Coroutines: what *can't* they do?

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Introduction

What are we talking about?

“Programming Languages — C++ Extensions for Coroutines”

aka N4680

a Technical Specification

henceforth: “the TS”

wg21.link/n4680

ISO/IEC JTC1 SC22 WG21 **N4680**

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Programming Languages — C++ Extensions for Coroutines

Langages de programmation — Extensions C++ pour les Coroutines

What's *that* talking about?

Coroutines, obviously!

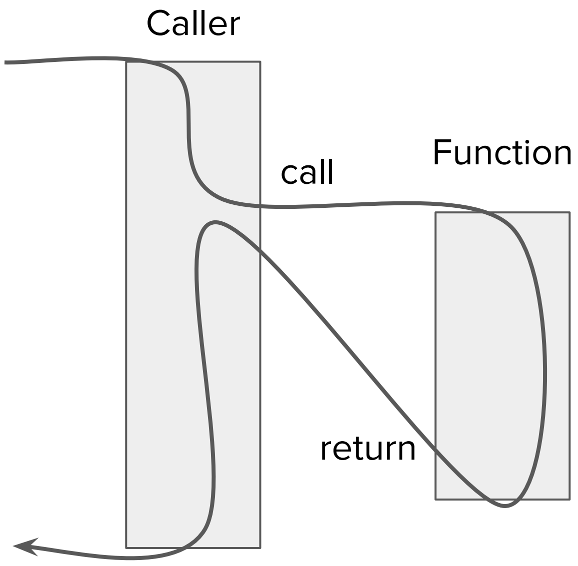
An extension to C++

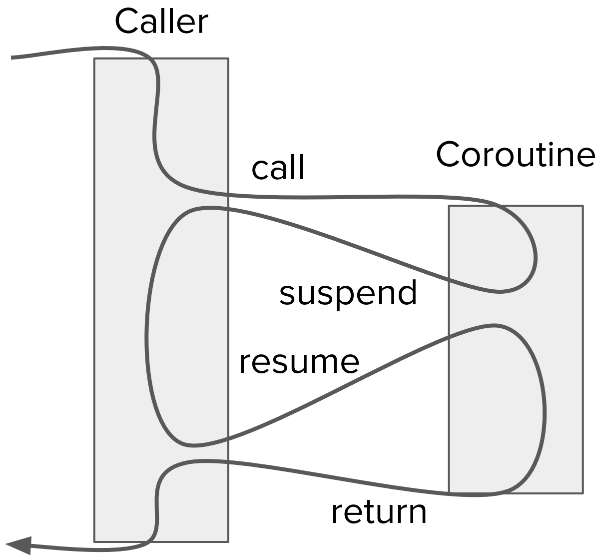
Three new keywords and some new customization points

