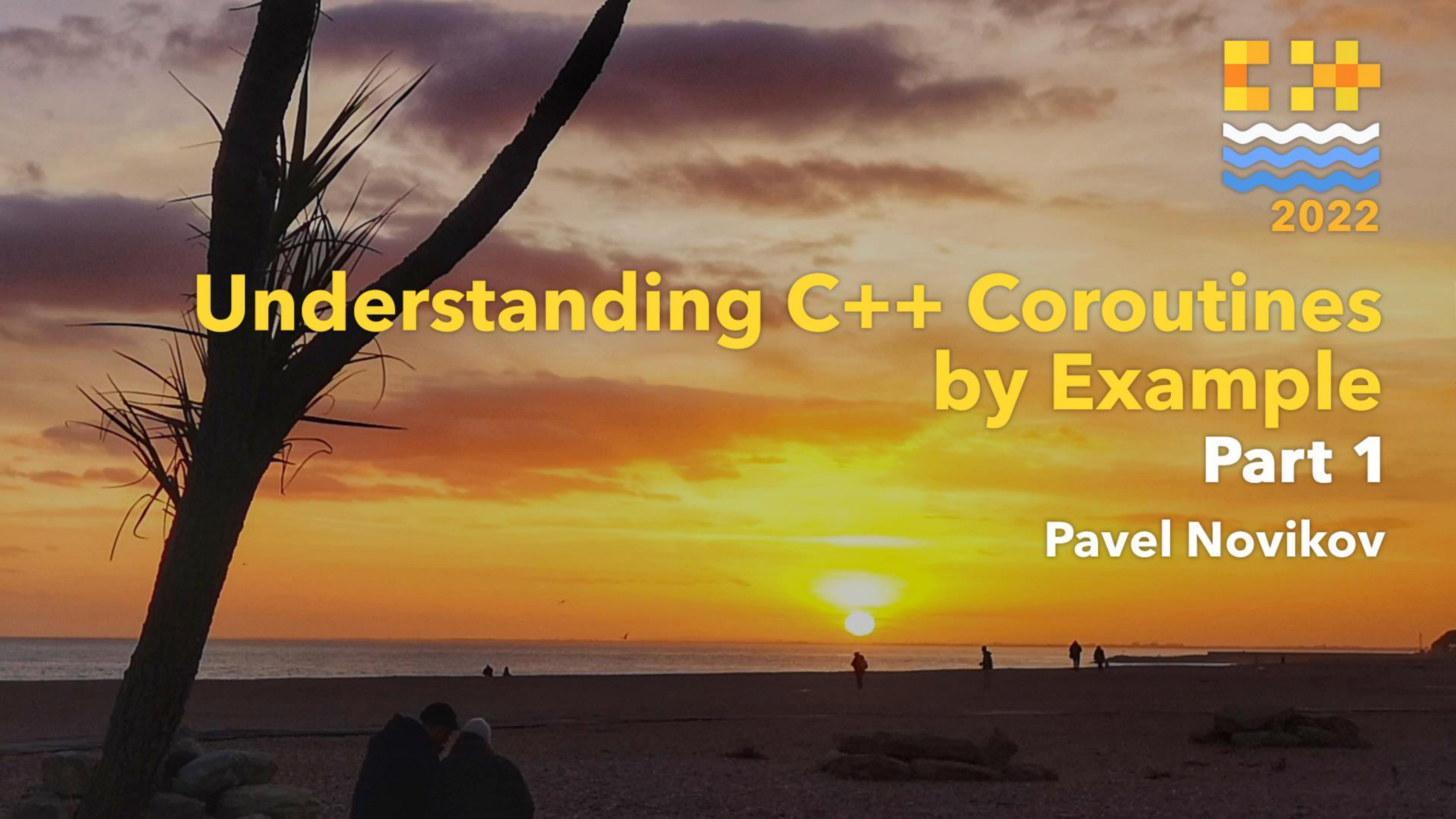

2022

Understanding C++ Coroutines by Example

Part 1

Pavel Novikov

Understanding C++ coroutines by example part 1

Pavel Novikov

@cpp_ape

No decent user facing support in C++20

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Use `cppcoro` by Lewis Baker *

https://github.com/lewissbaker/cppcoro

Thanks for coming!

Directed by
ROBERT B. WEIDE

Gameplan

- Iteration 0: my first coroutine
    - What is a C++ coroutine?
    - Demystifying compiler magic
- Iteration 1: awaiting tasks
    - Making tasks awaitable
    - Writing awaitable types
- Iteration 2:
    - Getting tasks result
    - Thread safety
- Analysis of the approach

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Iteration 0: my first coroutine

```
Task<int> foo() {
  co_return 42;
}
```

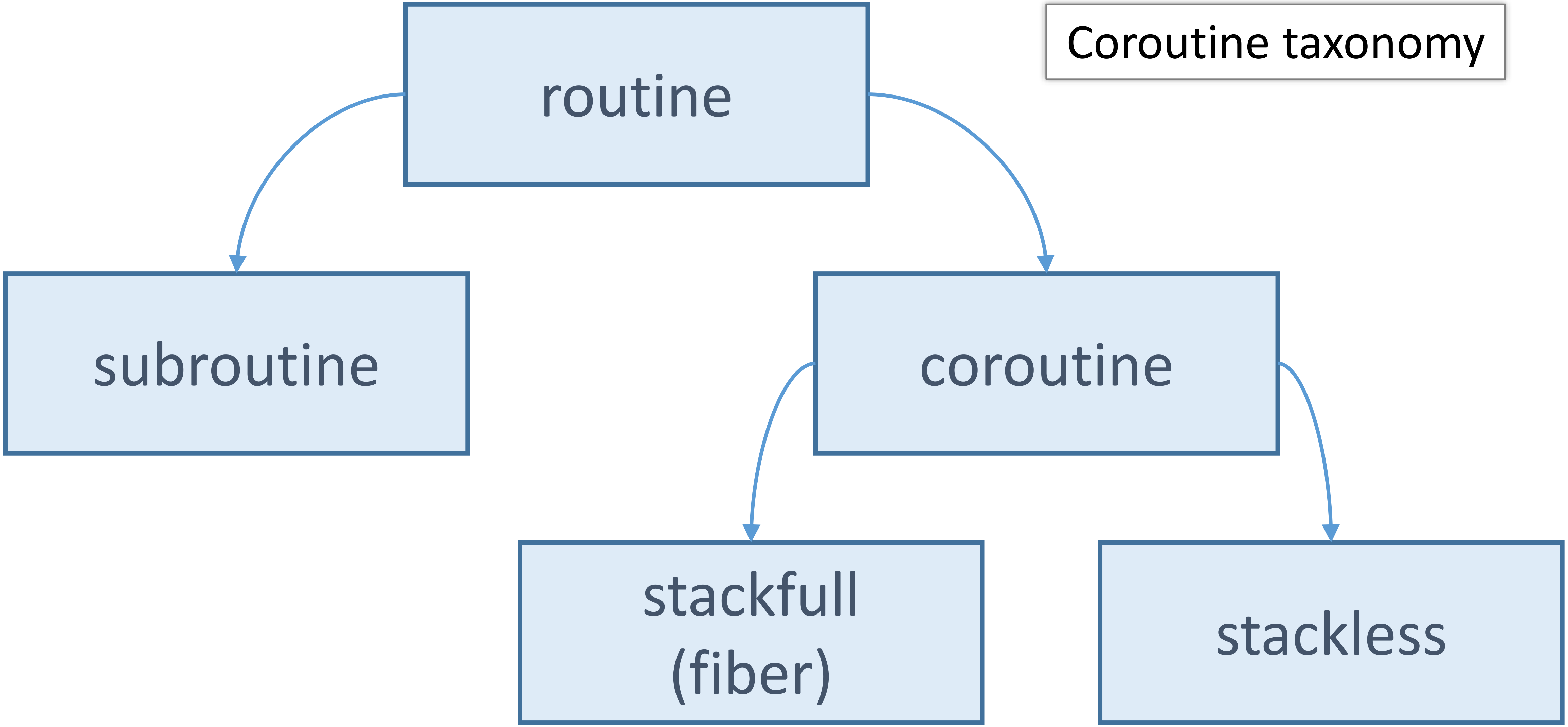
A function is a coroutine if it contains one of these:

`co_return` (coroutine return statement)

`co_await` (await expression)

`co_yield` (yield expression)

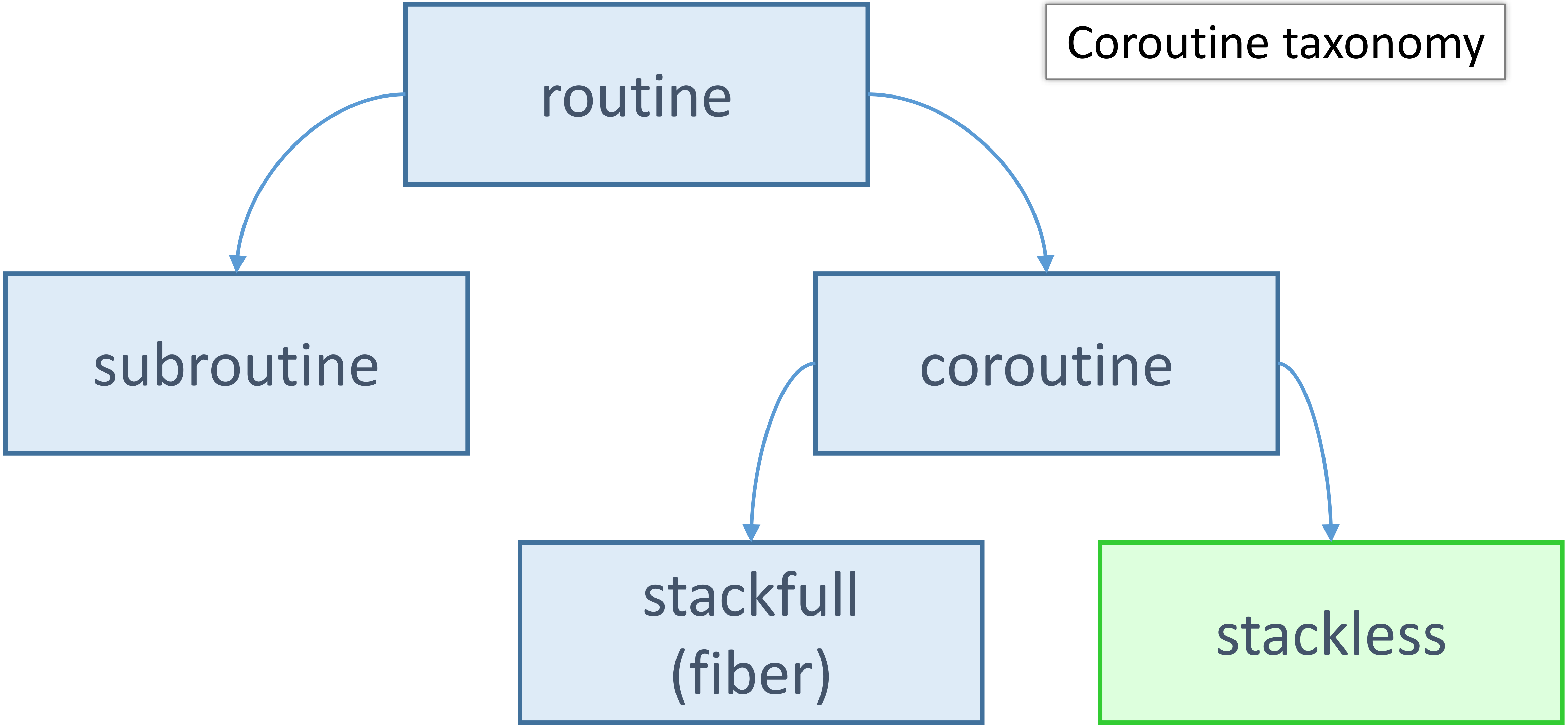
What is a C++ coroutine?



Coroutine taxonomy

What is a C++ coroutine?

Coroutine taxonomy



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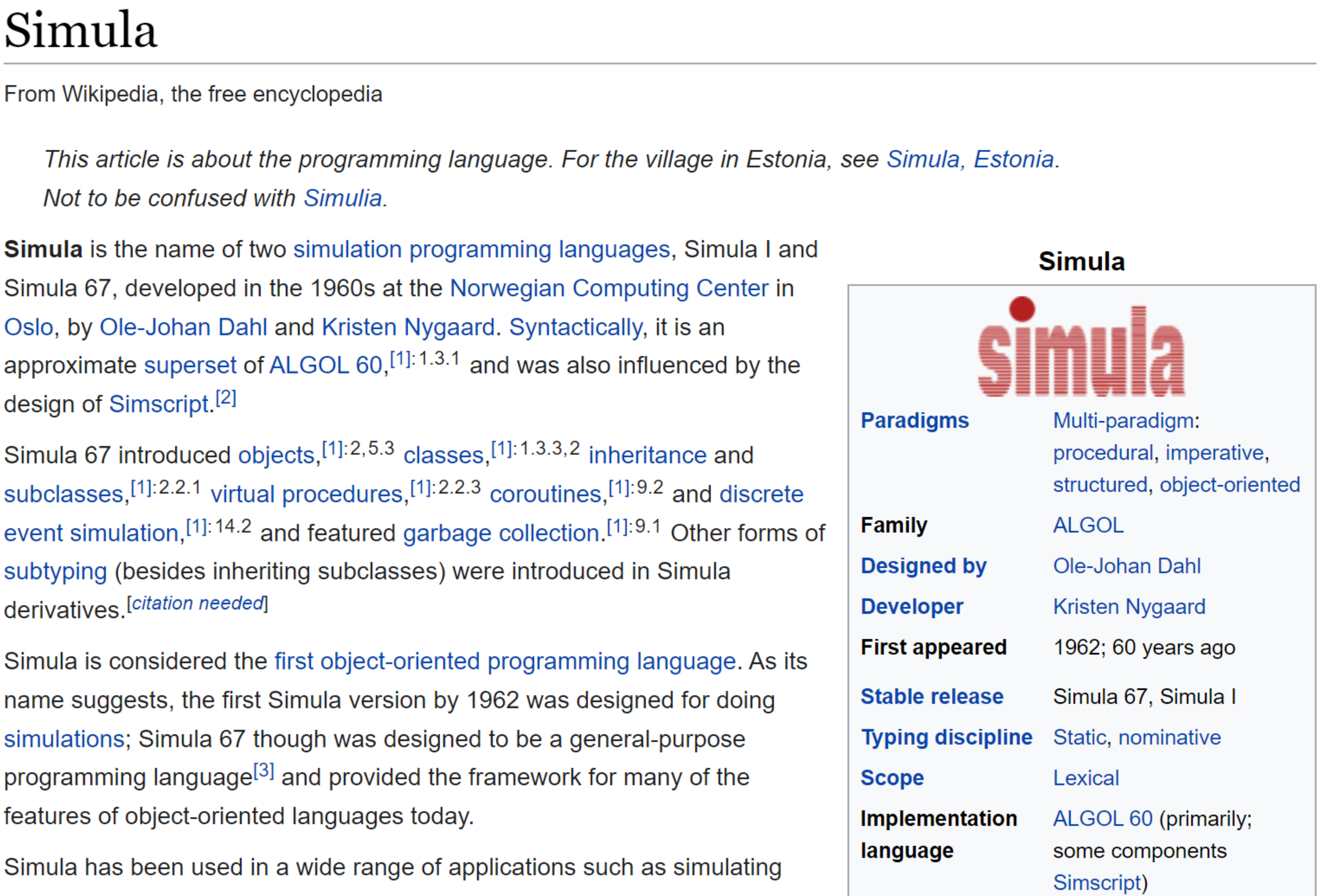


Simula

From Wikipedia, the free encyclopedia

This article is about the programming language. For the village in Estonia, see Simula, Estonia.

Not to be confused with Simulia.

Simula is the name of two simulation programming languages, Simula I and Simula 67, developed in the 1960s at the Norwegian Computing Center in Oslo, by Ole-Johan Dahl and Kristen Nygaard. Syntactically, it is an approximate superset of ALGOL 60,[1]:1.3.1 and was also influenced by the design of Simscript.[2]

Simula 67 introduced objects,[1]:2,5.3 classes,[1]:1.3.3,2 inheritance and subclasses,[1]:2.2.1 virtual procedures,[1]:2.2.3 coroutines,[1]:9.2 and discrete event simulation,[1]:14.2 and featured garbage collection.[1]:9.1 Other forms of subtyping (besides inheriting subclasses) were introduced in Simula derivatives.[*citation needed*]

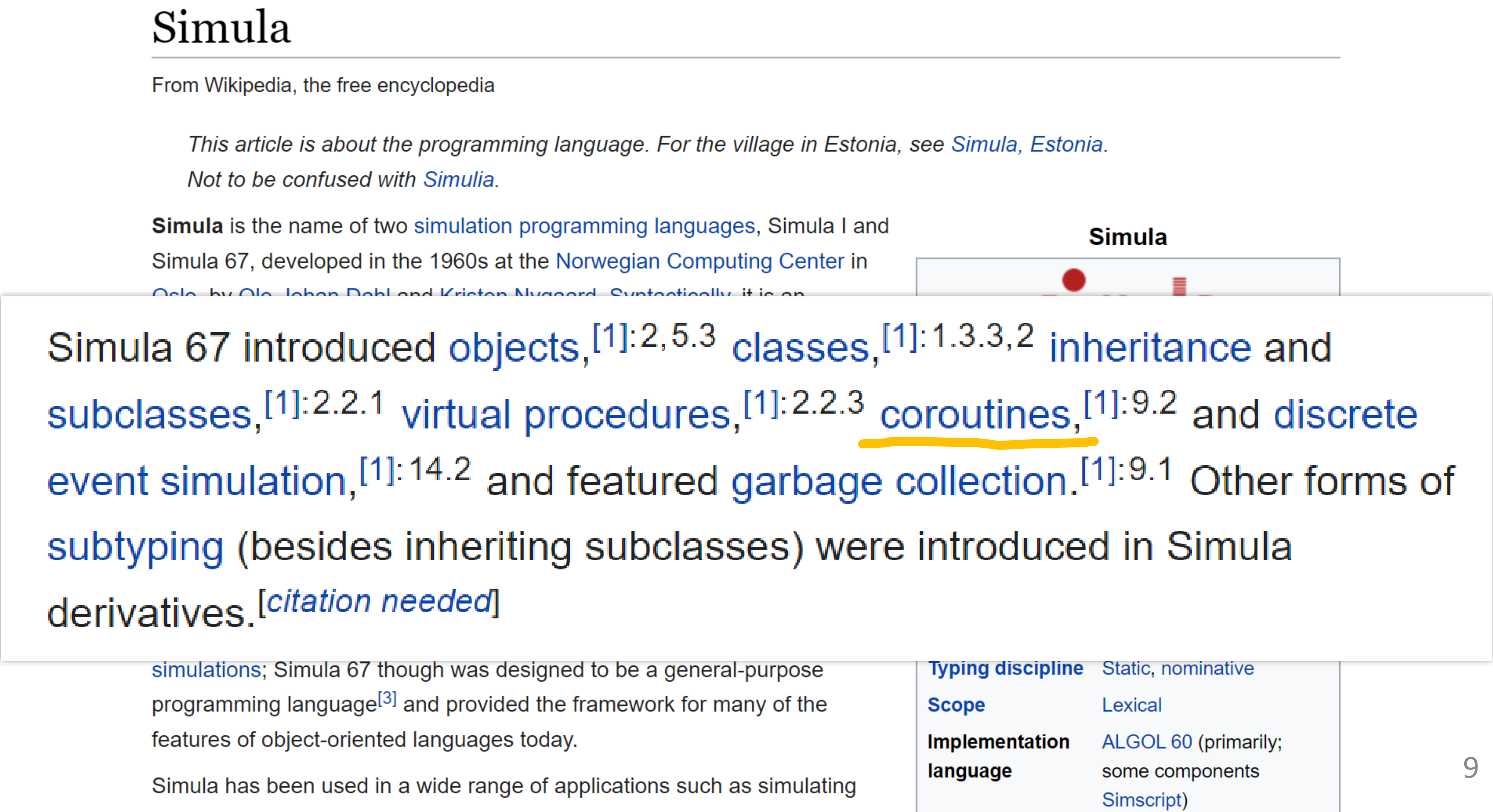
Simula is considered the first object-oriented programming language. As its name suggests, the first Simula version by 1962 was designed for doing simulations; Simula 67 though was designed to be a general-purpose programming language[3] and provided the framework for many of the features of object-oriented languages today.

