sec

pingPongConditionVariable.cpp
pingPongAtomicFlag.cpp
pingPongAtomicBool.cpp
pingPongSemaphore.cpp

Latches and Barriers (C++20)

A thread waits at a synchronization point until the counter becomes zero.

- `latch` is useful for managing one task by multiple threads.

Member Function	Description
`lat.count_down(upd = 1)`	Atomically decrements the counter by `upd` without blocking the caller.
`lat.try_wait()`	Returns `true` if `counter == 0`.
`lat.wait()`	Returns immediately if `counter == 0`. If not blocks until `counter == 0`.
`lat.arrive_and_wait(upd = 1)`	Equivalent to `count_down(upd); wait()`.

[workers.cpp]

Latches and Barriers (C++20)

- `barrier` is helpful to manage repetitive task throug muliple threads.

Member Function	Description
`bar.arrive(upd = 1)`	Atomically decrements counter by `upd`.
`bar.wait()`	Blocks at the synchronization point until the completion step is done.
`bar.arrive_and_wait()`	Equivalent to `arrive(); wait()`.
`bar.arrive_and_drop()`	Decrements the counter for the current and the subsequent phase by one.

- The constructor gets a callable.
- In the completion phase, the callable is executed by an arbitrary thread.

[`fullTimePartTimeWorkers.cpp`]

Cooperative Interruption (C++20)

Each running entity can be cooperatively interrupted.

- `std::jthread` and `std::condition_variable_any` support an explicit interface for the cooperative interruption.

Receiver (`std::stop_token stoken`)

Member Function	Description
`stoken.stop_possible()`	Returns `true` if `stoken` has an associated stop state.
`stoken.stop_requested()`	`true` if `request_stop()` was called on the associated `std::stop_source src`, otherwise `false`.

Cooperative Interruption (C++20)

Sender (`std::stop_source`)

Member Function	Description
`src.get_token()`	If `stop_possible()`, returns a `stop_token` for the associated stop state. Otherwise, returns a default-constructed (empty) `stop_token`.
`src.stop_possible()`	`true` if `src` can be requested to stop.
`src.stop_requested()`	`true` if `stop_possible()` and `request_stop()` was called by one of the owners.
`src.request_stop()`	Calls a stop request if `stop_possible()` and `!stop_requested()`. Otherwise, the call has no effect.

interruptJthread.cpp

Cooperative Interruption (C++20)

`std::stop_source` and `std::stop_token` are a general mechanism for sending a signal. They share a stop state.

➡ You can send a signal to any running entity.

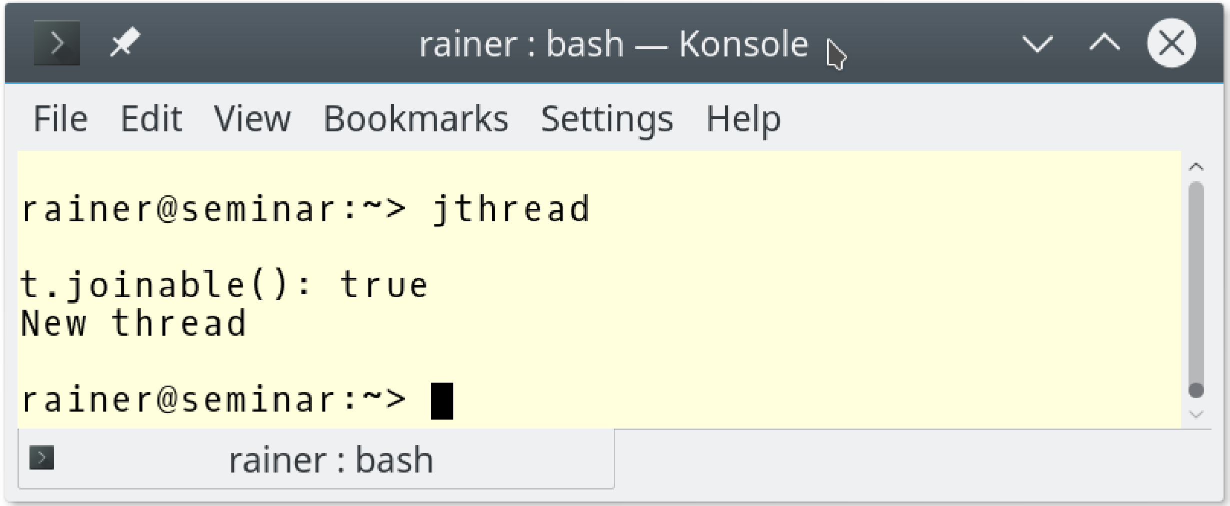
```
std::stop_source stopSource;
std::stop_token stopToken = stopSource.get_token();

void function(std::stop_token stopToken){
    if (stopToken.stop_requested()) return;
}

std::thread thr = std::thread(function, stopToken);
stopSource.request_stop();
```

signalStopRequests.cpp

`std::jthread` (C++20)

`std::jthread` joins automatically in its destructor.

```
std::jthread t{[]{ std::cout << "New thread"; }};
std::cout << "t.joinable(): " << t.joinable();
```



[thread.cpp]
[jthread.cpp]

Synchronized Output Streams (C++20)

Synchronized output streams allow threads to write without interleaving on the same output stream.

- Predefined synchronized output streams

  `std::osyncstream` for `std::basic_osyncstream<char>`
  `std::wosyncstream` for `std::basic_osyncstream<wchar_t>`

- Synchronized output streams
  - Output is written to the internal buffer of type `std::basic_syncbuf`
  - When the output stream goes out of scope, it outputs its internal buffer

Synchronized Output Streams (C++20)

- Permanent variable `synced_out`

```
{
    std::osyncstream synced_out(std::cout);
    synced_out << "Hello, ";
    synced_out << "World!";
    synced_out << std::endl; // no effect
    synced_out << "and more!\n";
}  // destroys the synced_output and emits the internal buffer
```

- Temporary Variable

```
std::osyncstream(std::cout) << "Hello, " << "World!\n";
```

[sequencedOutput.cpp]()

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