C++ now

Coroutines and Structured Concurrency in Practice

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Stackless coroutines are there in C++ for 3 years

Lots of talks at conferences

Still rarely used in production

Challenges we faced

A lot of existing code

mostly callback-based

A custom-built I/O event loop

predates Asio by a decade

fine-tuned for specific use cases

Somewhat conservative audience

real benefit needs to be demonstrated to justify switching

Callbacks vs coroutines

```cpp
// read length
auto len = make_unique<int32_t>();
async_read(socket,
  buffer(len.get(), sizeof(int32_t)),
  [len = move(len)](auto ec, size_t len1){
    if (!ec && len1 == sizeof(int32_t)) {
      // read data
      auto buf = make_unique<char[]>(*len);
      async_read(socket,
        buffer(buf.get(), *len),
        [buf = move(buf), len = *len]
        (auto ec, size_t len2) {
          if (!ec && len2 == len) {
            // ...handle data...
          } else {
            // ...handle error...
          }
        });
    } else {
      // ...handle error...
    }
  });
```

```cpp
// read length
int32_t len;
co_await async_read(s,
    buffer(&len, sizeof(len)),
    use_awaitable);

// read data
auto buf = make_unique<char[]>(len);
co_await async_read(s,
    buffer(buf.get(), len),
    use_awaitable);

// ...handle data...
```

Local variable

Manual lifetime management

Callbacks vs coroutines

```
// read length
auto len = make_unique<int32_t>();
async_read(socket,
  buffer(len.get(), sizeof(int32_t)),
  [len = move(len)](auto ec, size_t len1){
    if (!ec && len1 == sizeof(int32_t)) {
      // read data
      auto buf = make_unique<char[]>(*len);
      async_read(socket,
        buffer(buf.get(), *len),
        [buf = move(buf), len = *len]
        (auto ec, size_t len2) {
          if (!ec && len2 == len) {
            // ...handle data...
          } else {
            // ...handle error...
          }
        });
    } else {
      // ...handle error...
    }
  });
```

Use after move

```
// read length
int32_t len;
co_await async_read(s,
    buffer(&len, sizeof(len)),
    use_awaitable);

// read data
auto buf = make_unique<char[]>(len);
co_await async_read(s,
    buffer(buf.get(), len),
    use_awaitable);

// ...handle data...
```

Callbacks vs coroutines

```
// read length
auto len = make_unique<int32_t>();
async_read(socket,
  buffer(len.get(), sizeof(int32_t)),
  [len = move(len)](auto ec, size_t len1){
    if (!ec && len1 == sizeof(int32_t)) {
      // read data
      auto buf = make_unique<char[]>(*len);
      async_read(socket,
        buffer(buf.get(), *len),
        [buf = move(buf), len = *len]
        (auto ec, size_t len2) {
          if (!ec && len2 == len) {
            // ...handle data...
          } else {
            // ...handle error...
          }
        });
    } else {
      // ...handle error...
    }
  });
```

```
// read length
int32_t len;
co_await async_read(s,
    buffer(&len, sizeof(len)),
    use_awaitable);

// read data
auto buf = make_unique<char[]>(len);
co_await async_read(s,
    buffer(buf.get(), len),
    use_awaitable);

// ...handle data...
```

Errors raised from here as C++ exceptions

Manual error handling

Coroutines *may* simplify things

- Easier reasoning
- Easier object lifetime management
- Easier error propagation

But we need some structure

Structured concurrency

And why we care

A typical async framework

`class Task { ... }`

represents a unit of background work

`Task::join()`

explicit call to suspend the current task
until another task completes, and returns its result
propagates uncaught exceptions

`Task::detach()`

allows the task to run alongside the rest of the program

Detached tasks considered harmful

No way to figure out task lifetime

=> no automatic object lifetime management

```
// don’t do this
void bad(tcp::socket& s) {
    std::array<char> buf(1024);
    asio::co_spawn(
        ex,
        [&s, &buf]() -> asio::awaitable {
            co_await s.read_some(s,
                                 asio::buffer(buf),
                                 asio::use_awaitable);
        },
        asio::detached);
}
```

Detached tasks considered harmful

```
// don’t do this either
void slightly_better(tcp::socket& s) {
    auto buf = make_shared<char[]>(1024);
    asio::co_spawn(
        ex,
        [&s, buf]() -> asio::awaitable {
            co_await s.read_some(s,
                                 asio::buffer(buf.get(), 1024),
                                 asio::use_awaitable);
        },
        asio::detached);
}
```

Detached tasks considered harmful

```
// and also don’t do this
void slightly_better(tcp::socket& s) {
    auto buf = make_shared<char[]>(1024);
    asio::co_spawn(
        ex,
        [&s, buf]() -> asio::awaitable {
            try {
                co_await s.read_some(s,
                                     asio::buffer(buf.get(), 1024),
                                     asio::use_awaitable);
            } catch (std::exception& e) {
                // ...um?..
            }
        },
        asio::detached);
}
```

Can we fix things by just removing `detach()`?

Each task must be `join()`ed at some point

`join()` is an explicit call, we cannot *force* users to always call it

Also join in destructor?

Error propagation still problematic

Destructors are not supposed to throw

What if task destructor *is never reached*?

What if task destructor is never reached?

```
void reportLiveness();
Task serve(tcp::socket s);

Task mainTask() {
    Task liveness = []() -> Task {
        for (;;) {
            reportLiveness();
            co_await sleepFor(1_s);
        }
    }();

    for (;;) {
        tcp::socket = co_await accept();
        co_await serve(std::move(s));
    }

    // implicit liveness.~Task() call
}
```

If this throws

the exception gets reraised here

What if task destructor is never reached?

```
void reportLiveness();
Task serve(tcp::socket s);

Task mainTask() {
    Task liveness = []() -> Task {
        for (;;) {
            reportLiveness();
            co_await sleepFor(1_s);
        }
    }();


    for (;;) {
        tcp::socket = co_await accept();
        co_await serve(std::move(s));
    }

    std::unreachable();
    // implicit liveness.~Task() call
}
```

If this throws

we'll never find out

What if task destructor is never reached?

```
void reportLiveness();
Task serve(tcp::socket s);

Task mainTask() {
    Task liveness = []() -> Task {
        for (;;) {
            reportLiveness();
            co_await sleepFor(1_s);
        }
    }();

    for (;;) {
        tcp::socket = co_await accept();
        co_await serve(std::move(s));
    }

    std::unreachable();
    // implicit liveness.~Task() call
}
```

Executes in background

The ground rule:
No such thing as background execution

A task can only run when it's being awaited by another task

A task can only run when it's being awaited by another task

That awaiting task is a *caller*

Once the caller resumes, the callee is done
any resources it may have used can be freed

Any unhandled exception will get re-raised

https://vorpus.org/blog/notes-on-structured-concurrency-or-go-statement-considered-harmful/

Sketching an API

```
Task<void> greet() {
    cout << "going to greet "
         << "the world\n";
    co_await sleep_for(1s);
    cout << "Hello world!\n";
}

Task<void> greetTwice() {
    cout << "spawning tasks\n";
    auto task1 = greet();
    auto task2 = greet();
    cout << "awaiting tasks\n";
    co_await task1;
    co_await task2;
}
```

```
spawning tasks
awaiting tasks
going to greet the world
   <1 second pause>
Hello world!
going to greet the world
   <another 1 second pause>
Hello world!
```