Simula has been used in a wide range of applications such as simulating

Simula

Paradigms	Multi-paradigm: procedural, imperative, structured, object-oriented
Family	ALGOL
Designed by	Ole-Johan Dahl
Developer	Kristen Nygaard
First appeared	1962; 60 years ago
Stable release	Simula 67, Simula I
Typing discipline	Static, nominative
Scope	Lexical
Implementation language	ALGOL 60 (primarily; some components Simscript)

What is a C++ coroutine?



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A coroutine behaves as if its *function-body* were replaced by:

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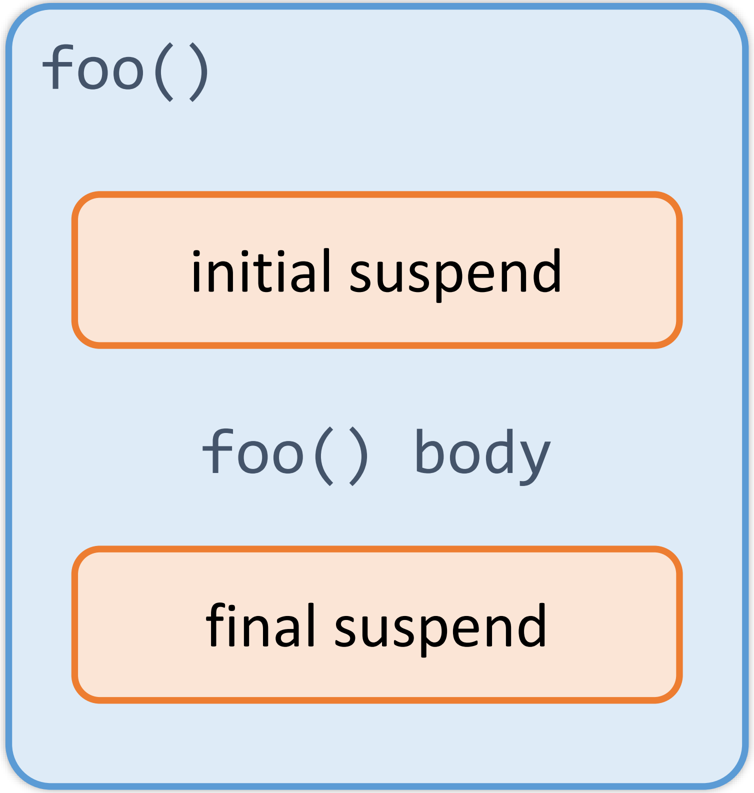

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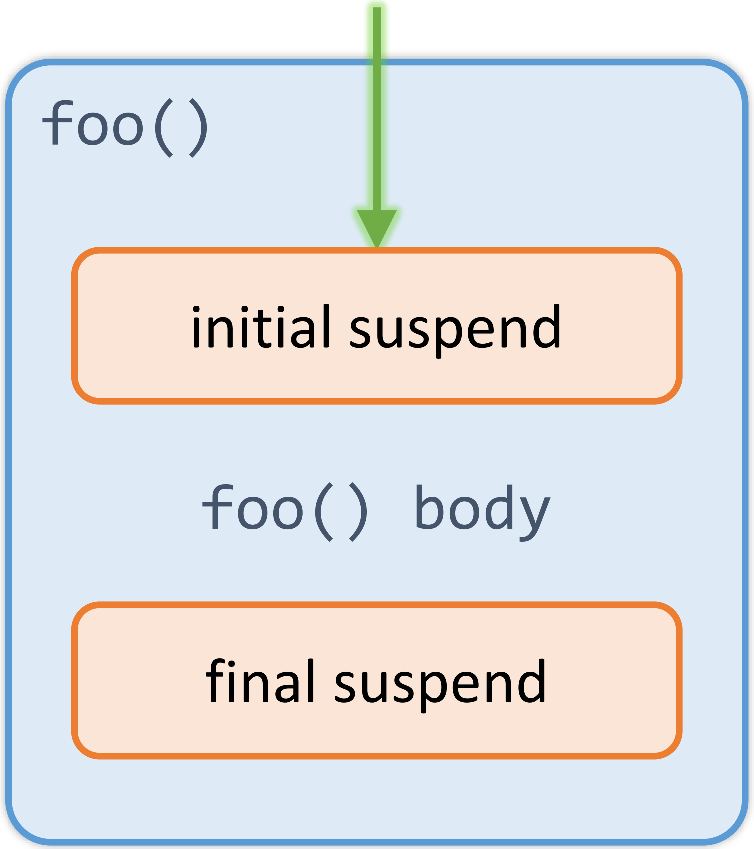

foo()

initial suspend

foo() body

final suspend

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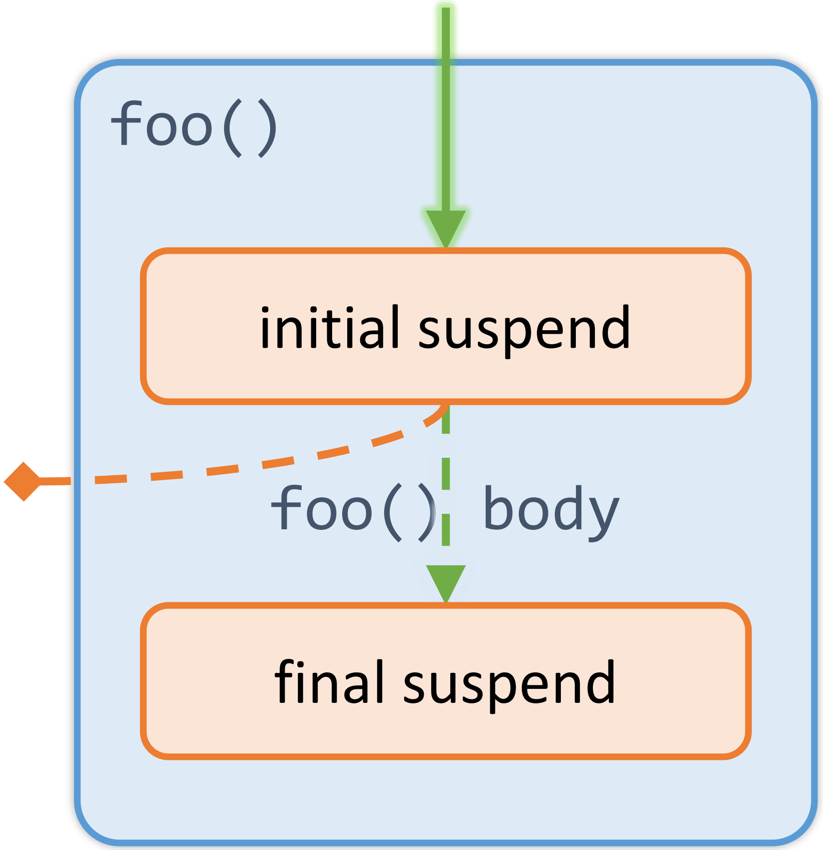

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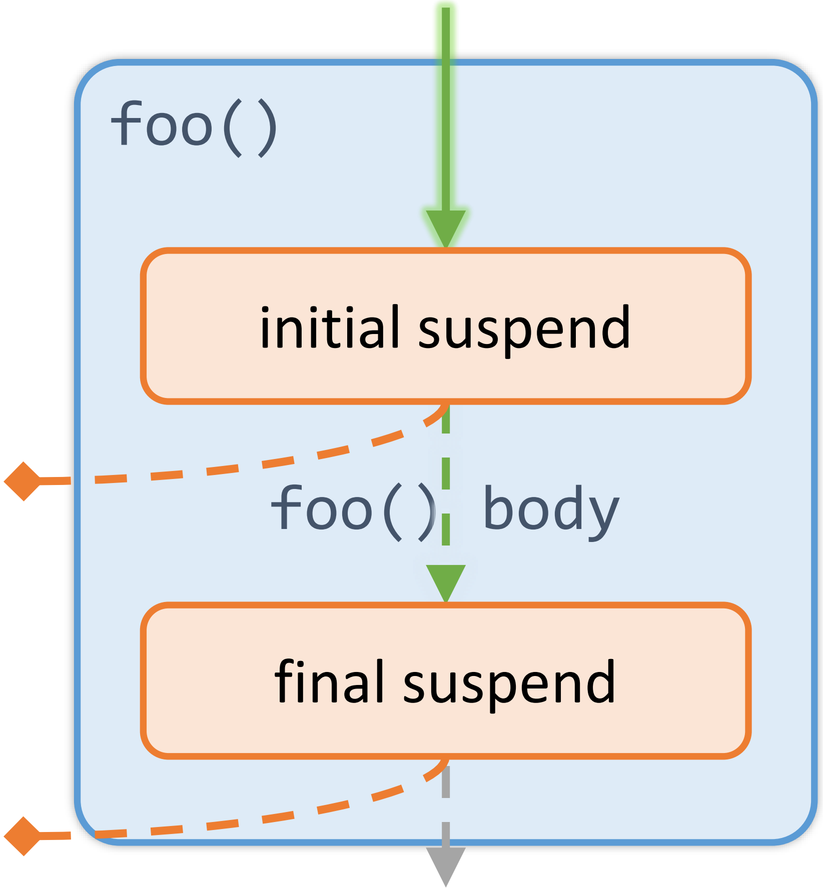

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Transformation by the compiler

```
Task<int> foo() {
  co_return 42;
}
```

original code

```
Task<int> foo() {







        co_return 42;














}
```

Transformation by the compiler

```
Task<int> foo() {
  co_return 42;
}
```

transformed code

```
Task<int> foo() {

        co_return 42;

}
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Transformation by the compiler

```
Task<int> foo() {
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```

```
Task<int> foo() {
  struct CoroFrame {
    Task<int>::promise_type promise;
    bool initial_await_resume_called = false;
    int state = 0;
    void operator()() {


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    }
  };
  auto coroFrame = new CoroFrame;
  auto returnObject{ coroFrame->promise.get_return_object() };
  (*coroFrame)();
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coroutine frame

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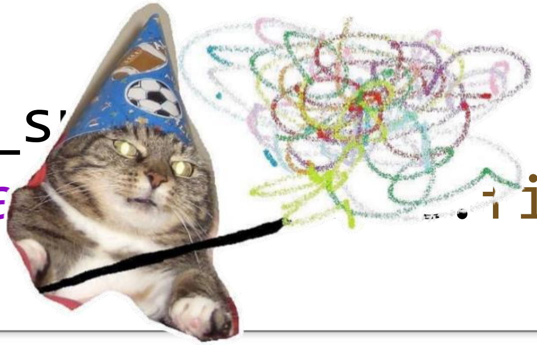

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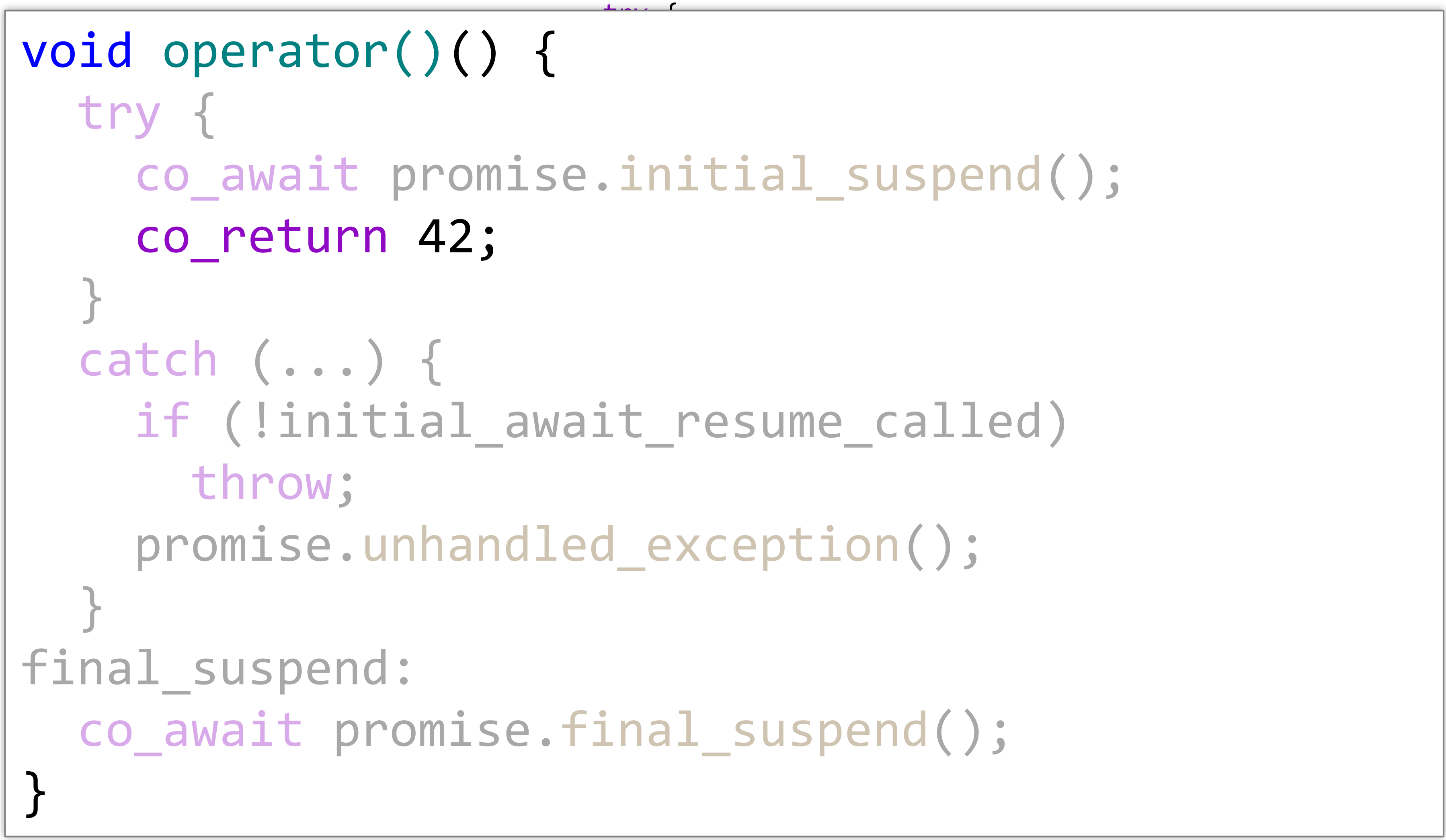

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Task<int> foo() {
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Sequence of operations:

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      co_await promise.final_suspend();
    }
   ;
  auto coroFrame = new CoroFrame;
  auto returnObject{ coroFrame->promise.get_return_object() };
  (*coroFrame)();
  return returnObject;
}
```

Transformation by the compiler

```
Task<int> foo() {
  co_return 42;
}
```

Sequence of operations:

```
Task<int>::promise_type promise;
promise.get_return_object();
  promise.initial_suspend();
  promise.return_value(42);
```

```
Task<int> foo() {
  struct CoroFrame {
    Task<int>::promise_type promise;
    bool initial_await_resume_called = false;
    int state = 0;
    void operator()() {
      try {
        co_await promise.initial_suspend();
        promise.return_value(42); goto final_suspend;
      }
      catch (...) {
        if (!initial_await_resume_called)
          throw;
        promise.unhandled_exception();
      }
    final_suspend:
      co_await promise.final_suspend();
    }
  ;
  auto coroFrame = new CoroFrame;
  auto returnObject{ coroFrame->promise.get_return_object() };
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;
  auto coroFrame = new CoroFrame;
  auto returnObject{ coroFrame->promise.get_return_object() };
  (*coroFrame)();
  return returnObject;
}
```

Task type

```
template<typename T> struct Promise;

template<typename T>
struct [[nodiscard]] Task {
  using promise_type = Promise<T>;
  Task() = default;

private:
  explicit Task(Promise<T> *promise) : promise{ promise } {}

  PromisePtr<T> promise = nullptr;

  template<typename> friend struct Promise;
};
```

Task type

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};
```

Task type

```
template<typename T> struct Promise;
struct CoroDeleter {
  template<typename Promise>
  void operator()(Promise *promise) const noexcept {
    using CoroHandle = std::coroutine_handle<Promise>;
    CoroHandle::from_promise(*promise).destroy();
  }
};
template<typename T>
using PromisePtr = std::unique_ptr<Promise<T>, CoroDeleter>;
  PromisePtr<T> promise = nullptr;

  template<typename> friend struct Promise;
};
```

Task type

```
template<typename T> struct Promise;

template<typename T>
struct [[nodiscard]] Task {
  using promise_type = Promise<T>;
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private:
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```

Promise type

```cpp
template<typename T>
struct Promise {
  Task<T> get_return_object() noexcept { return Task<T>{ this }; }
  std::suspend_never initial_suspend() noexcept { return {}; }
  std::suspend_always final_suspend() noexcept { return {}; }
  template<typename U>
  void return_value(U &&value)

  void unhandled_exception()

  bool isReady() const noexcept { return result.index() != 0; }
  T &&getResult();

  std::variant<std::monostate, T, std::exception_ptr> result;
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Promise type

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template<typename T>
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```

```
Task<int> foo() {
  struct CoroFrame {
    Task<int>::promise_type promise;
    //...
  };
  auto coroFrame = new CoroFrame;
  auto returnObject = coroFrame->promise.get_return_object();
  (*coroFrame)();
  return returnObject;
}
```