That enable some new (to C++) kinds of control flow

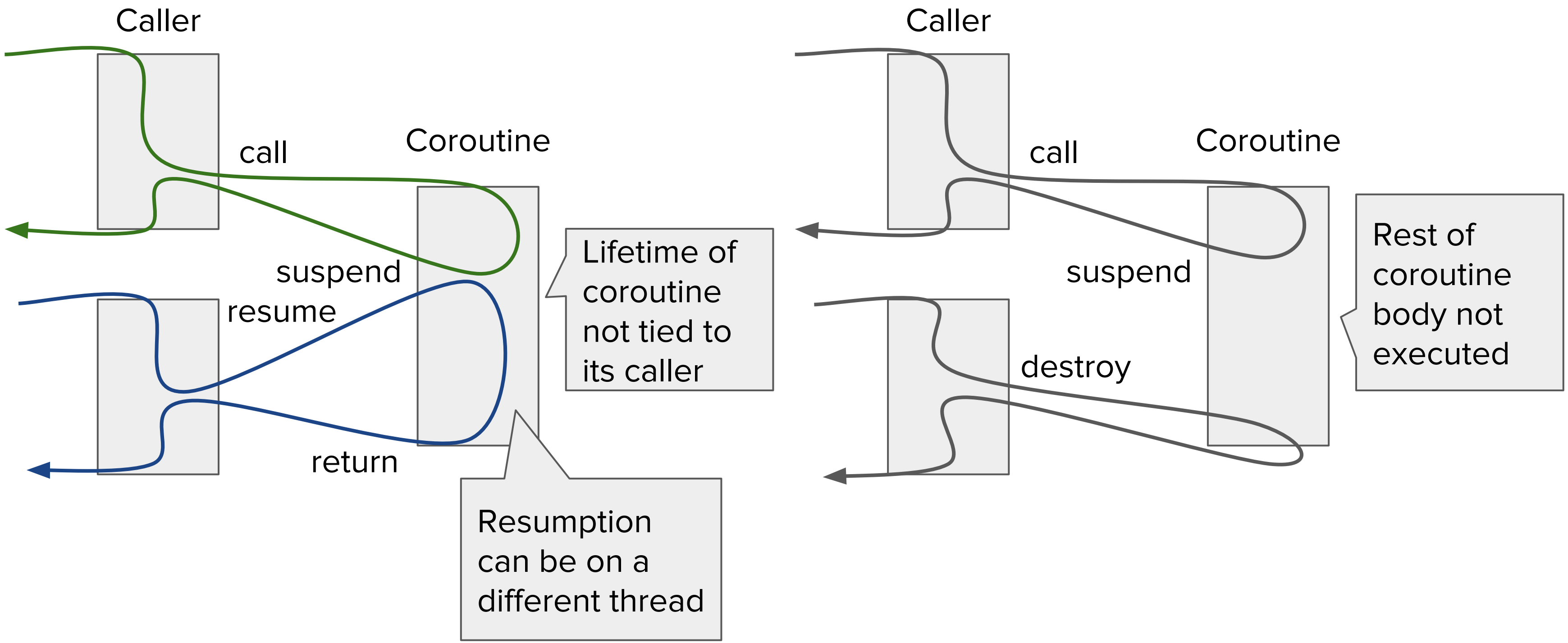
Coroutine transformations and customization points

A coroutine is a generalization of a function



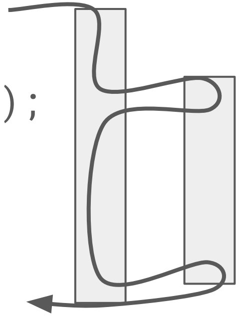


A coroutine is a generalization of a function



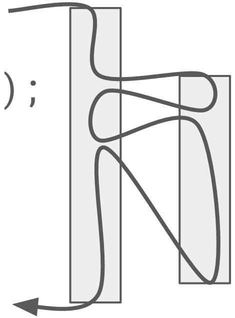
Very simple coroutine

```
void caller() {
  auto lazy_result = calculate();

}
```



```
lazy<int> calculate() {
  int result = hard_work();
  co_return result;
}
```

```
int caller() {
  auto lazy_result = calculate();
  return lazy_result.get();

}
```



```
lazy<int> calculate() {
  int result = hard_work();
  co_return result;
}
```

Coroutine body transformation

```
lazy<int> calculate()

{




   int result = hard_work();
   co_return result;







}
```

the promise is actually stored in the coroutine state

local variables are actually stored in the coroutine state

```
using promise_type =
    coroutine_traits<lazy<int>>::promise_type;
{
  promise_type p;
  auto r = p.get_return_object();
  co_await p.initial_suspend();
  try {
    int result = hard_work();
    p.return_value(result);
    goto final_suspend;
  } catch (...) {
    p.unhandled_exception();
  }
final_suspend:
  co_await p.final_suspend();
destroy:
}
```

the return object is really like a local variable

Coroutine state

stores promise, parameter copies, local variables and any information needed to resume the coroutine at the correct point

dynamically allocated (can be elided in certain circumstances)

created when the coroutine is called

destroyed when control flows off the end of the transformed coroutine body

promise
parameter copies
local variables
resume point

`co_await` transformation

All coroutines `co_await` at least once, on `p.initial_suspend()`

```
auto y = co_await x;
```

```
auto h = coroutine_handle<P>::from_promise(p);
auto a = p.await_transform(x); // optional
auto e = operator co_await(a); // optional
if (!e.await_ready()) {
  // suspended
  e.await_suspend(h);
  if (/* still suspended */)
    // return to caller
resume:
  }
  // resumed
}
auto y = e.await_resume();
```

