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Concurrency in C++20 and Beyond

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Concurrency in C++20 and beyond

- New Concurrency Features in C++20
- New Concurrency Features for Future Standards

New Concurrency Features in C++20

New Concurrency Features in C++20

C++20 is a **huge** release, with lots of new features, including Concurrency facilities:

- Support for cooperative cancellation of threads
- A new thread class that automatically joins
- New synchronization facilities
- Updates to atomics
- Coroutines

Cooperative Cancellation

Cooperative Cancellation

- GUIs often have “Cancel” buttons for long-running operations.
- You don’t need a GUI to want to cancel an operation.
- Forcibly stopping a thread is undesirable

Cooperative Cancellation II

C++20 provides `std::stop_source` and `std::stop_token` to handle cooperative cancellation.

Purely cooperative: if the target task doesn't check, nothing happens.

Cooperative Cancellation III

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3. Pass the `std::stop_token` to a new thread or task
4. When you want the operation to stop call `source.request_stop()`
5. Periodically call `token.stop_requested()` to check
   $\Rightarrow$ Stop the task if stopping requested

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2. Obtain a `std::stop_token` from the `std::stop_source`
3. Pass the `std::stop_token` to a new thread or task
4. When you want the operation to stop call `source.request_stop()`
5. Periodically call `token.stop_requested()` to check
   ⇒ Stop the task if stopping requested
6. **If you do not check `token.stop_requested()`, nothing happens**

Cooperative Cancellation IV

`std::stop_token` integrates with `std::condition_variable_any`, so if your code is waiting for something to happen, the wait can be interrupted by a stop request.

Cooperative Cancellation V

```
std::mutex m;
std::queue<Data> q;
std::condition_variable_any cv;

Data wait_for_data(std::stop_token st){
  std::unique_lock lock(m);
  if(!cv.wait_until(lock,[]{return !q.empty();},st))
    throw op_was_cancelled();
  Data res=q.front();
  q.pop_front();
  return res;
}
```

Cooperative Cancellation VI

You can also use `std::stop_callback` to provide your own cancellation mechanism. e.g. to cancel some async IO.

```
Data read_file(
    std::stop_token st,
    std::filesystem::path filename ){
  auto handle=open_file(filename);
  std::stop_callback cb(st,[&]{ cancel_io(handle);});
  return read_data(handle); // blocking
}
```

New thread class

New thread class: `std::jthread`

`std::jthread` integrates with `std::stop_token` to support cooperative cancellation.

Destroying a `std::jthread` calls `source.request_stop()` and `thread.join()`.

The thread still needs to check the stop token passed in to the thread function.

New thread class II

```
void thread_func(
    std::stop_token st,
    std::string arg1,int arg2){
  while(!st.stop_requested()){
    do_stuff(arg1,arg2);
  }
}

void foo(std::string s){
  std::jthread t(thread_func,s,42);
  do_stuff();
} // destructor requests stop and joins
```

New synchronization facilities

New synchronization facilities

- Latches
- Barriers
- Semaphores

Latches

Latches

`std::latch` is a single-use counter that allows threads to wait for the count to reach zero.

1. Create the latch with a non-zero count
2. One or more threads decrease the count
3. Other threads may wait for the latch to be signalled.
4. When the count reaches zero it is permanently signalled and all waiting threads are woken.

Waiting for background tasks with a latch

```
void foo(){
  unsigned const thread_count=...;
  std::latch done(thread_count);
  my_data data[thread_count];
  std::vector<std::jthread> threads;
  for(unsigned i=0;i<thread_count;++i)
    threads.push_back(std::jthread([&,i]{
      data[i]=make_data(i);
      done.count_down();
      do_more_stuff();
    }));
  done.wait();
  process_data();
}
```

Synchronizing Tests with Latches

Using a latch is great for multithreaded tests:

1. Set up the test data
2. Create a latch
3. Create the test threads
   $\Rightarrow$ The first thing each thread does is `test_latch.arrive_and_wait()`
4. When all threads have reached the latch they are unblocked to run their code

Barriers

Barriers

`std::barrier<>` is a reusable barrier.