Running things concurrently

```
Task<void> greet() {
    cout << "going to greet "
         << "the world\n";
    co_await sleep_for(1s);
    cout << "Hello world!\n";
}

Task<void> greetTwice() {
    co_await allOf(greet(),
                   greet());
}
```

```
going to greet the world
going to greet the world
   <1 second pause>
Hello world!
Hello world!
```

allOf() combiner

- Upon `co_await`, starts all children
- Once all children complete,
  returns `std::tuple<>` of their results
- If any child raises an exception,
  cancels anything still running and re-raises

anyOf() combiner

- Upon `co_await`, starts all children
- Once any of them completes, *cancels* the others
- Once cancellation completes,
  returns `std::variant<>` of their results
- If any child raises an exception,
  cancels anything still running and re-raises

anyOf() use cases

Attaching a timeout to a long-running operation

```
Task<void> longRunning();
```

anyOf() use cases

Attaching a timeout to a long-running operation

```
Task<void> longRunning(chrono::milliseconds timeout);
```

https://vorpus.org/blog/timeouts-and-cancellation-for-humans/

anyOf() use cases

Attaching a timeout to a long-running operation

```
Task<void> longRunning();

Task<void> bounded() {
    co_await anyOf(longRunning(),
                   sleepFor(200ms));
}
```

anyOf() use cases

Making an operation externally cancellable

```
Task<void> longRunning();

Event* evt = nullptr;

Task<void> cancellable() {
    Event e;
    evt = &e;

    co_await anyOf(longRunning(), e);
}

void cancel() { evt->trigger(); }
```

anyOf() use cases: clean shutdown

```
class Server {
public:
    Task<void> serve(); // runs forever
};

int main() {
    Server srv;
    run(anyOf(srv.serve(),
              signalReceived({SIGTERM, SIGINT})));
}
```

anyOf() use cases: racing

```
Task<ip::addr> resolveOn(const string& name,
                         const string& dnsServer);

Task<ip::addr> resolve(const string& name) {
    auto v = co_await anyOf(
        resolveOn(name, "8.8.8.8"),
        [&]() -> Task<ip::addr> {
            co_await sleepFor(100ms);
            co_return co_await resolveOn(name, "1.1.1.1");
        });

    co_return visit(identity{}, v);
}
```

Structured concurrency

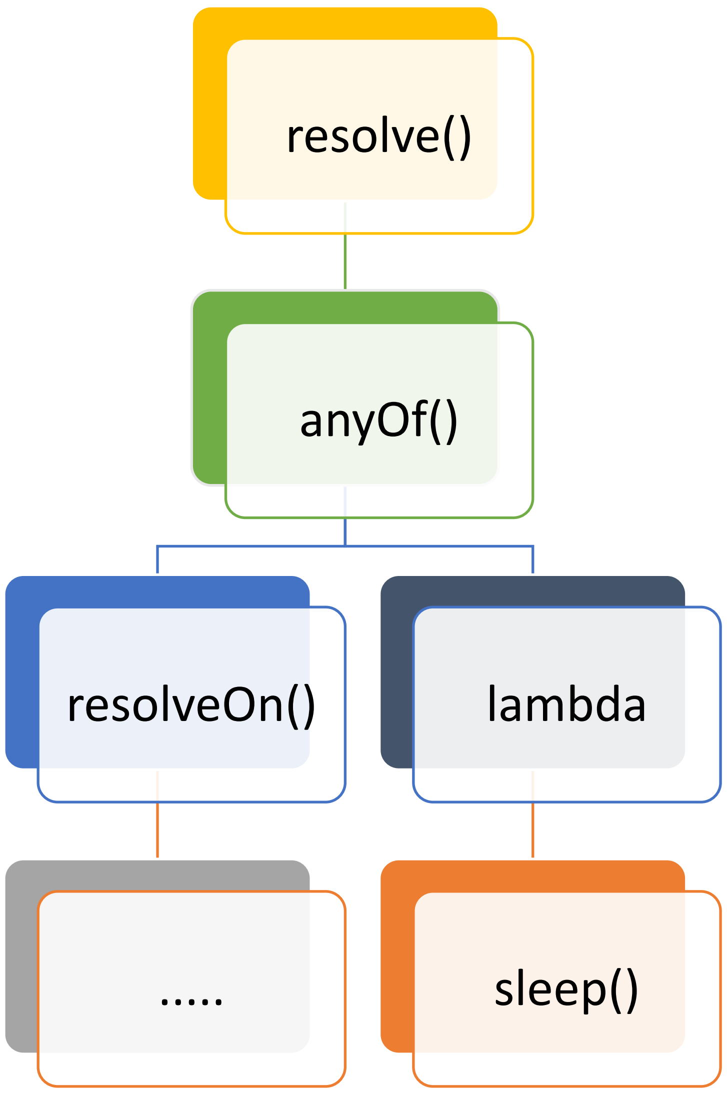
Tasks naturally form a "call tree"

- coroutines
- leaf awaitables (sleeping, I/O, etc)
- combiners (`allOf()`, `anyOf()`)