```
};
```

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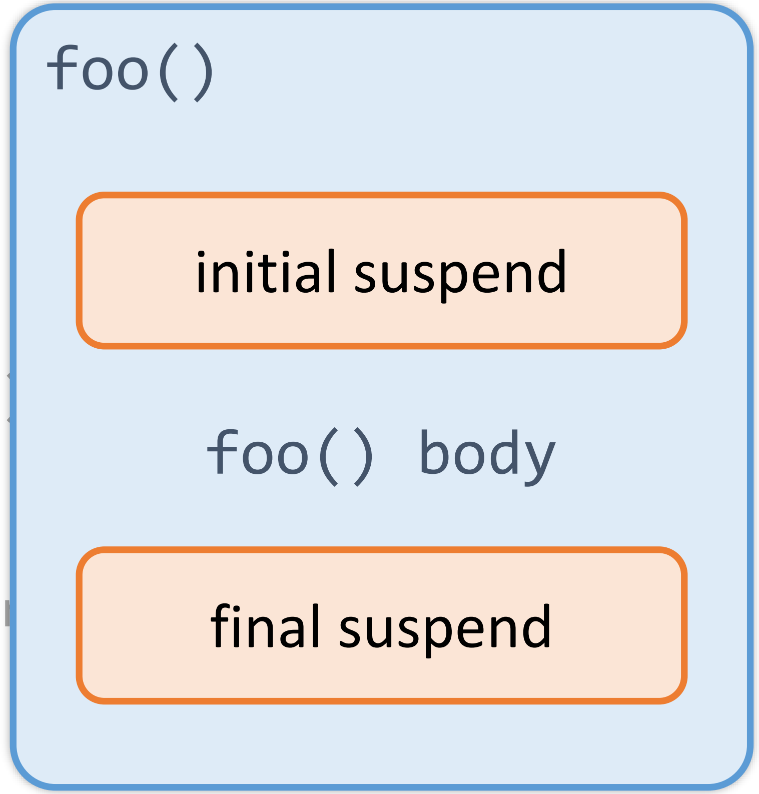
```



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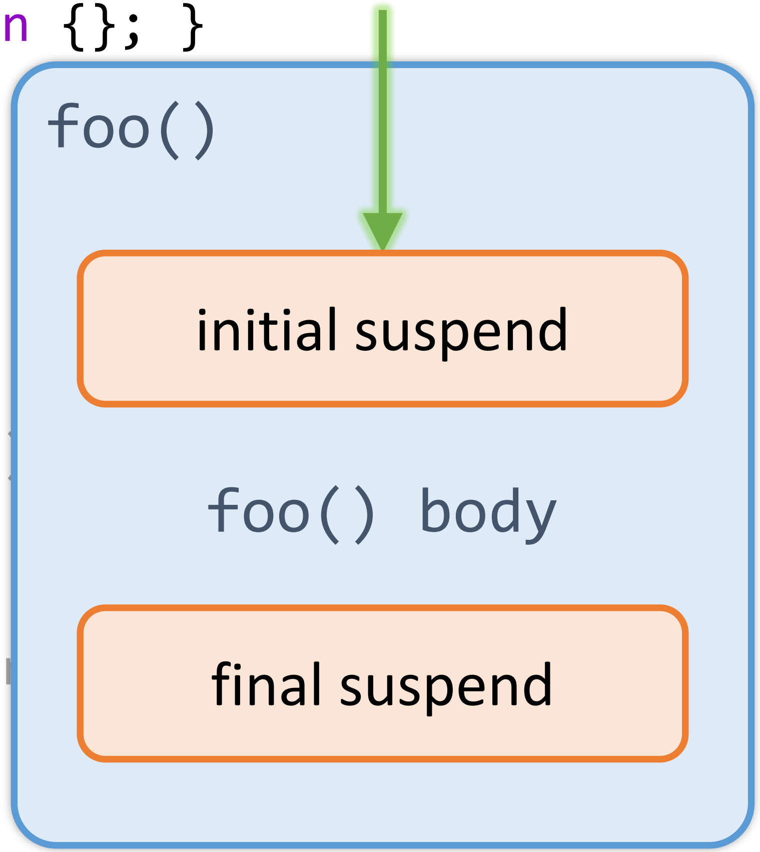

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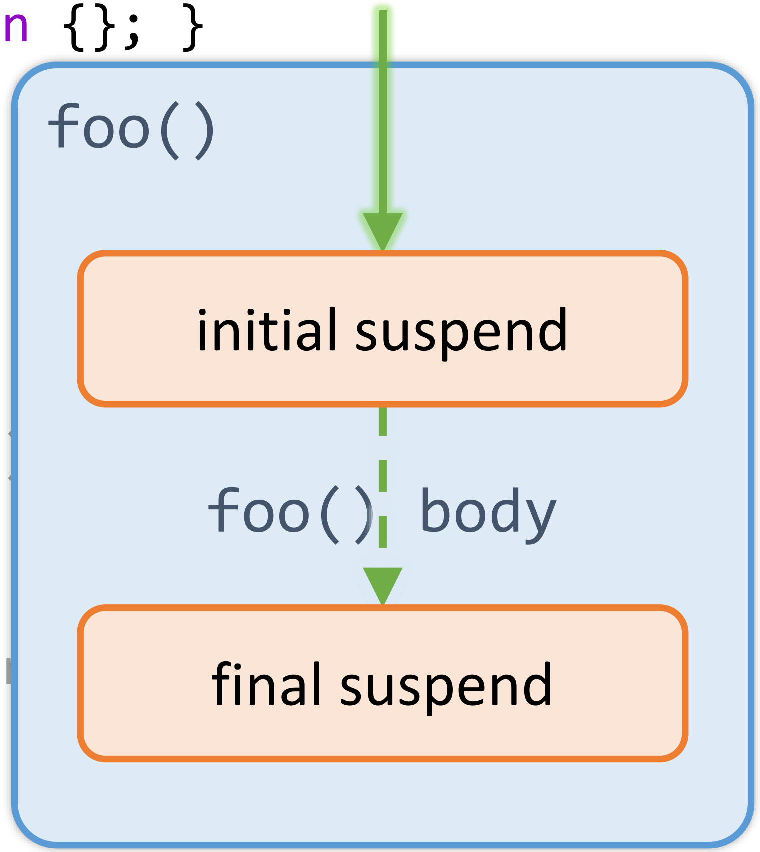

foo()

initial suspend

foo() body

final suspend

Promise type

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template<typename T>
struct Promise {
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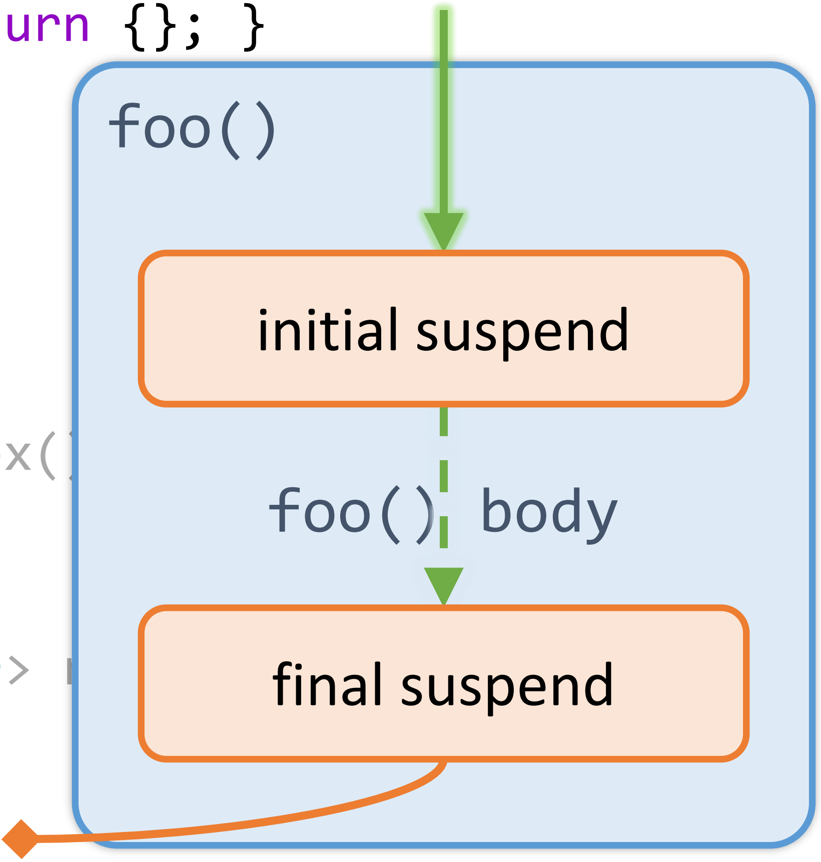

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```

```
void operator()() {
  try {
    co_await promise.initial_suspend();
    promise.return_value(42); goto final_suspend;
  }
  catch (...) { /*...*/ }
final_suspend:
  co_await promise.final_suspend();
}
```

Promise type

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struct Promise {
  Task<T> get_return_object() noexcept { return Task<T>{ this }; }
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  template<typename U>
  void return_value(U &&value)
    noexcept(std::is_nothrow_constructible_v<T, decltype(std::forward<U>(value))>);
  void unhandled_exception()

  bool isReady() const noexcept { return result.index() != 0; }
  T &&getResult();

  std::variant<std::monostate, T, std::exception_ptr> result;
};
```

Promise type

```
void return_value(U &&value)
  noexcept(std::is_nothrow_assignable_v<decltype(result), decltype(std::forward<U>(value))>)
{
  result.template emplace<1>(std::forward<U>(value));
}
```

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    void return_value(U &&value)
      noexcept(std::is_nothrow_constructible_v<T, decltype(std::forward<U>(value))>);
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```

```
void operator()() {
  try {
    //...
  }
  catch (...) {
    //...
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  std::variant<std::monostate, T, std::exception_ptr> result;
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Promise type

```
template<typename T>
struct Promise {
```

```
void unhandled_exception()
  noexcept(std::is_nothrow_assignable_v<decltype(result), std::exception_ptr>)
{
  result.template emplace<2>(std::current_exception());
}
```

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    void unhandled_exception()
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```

```
T &&getResult() {
  if (result.index() == 2)
    std::rethrow_exception(std::get<2>(result));
  return std::move(std::get<1>(result));
}
```

```
  T &&getResult();

  std::variant<std::monostate, T, std::exception_ptr> result;
};
```

Promise type

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```

Iteration 0: my first coroutine

```
Task<int> foo() {
  std::cout << "foo(): about to return\n";
  co_return 42;
}

auto task = foo();
```

Iteration 0: my first coroutine

```
Task<int> foo() {
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  co_return 42;
}

auto task = foo();
```

output:

```
foo(): about to return
```

Iteration 0: my first coroutine

```
Task<void> foo() {
  co_return;
}

template<typename T>
struct Promise {
  //...
  void return_void() noexcept;
  //...
};
```

Iteration 0: my first coroutine

```
Task<void> foo()
  co_return;
}

template<typename
struct Promise {
  //...
  void return_void() noexcept;
  //...
};
```

```
void operator()() {
  try {
    co_await promise.initial_suspend();
    promise.return_void(); goto final_suspend;
  }
  catch (...) { /*...*/ }
final_suspend:
  co_await promise.final_suspend();
}
```

Let's recap

A promise_type is used to communicate with the compiler backend.

```
Task<int> foo() {
  co_return 42;
}
```

```
Task<int>::promise_type promise;
promise.get_return_object();
promise.initial_suspend();
promise.return_value(42);
promise.unhandled_exception();
promise.final_suspend();
```

Let's recap

A promise_type is u backend.

```
Task<int> foo()
  co_return 42;
}
```

```
Task<int>::promi
promise.get_retu
promise.initial_
promise.return_v
promise.unhandled_exception();
promise.final_suspend();
```

Iteration 1: awaiting tasks

```
Task<int> bar() {
  const auto result = foo();
  const int i = co_await result;
  co_return i + 23;
}
```

Awaiting: rough idea

```
 co_await result;


 auto awaitable{ getAwaitable(result) };
 if (!awaitable.await_ready()) {
  awaitable.await_suspend(thisCoroHandle);
  // suspend coroutine
 }
resume:
 awaitable.await_resume();
```

Transformation by the compiler

```
Task<int> bar() {
  const auto result = foo();
  const int i = co_await result;
  co_return i + 23;
}
```

original code

```
Task<int> bar() {
  struct CoroFrame {
    Task<int>::promise_type promise;
    bool initial_await_resume_called = false;
    int state = 0;
    //...
    void operator()();
  };
  auto coroFrame = new CoroFrame;
  auto returnObject{
    coroFrame->promise.get_return_object()
  };
  (*coroFrame)();
  return returnObject;
}
```

Transformation by the compiler

```
Task<int> bar() {
  const auto result = foo();
  const int i = co_await result;
  co_return i + 23;
}
```

transformed code

```
Task<int> bar() {
  struct CoroFrame {
    Task<int>::promise_type promise;
    bool initial_await_resume_called = false;
    int state = 0;
    //...
    void operator()();
  };
  auto coroFrame = new CoroFrame;
  auto returnObject{
    coroFrame->promise.get_return_object()
  };
  (*coroFrame)();
  return returnObject;
}
```

Transformation by the compiler

```
void operator()() {
  try {
    switch (state)
    {
    case 0:
      break;
    case 1:
      goto initialResume;
    case 2:
      goto resume2;
    default:
      break; //bad ☹
    }
  //...
```

Transformation by the compiler

```
void operator()() {
  try {
    switch (state)
    {
    case 0:
      break;
    case 1:
      goto initialResume;
    case 2:
      goto resume2;
    default:
      break; //bad ☹
    }
  //...
```

Transformation by the compiler

```
void operator()() {
  try {
    switch (state)
    {
    case 0:
      break;
    case 1:
      goto initialResume;
    case 2:
      goto resume2;
    default:
      break; //bad ☹
    }
  //...
```

```
struct CoroFrame {
  Task<int>::promise_type promise;
  bool initial_await_resume_called = false;
  int state = 0;
  //...
  void operator()();
};
```

Transformation by the compiler

```
void operator()() {
  try {
    switch (state)
    {
    case 0:
      break;
    case 1:
      goto initialResume;
    case 2:
      goto resume2;
    default:
      break; //bad ☹
    }
  //...
```

```
struct CoroFrame {
  Task<int>::promise_type promise;
  bool initial_await_resume_called = false;
  int state = 0;
  //...
  void operator()();
};
```

Transformation by the compiler

```
void operator()() {
  try {
    switch (state)
    {
    case 0:
      break;
    case 1:
      goto initialResume;
    case 2:
      goto resume2;
    default:
      break; //bad ☹
    }
  //...
```

```
struct CoroFrame {
  Task<int>::promise_type promise;
  bool initial_await_resume_called = false;
  int state = 0;
  //...
  void operator()();
};
```

Transformation by the compiler

```
co_await promise.initial_suspend();
```

```
void operator()() {
  //...
    state = 1;
    awaitable0   ???   getAwaitable(promise.initial_suspend());
    if (!awaitable0->await_ready()) {
      awaitable0->await_suspend(thisCoroHandle);
      // suspend
      return;
    }
  initialResume:
    initial_await_resume_called = true;
    awaitable0->await_resume();
  //...
```

Transformation by the compiler

```
co_await promise.initial_suspend();
```

```
void operator()() {
  //...
    state = 1;
    awaitable0 ←-???---getAwaitable(promise.initial_suspend());
    if (!awaitable0->await_ready()) {
      awaitable0->await_suspend(thisCoroHandle);
      // suspend
      return;
    }
  initialResume:
    initial_await_resume_called = true;
    awaitable0->await_resume();
  //...
```

Transformation by the compiler

```
co_await promise.initial_suspend();
```

```
void operator()() {
  //...
    state = 1;
    awaitable0 ← ??? getAwaitable(promise.initial_suspend());
    if (!awaitable0->await_ready()) {
      awaitable0->await_suspend(thisCoroHandle);
      // suspend
      return;
    }
  initialResume:
    initial_await_resume_called = true;
    awaitable0->await_resume();
  //...
```

Transformation by the compiler

```
co_await promise.initial_suspend();
```

```
void operator()() {
  //...
    state = 1;
    awaitable0 ← ??? getAwaitable(promise.initial_suspend());
    if (!awaitable0->await_ready()) {
      awaitable0->await_suspend(thisCoroHandle);
      // suspend
      return;
    }
  initialResume:
    initial_await_resume_called = true;
    awaitable0->await_resume();
  //...
```

Transformation by the compiler

```
co_await promise.initial_suspend();
```

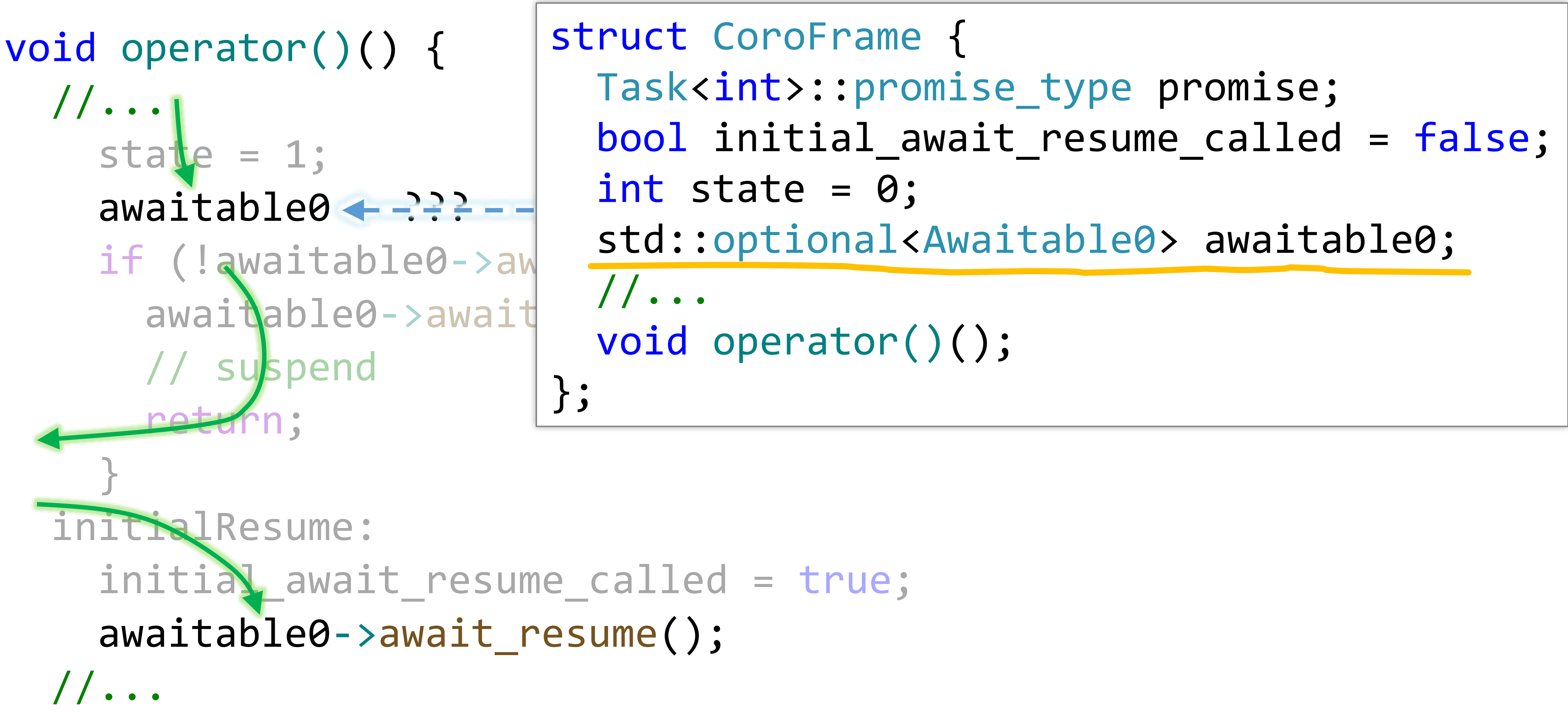
```
void operator()() {
  //...
    state = 1;
    awaitable0 ??? getAwaitable(promise.initial_suspend());
    if (!awaitable0->await_ready()) {
      awaitable0->await_suspend(thisCoroHandle);
      // suspend
      return;
    }
  initialResume:
    initial_await_resume_called = true;
    awaitable0->await_resume();
  //...
```