Synchronization is done in **phases**:

1. Construct a barrier, with a non-zero count and a **completion function**
2. One or more threads arrive at the barrier
3. These or other threads wait for the barrier to be signalled
4. When the count reaches zero, the barrier is signalled, the **completion function** is called and the count is reset

Barriers II

Barriers are great for loop synchronization between parallel tasks.

The **completion function** allows you to do something between loops: pass the result on to another step, write to a file, etc.

Barriers III

```
unsigned const num_threads=...;
void finish_task();

std::barrier<std::function<void()>> b(
  num_threads,finish_task);

void worker_thread(std::stop_token st,unsigned i){
  while(!st.stop_requested()){
    do_stuff(i);
    b.arrive_and_wait();
  }
}
```

Semaphores

Semaphores

A semaphore represents a number of available “slots”. If you **acquire** a slot on the semaphore then the count is decreased until you **release** the slot.

Attempting to acquire a slot when the count is zero will either block or fail.

A thread may release a slot without acquiring one and vice versa.

Semaphores II

Semaphores can be used to build just about any synchronization mechanism, including latches, barriers and mutexes.

A **binary semaphore** has 2 states: 1 slot free or no slots free. It can be used as a mutex.

Semaphores in C++20

C++20 has `std::counting_semaphore<max_count>`
`std::binary_semaphore` is an alias for `std::counting_semaphore<1>`.

As well as **blocking** `sem.acquire()`, there are also `sem.try_acquire()`, `sem.try_acquire_for()` and `sem.try_acquire_until()` functions that fail instead of blocking.

Semaphores in C++20 II

```
std::counting_semaphore<5> slots(5);

void func(){
  slots.acquire();
  do_stuff(); // at most 5 threads can be here
  slots.release();
}
```

Updates to Atomics

Updates to Atomics

- Low-level waiting for atomics
- Atomic Smart Pointers
- `std::atomic_ref`

Low-level waiting for atomics

`std::atomic<T>` now provides a `var.wait()` member function to wait for it to change.

`var.notify_one()` and `var.notify_all()` wake one or all threads blocked in `wait()`.

Like a low level `std::condition_variable`.

Atomic smart pointers

C++20 provides `std::atomic<std::shared_ptr<T>>` and `std::atomic<std::weak_ptr<T>>` specializations.

- May or may not be **lock-free**
- If lock-free, can simplify lock-free algorithms.
- If not lock-free, a better replacement for `std::shared_ptr<T>` and a mutex.
- Can be slow under high contention.

Lock-free stack with `atomic<shared_ptr<T>>`

```
template<typename T> class stack{
  struct node{
    T value;
    shared_ptr<node> next;
    node(){} node(T&& nv):value(std::move(nv)){}
  };
  std::atomic<shared_ptr<node>> head;
public:
  stack():head(nullptr){}
  ~stack(){ while(head.load()) pop(); }
  void push(T);
  T pop();
};
```

Lock-free stack with atomic<shared_ptr<T>> II

```
template<typename T>
void stack<T>::push(T val){
  auto new_node=std::make_shared<node>(
    std::move(val));
  new_node->next=head.load();
  while(!head.compare_exchange_weak(
    new_node->next,new_node)){}
}
```

Lock-free stack with atomic<shared_ptr<T>> III

```
template<typename T>
T stack<T>::pop(){
  auto old_head=head.load();
  while(old_head){
    if(head.compare_exchange_strong(
         old_head,old_head->next))
      return std::move(old_head->value);
  }
  throw std::runtime_error("Stack empty");
}
```

`std::atomic_ref`

`std::atomic_ref` allows you to perform atomic operations on non-atomic objects.

This can be important when sharing headers with C code, or where a `struct` needs to match a specific binary layout so you can't use `std::atomic`.

If you use `std::atomic_ref` to access an object, all accesses to that object must use `std::atomic_ref`.

std::atomic_ref

```
struct my_c_struct{
  int count;
  data* ptr;
};

void do_stuff(my_c_struct* p){
  std::atomic_ref<int> count_ref(p->count);
  ++count_ref;
  // ...
}
```

Coroutines

What is a Coroutine?

A **coroutine** is a function that can be **suspended** mid execution and **resumed** at a later time.

Resuming a coroutine continues from the suspension point; local variables have their values from the original call.