Every task in the tree has another suspended task waiting for its completion

Exceptions propagate up the tree

Cancellation propagates down the tree

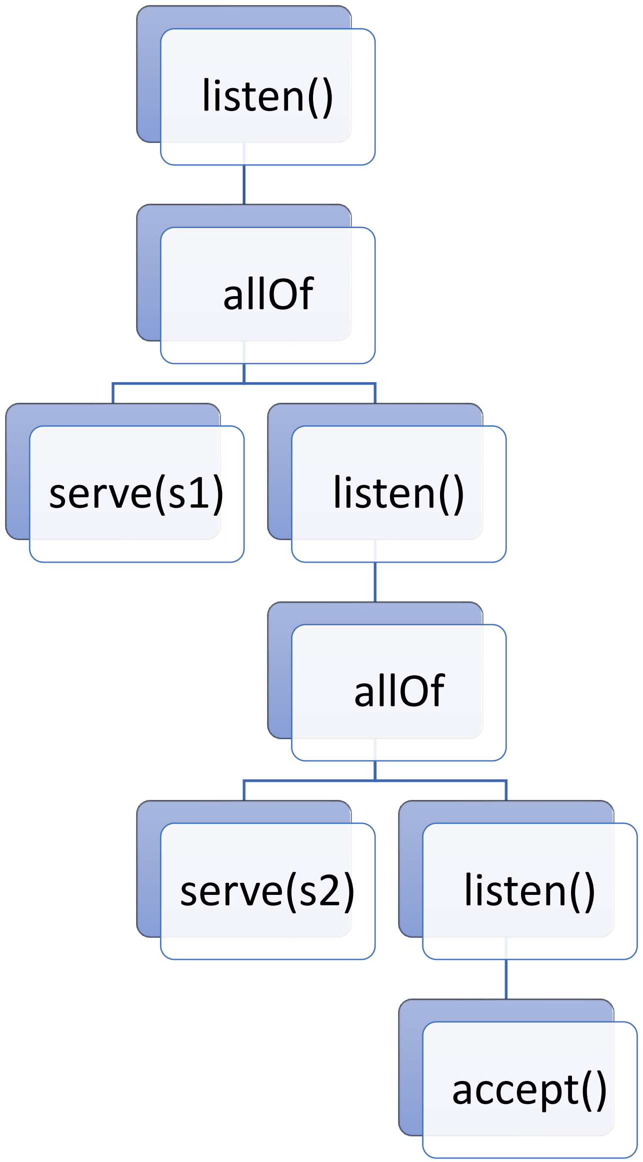


Giving it a shot: a simple TCP echo server

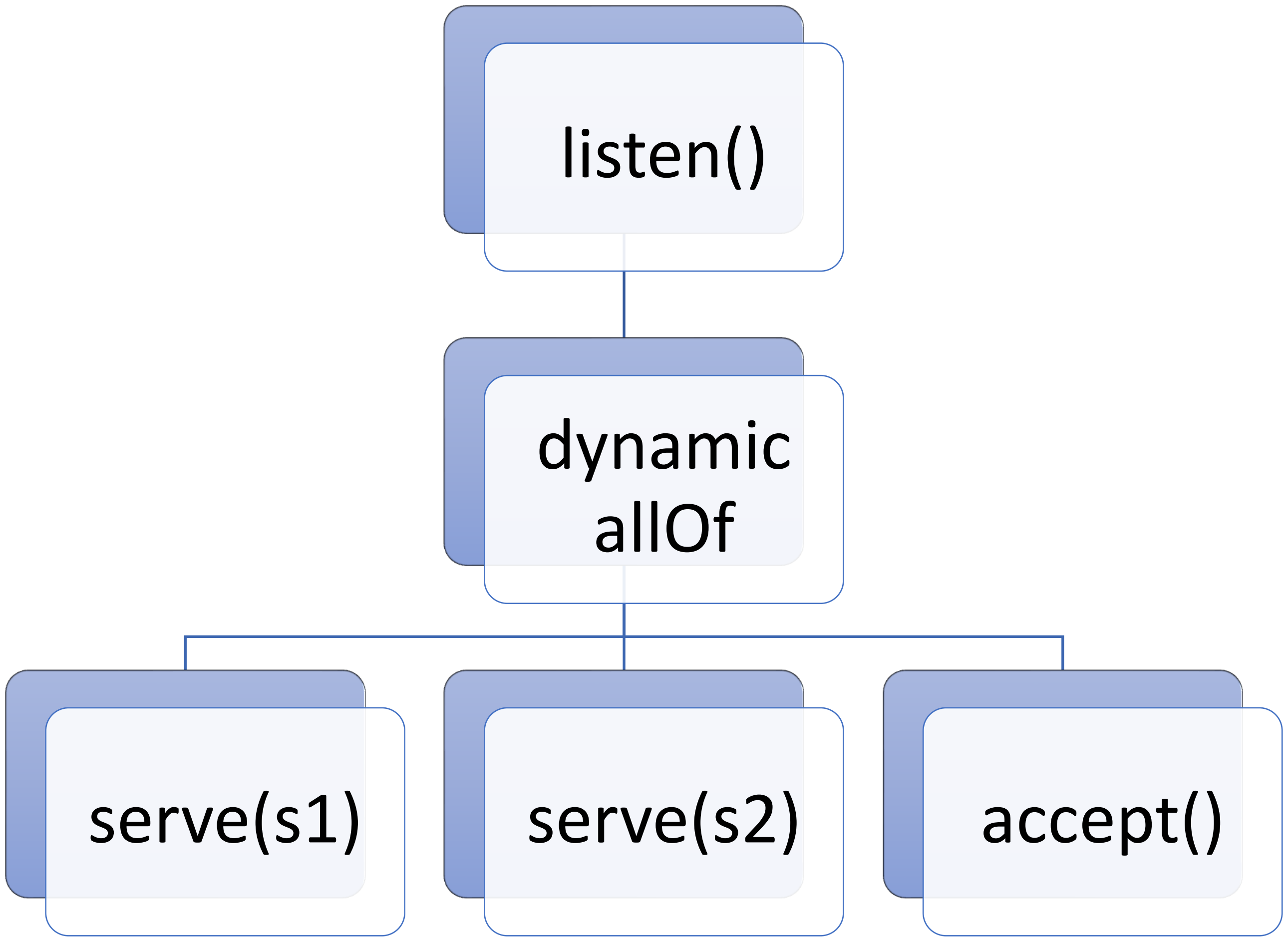
```
Task<void> serve(tcp::socket s) {
    std::array<char> buf(1024);
    try {
        for (;;) {
            size_t len = co_await s.async_read_some(
                asio::buffer(buf), asio::use_awaitable);
            co_await async_write(s, asio::buffer(buf, len),
                                 asio::use_awaitable);
        }
    } catch (std::exception&) { /*connection closed or I/O error*/ }
}

Task<void> listen(tcp::acceptor& acc) {
    for (;;) {
        tcp::socket s = co_await acc.async_accept(io_context,
                                                  asio::use_awaitable);

        // ???
```

Giving it a shot: a simple echo server

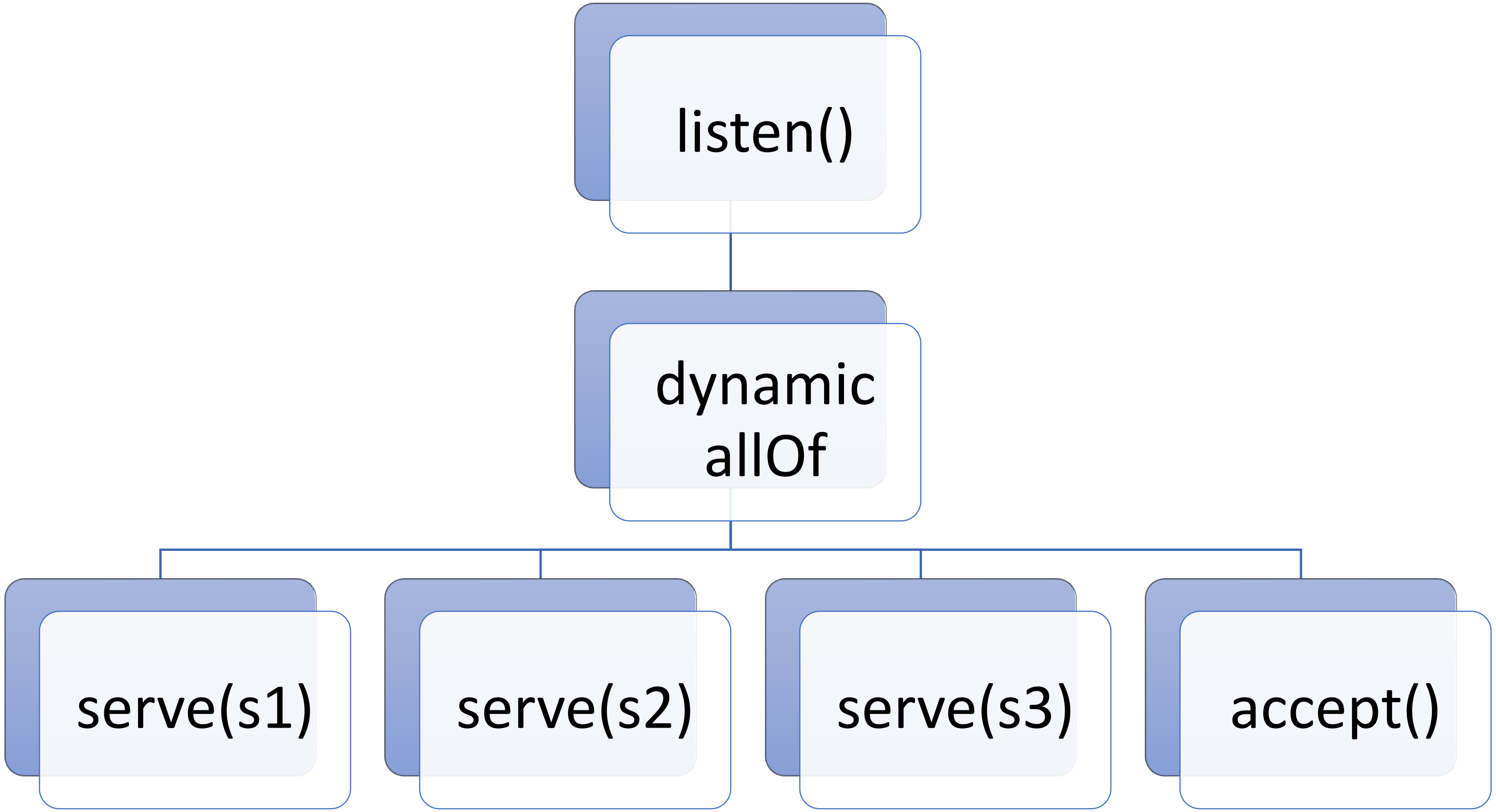
```
Task<void> serve(tcp::socket s) {
    std::array<char> buf(1024);
    try {
        for (;;) {
            size_t len = co_await s.async_read_some(
                asio::buffer(buf), use_awaitable);
            co_await async_write(s, asio::buffer(buf, len),
                                 asio::use_awaitable);
        }
    } catch (std::exception&) { /*connection closed or I/O error*/ }
}

Task<void> listen(tcp::acceptor& acc) {
    tcp::socket s = co_await acc.async_accept(io_context,
                                              asio::use_awaitable);

    co_await anyOf(serve(std::move(s)), accept(acc));
}
```


listen()
allOf
serve(s1)
listen()
allOf
serve(s2)
listen()
accept()