Transformation by the compiler

```
co_await promise.initial_suspend();
```

```
void operator()() {
  //...
    state = 1;
    awaitable0 ??? getAwaitable(promise.initial_suspend());
    if (!awaitable0->await_ready()) {
      awaitable0->await_suspend(thisCoroHandle);
      // suspend
      return;
    }
  initialResume:
    initial_await_resume_called = true;
    awaitable0->await_resume();
  //...
```

Transformation by the compiler



```
void operator()() {
  //...
    state = 1;
    awaitable0
    if (!awaitable0->aw
      awaitable0->await
      // suspend
      return;
    }
  initialResume:
    initial_await_resume_called = true;
    awaitable0->await_resume();
  //...
```

```
struct CoroFrame {
  Task<int>::promise_type promise;
  bool initial_await_resume_called = false;
  int state = 0;
  std::optional<Awaitable0> awaitable0;
  //...
  void operator()();
};
```

Transformation by the compiler

```
co_await promise.initial_suspend();
```

```
void operator()() {
  //...
    state = 1;
    awaitable0.emplace(getAwaitable(promise.initial_suspend()));
    if (!awaitable0->await_ready()) {
      awaitable0->await_suspend(thisCoroHandle);
      // suspend
      return;
    }
  initialResume:
    initial_await_resume_called = true;
    awaitable0->await_resume();
  //...
```

Transformation by the compiler

```
co_await promise.initial_suspend();
```

```
void operator()() {
  //...
    state = 1;
    awaitable0.emplace(getAwaitable(promise.initial_suspend()));
    if (!awaitable0->await_ready()) {
      awaitable0->await_suspend(thisCoroHandle);



  ir



  //
```

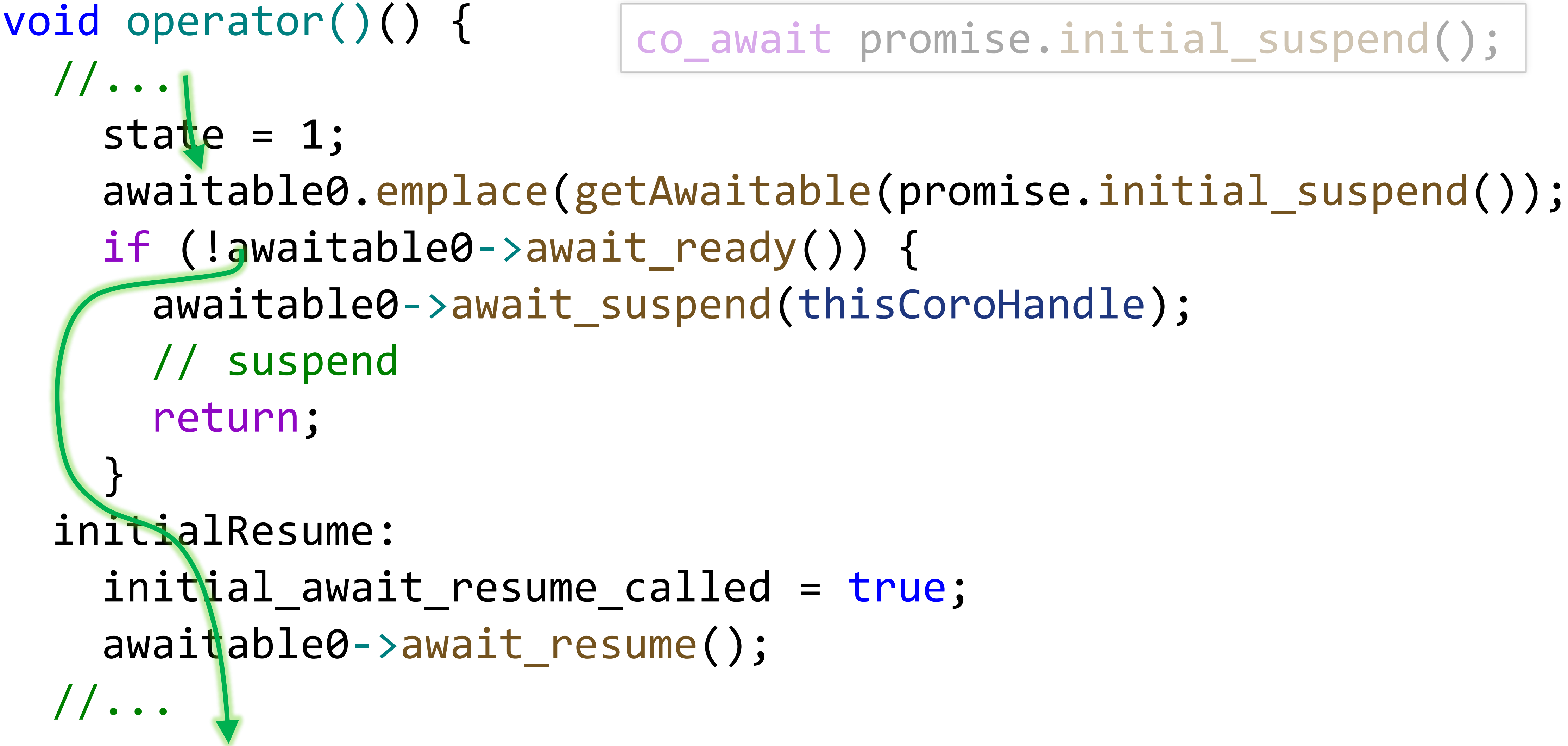
```
struct suspend_never {
  bool await_ready() noexcept {
    return true;
  }
  void await_suspend(coroutine_handle<>) noexcept {}
  void await_resume() noexcept {}
};
```

Transformation by the compiler

```
co_await promise.initial_suspend();
```

```
void operator()() {
  //...
    state = 1;
    awaitable0.emplace(getAwaitable(promise.initial_suspend());
    if (!awaitable0->await_ready()) {
      awaitable0->await_suspend(thisCoroHandle);
      // suspend
      return;
    }
  initialResume:
    initial_await_resume_called = true;
    awaitable0->await_resume();
  //...
```

Transformation by the compiler



```
co_await promise.initial_suspend();
```

```
void operator()() {
  //...
    state = 1;
    awaitable0.emplace(getAwaitable(promise.initial_suspend()));
    if (!awaitable0->await_ready()) {
      awaitable0->await_suspend(thisCoroHandle);
      // suspend
      return;
    }
  initialResume:
    initial_await_resume_called = true;
    awaitable0->await_resume();
  //...
```

Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```

```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```

```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```

```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
```

```
struct Awaitable {
  bool await_ready() const noexcept;
  using CoroHandle = std::coroutine_handle<>;
  CoroHandle await_suspend(CoroHandle) const noexcept;
  T &&await_resume() const;
};
```

```
  //...
```

Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```

```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```

```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

symmetric control transfer

Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```

```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

current coroutine to suspend

symmetric control transfer

Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```

```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

symmetric control transfer

returned coroutine is resumed

Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```

```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```

```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

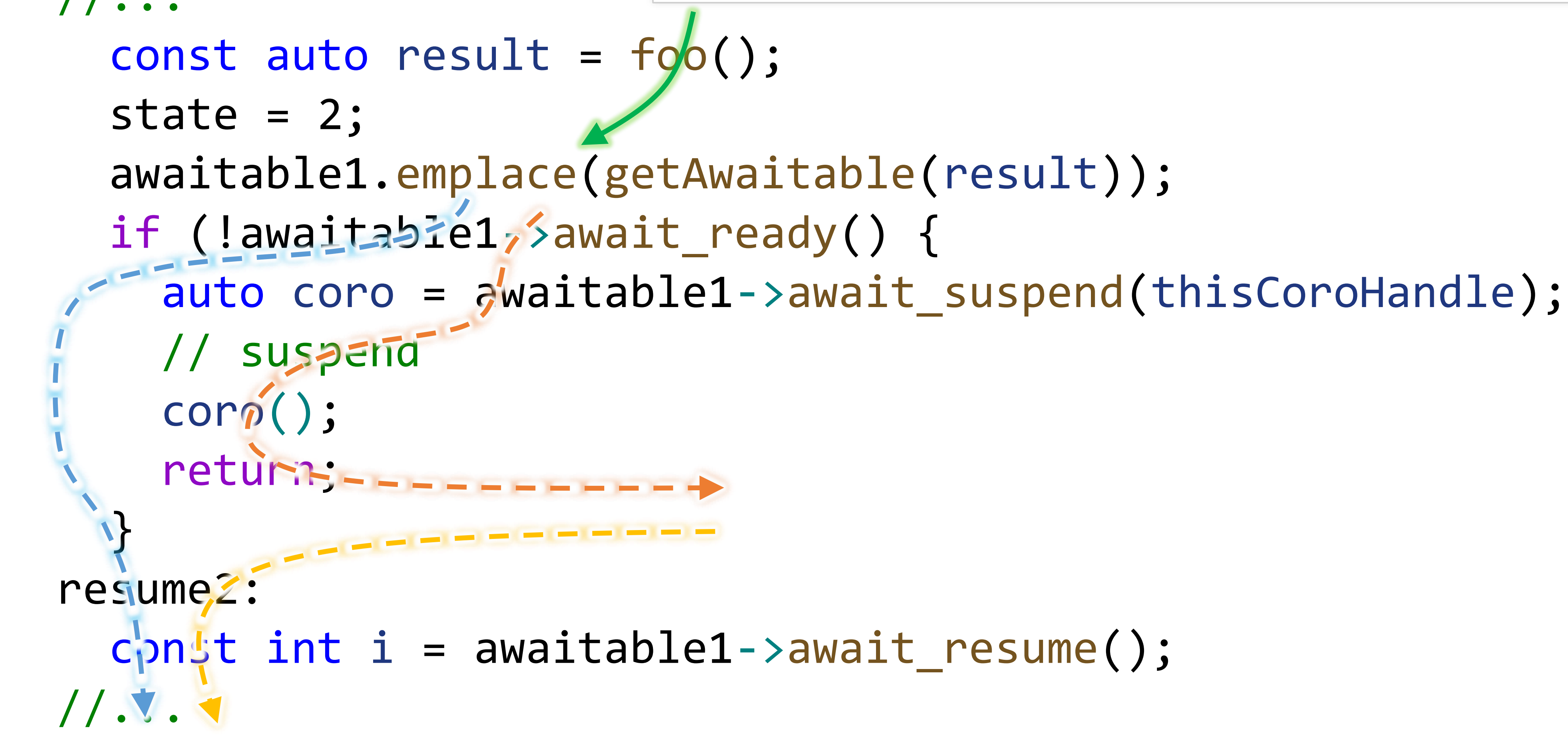
Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```

```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

Transformation by the compiler

```
const auto result = foo();
const int i = co_await result;
```



```
void operator()() {
  //...
    const auto result = foo();
    state = 2;
    awaitable1.emplace(getAwaitable(result));
    if (!awaitable1->await_ready() {
      auto coro = awaitable1->await_suspend(thisCoroHandle);
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

Transformation by the compiler

```
void operator()() {
  //...
    const auto result =
    state = 2;
    awaitable1.emplace(
    if (!awaitable1->aw
      auto coro = await
      // suspend
      coro();
      return;
    }
  resume2:
    const int i = awaitable1->await_resume();
  //...
```

```
struct CoroFrame {
  Task<int>::promise_type promise;
  bool initial_await_resume_called = false;
  int state = 0;
  std::optional<Awaitable0> awaitable0;
  std::optional<Awaitable1> awaitable1;
  void operator()();
};
```

Transformation by the compiler

```
co_return i + 23;
```

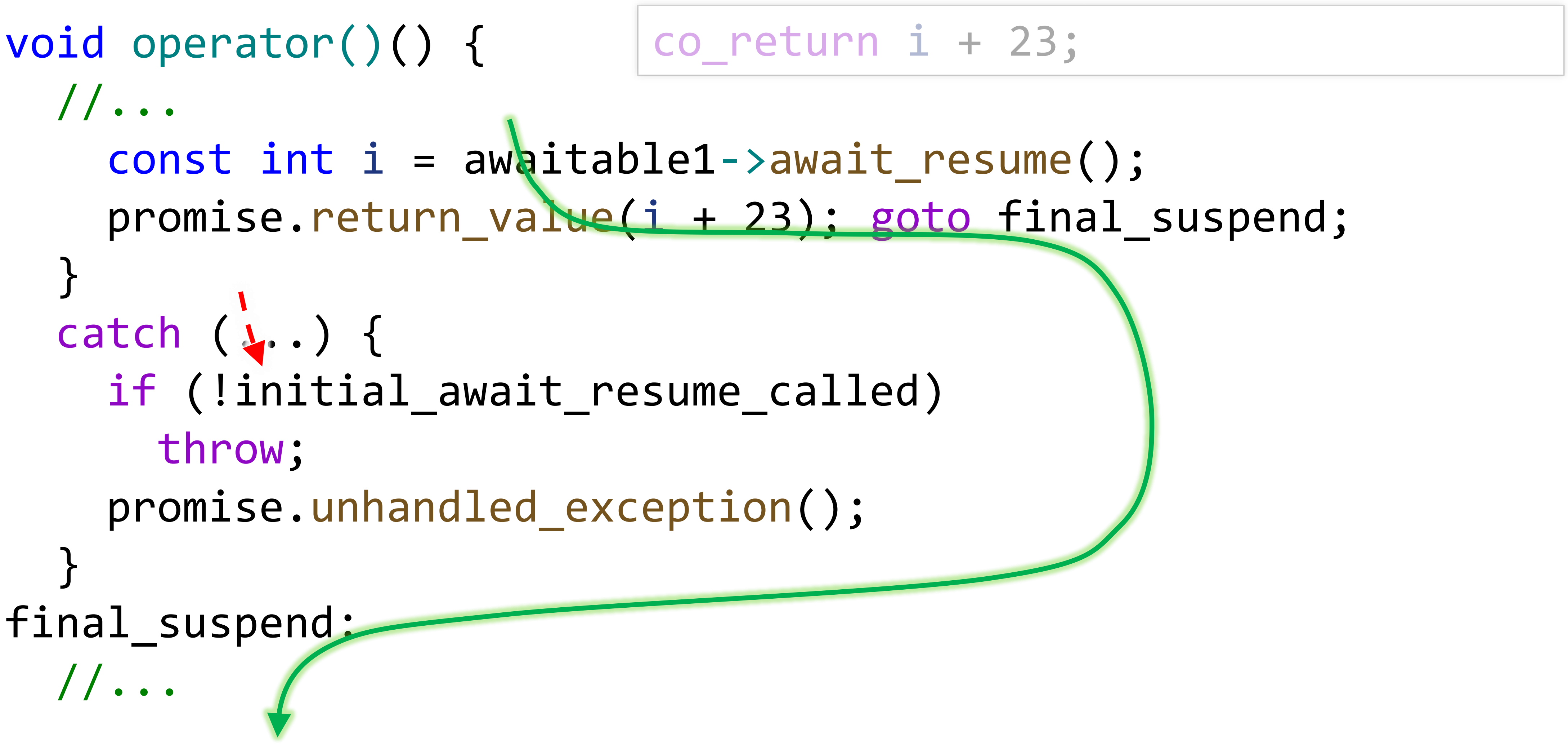
```
void operator()() {
  //...
    const int i = awaitable1->await_resume();
    promise.return_value(i + 23); goto final_suspend;
  }
  catch (...) {
    if (!initial_await_resume_called)
      throw;
    promise.unhandled_exception();
  }
final_suspend:
  //...
```

Transformation by the compiler

```
co_return i + 23;
```

```
void operator()() {
  //...
    const int i = awaitable1->await_resume();
    promise.return_value(i + 23); goto final_suspend;
  }
  catch (...) {
    if (!initial_await_resume_called)
      throw;
    promise.unhandled_exception();
  }
final_suspend:
  //...
```

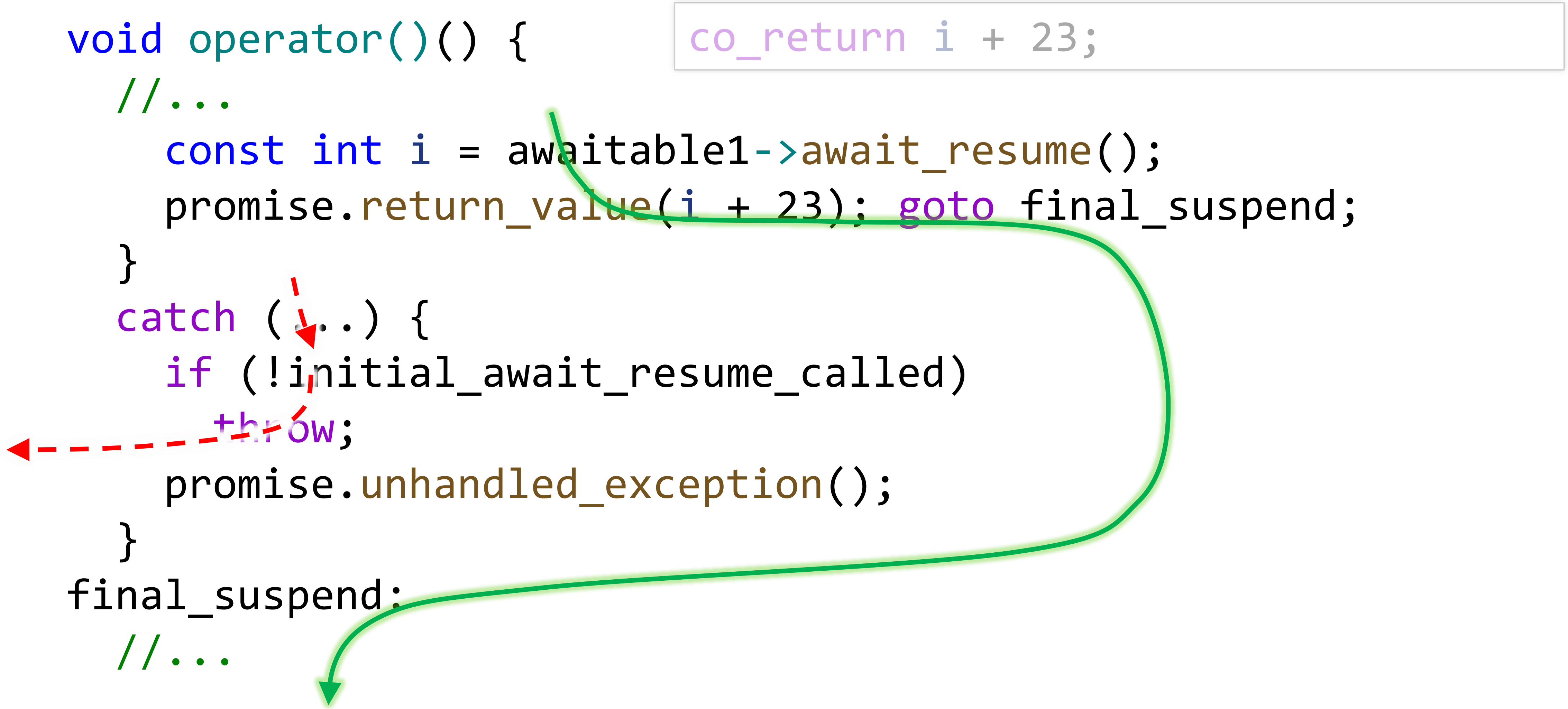
Transformation by the compiler



```
void operator()() {
  //...
    const int i = awaitable1->await_resume();
    promise.return_value(i + 23); goto final_suspend;
  }
  catch (...) {
    if (!initial_await_resume_called)
      throw;
    promise.unhandled_exception();
  }
final_suspend:
  //...
```

```
co_return i + 23;
```