Stackless Coroutines

C++20 provides **stackless coroutines**

- Only the locals for the current function are saved
- Everything is localized
- Minimal memory allocation — can have millions of in-flight coroutines
- Whole coroutine overhead can be eliminated by the compiler — Gor's "disappearing coroutines"

Waiting for others

```
future<remote_data>
async_get_data(key_type key);

future<data> retrieve_data(
  key_type key){
  auto rem_data=
    co_await async_get_data(key);
  co_return process(rem_data);
}
```

What C++20 coroutines are missing

C++20 has no library support for coroutines:

$\implies$ you need to write your own support code (hard) or use a third party library.

e.g. `https://github.com/lewissbaker/cppcoro`

New Concurrency Features for Future Standards

New Concurrency Features for Future Standards

Additional concurrency facilities are under development for future standards. These include:

- A synchronization wrapper for ordinary objects
- Enhancements for `std::future`
- Executors — thread pools and more
- Coroutine library support for concurrency
- Concurrent Data Structures
- Safe Memory Reclamation Facilities

A synchronization wrapper for ordinary objects

A synchronization wrapper for ordinary objects

`synchronized_value` encapsulates a mutex and a value.

- Cannot forget to lock the mutex
- It's easy to lock across a whole operation
- Multi-value operations are just as easy

A synchronization wrapper for ordinary objects II

```
synchronized_value<std::string> sv;

std::string get_value(){
  return apply([](std::string& s){
    return s;
  },sv);
}

void append_string(std::string extra){
  apply([&](std::string& s){
    s+=extra;
  },sv);
}
```

A synchronization wrapper for ordinary objects III

```
synchronized_value<std::string> sv;
synchronized_value<std::string> sv2;

std:string combine_strings(){
  return apply(
    [&](std::string& s,std::string & s2){
      return s+s2;
    },sv,sv2);
}
```

Enhancements for `std::future`

Enhancements for `std::future`

The Concurrency TS specified enhancements for `std::future`

- Continuations
- Waiting for **all of** a set of futures
- Waiting for **one of** a set of futures

All in `std::experimental` namespace — I use `stdexp` for brevity.

Continuations and `stdexp::future`

- A continuation is a new task to run when a future becomes ready
- Continuations are added with the new `then` member function
- Continuation functions must take a `stdexp::future` as the only parameter
- The source future is no longer `valid()`
- Only one continuation can be added

Continuations and `stdexp::future`

```
stdexp::future<int> find_the_answer();
std::string process_result(stdexp::future<int>);

auto f=find_the_answer();
auto f2=f.then(process_result);
```

Continuations and `stdexp::shared_future`

- Continuations work with `stdexp::shared_future` as well
- The continuation function must take a `stdexp::shared_future`
- The source future remains `valid()`
- Multiple continuations can be added

Waiting for the first future to be ready

`stdexp::when_any` waits for the first future in the supplied set to be ready.

`stdexp::when_any` is ideal for:

- Waiting for speculative tasks
- Waiting for first results before doing further processing

Waiting for the first future to be ready II

```
auto f1=spawn_async(foo);
auto f2=spawn_async(bar);
auto f3=stdexp::when_any(std::move(f1),std::move(f2));

auto final_result=f3.then(process_ready_result);

do_stuff(final_result.get());
```

Waiting for all futures to be ready

`stdexp::when_all` waits for all futures in the supplied set to be ready.

`stdexp::when_all` is ideal for waiting for all sub-tasks before continuing. Better than calling `wait()` on each in turn

Waiting for all futures to be ready II

```
auto f1=spawn_async(subtask1);
auto f2=spawn_async(subtask2);
auto f3=spawn_async(subtask3);
auto results=stdexp::when_all(
  std::move(f1),std::move(f2),std::move(f3));

results.then(process_all_results);
```

Executors

Executors

Executor

An object that controls how, where and when a task is executed

Thread pools are a special case of **Executors**.

Basic executor

The basic requirements are simple. Executors must:

- be **CopyConstructible**,
- be **EqualityComparable**,
- provide an `execute(f)` member function or `execute(e,f)` free function.

The framework can build everything else from there.