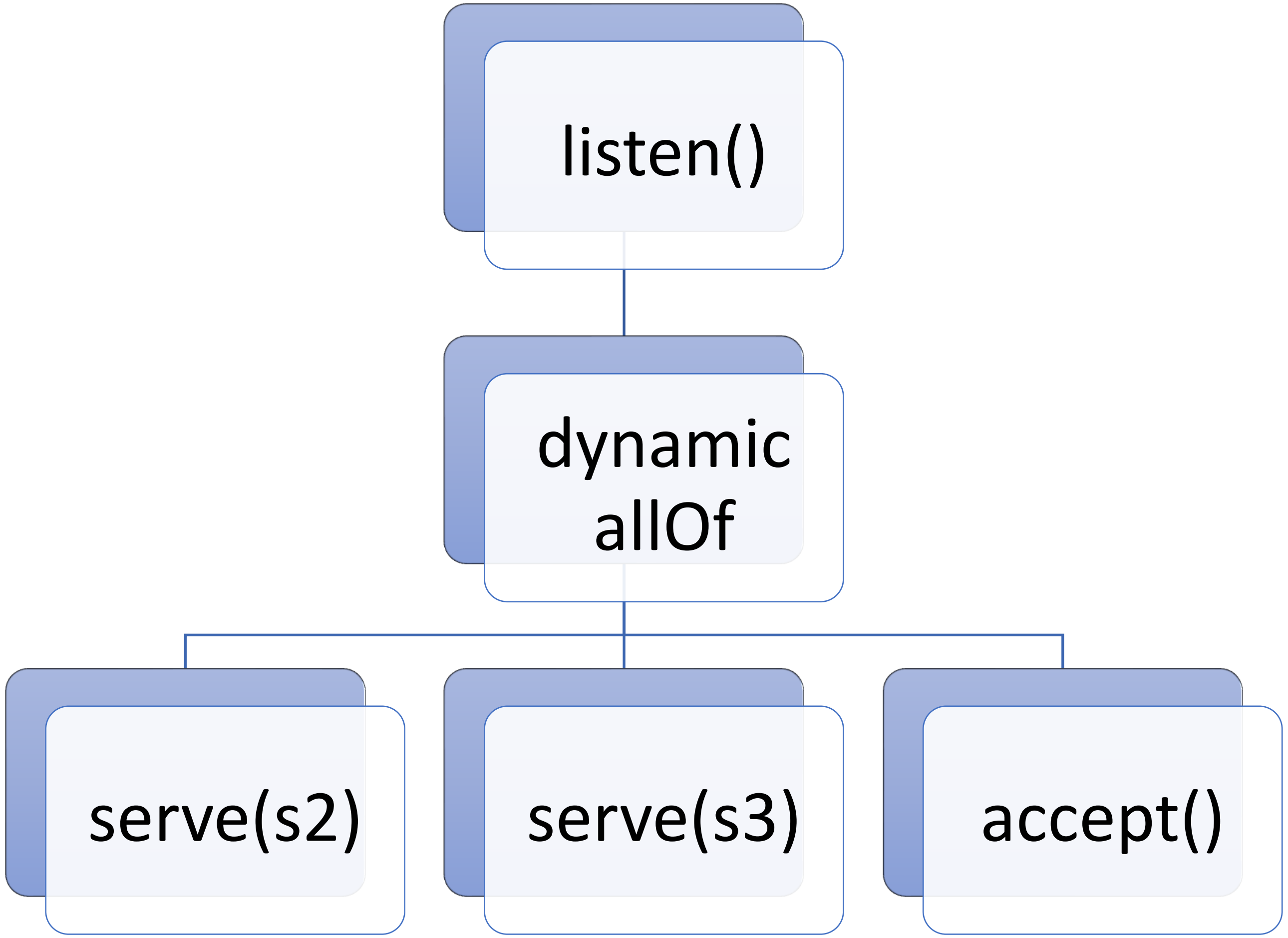
Dynamic allOf()?



Dynamic allOf()?



Dynamic allOf()?



Dynamic allOf()?

```
Task<void> serve(tcp::socket);

Task<void> listen(tcp::acceptor& acc) {
    DynamicAllOf tasks;

    for (;;) {
        tcp::socket s =
            co_await acc.async_accept(
                io_context, use_awaitable);
        tasks.add(serve(move(s)));
    }
}
```

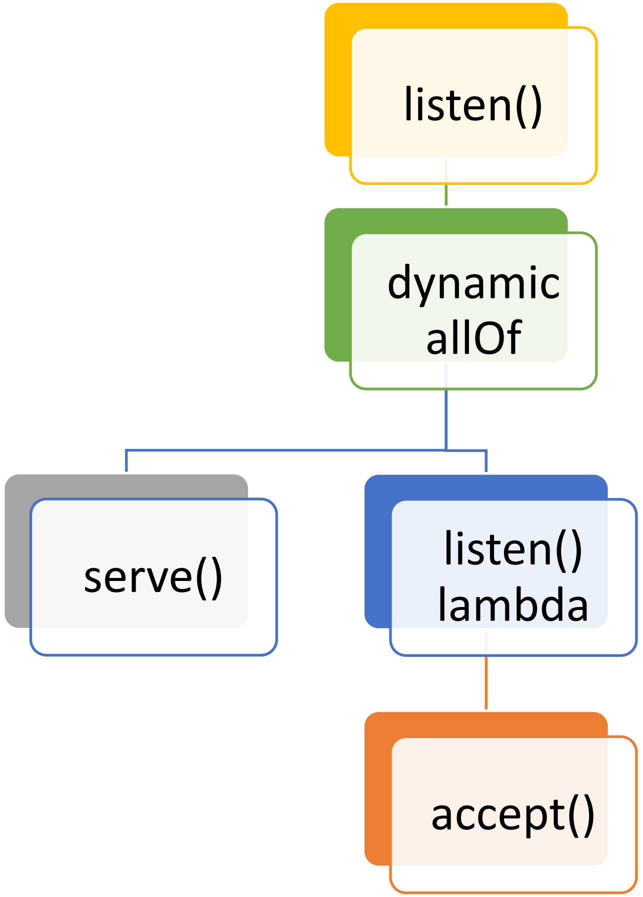
This runs unsupervised
=> ground rule violated

Dynamic allOf()

```
Task<void> serve(tcp::socket);

Task<void> listen(tcp::acceptor& acc) {

    co_await dynamicAllOf(
            [&](DynamicAllOf& tasks) -> Task<void> {

                for (;;) {
                    tcp::socket s =
                        co_await acc.async_accept(
                            io_context, use_awaitable);

                    tasks.add( serve(move(s)) );
                }

            });

}
```