Transformation by the compiler

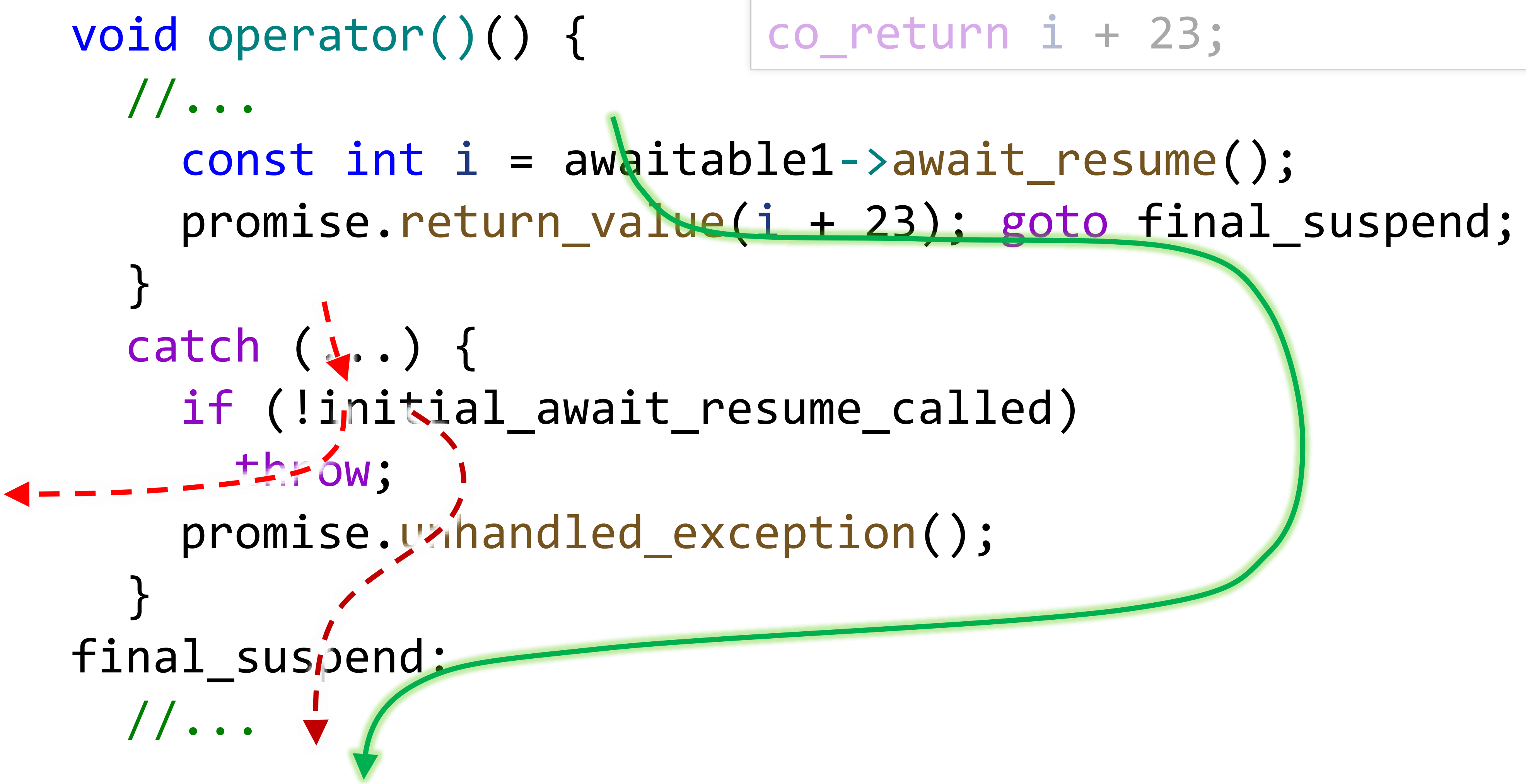


```
co_return i + 23;
```

```
void operator()() {
 //...
  const int i = awaitable1->await_resume();
  promise.return_value(i + 23); goto final_suspend;
 }
 catch (...) {
  if (!initial_await_resume_called)
   throw;
  promise.unhandled_exception();
 }
final_suspend:
 //...
```

Transformation by the compiler

```
co_return i + 23;
```



```
void operator()() {
 //...
  const int i = awaitable1->await_resume();
  promise.return_value(i + 23); goto final_suspend;
 }
 catch (...) {
  if (!initial_await_resume_called)
   throw;
  promise.unhandled_exception();
 }
final_suspend:
 //...
```

Transformation by the compiler

```
co_await promise.final_suspend();
```

```
void operator()() {
  //...
final_suspend:
  auto finalAwaitable{ getAwaitable(promise.final_suspend()) };
  if (!finalAwaitable.await_ready()) {
    finalAwaitable.await_suspend(thisCoroHandle);
    return;
  }
  delete this;
}
```

Transformation by the compiler

```
co_await promise.final_suspend();
```

```
void operator()() {
  //...
final_suspend:
  auto finalAwaitable{ getAwaitable(promise.final_suspend()) };
  if (!finalAwaitable.await_ready()) {
    finalAwaitable.await_suspend(thisCoroHandle);
    return;
  }
  delete this;
}
```

Transformation by the compiler

```
co_await promise.final_suspend();
```

```
void operator()() {
  //...
final_suspend:
  auto finalAwaitable{ getAwaitable(promise.final_suspend()) };
  if (!finalAwaitable.await_ready()) {
    finalAwaitable.await_suspend(thisCoroHandle);

  }
  de
}
```

```
struct suspend_always {
  bool await_ready() noexcept {
    return false;
  }
  void await_suspend(coroutine_handle<>) noexcept {}
  void await_resume() noexcept {}
};
```

Transformation by the compiler

```
co_await promise.final_suspend();
```

```
void operator()() {
  //...
final_suspend:
  auto finalAwaitable{ getAwaitable(promise.final_suspend()) };
  if (!finalAwaitable.await_ready()) {
    finalAwaitable.await_suspend(thisCoroHandle);
    return;
  }
  delete this;
}
```

Transformation by the compiler

```
co_await promise.final_suspend();
```

```
void operator()() {
  //...
final_suspend:
  auto finalAwaitable{ getAwaitable(promise.final_suspend()) };
  if (!finalAwaitable.await_ready()) {
    finalAwaitable.await_suspend(thisCoroHandle);
    return;
  }
  delete this;
}
```

Awaiting: Task

```
template<typename T>
struct [[nodiscard]] Task {
  using promise_type = Promise<T>;
  Task() = default;
  auto operator co_await() const noexcept;

private:
  explicit Task(Promise<T> *promise) : promise{ promise } {}

  PromisePtr<T> *promise = nullptr;

  template<typename> friend struct Promise;
};
```

Task::operator co_await

```cpp
auto operator co_await() const noexcept {
  struct Awaitable {
    //...
    Promise<T> &promise;
  };
  return Awaitable{ *promise };
}
```

Task::operator co_await

```
struct Awaitable {
  bool await_ready() const noexcept {
    return promise.isReady();
  }
  using CoroHandle = std::coroutine_handle<>;
  CoroHandle await_suspend(CoroHandle continuation) const noexcept {
    promise.continuation = continuation;
    return std::coroutine_handle<Promise<T>>::from_promise(promise);
  }
  T &&await_resume() const {
    return promise.getResult();
  }

  Promise<T> &promise;
};
```

Task::operator co_await

```
struct Awaitable {
  bool await_ready() const noexcept {
    return promise.isReady();
  }
  using CoroHandle = std::coroutine_handle<>;
  CoroHandle await_suspend(CoroHandle continuation) const noexcept {
    promise.continuation = continuation;
    return std::coroutine_handle<Promise<T>>::from_promise(promise);
  }
  T &&await_resume() const {
    return promise.getResult();
  }

  Promise<T> &promise;
};
```

symmetric control transfer

Task::operator co_await

```cpp
struct Awaitable {
  bool await_ready() const noexcept {
    return promise.isReady();
  }
  using CoroHandle = std::coroutine_handle<>;
  CoroHandle await_suspend(CoroHandle continuation) const noexcept {
    promise.continuation = continuation;
    return std::coroutine_handle<Promise<T>>::from_promise(promise);
  }
  T &&await_resume() const {
    return promise.getResult();
  }

  Promise<T> &promise;
};
```

symmetric control transfer

current coroutine is suspended and becomes the continuation

Task::operator co_await

```
struct Awaitable {
  bool await_ready() const noexcept {
    return promise.isReady();
  }
  using CoroHandle = std::coroutine_handle<>;
  CoroHandle await_suspend(CoroHandle continuation) const noexcept {
    promise.continuation = continuation;
    return std::coroutine_handle<Promise<T>>::from_promise(promise);
  }
  T &&await_resume() const {
    return promise.getResult();
  }

  Promise<T> &promise;
};
```

symmetric control transfer

suspended coroutine is returned and resumed

Task::operator co_await

```
struct Awaitable {
  bool await_ready() const noexcept {
    return promise.isReady();
  }
  using CoroHandle = std::coroutine_handle<>;
  CoroHandle await_suspend(CoroHandle continuation) const noexcept {
    promise.continuation = continuation;
    return std::coroutine_handle<Promise<T>>::from_promise(promise);
  }
  T &&await_resume() const {
    return promise.getResult();
  }

  Promise<T> &promise;
};
```

Task::operator co_await

```
struct Awaitable {
  bool await_ready() const noexcept {
    return promise.isReady();
  }
  using CoroHandle = std::coroutine_handle<>;
  CoroHandle await_suspend(CoroHandle continuation) const noexcept {
    promise.continuation = continuation;
    return std::coroutine_handle<Promise<T>>::from_promise(promise);
  }
  T &&await_resume() const {
    return promise.getResult();
  }

  Promise<T> &promise;
};
```

Awaiting: Promise

```
template<typename T>
struct Promise {
  //...
  // std::suspend_always final_suspend() noexcept { return {}; }
  auto final_suspend() noexcept {
    struct FinalAwaitable { /*...*/ };
    return FinalAwaitable{};
  }
  //...
  std::variant<std::monostate, T, std::exception_ptr> result;
  std::coroutine_handle<> continuation;
};
```

Awaiting: Promise

```
template<typename T>
struct Promise {
  //...
  // std::suspend_always final_suspend() noexcept { return {}; }
  auto final_suspend() noexcept {
    struct FinalAwaitable { /*...*/ };
    return FinalAwaitable{};
  }
  //...
  std::variant<std::monostate, T, std::exception_ptr> result;
  std::coroutine_handle<> continuation;
};
```

Awaiting: Promise

```
template<typename T>
struct Promise {
  //...
```

```
struct FinalAwaitable {
  bool await_ready() const noexcept { return false; }
  void await_suspend(std::coroutine_handle<Promise<T>> thisCoro) noexcept {
    auto &promise = thisCoro.promise();
    if (promise.continuation)
      promise.continuation();
  }
  void await_resume() const noexcept {}
};
```

```
  std::coroutine_handle<> continuation;
};
```

Awaiting: Promise

```
template<typename T>
struct Promise {
  //...
```

```
struct FinalAwaitable {
  bool await_ready() const noexcept { return false; }
  void await_suspend(std::coroutine_handle<Promise<T>> thisCoro) noexcept {
    auto &promise = thisCoro.promise();
    if (promise.continuation)
      promise.continuation();
  }
  void await_resume() const noexcept {}
};
```

```
  std::coroutine_handle<> continuation;
};
```

Awaiting: Promise

```
template<typename T>
struct Promise {
  //...
```

```
struct FinalAwaitable {
  bool await_ready() const noexcept { return false; }
  void await_suspend(std::coroutine_handle<Promise<T>> thisCoro) noexcept {
    auto &promise = thisCoro.promise();
    if (promise.continuation)
      promise.continuation();
  }
  void await_resume() const noexcept {}
};
```

```
  std::coroutine_handle<> continuation;
};
```

Iteration 1: awaiting tasks

```
Task<int> bar() {
  const auto result = foo();
  std::cout << "bar(): about to co_await\n";
  const int i = co_await result;
  std::cout << "bar(): about to return\n";
  co_return i + 23;
}


auto task = bar();
```

output:

```
foo(): about to return
bar(): about to co_await
bar(): about to return
```

Iteration 1: awaiting tasks

```
Task<int>
   const au
   std::cou                                         ;
   const in
   std::cou
   co_retur
}

auto task
```

```
                  rn
                  wait
bar(): about to return
```

Helpful tip

Write constructor and destructor for promise types.

```
template<typename T>
struct Promise {
  Promise() {
    std::cout << "Promise: ctor\n";
  }
  ~Promise() {
    std::cout << "Promise: dtor\n";
  }
  //...
```

Writing an awaitable

```
struct Sleep {
  bool await_ready() const noexcept {
    return duration == duration.zero();
  }
  void await_suspend(std::coroutine_handle<> coro) const {
    std::this_thread::sleep_for(duration);
    coro();
  }
  void await_resume() const noexcept {}

  std::chrono::milliseconds duration;
};
```

Writing an awaitable

```
struct Sleep {
  bool await_ready() const noexcept {
    return duration == duration.zero();
  }
  void await_suspend(std::coroutine_handle<> coro) const {
    std::this_thread::sleep_for(duration);
    coro();
  }
  void await_resume() const noexcept {}

  std::chrono::milliseconds duration;
};
```

suspended coroutine

Writing an awaitable

```
struct Sleep {
  bool await_ready() const noexcept {
    return duration == duration.zero();
  }
  void await_suspend(std::coroutine_handle<> coro) const {
    std::this_thread::sleep_for(duration);
    coro();
  }
  void await_resume() const noexcept {}

  std::chrono::milliseconds duration;
};
```

puts thread to sleep

Writing an awaitable

```
struct Sleep {
  bool await_ready() const noexcept {
    return duration == duration.zero();
  }
  void await_suspend(std::coroutine_handle<> coro) const {
    std::this_thread::sleep_for(duration);
    coro();
  }
  void await_resume() const noexcept {}

  std::chrono::milliseconds duration;
};
```

resumes the suspended coroutine

Writing an awaitable

```
struct Sleep {
  bool await_ready() const noexcept {
    return duration == duration.zero();
  }
  void await_suspend(std::coroutine_handle<> coro) const {
    std::this_thread::sleep_for(duration);
    coro();
  }
  void await_resume() const noexcept {}

  std::chrono::milliseconds duration;
};
```

Writing an awaitable

```cpp
struct Sleep {
  bool await_ready() const noexcept {
    return duration == duration.zero();
  }
  void await_suspend(std::coroutine_handle<> coro) const {
    std::this_thread::sleep_for(duration);
    coro();
  }
  void await_resume() const noexcept {}

  std::chrono::milliseconds duration;
};
```

Writing an awaitable

```
struct Sleep {
  bool await_ready() const noexcept {
    return duration == duration.zero();
  }
  void await_suspend(std::coroutine_handle<> coro) const {
    std::this_thread::sleep_for(duration);
    coro();
  }
  void await_resume() const noexcept {}

  std::chrono::milliseconds duration;
};
```

Writing an awaitable

```
Task<void> sleepy() {
  std::cout << "sleepy(): about to sleep\n";
  co_await Sleep{ std::chrono::seconds{ 1 } };
  std::cout << "sleepy(): about to return\n";
}

auto task = sleepy();
```

output:

Writing an awaitable

```
Task<void> sleepy() {
  std::cout << "sleepy(): about to sleep\n";
  co_await Sleep{ std::chrono::seconds{ 1 } };
  std::cout << "sleepy(): about to return\n";
}

auto task = sleepy();
```

output:

```
Promise: ctor
sleepy(): about to sleep
```

Writing an awaitable

```cpp
Task<void> sleepy() {
  std::cout << "sleepy(): about to sleep\n";
  co_await Sleep{ std::chrono::seconds{ 1 } };
  std::cout << "sleepy(): about to return\n";
}


auto task = sleepy();
```

output:

```
Promise: ctor
sleepy(): about to sleep
sleepy(): about to return
Promise: dtor
```

Writing an awaitable

```
Task<void> sleepy() {
  std::
  co_aw
  std::
}

auto ta
```

```
eep
turn
```

Asyncronously reading a file

```
struct AsyncReadFile {
  AsyncReadFile(std::filesystem::path path) :
    path{ std::move(path) } {}
  bool await_ready() const noexcept { return false; }
  void await_suspend(std::coroutine_handle<> coro);
  std::string await_resume() noexcept {
    return std::move(result);
 }

private:
  std::filesystem::path path;
  std::string result;
};
```

Asyncronously reading a file

```
struct AsyncReadFile {
  AsyncReadFile(std::filesystem::path path) :
    path{ std::move(path) } {}
  bool await_ready() const noexcept { return false; }
  void await_suspend(std::coroutine_handle<> coro);
  std::string await_resume() noexcept {
    return std::move(result);
 }

private:
  std::filesystem::path path;
  std::string result;
};
```

Asyncronously reading a file

```
struct AsyncReadFile {
  AsyncReadFile(std::filesystem::path path) :
    path{ std::move(path) } {}
  bool await_ready() const noexcept { return false; }
  void await_suspend(std::coroutine_handle<> coro);
  std::string await_resume() noexcept {
    return std::move(result);
 }

private:
  std::filesystem::path path;
  std::string result;
};
```

Asyncronously reading a file

```
struct AsyncReadFile {
  AsyncReadFile(std::filesystem::path path) :
    path{ std::move(path) } {}
  bool await_ready() const noexcept { return false; }
  void await_suspend(std::coroutine_handle<> coro);
  std::string await_resume() noexcept {
    return std::move(result);
 }

private:
  std::filesystem::path path;
  std::string result;
};
```