`co_yield` transformation

`co_yield` is almost the same as `co_await`

```
auto y = co_yield x;
```

```
auto h = coroutine_handle<P>::from_promise(p);
auto a = p.yield_value(x);
auto e = operator co_await(a); // optional
if (!e.await_ready()) {
  // suspended
  e.await_suspend(h);
  if (/* still suspended */)
    // return to caller
resume:
  }
  // resumed
}
auto y = e.await_resume();
```

`for co_await` transformation

```
for co_await (auto x : xs) {




  use(x);
}
```

```
{
  auto __end = xs.end();
  for (auto __begin = co_await xs.begin();
       __begin != __end;
       co_await ++__begin) {
    auto x = *__begin;
    use(x);
  }
}
```

Coroutine handle

might not refer to a coroutine at all

provides access to the promise

can get one from the promise

only way to resume or destroy a coroutine

non-owning; destructor doesn’t do anything

```
template <typename Promise>
struct coroutine_handle {
  constexpr explicit
    operator bool() const noexcept;

  Promise& promise() const;

  static coroutine_handle
    from_promise(Promise&);

  void resume();
  void destroy();
};
```

Return values

Whenever a coroutine suspends or returns, it returns control to its caller (the first time) or its resumer (subsequent times).

```
lazy<int> v = calculate(); // caller
```

When returning to its caller, the return object is used - it is converted to the return type of the coroutine.

```
h.resume(); // resumer
h.destroy(); // resumer
```

When returning to a resumer there is no return value.

Implementation for `lazy` 1/n

```
namespace stdx = std::experimental;

template <typename T>
struct lazy_promise;

template <typename T>
class lazy {
 private:
```

for brevity; don't do this in a header file!

`lazy` and `lazy_promise` refer to each other

to control the coroutine

to store the lazily-computed value

```
using handle_type =
    stdx::coroutine_handle<
        lazy_promise<T>>;

lazy(lazy_promise<T>& p)
    : h(handle_type::
            from_promise(p)) {}

handle_type h;
std::optional<T> value;

friend lazy_promise<T>;
```

Implementation for `lazy` 2/n

```
public:
  T get() {
    if (!value) {
      h.promise().dest = &value;
      h.resume();
      h = {};
    }
    return *value;
  }

  ~lazy() {
    if (h) h.destroy();
  }
};
```

executes remainder of coroutine synchronously

also need copy/move constructor and assignment

```
template <typename T>
struct lazy_promise {
  std::optional<T>* dest;

  auto get_return_object() {
    return lazy<T>(*this); }
  auto initial_suspend() {
    return stdx::suspend_always{}; }
  void return_value(T x) {
    *dest = std::move(x); }
  void unhandled_exception() {}
  auto final_suspend() {
    return stdx::suspend_never{}; }
};
```

Implementation for `lazy` 3/3

```
namespace std::experimental {
  template <typename T, typename... Args>
  struct coroutine_traits<lazy<T>, Args...> {
    using promise_type = lazy_promise<T>;
  };
}
```

Lazy sequences and async - the usual suspects

Lazy sequences aka generators

```
void print_primes() {
  for (auto x : primes()) {
    print(x);
    if (x > 100) break;
  }
}
```

```
bool is_prime(int);

generator<int> primes() {
  for (int i = 0; ; ++i) {
    if (is_prime(i))
      co_yield i;
  }
}
```

Async

The caller is a coroutine as well.

```
task<void> async_print_primes() {
  for (int x = 0; ; ++x)
    if (co_await is_prime_async(x)) {
      print(x);
      if (x > 100) break;
    }
}
```

Imagine we have a web service for testing primes.

```
task<bool> is_prime_async(int x) {
  auto server = co_await connect();
  auto response =
      co_await server.is_prime(x);
  co_return parse_bool(response);
}
```

Code as though everything is synchronous.

Async generators

```
task<void> async_print_primes() {
  for co_await (auto x : async_primes()) {
    print(x);
    if (x > 100) break;
  }
}
```

from the previous slide

```
task<bool> is_prime_async(int);

async_generator<int> async_primes() {
  for (int x = 0; ; ++x)
    if (co_await is_prime_async(x))
      co_yield x;
}
```

uses both `co_await` and `co_yield`

I want to use this stuff now!