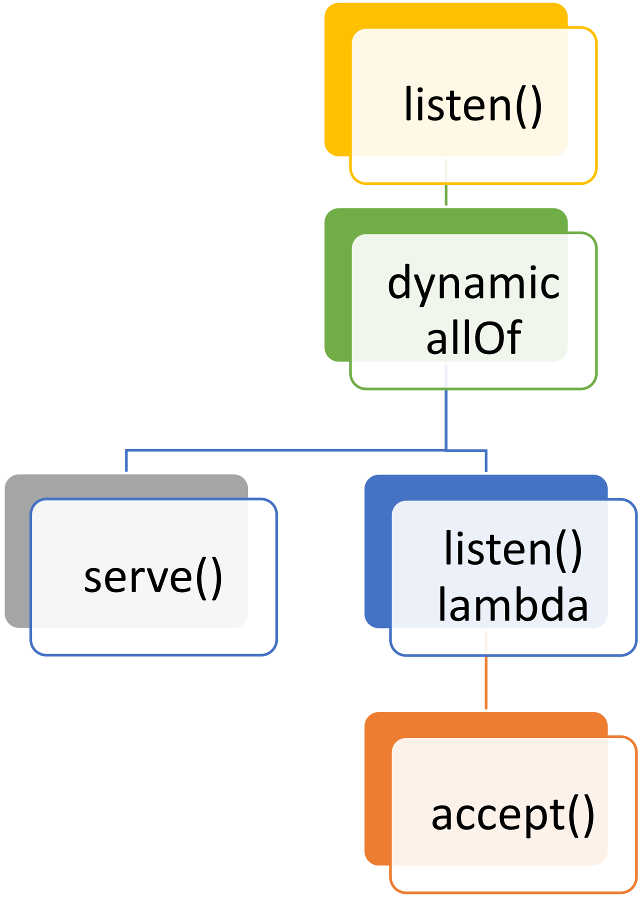
Dynamic allOf()

```
Task<void> serve(tcp::socket);

Task<void> listen(tcp::acceptor& acc) {
    co_await dynamicAllOf(
        [&](DynamicAllOf& tasks) -> Task<void> {
            for (;;) {
                tcp::socket s =
                    co_await acc.async_accept(
                        io_context, use_awaitable);

                tasks.add( serve(move(s)) );
            }

        });
}
```



Dynamic allOf()

```
co_await dynamicAllOf(
    [&](DynamicAllOf& tasks) -> Task<void> {
        for (;;) {
            tcp::socket s =
                co_await acc.async_accept(
                    io_context, use_awaitable);

            tasks.add( serve(move(s)) );
        }

    });
}
```



Dynamic allOf()

```
co_await dynamicAllOf(
        [&](DynamicAllOf& tasks) -> Task<void> {
```

We have a *named node* in our task tree

Maybe add a bunch of functions there?

`add()`

`size()`

maybe `cancel()`?

No longer a simple allOf()

Dynamic allOf()

We have created a fundamental primitive
of structured concurrency

- *nursery* in Python trio
- *task group* in Python asyncio
- *task scope* in Rust
- *coroutine scope* in Kotlin

We also call it a *nursery*
(mnemonics: a place where your children are)

Dynamic allOf()

```
Task<void> serve(tcp::socket);

Task<void> listen(tcp::acceptor& acc) {

    co_await openNursery(
             [&](Nursery& nursery) -> Task<void> {

                  for (;;) {
                      tcp::socket s =
                          co_await acc.async_accept(
                              io_context, use_awaitable);
                      n.start(serve(move(s)));
                 }

             });

}
```

Nurseries

```
Task<void> serve(tcp::socket);

Task<void> listen(tcp::acceptor& acc) {
    WITH_NURSERY(nursery) {
        for (;;) {
            tcp::socket s =
                co_await acc.async_accept(
                    io_context, use_awaitable);
            nursery.start(serve(move(s)));
        }
    };
}
```

Properties of nurseries and combiners

Act as nodes in the task tree

Wait until all children complete

Propagate any exceptions from any children back to the parent

Cancel any children still running before completing

No task is ever left behind

Bending the rules

What if you need to spawn a coroutine which will outlive the spawner?

What if the spawner is not even a coroutine?

Pass the spawner a reference to a nursery

Bending the rules

```
void beginListen(Nursery& n, io_context& io, uint16_t port) {
    n.start([&]() -> Task<void> {
        tcp::acceptor acc(io, tcp::endpoint(tcp::v4(), port));
        for (;;) {
            auto s = co_await acc.async_accept(io, use_awaitable);
            n.start(serve(move(s)));
        }
    });
}
```

Bending the rules – to a degree

Every task still has a caller

- the caller is not what called us – it’s what we’re going to *return* control to
- the caller will get any unhandled exceptions

Some room for dangling references

- passing nurseries around is an advanced technique that attracts extra scrutiny

Task lifetime is still bounded by nursery liftetime

Function behavior is deduced from its signature

Bending the rules – to a degree

Function behavior is deduced from its signature

void func()	cannot spawn any child coroutines
Task<void> func()	can spawn coroutines, but will join them before returning
void func(Nursery&) Task<void> func(Nursery&)	can (and likely will) spawn coroutines that might outlive it (beware!)

Active objects

```
class ProcessSupervisor {
public:
  void start(const string& cmdline);


private:
  // suspends until the process completes
  Task<void> runProcess(const string& cmdline);
};
```

Active objects

```
class ProcessSupervisor {
  Nursery* nursery = nullptr;
public:
  void start(const string& cmdline) {
    nursery->start(runProcess(cmdline));
  }
private:
  // suspends until the process completes
  Task<void> runProcess(const string& cmdline);
};
```

Active objects

```
class ProcessSupervisor {
  Nursery* nursery = nullptr;
```

How to initialize `ProcessSupervisor::nursery`?

An obvious approach:
accept it as an argument in class constructor

Active objects

An obvious (and wrong) approach:
accept it as an argument in class constructor

```
Task<void> workWithSupervisor() {
  WITH_NURSERY(n) {
    ProcessSupervisor ps(n);
    ps.start("/bin/true");
    // ...stuff...
  };
}
```

supervisor goes out of scope here
but tasks spawned in the nursery continue running

~~Good~~ old two-phase initialization to the rescue

```cpp
class ProcessSupervisor {
  Nursery* nursery = nullptr;
public:
  Task<void> run() {
    WITH_NURSERY(n) {
      nursery = &n;
      co_await SuspendForever{};
    };
  }
};
```

```cpp
Task<void>
workWithSupervisor()
{
  ProcessSupervisor s;
  co_await anyOf(
    s.run(),
    [&]() -> Task<> {
      s.start("true");
      // ...stuff...
    });
}
```

Awaitable interface

And implementing your own awaitables

Awaitable interface

```
void await_suspend(std::coroutine_handle<> h)
```

Initiate the asynchronous operation, and arrange h.resume() to be called when it completes

```
auto await_resume()
```

Fetch the result of the operation, or (re)throw an exception.

```
bool await_ready() const noexcept
```

Performance optimization

Awaitable example

```
typedef void (*ares_addrinfo_callback)(void* arg, int status,
                                       int timeouts,
                                       struct ares_addrinfo* result);

void ares_getaddrinfo(ares_channel_t*,
                      const char* name, const char* service,
                      const struct ares_addrinfo_hints* hints,
                      ares_addrinfo_callback, void* arg);
```

Awaitable example

```
class DNSQuery {
    ares_channel_t* channel;
    const char* name;
    struct sockaddr_in result;
    int status;
    std::coroutine_handle<> parent;

public:
    void await_ready() const noexcept { return false; }
    void await_suspend(std::coroutine_handle<> h);
    struct sockaddr_in await_resume();
};
```

Awaitable example

```
void DNSQuery::await_suspend(std::coroutine_handle<> h) {
    parent = h;
    ares_getaddrinfo(
        channel, name, /*service=*/ nullptr, /*hints=*/ nullptr,
        [](void* arg, int status, int /*timeouts*/,
           struct ares_addrinfo* ai)
        {
            auto self = static_cast<DNSQuery*>(arg);
            // Copy result back into the awaitable object
            self->status = status;
            if (ai) {
                memcpy(self->result, ai->nodes->ai_addr,
                       sizeof(struct sockaddr_in));
            }
            // Resume the parent
            self->parent.resume();
        }, this);
}
```