Execution Semantics

The basic mechanism for executing tasks with an executor is to call `execute`:

```
execute(my_executor,some_func);
```

If you need specific execution properties, you ask for them with `require`:

```
auto new_executor=
  std::require(my_executor,
  std::execution::blocking.never);

execute(new_executor,some_func); // won't block
```

Static thread pool

The executor paper provides `std::static_thread_pool`, which is a thread pool with a static number of threads specified at construction time.

```
std::static_thread_pool pool(16);
auto ex = pool.executor();
execute(ex,some_func); // will run on pool
```

Senders and Receivers

As well as straight-forward execution with `execute`, the executor paper allows you to split things into **senders** and **receivers**.

Sender
: An object that represents initial work to be done, and the executor to do it on.

Receiver
: An object that accepts the result of the work from the sender.

The **Receiver** may either do more work, or just store the result from the sender.

Receivers

A receiver provides three sets of function overloads:

set_value

    Receive a value or values from the sender

set_error

    Receive an error from the sender

set_done

    Receive notification that the sender was cancelled

Scheduling Senders and Receivers

The simplest way to connect things is to `submit` them:

```
std::execution::submit(sender,receiver);
```

But you can also `connect` them and then `start`:

```
auto state=std::execution::connect(sender,receiver);
std::execution::start(state);
```

Simple sender

For simple cases, the **Sender** can be obtained directly from an executor:

```
auto sender=std::execution::schedule(ex);
```

This **Sender** does not provide a value, so the receiver must provide a `set_value` function without value parameters.

Simple receiver

A simple **Receiver** to go with our simple **Sender** needs to implement `set_value` to do the required work:

```
struct MyReceiver{
  void set_value(){
    do_work();
  }
};
```

Libunifex

`https://github.com/facebookexperimental/libunifex`

Provides a sample implementation of the executor model and extensive documentation.

Coroutine support for concurrency

Coroutine support for concurrency

I hope to see things like `task<T>` that allows you to write a coroutine intended to run as an async task, and **Executors** that support coroutines:

```
task<int> task1();
task<int> task2();

task<int> sum(){
  int r1=co_await task1();
  int r2=co_await task2();
  co_return r1+r2;
}

some_executor ex;
ex.execute(sum());
```

Concurrent Data Structures

Concurrent Data Structures

Developers commonly need data structures that allow concurrent access.

Proposals for standardization include:

- Concurrent Queues
- Concurrent Hash Maps

Concurrent Data Structures: Queues

Queues are a core mechanism for communicating between threads.

```
concurrent_queue<MyData> q;

void producer_thread(){
  q.push(generate_data());
}
void consumer_thread(){
  process_data(q.value_pop());
}
```

Concurrent Data Structures: Hash Maps

- Hash maps are often used for fast look-up of data
- Using a mutex for synchronization can hurt performance
- Special implementations designed for concurrent access can be better

Safe Memory Reclamation Facilities

Safe Memory Reclamation Facilities

Lock-free algorithms need a way to delete data when no other thread is accessing it.

RCU provides a lock-free read side. Deletion is either blocking or deferred on a background thread.

Hazard pointers defer deletion, and provide a different set of performance trade-offs.

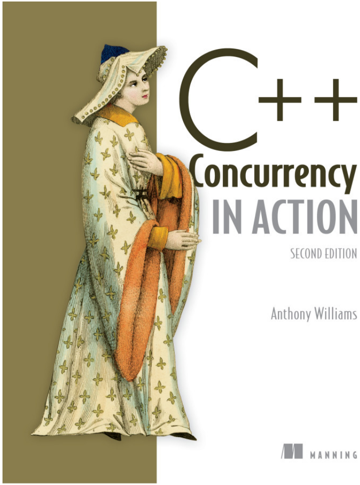
Both mechanisms are proposed for future C++ standards

Proposals

Here are the papers for those future things that have proposals:

- Synchronized Value: P0290
- Concurrency TS1 (for `future` continuations): N4399
- Executors: P0443
- Concurrent Queues: P0260
- Concurrent Hash Map: P0652 P1761
- RCU: P1122
- Hazard Pointers: P1121

My Book



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Covers C++17 and the Concurrency TS

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Questions?