Working coroutine implementations:

- Visual Studio 2017 (`/await`)
- clang 5.0 with libc++ 5.0 (`-fcoroutines-ts -stdlib=libc++`)

Coroutine abstraction libraries:

- cppcoro (https://github.com/lewissbaker/cppcoro)
    - task, generator, async_generator, async_mutex, ...
- range-v3 (https://github.com/ericniebler/range-v3)
    - generator
- others? Let me know!

Some unexpected things you can do

Some operations returning `optional`

```
optional<string> read_word(istream& s);
optional<int> parse_int(istream& s);
optional<double> parse_double(istream& s);

// “3 1.2 3.4 5.6” -> vector{1.2, 3.4, 5.6}
optional<vector<double>> parse_vector(istream& s);
```

Composing operations returning `optional`

```
optional<vector<double>> parse_vector(istream& s) {
  optional<int> n = parse_int(s);
  if (!n) return {};
  vector<double> result;
  for (int i = 0; i < *n; ++i) {
    optional<double> x = parse_double(s);
    if (!x) return {};
    result.push_back(*x);
  }
  return result;
}
```

Composing operations in a coroutine

```
optional<vector<double>> parse_vector(istream& s) {
  int n = co_await parse_int(s);

  vector<double> result;
  for (int i = 0; i < n; ++i) {


    result.push_back(co_await parse_double(s));
  }
  co_return result;
}
```

How can this be?

need to specialize `coroutine_traits` for functions returning `optional`

```
namespace std::experimental {
  template <typename T, typename... Args>
  struct coroutine_traits<optional<T>, Args...> { // UB!
    using promise_type = optional_promise<T>;
  };
}
```

- this is not allowed if we're talking about std::optional - there needs to be a user-defined type in there somewhere
- but it works anyway

How does it work?

It’s all in the awaitable:

```
template <typename T>
struct optional_promise {
  template <typename U>
  auto await_transform(optional<U> e) {
    return optional_awaitable<U>{move(e)};
  }
};
```

It’s all in the awaitable

```
template <typename U>
struct optional_awaitable {
  optional<U> o;

  auto await_ready() { return o.has_value(); }
  auto await_resume() { return o.value(); }

  template <typename T>
  void await_suspend(coroutine_handle<maybe_promise<T>> h) {
    h.promise().data->emplace(nullopt);
    h.destroy();
  }
};
```

suspend if the optional does not contain a value

if it does contain a value, return that value

if no value, destroy the coroutine

But I want more information about what failed

Luckily for you, the exact same approach works with types like `expected`.

```
enum class ParseError { EndOfStream, BadFormat };

template <typename Value>
using parse_result = expected<Value, ParseError>;

parse_result<string> read_word(istream& s);
parse_result<int> parse_int(istream& s);
parse_result<double> parse_double(istream& s);
parse_result<vector<double>> parse_vector(istream& s);
```

I want to play with `optional` coroutines

- https://github.com/toby-allsopp/coroutine_monad
  - works with `std::optional`
  - but only on clang
  - has a basic `expected` implementation
- `folly::Optional` (https://github.com/facebook/folly)
  - not `std::optional`
  - works on clang *and* MSVC
  - would be pretty easy to get `folly::Expected` working as well

Type-erased callable

- This idea is from Gor Nishanov
- The observation is that the coroutine body can hold onto more type information than is reflected in the return type of the coroutine

Type-erased callable

```
template <typename Ret,
          typename... Args>
class func {
  template <typename F>
  static func create(F f) {
    co_yield f;
  }

  Ret operator()(Args… args) {
    h.promise().args = {args…};
    h.resume();
    return h.promise().ret;
  }
};
```

function type erased here

function type recovered here

```
template <typename Ret,
          typename... Args>
struct func_promise() {
  tuple<Args…> args;
  Ret ret;

  template <typename F>
  void yield_value(F f) {
    ret = apply(f, args);
  }
};
```

Type-erased callable

- If the compiler can see what you put in and where you call it then all of the coroutine machinery can be optimized away
- Otherwise, overhead is probably similar to `std::function`
- An intriguing technique
- Some code to start playing with: https://github.com/toby-allsopp/coroutine_func

Summary

Coroutines are a generalization of functions that allow for many new and interesting control flows.

Usual suspects: generators, async, async generators

Unusual applications: composing optional/expected operations, type-erasure

Thank you!