Awaitable example

```
struct sockaddr_in DNSQuery::await_resume() {
    if (status == ARES_SUCCESS) {
        return result;
    } else {
        throw std::runtime_error(std::format(
            “cannot resolve {}: {}”, name, ares_strerror(status)));
    }
}
```

Awaitable example

Any operation modeled as

```
void beginThing(std::function<void()> doneCB);
```

can be rewritten as an awaitable with

```
void await_suspend(std::coroutine_handle<> h) {
    beginThing([h]{ h.resume(); });
}
```

Task cancellation

Cancellation properties

Implicit: no `if (cancelled) return` scattered throughout code

Fast: no C++ exceptions involved

Asynchronous

Cancellation properties: *asynchronous*

Some async operations are (or can be made) immediately cancellable

Some lack cancellation support in its API

```
void begin_thing(void (*callback)(result_t, void* cookie),
                 void* cookie);
```

Some operations inherently cannot be cancelled synchronously

Cancellation properties: *asynchronous*

Some operations inherently cannot be cancelled synchronously

- a running subprocess

you can SIGKILL it, but you still need to wait() for its completion

```
Task<void> execInChroot(string_view chrootPath,
                        string_view cmdline) {
    copyChrootEnv();
    auto procMnt = BindMount("/dev", format("{}/dev", chrootPath));
    co_await runAsync(format("chroot {} sh -c '{}'",
                      chrootPath, cmdline));
    // implicit procMnt.~BindMount()
}
```

This needs to complete before this can unmount

Cancellation properties: *asynchronous*

Some operations inherently cannot be cancelled synchronously

- io_uring or overlapped I/O

```
BOOL ReadFileEx(HANDLE file, void* buf, DWORD len, OVERLAPPED*,
                void (*)(DWORD err, DWORD len, OVERLAPPED*));

BOOL CancelIoEx(HANDLE file, OVERLAPPED*);
```

Cancellation happens asynchronously

Callback *will* be called, delivering STATUS_CANCELED
or completion result

https://devblogs.microsoft.com/oldnewthing/?p=11613

Cancellation properties: *asynchronous*

Some operations inherently cannot be cancelled synchronously

If we only support synchronous cancellation,
we are opting out from ever supporting any of these

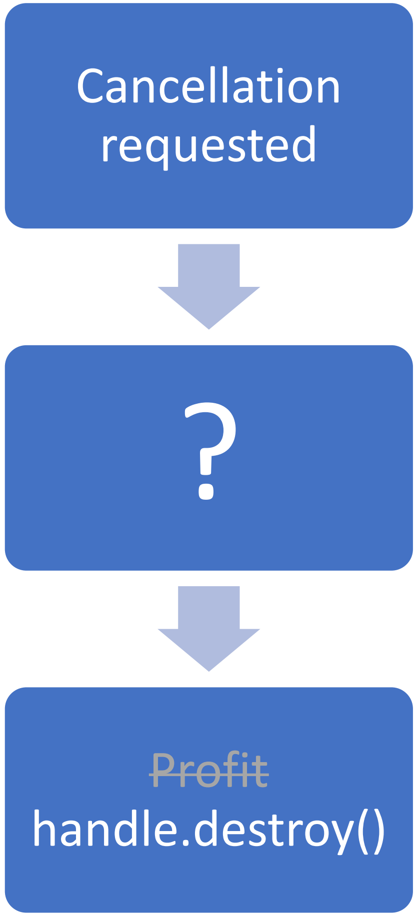
Rust developers learned that the hard way

https://carllerche.com/2021/06/17/six-ways-to-make-async-rust-easier/

Sketching cancellation procedure

std::coroutine_handle<void>::destroy()

Destroys the suspended coroutine frame and any arguments and local variables of the coroutine still in scope



Cancellation procedure: Phase 2

We need cooperation from the awaitable

```
bool await_ready() const noexcept;
void await_suspend(std::coroutine_handle<> h);
auto await_resume();
```

Cancellation procedure: Phase 2

We need cooperation from the awaitable

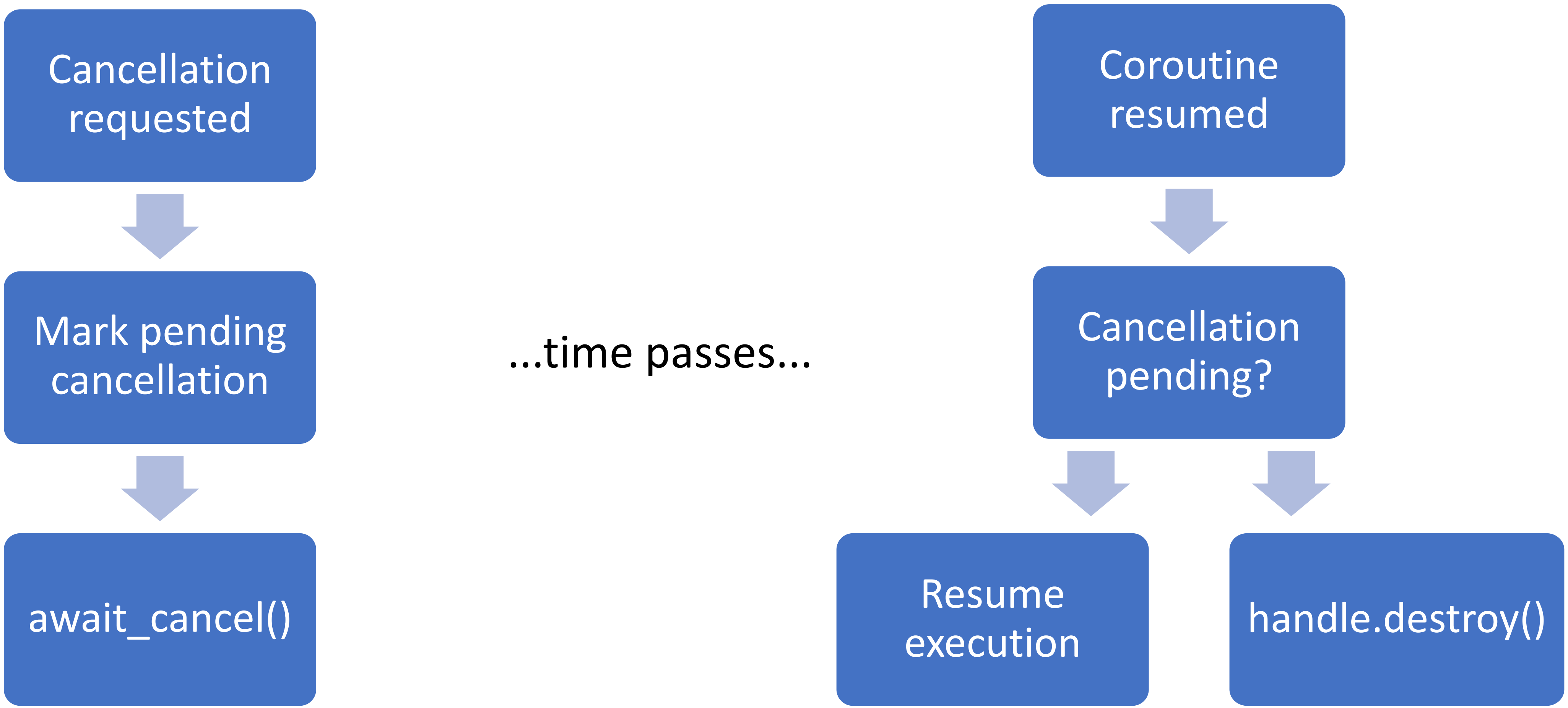
```
bool await_ready() const noexcept;
void await_suspend(std::coroutine_handle<> h);
auto await_resume();
```

```
void await_cancel(std::coroutine_handle<> h) noexcept;
```

Requests cancellation of the in-progress asynchronous operation.
Upon confirmation, should invoke `h.resume()`.