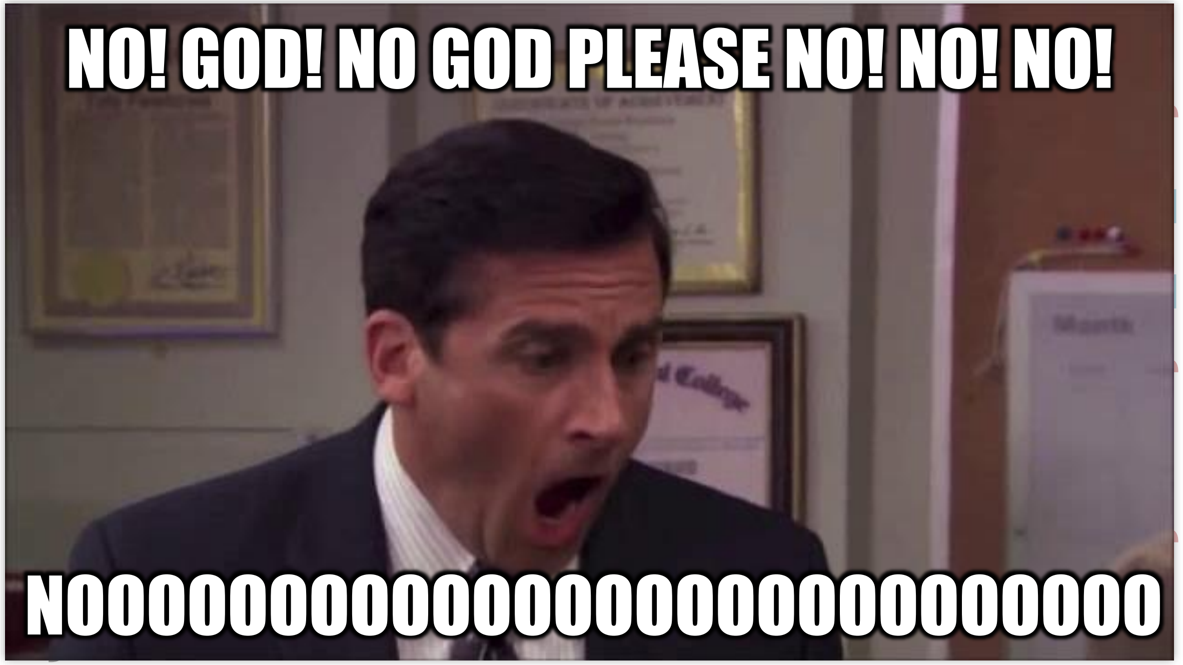
Asyncronously reading a file

```
void await_suspend(std::coroutine_handle<> coro) {
  auto work = [this, coro]() {
    std::cout << tid << " worker thread: opening file\n";
    auto stream = std::ifstream{ path };
    std::cout << tid << " worker thread: reading file\n";
    result.assign(std::istreambuf_iterator<char>{stream},
                  std::istreambuf_iterator<char>{});
    std::cout << tid << " worker thread: resuming coro\n";
    coro();
    std::cout << tid << " worker thread: exiting\n";
  };
  std::thread{ work }.detach();
}
```

Asyncronously reading a file

```
void await_suspend(std::coroutine_handle<> coro) {
  auto work = [this, coro]() {
    std::cout << tid << " worker thread: opening file\n";
                path };
               ' thread: reading file\n";
                f_iterator<char>{stream},
                f_iterator<char>{});
               ' thread: resuming coro\n";

               ' thread: exiting\n";
  std::thread{ work }.detach();
}
```


NO! GOD! NO GOD PLEASE NO! NO! NO!
NOOOOOOOOOOOOOOOOOOOOOOOOOOOOOOO

Asyncronously reading a file

```
Task<size_t> readFile() {
  std::cout << tid << " readFile(): about to read file async\n";
  const auto result = co_await AsyncReadFile{ "main.cpp" };
  std::cout << tid << " readFile(): about to return (size "
    << result.size() << ")\n";
  co_return result.size();
}


int main() {
  auto task = readFile();
}
```

Asyncronously reading a file

```
Task<size_t> readFile() {
  std::cout << tid << " readFile(): about to read file async\n";
  const auto result = co_await AsyncReadFile{ "main.cpp" };
  std::cout << tid << " readFile(): about to return (size "
    << result.size() << ")\n";
  co_return result.size();
}


int main() {
  auto task = readFile();
}
```

output:

```
Promise: ctor
(tid=38216) readFile(): about to read file async
Promise: dtor
```

Asyncronously reading a file

Thread A

```
Task<size_t> readFile() {
  const auto result =
    co_await AsyncReadFile{ "main.cpp" };
  co_return contents.size();
}
```

Asyncronously reading a file

Thread A

```
Task<size_t> readFile() {
  const auto result =
    co_await AsyncReadFile{ "main.cpp" };
  co_return contents.size();
}
```

Asyncronously reading a file

Thread A

```
Task<size_t> readFile() {
  const auto result =
    co_await AsyncReadFile{ "main.cpp" };
  co_return contents.size();
}
```

Thread B

```
auto work = [this, coro]() {
  //...
  coro();
  //...
};
```

Asyncronously reading a file

Thread A

```
Task<size_t> readFile() {
  const auto result =
    co_await AsyncReadFile{ "main.cpp" };
  co_return contents.size();
}
```

coroutine is suspended

Thread B

```
auto work = [this, coro]() {
  //...
  coro();
  //...
};
```

Asyncronously reading a file

Thread A

```
Task<size_t> readFile() {
  const auto result =
    co_await AsyncReadFile{ "main.cpp" };
  co_return contents.size();
}
```

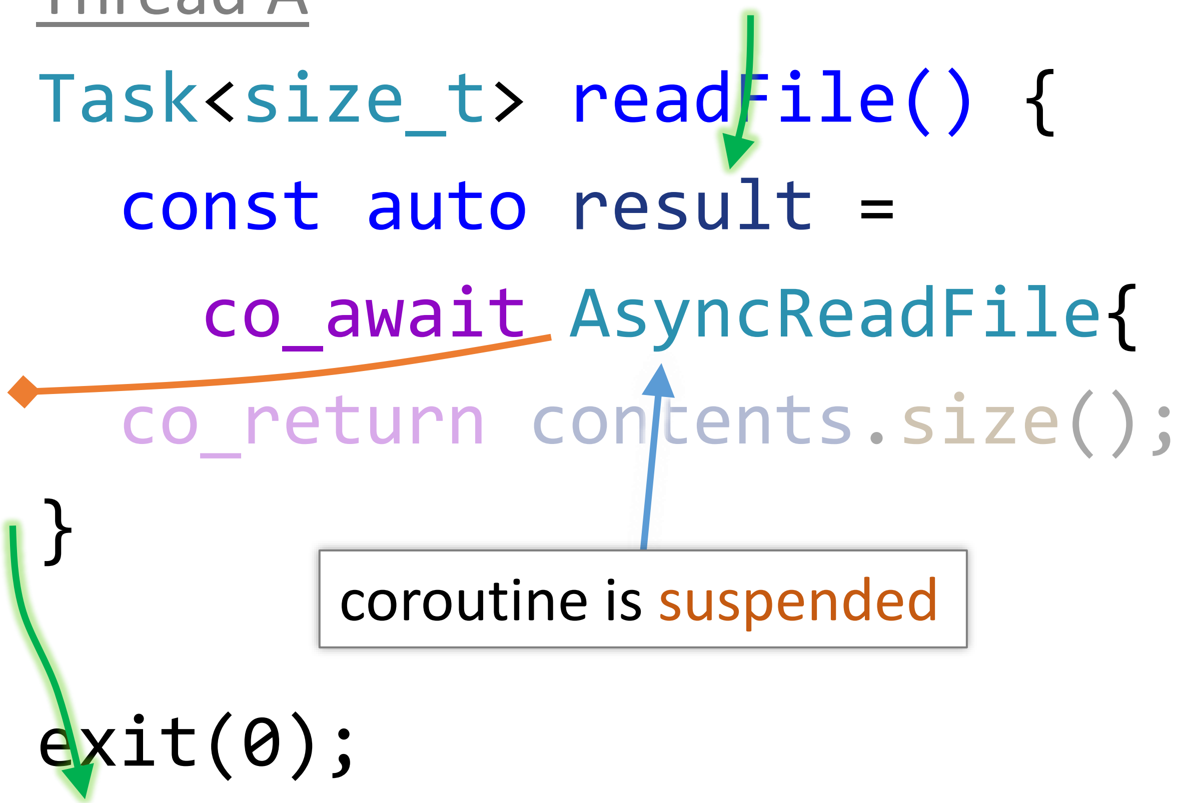
coroutine is suspended

Thread B

```
auto work = [this, coro]() {
  //...
  coro();
  //...
};
```

Asyncronously reading a file

Thread A



```
Task<size_t> readFile() {
  const auto result =
    co_await AsyncReadFile{ "main.cpp" };
  co_return contents.size();
}

exit(0);
```

coroutine is suspended

Thread B

```
auto work = [this, coro]() {
  //...
  coro();
  //...
};
```

Iteration 2

In which we learn how to get result out of a task and make awaiting thread-safeish

Getting result from task

Where is the result?

```
auto task = bar();
```

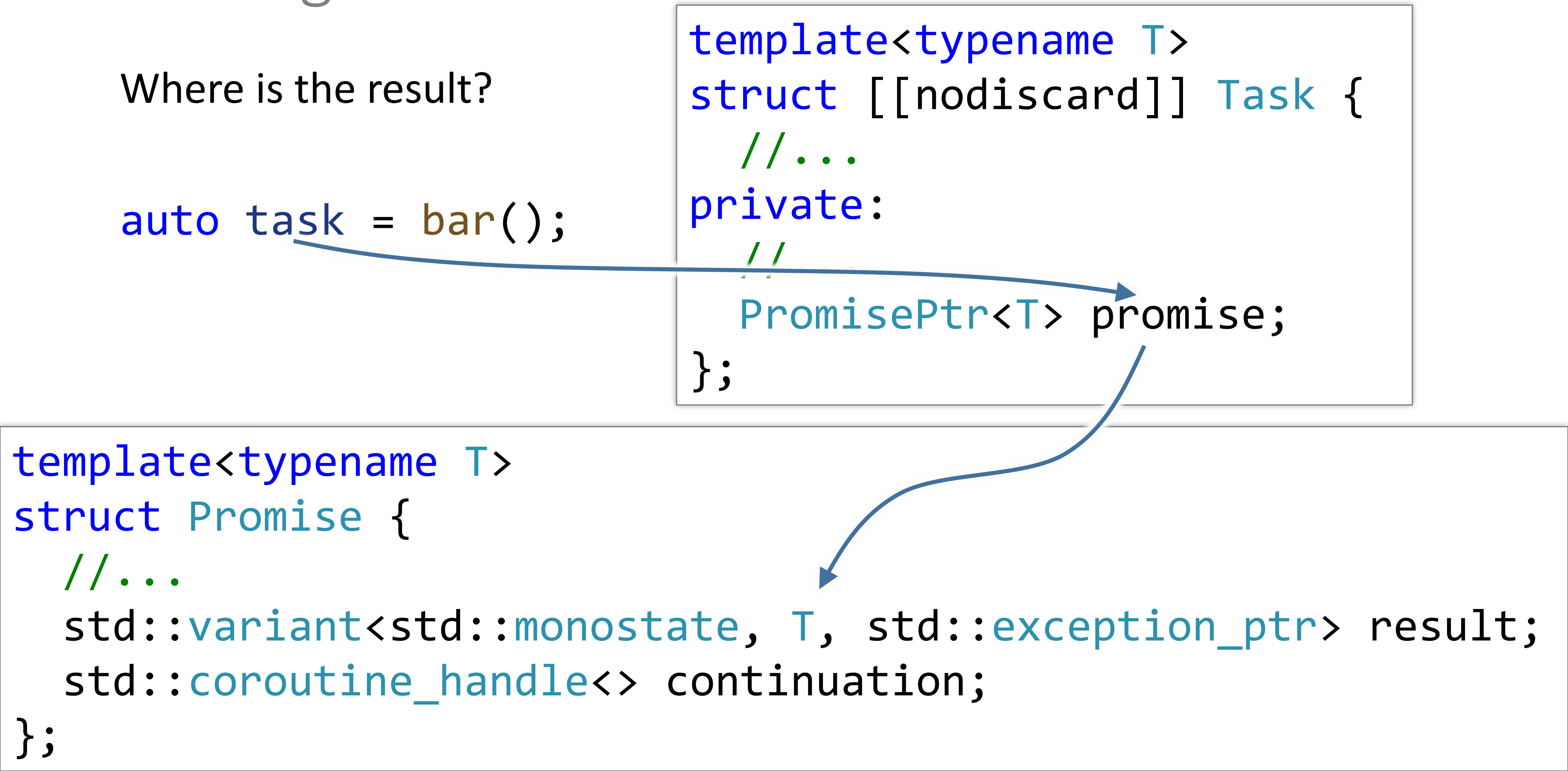
Getting result from task

Where is the result?

```
auto task = bar();
```

```
template<typename T>
struct [[nodiscard]] Task {
  //...
private:
  //...
  PromisePtr<T> promise;
};
```

Getting result from task



Where is the result?

```cpp
auto task = bar();
```

```cpp
template<typename T>
struct [[nodiscard]] Task {
  //...
private:
  //...
  PromisePtr<T> promise;
};
```

```cpp
template<typename T>
struct Promise {
  //...
  std::variant<std::monostate, T, std::exception_ptr> result;
  std::coroutine_handle<> continuation;
};
```

Getting result from task

Thread A

```
auto task = baz();
//...
```

Thread B

Getting result from task

Thread A

```
auto task = baz();
//...
```

Thread B

continues to execute on thread B

```
Task<void> baz() {
⇨ //...
  co_return;
}
```

Getting result from task

Thread A

```
auto task = baz();
//...
// are we there yet?
auto result =
  getResult(task);
```

Thread B

continues to execute on thread B

```
Task<void> baz() {
  //...
  co_return;
}
```

Getting result from task

Thread A

```
auto task = baz();
```

Thread B

continues to execute on thread B

```
Task<void> baz() {
⇨ //...
  co_return;
}
```

Getting result from task

Thread A

```
auto task = baz();



std::future<void> result;
result.get();
```

Thread B

continues to execute on thread B

```
Task<void> baz() {
⇨ //...
  co_return;
}
```

Getting result from task

Thread A

```
auto task = baz();


std::future<void> result;
result.get();
```

Thread B

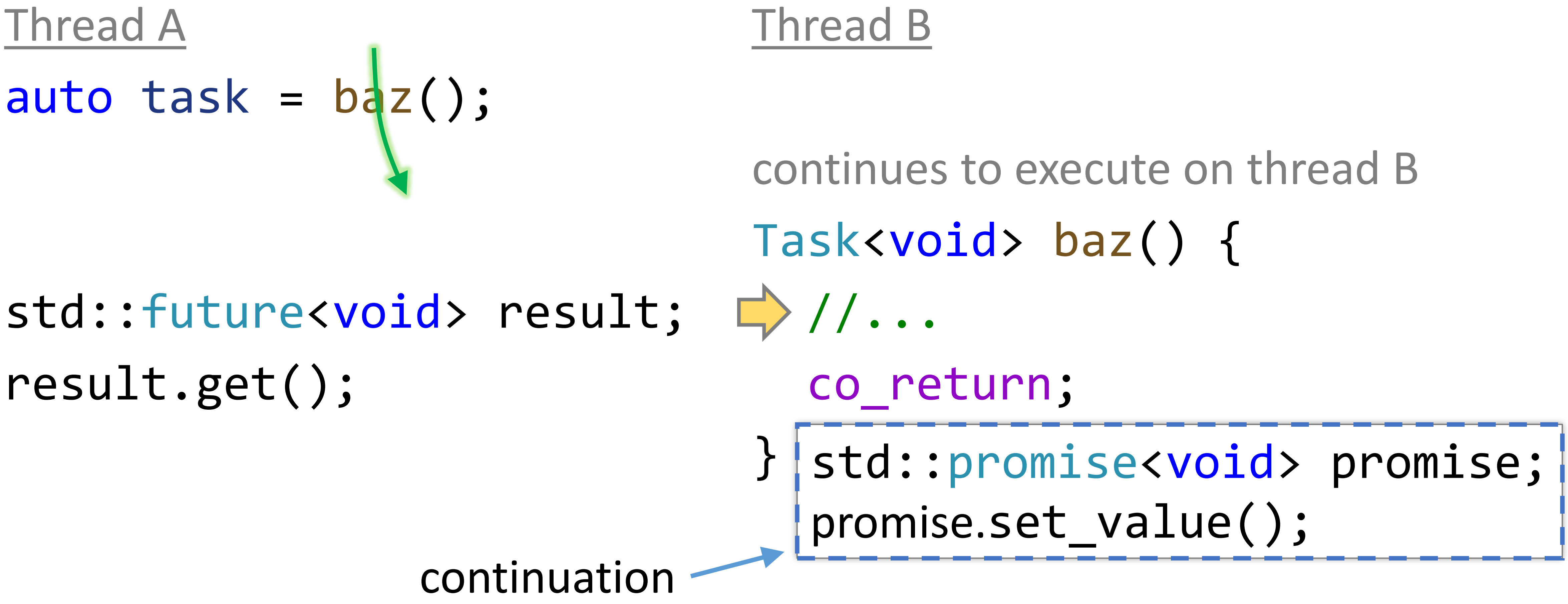
continues to execute on thread B

```
Task<void> baz() {
  //...
  co_return;
}
```

continuation

```
std::promise<void> promise;
promise.set_value();
```

Getting result from task



Thread A

```
auto task = baz();


std::future<void> result;
result.get();
```

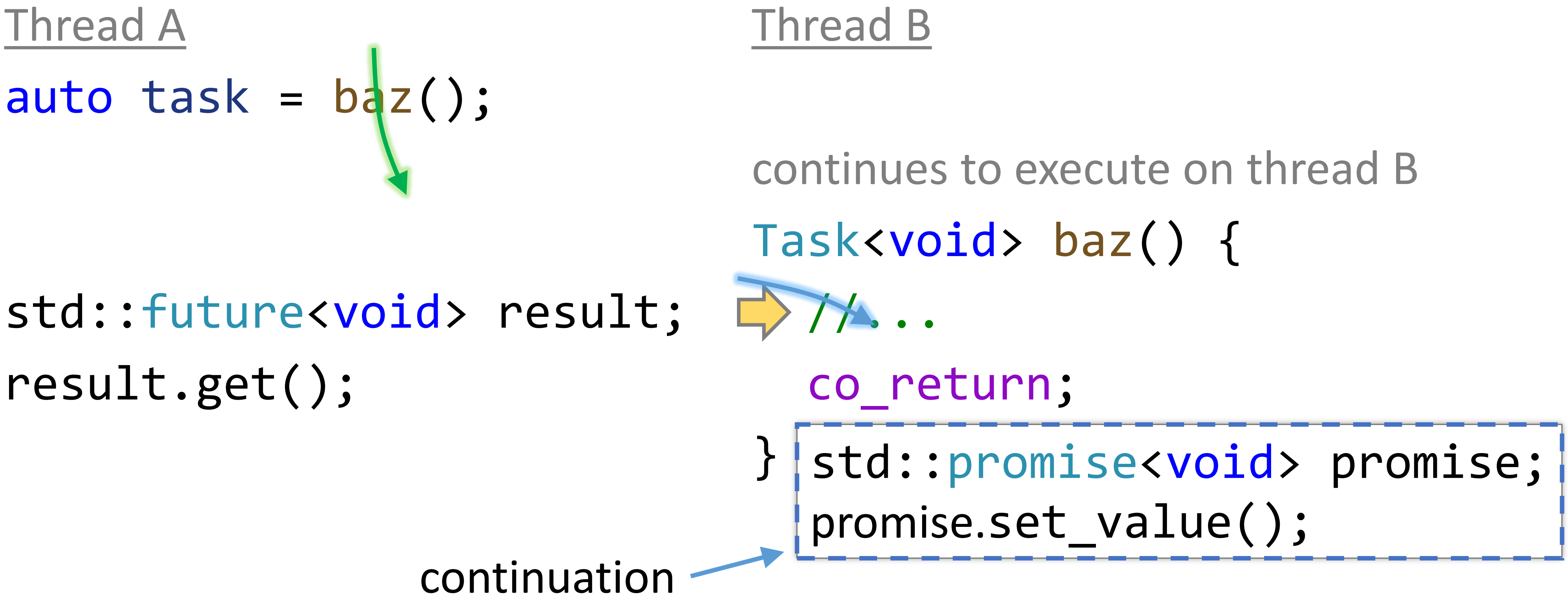
Thread B

continues to execute on thread B

```
Task<void> baz() {
  //...
  co_return;
} std::promise<void> promise;
  promise.set_value();
```