Handle will match passed to `await_suspend()`,
so `void await_cancel(auto) {}` is a legit implementation.

Cancellation procedure: Phase 2



We need access to the awaitable

A suspended coroutine knows neither the awaitable nor its type

We need to somehow stash it before suspending

`Promise::await_transform()` to the rescue

- Any awaitable is passed through `await_transform()`
- We can use it to stash a type-erased pointer to the awaitee

```
class Promise {

  void* awaitee_ = nullptr;
  void (*cancelFn_)(void*,
                    coroutine_handle<>)
    = nullptr;
  bool cancelling_ = false;

  template<class T>
  auto await_transform(T&& t) {
    return Interceptor<T>{this, &t};
  }

  template<class T> struct Interceptor {
    Promise* p;
    T* t;

    auto await_suspend(coroutine_handle<> h) {

      // Stash a type-erased reference
      // to the awaitee
      p->awaitee_ = t;

      p->cancelFn_ = +[](void* ptr,
                         coroutine_handle<> h){
        reinterpret_cast<T*>(ptr)
            ->await_cancel(h);
      };

      return t->await_suspend(h);
    }
```

```
    decltype(auto) await_resume() {
      p->awaitee_ = nullptr;
      p->cancelFn_ = nullptr;
      return forward<T>(*t).await_resume();
    }

    bool await_ready() const noexcept {
      return t->await_ready();
    }

  };


  void cancel() {
    cancelling_ = true;

    if (awaitee_) {
      cancelFn_(
        awaitee_,
        coroutine_handle<Promise>::
            from_promise(*this));
    }
  }

};
```

Destroying the coroutine

`coroutine_handle::destroy()` can only be called on a *suspended* coroutine

Once the awaitee `resume()`d the coroutine handle, the coroutine is no longer suspended

Awaitables cannot do anything else to the coroutine handle

A coroutine frame

```
struct coroutine_frame {
    // resume index
    // promise object
    // ...parameters...
    // ...local variables...
    // ...temporary objects...
    // other bookkeeping
};
```

A coroutine frame

```
struct coroutine_frame {
    void (*resume_fn)(coroutine_frame*);
    void (*destroy_fn)(coroutine_frame*);

    // resume index
    // promise object
    // ...parameters...
    // ...local variables...
    // ...temporary objects...
    // other bookkeeping
};
```

A coroutine frame

```
struct coroutine_frame {
    void (*resume_fn)(coroutine_frame*);
    void (*destroy_fn)(coroutine_frame*);
    // ...
};
```

A coroutine frame

```
struct coroutine_frame {
    void (*resume_fn)(coroutine_frame*);
    void (*destroy_fn)(coroutine_frame*);
    // ...
};

void coroutine_handle<void>::resume() {
   auto f =
      reinterpret_cast<coroutine_frame>(address());
   f->resume_fn(f);
}
```

A phony coroutine frame

```
struct CoroutineHeader {
  void (*resume_fn)(CoroutineHeader*);
  static coroutine_handle<> toHandle() {
    return coroutine_handle<>::from_address(this);
  }
};

class Promise: private CoroutineHeader {
  auto realHandle() {
    return coroutine_handle<Promise>::from_promise(*this);
  }

  auto proxyHandle() { return CoroutineHeader::toHandle(); }

  void onResume();

public:
  Promise() {
    this->resume_fn = [](void* self) {
      static_cast<Promise*>(self)->onResume();
    };
  }

};
```

A phony coroutine frame

```
class Promise: private CoroutineHeader {
  auto realHandle() {
    return coroutine_handle<Promise>::from_promise(*this);
  }

  auto proxyHandle() { return CoroutineHeader::toHandle(); }

  void onResume();

public:
  Promise() {
    this->resume_fn = [](void* self) {
      static_cast<Promise*>(self)->onResume();
    }
  }

};
```

A phony coroutine frame

```
class Promise: private CoroutineHeader {
  auto realHandle();
  auto proxyHandle();

  template<class T> struct Interceptor {
    Promise* p;
    T* t;

    auto await_suspend(coroutine_handle<>) {
      // populate awaitee_ and cancelFn_
      return t->await_suspend(p->proxyHandle());
    }
  };

  void onResume() {
    if (cancelling_) {
      realHandle().destroy();
    } else {
      realHandle().resume();
    }
  }

};
```

Rejected cancellation

A cancelled awiatable may complete successfully
and deliver a result

That result may or may not be safely destroyed

```
int fd = co_await asyncOpen("/mnt/nfs/remote/file");
```

An awaitable may need an option
to request resumption of the parent

Rejected cancellation

Expanding awaitable interface again

```
bool await_ready() const noexcept;
void await_suspend(std::coroutine_handle<> h);
auto await_resume();
void await_cancel(std::coroutine_handle<> h);
```

```
bool await_must_resume() const noexcept;
```

Called after resuming an awaiter pending cancellation.
If returns `false`, parent will be destroyed
(`await_resume()` will not be called);
otherwise resumed normally.

Notes on implementing awaitables

Paired functions: constructor/destructor
and `await_suspend()`/`await_cancel()`

`await_cancel()` reverses `await_suspend()`,
destructor reverses constructor

Ideally an awaitable object should be dormant until `await_suspend()`

- Otherwise, need to account for completion before `await_suspend()`
- Also need to account for early cancellation

Resource management

RAII even more important than before

```
// don't do this
Task<void> bad() {
    int fd = ::open("/etc/passwd", O_RDONLY);

    std::array<char, 65536> buf;
    ssize_t len = ::read(fd, buf.data(), buf.size());
    co_await publishOnFacebook(buf.data(), len);

    ::close(f);
}
```

RAII even more important than before

```
// don't do this either
Task<void> also_bad() {
    int fd = ::open("/etc/passwd", O_RDONLY);
    try {
        std::array<char, 65536> buf;
        ssize_t len = ::read(fd, buf.data(), buf.size());
        co_await publishOnFacebook(buf.data(), len);
        ::close(f);
    }
    catch (...) {
        ::close(f);
        throw;
    }
}
```

Third option:
We might get cancelled here
without any exceptions involved

RAII even more important than before

```
// maybe do this
Task<void> better() {
    int fd = ::open("/etc/passwd", O_RDONLY);
    auto _ = gsl::finally([fd]{ ::close(fd); });

    std::array<char, 65536> buf;
    ssize_t len = ::read(fd, buf.data(), buf.size());
    co_await publishOnFacebook(buf.data(), len);
}

// better yet, use std::ifstream
```

Asynchronous resource cleanup

```
struct AsyncFile {
    static Task<AsyncFile> open(fs::path);
    Task<void> close();
    Task<ssize_t> readInto(span<byte> buffer);
};

Task<void> func() {
    auto f = co_await AsyncFile::open("/etc/passwd");
    // ...work with file...
    std::arary<char, 1024> buf;
    ssize_t len = co_await f.readInto(buf);

    // bad idea
    co_await f.close();
}
```

Asynchronous resource cleanup

```
struct AsyncFile {
    static Task<AsyncFile> open(fs::path);
    Task<void> close();
    Task<ssize_t> readInto(span<byte> buffer);
};

Task<void> func() {
    auto f = co_await AsyncFile::open("/etc/passwd");
    // a better idea, but does not work
    auto _ = gsl::finally([&f]{ co_await f.close(); });

    // ...work with file...
    std::arary<char, 1024> buf;
    ssize_t len = co_await f.readInto(buf);
}
```

Asynchronous resource cleanup

```
struct AsyncFile {
    static Task<AsyncFile> open(fs::path);
    Task<void> close();
    Task<ssize_t> readInto(span<byte> buffer);
};

Task<void> func() {
    auto f = co_await AsyncFile::open("/etc/passwd");
    co_await anyOf([&]() -> Task<> {
        // ...work with file...
        std::arary<char, 1024> buf;
        ssize_t len = co_await f.readInto(buf);
    }, untilCancelledAnd(f.close()));
}
```

Executors and interruption points

Let's write an Event

A very basic synchronization primitive

Allows one-time, one way transition
from not-triggered to triggered state

Let's write an Event

```
class Event {
  class Awaitable;
  std::set<Awaitable*> awaitables;
  bool triggered;

public:
  void trigger();
  auto operator co_await();
}

class Event::Awaitable {
  Event* evt;
  coroutine_handle<> awaiter;

public:
  explicit Awaitable(Event* e):
    evt(e) {}

  bool await_ready() const noexcept {
    return evt->triggered;
  }

  void await_suspend(coroutine_handle<> h) {
    awaiter = h;
    evt->awaitables.insert(this);
  }

  void await_cancel(coroutine_handle<> h) {
    evt->awaitables.erase(this);
    h.resume();
  }

  void await_resume() {}
  bool await_must_resume() const noexcept {
    return false;
  }
};

auto Event::operator co_await() {
  return Awaitable{this};
}

void Event::trigger() {
  triggered = true;
  auto set = std::move(awaitables);
  for (Awaitable* a: set)
    set->awaiter.resume();
}
```

Giving it a shot

```
Event evt;
co_await allOf([&]() -> Task<> {
  cout << "a: waiting for event\n";
  co_await evt;
  cout << "a: done waiting\n";
}, [&]() -> Task<> {
  co_await sleepFor(100ms);
  cout << "b: setting event\n";
  evt.set();
  cout << "b: done setting\n";
});
```

```
a: waiting for event
      <100ms pause>
b: setting event
a: done waiting
b: done setting
```

No suspension points here

Yet something squeezed in

Giving it a shot

```
Event evt;
co_await allOf([&]() -> Task<> {
  cout << "a: waiting for event\n";
  co_await evt;
  cout << "a: done waiting\n";
}, [&]() -> Task<> {
  co_await sleepFor(100ms);
  cout << "b: setting event\n";
  evt.set();
  cout << "b: done setting\n";
});
```

Local reasoning at risk

```
Event evt;
auto th = make_unique<Thing>;
co_await allOf([&]() -> Task<> {
  co_await evt;
  th = nullptr; // evil laugh
}, [&]() -> Task<> {
  co_await sleepFor(100ms);
  poorVictim(th);
});
```

```
void somethingTotallyUnrelated() {
  evt.trigger();
}

void poorVictim(unique_ptr<Thing>& th)
{
  assert(th);
  somethingTotallyUnrelated();
  cout << th->name();
}
```

nullptr dereference

We need another ground rule

Each coroutine runs uninterrupted until its next `co_await`

Make it happen

```
class Promise: private CoroutineHeader {
  auto proxyHandle();
  auto realHandle();

  void onResume() {
    if (cancelling_) {
      realHandle().destroy();
    } else {
      realHandle().resume();
    }
  }
};
```

We need an executor

```
class Promise: private CoroutineHeader {
  auto proxyHandle();
  auto realHandle();

  void onResume() {
    if (cancelling_) {
      realHandle().destroy();
    } else {
      executor_.defer([h = realHandle()]{ h.resume(); });
    }
  }
};
```

We need an executor, let's write one

```
class Executor {
  queue<coroutine_handle<>> queue_;
  bool running_ = false;

public:
  void runSoon(coroutine_handle<> h) {
    queue_.push(h);

    if (!running) {
      running = true;

      while (!queue_.empty()) {
        auto h = queue_.top();
        queue_.pop();
        h.resume();
      }

      running_ = false;
    }

  }

};
```

```
thread_local Executor* g_executor;


class Promise {
  void onResume() {
    if (cancelling_) {
      realHandle().destroy();
    } else {
      g_executor->runSoon(
        realHandle());
    }
  }
};
```

Top-level coroutine

```
template<class EventLoop>
struct EventLoopTraits {
  void run(EventLoop&);
  void stop(EventLoop&);
};

auto run(auto& eventLoop, auto&& awaitable);
```

Starts *awaitable* and runs *eventLoop* until it completes.

Bridging to legacy code

Bridging to legacy code

Most code is likely old-style

Coroutine part needs to cooperate

Coroutines to callbacks

```
void beginThing(std::function<void(int /*result*/)> cb);

Task<void> workWithThing() {
    int x = co_await beginThing(/*???*/);
}
```

Coroutines to callbacks: wrap to the awaitable

```
void beginThing(std::function<void(int /*result*/)> cb);

class Thing {
    std::coroutine_handle<> parent;
    int result;
public:
    bool await_ready() const noexcept { return false; }
    void await_suspend(std::coroutine_handle<> h) {
        parent = h;
        beginThing([this](int res) {
            result = res;
            parent.resume();
        });
    }
    int await_resume() { return result; }
};


Task<void> workWithThing() {
    int x = co_await Thing{};
}
```

Callbacks to coroutines

```
struct ILegacyReader {
    virtual void read(span<byte> dst, function<void(ssize_t)> cb) = 0;
};

class OurReader: public ILegacyReader {
public:
    void read(span<byte> dst, function<void(ssize_t)> cb) override;
private:
    Task<size_t> doRead(span<byte> dst);
};
```

Callbacks to coroutines

```
class OurReader: public ILegacyReader {
public:
    void read(span<byte> dst, function<void(ssize_t)> cb) override;
private:
    Task<size_t> doRead(span<byte> dst);
};
```

Callbacks to coroutines

```
class OurReader: public ILegacyReader {
    Nursery* nursery = /*...*/;
public:
    void read(span<byte> dst, function<void(ssize_t)> cb) override {
        nursery->start([=]() -> Task {
            size_t ret = co_await doRead(dst);
            cb(ret);
        });
    }
private:
    Task<size_t> doRead(span<byte> dst);
};
```

Callbacks to coroutines

```
class OurReader: public ILegacyReader {
    Nursery* nursery = /*...*/;
public:
    void read(span<byte> dst, function<void(ssize_t)> cb) override {
        nursery->start([=]() -> Task {
            try {
                size_t ret = co_await doRead(dst);
                cb(ret);
            } catch (std::exception&) {
                cb(-1);
            }
        });
    }
private:
    Task<size_t> doRead(span<byte> dst);
};
```

Callbacks to coroutines

```
class OurReader: public ILegacyReader {
    Nursery* nursery = nullptr;

public:
    void read(span<byte> dst, function<void(ssize_t)> cb) override;

    Task<void> run() {
        WITH_NURSERY(n) {
            nursery = &n;
            co_await SuspendForever{};
        };
    }

private:
    Task<size_t> doRead(span<byte> dst);

};
```

Unsafe nurseries

```
class OurReader: public ILegacyReader {
    UnsafeNursery nursery;
public:
    void read(span<byte> dst, function<void(ssize_t)> cb) override {
        nursery.start([=]() -> Task {
            try {
                size_t ret = co_await doRead(dst);
                cb(ret);
            } catch (std::exception&) {
                cb(-1);
            }
        });
    }
private:
    Task<size_t> doRead(span<byte> dst);
};
```

Unsafe nurseries: back to slide one

Unhandled exceptions have nowhere to go

`terminate()` if we got any

Destructor must not leave running coroutines behind

make one attempt to cancel any tasks still alive

if that did not help, `terminate()`

Bridging different paradigms is toilsome anyway

Our own experience

First version merged in Dec 2021

Used in several I/O-bound services

Our own experience

About 40-50% code size reduction

Easier control flow

Uniform handling of cancellation and timeouts

There is a learning curve

There are performance implications

Our own experience

About 40-50% code size reduction

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github.com/hudson-trading/corral

Thank you!

Questions?

github.com/hudson-trading/corral