continuation

Getting result from task



Thread A

```
auto task = baz();


std::future<void> result;
result.get();
```

Thread B

continues to execute on thread B

```
Task<void> baz() {
  //...
  co_return;
}
```

```
std::promise<void> promise;
promise.set_value();
```

continuation

Getting result from task

Thread A

```
auto task = baz();


std::future<void> result;
result.get();
```

Thread B

continues to execute on thread B

```
Task<void> baz() {
  //...
  co_return;
}
```

```
std::promise<void> promise;
promise.set_value();
```

continuation

Getting result from task

Thread A

```
auto task = baz();


std::future<void> result;
result.get();
```

Thread B

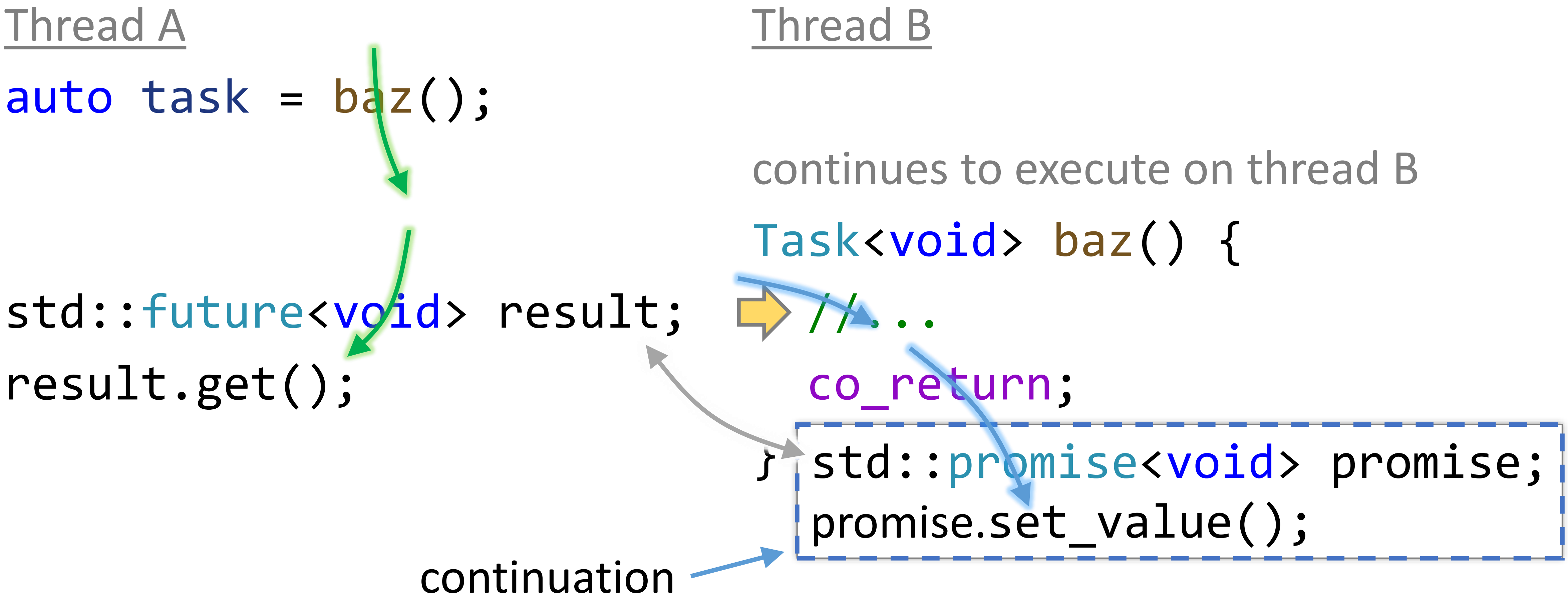
continues to execute on thread B

```
Task<void> baz() {
  //...
  co_return;
}
```

```
std::promise<void> promise;
promise.set_value();
```

continuation

Getting result from task



Thread A

```
auto task = baz();


std::future<void> result;
result.get();
```

Thread B

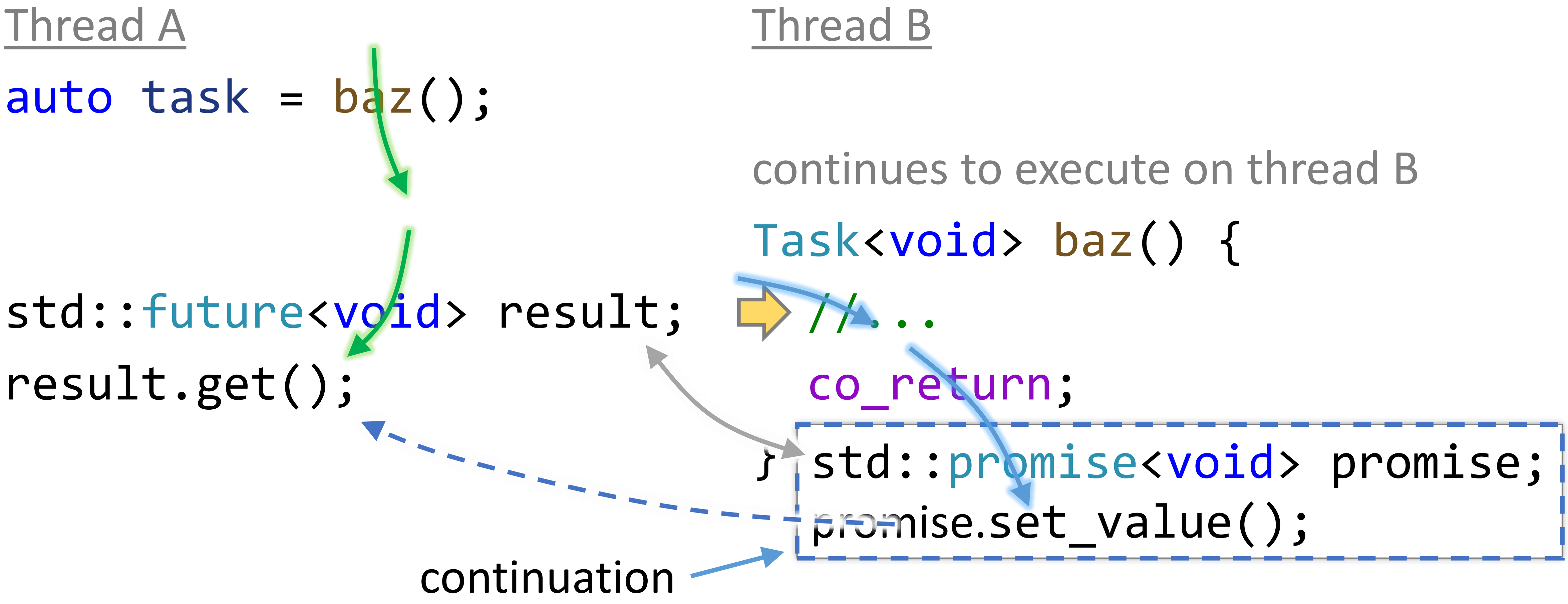
continues to execute on thread B

```
Task<void> baz() {
  //...
  co_return;
}
```

```
std::promise<void> promise;
promise.set_value();
```

continuation

Getting result from task



Thread A

```
auto task = baz();


std::future<void> result;
result.get();
```

Thread B

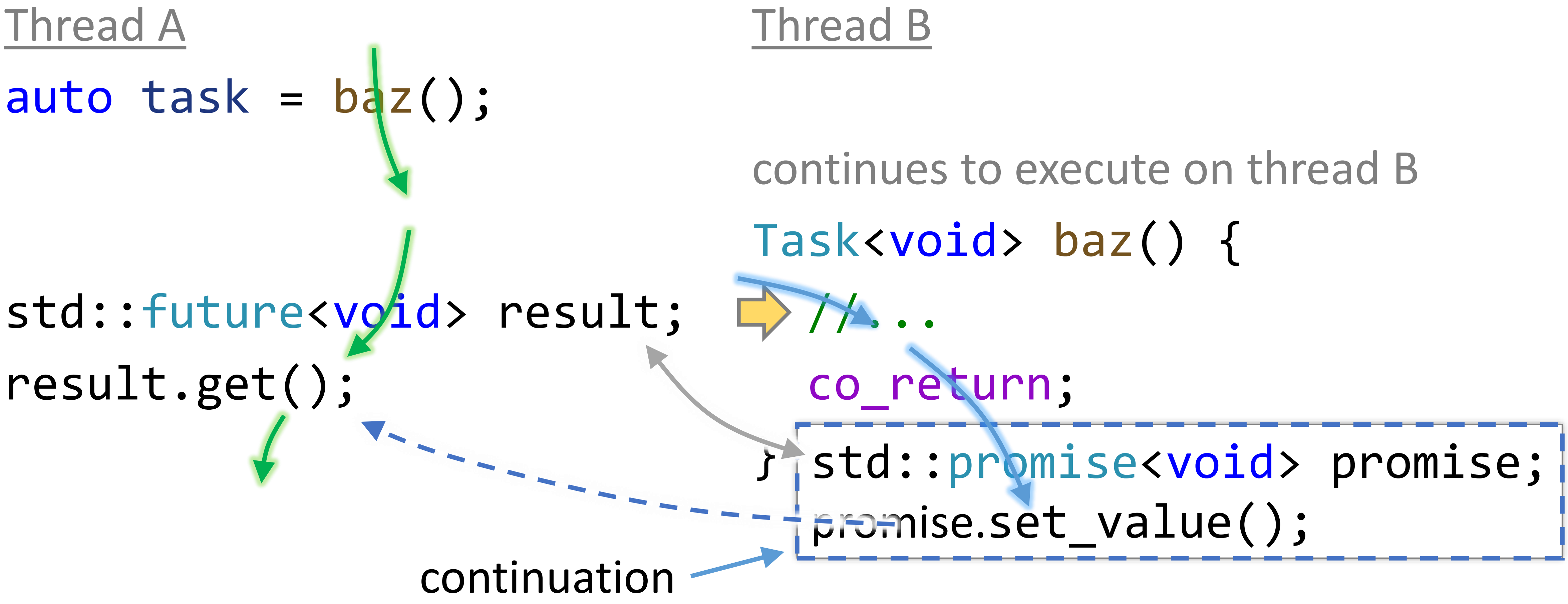
continues to execute on thread B

```
Task<void> baz() {
  //...
  co_return;
}
```

```
std::promise<void> promise;
promise.set_value();
```

continuation

Getting result from task



Thread A

```
auto task = baz();

std::future<void> result;
result.get();
```

Thread B

continues to execute on thread B

```
Task<void> baz() {
  //...
  co_return;
}
```

```
std::promise<void> promise;
promise.set_value();
```

continuation

Getting result from task

```
template<typename T>
SyncWaitImpl<ResultOfAwait<T&&>> syncWaitImpl(T &&task) {
  co_return co_await std::forward<T>(task);
}

template<typename T>
auto syncWait(T &&task) {
  return syncWaitImpl(std::forward<T>(task))
    .result.get();
}
```

Getting result from task

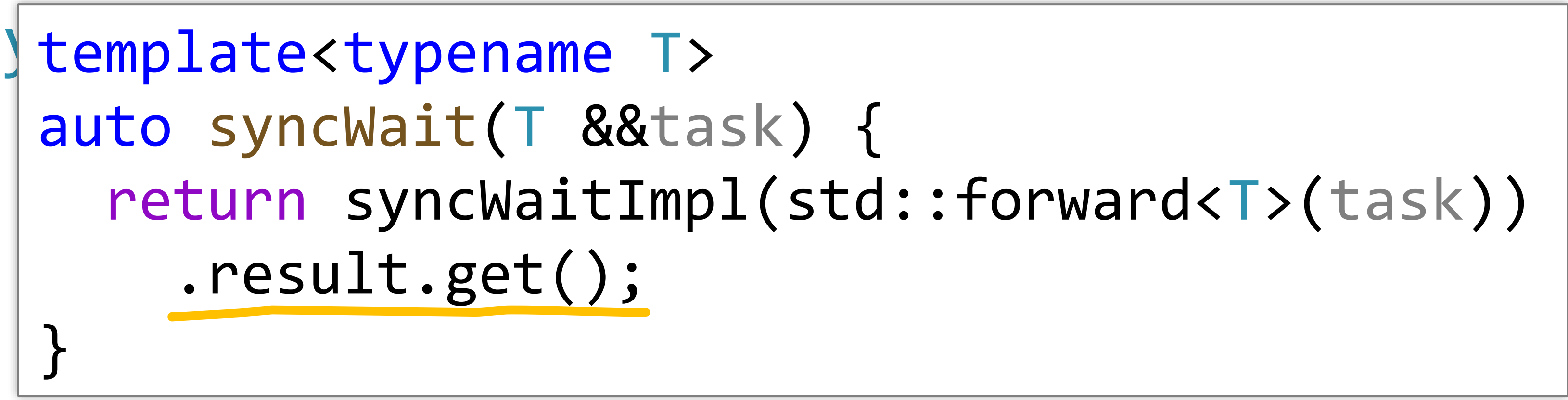
```
template<typename T>
struct SyncWaitImpl {
  struct promise_type {
    //...
  };

  std::future<T> result;
};
```

Getting result from task

```
template<typename T>
struct SyncWaitImpl {
  struct promise_ty
    //...
  };

  std::future<T> result;
};
```



```
template<typename T>
auto syncWait(T &&task) {
  return syncWaitImpl(std::forward<T>(task))
    .result.get();
}
```

Getting result from task

```
struct promise_type {
  SyncWaitImpl get_return_object() {
    return { promise.get_future() };
  }
  std::suspend_never initial_suspend() noexcept { return {}; }
  std::suspend_never final_suspend() noexcept { return {}; }
  void return_value(T &&value) {
    promise.set_value(std::move(value));
  }
  void unhandled_exception() {
    promise.set_exception(std::current_exception());
  }

  std::promise<T> promise;
};
```

Getting result from task

```
struct promise_type {
  SyncWaitImpl get_return_object() {
    return { promise.get_future() };
  }
  std::suspend_never initial_suspend() noexcept { return {}; }
  std::suspend_never final_suspend() noexcept { return {}; }
  void return_value(T &&value) {
    promise.set_value(std::move(value));
  }
  void unhandled_exception() {
    promise.set_exception(std::current_exception());
  }

  std::promise<T> promise;
};
```

Getting result from task

```
struct promise_type {
  SyncWaitImpl get_return_object() {
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  std::suspend_never final_suspend() noexcept { return {}; }
  void return_value(T &&value) {
    promise.set_value(std::move(value));
  }
  void unhandled_exception() {
    promise.set_exception(std::current_exception());
  }

  std::promise<T> promise;
};
```

Getting result from task

```
struct promise_type {
  SyncWaitImpl get_return_object() {
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  }
  std::suspend_never initial_suspend() noexcept { return {}; }
  std::suspend_never final_suspend() noexcept { return {}; }
  void return_value(T &&value) {
    promise.set_value(std::move(value));
  }
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    promise.set_exception(std::current_exception());
  }

  std::promise<T> promise;
};
```

Getting result from task

```
auto task = bar();
auto result = syncWait(task);
```

Getting result from task

```
Task<int> foo() {
  std::cout << "foo(): about to return\n";
  co_return 42;
}
Task<int> bar() {
  const auto result = foo();
  std::cout << "bar(): about to co_await\n";
  const int i = co_await result;
  std::cout << "bar(): about to return\n";
  co_return i + 23;
}

auto result = syncWait(bar());
```

Making awaiting thread-safeish

`Task<T> Promise<T>`

Making awaiting thread-safeish

`Task<T> Promise<T>`

Making awaiting thread-safeish

```
template<typename T>
struct Promise {
  //...
  auto final_suspend() noexcept {
    struct FinalAwaitable { /*...*/ };
    return FinalAwaitable{};
  }
  //...
  bool isReady() const noexcept;
  //...
  std::variant<std::monostate, T, std::exception_ptr> result;
  std::coroutine_handle<> continuation;
  enum class State { Started, AttachedContinuation, Finished };
  std::atomic<State> state = { State::Started };
};
```

Making awaiting thread-safeish

```
template<typename T>
struct Promise {
  //...
  auto final_suspend() noexcept {
    struct FinalAwaitable { /*...*/ };
    return FinalAwaitable{};
  }
  //...
};
```

```
enum class State {
  Started,
  AttachedContinuation,
  Finished
};
std::atomic<State> state = { State::Started };
```

Making awaiting thread-safeish

```
template<typename T>
struct Promise {
  //...
  auto final_suspend() noexcept {
    struct FinalAwaitable { /*...*/ };
    return FinalAwaitable{};
  }
  //...
  bool isReady() const noexcept;
  //...
  std::variant<std::monostate, T, std::exception_ptr> result;
  std::coroutine_handle<> continuation;
  enum class State { Started, AttachedContinuation, Finished };
  std::atomic<State> state = { State::Started };
};
```

Making awaiting thread-safeish

```
template<typename T>
struct Promise {
  //...
  auto final_suspend() noexcept {
    struct FinalAwaitable { /*...*/ };
    return FinalAwaitable{};
  }
  //...
  bool isReady() const noexcept;
  //...
  std::variant<std::monostate, T, std::exception_ptr> result;
  std::coroutine_handle<> continuation;
  enum class State { Started, AttachedContinuation, Finished };
  std::atomic<State> state = { State::Started };
};
```

Making awaiting thread-safeish

```
template<typename T>
struct Promise {
  //...
  auto final_suspend() noexcept {
    struct FinalAwaitable { /*...*/ };
```

```
struct FinalAwaitable {
  bool await_ready() const noexcept { return false; }
  void await_suspend(std::coroutine_handle<Promise<T>> thisCoro) noexcept {
    auto &promise = thisCoro.promise();
    const auto oldState = promise.state.exchange(State::Finished);
    if (oldState == State::AttachedContinuation)
      promise.continuation();
  }
  void await_resume() const noexcept {}
};
```

Making awaiting thread-safeish

```
template<typename T>
struct Promise {
  //...
  auto final_suspend() noexcept {
    struct FinalAwaitable { // };
    return FinalAwaitable{};
  }
  //...
  bool isReady() const noexcept;
  //...
  std::variant<std::monostate, T, std::exception_ptr> result;
  std::coroutine_handle<> continuation;
  enum class State { Started, AttachedContinuation, Finished };
  std::atomic<State> state = { State::Started };
};
```

Making awaiting thread-safeish

```
bool isReady() const noexcept {
  // return result.index() != 0;
  return state == State::Finished;
}
```

```
template<typename T>
struct Promise {
  //...
  bool isReady() const noexcept;
  //...
  std::variant<std::monostate, T, std::exception_ptr> result;
  std::coroutine_handle<> continuation;
  enum class State { Started, AttachedContinuation, Finished };
  std::atomic<State> state = { State::Started };
};
```

Making awaiting thread-safeish

```
template<typename T>
struct [[nodiscard]] Task {
  //...
  using Coro = std::coroutine_handle<>;
  bool await_suspend(Coro continuation) const noexcept {
    using State = typename Promise<T>::State;
    promise.continuation = continuation;
    auto expectedState = State::Started;
    return promise.state
      .compare_exchange_strong(expectedState,
                               State::AttachedContinuation);
  }
  //...
};
```

Making awaiting thread-safeish

```
template<typename T>
struct [[nodiscard]] Task {
  //...
    promise.continuation = continuation;
    auto expectedState = State::Started;
    return promise.state
      .compare_exchange_strong(expectedState,
                               State::AttachedContinuation);
  }
  //...
};
```

If `state` was `Started`

compare-exchange succeeds

returning `true` → coroutine is suspended

If `state` was `Finished`

compare-exchange fails

returning `false` → coroutine is not suspended

Iteration 2

```
Task<size_t> readFile() {
  std::cout << tid << " readFile(): about to read file async\n";
  const auto result = co_await AsyncReadFile{ "main.cpp" };
  std::cout << tid << " readFile(): about to return (size "
    << result.size() << ")\n";
  co_return result.size();
}

int main() {
  auto task = readFile();
  std::cout << tid << " result: " << syncWait(task) << '\n';
}
```

Iteration 2

```
Task<size_t> readFile() {
  std::cout << tid << " readFile(): about to read file async\n";
  const auto result = co_await AsyncReadFile{ "main.cpp" };
  std::cout << tid << " readFile(): about to return (size "
    << result.si
  co_return res
}

int main() {
  auto task = r
  std::cout <<
}
```

```
output:
Promise: ctor
(tid=43568) readFile(): about to read file async
(tid=17096) worker thread: opening file
(tid=17096) worker thread: reading file
(tid=17096) worker thread: resuming coro
(tid=17096) readFile(): about to return (size 120)
(tid=43568) result: 120
(tid=17096) worker thread: exiting
Promise: dtor
```

Iteration 2

```
Task<size_t> readFile() {
  std::cout << tid << " readFile(): about to read file async\n";
  const auto result = co_await AsyncReadFile{ "main.cpp" };
  std::cout << tid << " readFile(): about to return (size "
    << result.si
  co_return res
}

int main() {
  auto task = r
  std::cout <<
}
```

```
output:
Promise: ctor
(tid=11840) readFile(): about to read file async
(tid=43572) worker thread: opening file
(tid=43572) worker thread: reading file
(tid=43572) worker thread: resuming coro
(tid=43572) readFile(): about to return (size 120)
(tid=(tid=11840)43572) worker thread: exiting
 result: 120
Promise: dtor
```

Iteration 2

```
Task<size_t
  std::cout                                   file async\n";
  const aut                                   'main.cpp" };
  std::cout                                   n (size "
    << resu
  co_return
}

int main()
  auto task
  std::cout
}
```

```
ead file async
; file
; file
g coro
eturn (size 120)
ead: exiting
 result: 120
Promise: dtor
```

Drawbacks of eager tasks

```
void qux() {
  auto task = readFile();
  throw "oops...";
  syncWait(task);
}
```

Drawbacks of eager tasks

Thread A

```
void qux() {
  auto task = readFile();
  throw "oops...";
  syncWait(task);
}
```

Thread B

continues to execute on thread B

```
auto work = [this, coro]() {
  //...
⇨ coro();
  //...
};
```

Drawbacks of eager tasks

Thread A

```
void qux() {
  auto task = readFile();
  throw "oops...";
  task.~Task() ;
}
```

Thread B

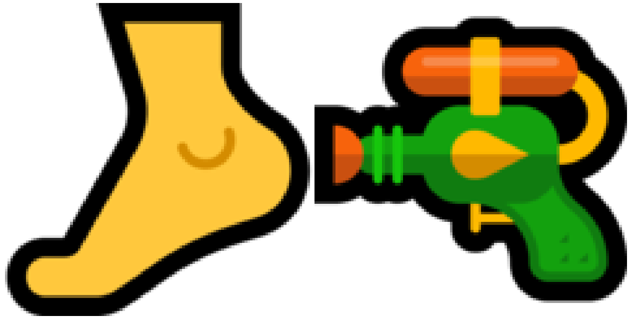
continues to execute on thread B

```
auto work = [this, coro]() {
  //...
⇨ coro();
  //...
};
```

Drawbacks of eager tasks

Thread A

```
void qux() {
   auto task = readFile();
   throw "oops...";
   task.~Task() ;
}
```



Thread B

continues to execute on thread B

```
auto work = [this, coro]() {
   //...
⇨  coro();
   //...
};
```

Drawbacks of eager tasks

Thread A

```
void qux() {
  auto task = readFile();
  throw "oops...";
  task.~Task() ;
}
```

Thread B

continues to execute on thread B

```
auto work = [this, coro]() {
    //...
⇨  coro();
    //...
};
```

State of the art solution so far: lazy tasks

Use `cppcoro` by Lewis Baker *

https://github.com/lewissbaker/cppcoro

State of the art solution so far: lazy tasks

code from Iteration 1

```
template<typename T>
struct Promise {
  Task<T> get_return_object() noexcept { return { this }; }
  std::suspend_never initial_suspend() noexcept { return {}; }
  auto final_suspend() noexcept;
  template<typename U>
  void return_value(U &&value)
    noexcept(std::is_nothrow_constructible_v<T, decltype(std::forward<U>(value))>);
  void unhandled_exception()
    noexcept(std::is_nothrow_constructible_v<std::exception_ptr, std::exception_ptr>);
  bool isReady() const noexcept;
  T &&getResult();

  std::variant<std::monostate, T, std::exception_ptr> result;
  std::coroutine_handle<> continuation;
};
```

State of the art solution so far: lazy tasks

code from Iteration 1

```
template<typename T>
struct Promise {
  Task<T> get_return_object() noexcept { return { this }; }
  std::suspend_always initial_suspend() noexcept { return {}; }
  auto final_suspend() noexcept;
  template<typename U>
  void return_value(U &&value)
    noexcept(std::is_nothrow_constructible_v<T, decltype(std::forward<U>(value))>);
  void unhandled_exception()
    noexcept(std::is_nothrow_constructible_v<std::exception_ptr, std::exception_ptr>);
  bool isReady() const noexcept;
  T &&getResult();

  std::variant<std::monostate, T, std::exception_ptr> result;
  std::coroutine_handle<> continuation;
};
```

State of the art solution so far: lazy tasks

```cpp
void qux() {
  auto task = readFile();  // does not start yet
  throw "oops...";  // safe to cleanup
  syncWait(task);   // awaiting starts the operation
}
```

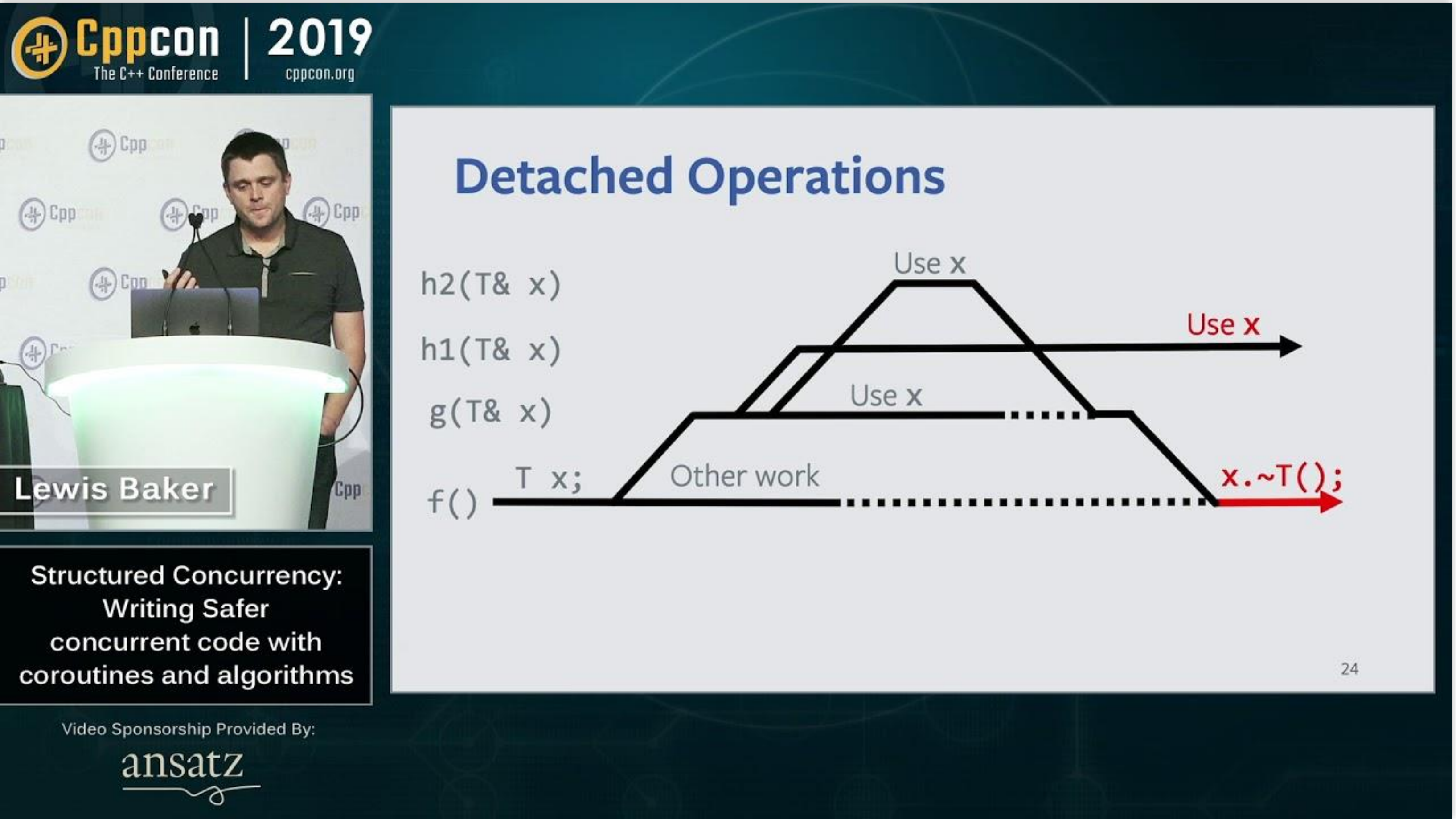
`std::lazy`

- **P2506**: `std::lazy`: a coroutine for deferred execution
  by Casey Carter http://wg21.link/p2506
- lightweight,
  starts execution when waited on (via `co_await` in a coroutine, or synchronously)

State of the art solution so far: lazy tasks

Use cppcoro by Lewis Baker *

https://github.com/lewissbaker/cppcoro



CppCon | 2019
The C++ Conference cppcon.org

Lewis Baker

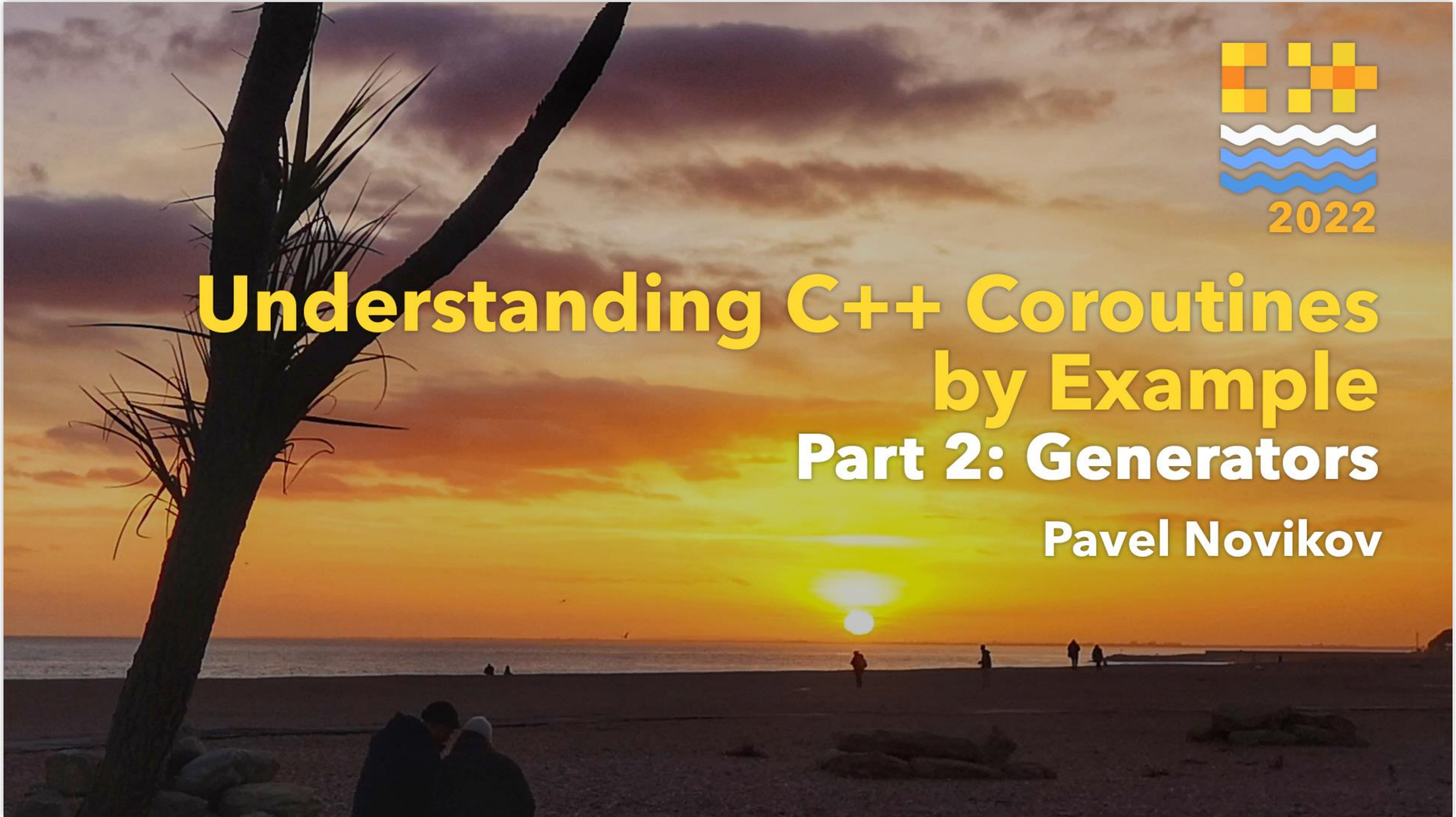
Structured Concurrency: Writing Safer concurrent code with coroutines and algorithms

Video Sponsorship Provided By: ansatz

Detached Operations

https://youtu.be/1Wy5sq3s2rg

You may want to watch



2022

Understanding C++ Coroutines by Example

Part 2: Generators

Pavel Novikov

Thanks for listening!

Understanding C++ coroutines by example part 1

Pavel Novikov

@cpp_ape

Thanks to Lewis Baker for feedback!

I owe you beer 🍻

Slides: https://bit.ly/3ulr5Ta

References

- Lewis Baker "Structured Concurrency: Writing safer concurrent code with coroutines and algorithms" https://youtu.be/1Wy5sq3s2rg
- P2506: `std::lazy`: a coroutine for deferred execution http://wg21.link/p2506

Bonus slides

getAwaitable()

```
template<typename T>
auto getAwaitableImpl(T &&a, int) ->
  decltype(std::forward<T>(a).operator co_await()) {
  return std::forward<T>(a).operator co_await();
}
template<typename T>
auto getAwaitableImpl(T &&a, long) ->
  decltype(operator co_await(std::forward<T>(a))) {
  return operator co_await(std::forward<T>(a));
}
template<typename T, typename U>
T &&getAwaitableImpl(T &&a, U) {
  return static_cast<T&&>(a);
}
```

```
template<typename T>
auto getAwaitable(T &&a) {
  return getAwaitableImpl(a, 42);
}
```

ResultOfAwait<T>

```
template<typename T>
using ResultOfAwait =
  std::decay_t<decltype(
    getAwaitable(std::declval<T>()).await_resume()
  )>;
```

tid

```
struct TidMark {
  friend
  std::ostream &operator<<(std::ostream &s, TidMark) {
    s << "(tid=" << std::this_thread::get_id() << ')';
    return s;
  }
} const tid;

std::cout << tid;
```

State machine using coroutines

Events:

```
struct Open {};
struct Close {};
struct Knock {};
```

```
enum class State {
  Closed,
  Open
};

struct Door {
  State state = State::Closed;
  template<typename E>
  void onEvent(E);
};
```

State machine using coroutines

```
void onEvent(E) {
  switch (state) {
  case State::Closed:
    if constexpr (isSame<E, Open>) {
      state = State::Open;
    }
    else if constexpr (isSame<E, Knock>) {
      shout("Come in, it's open!"); // no transition
    }
    break;
  case State::Open:
    if constexpr (isSame<E, Close>)
      state = State::Closed;
  }
}
```

State machine using ~~coroutines~~ switch

```
void onEvent(E) {
  switch (state) {
  case State::Closed:
    if constexpr (isSame<E, Open>) {
      state = State::Open;
    }
    else if constexpr (isSame<E, Knock>) {
      shout("Come in, it's open!"); // no transition
    }
    break;
  case State::Open:
    if constexpr (isSame<E, Close>)
      state = State::Closed;
  }
}
```

State machine using ~~coroutines~~ switch

```
Door door;
door.onEvent(Open{});  // Closed -> Open
door.onEvent(Close{}); // Open -> Closed
door.onEvent(Knock{});
door.onEvent(Close{}); // Closed -> Closed
```

output:

```
Come in, it's open!
```

State machine using coroutines

```
StateMachine getDoor() {
  for (;;) {
    //closed
    auto e = co_await Event<Open, Knock>{};
    if (std::holds_alternative<Knock>(e)) {
      shout("Come in, it's open!");
    }
    else if (std::holds_alternative<Open>(e)) {
      // open
      co_await Event<Close>{};
    }
  }
}
```

State machine using coroutines

```
StateMachine getDoor() {
closed:
 for (;;) {
  auto e = co_await Event<Open, Knock>{};
  if (std::holds_alternative<Knock>(e)) {
   shout("Come in, it's open!");
  }
  else if (std::holds_alternative<Open>(e)) {
   goto open;
  }
 }
open:
 co_await Event<Close>{};
 goto closed;
}
```

State machine using coroutines

```
template<typename... Events>
struct Event {};

struct StateMachine {
  struct promise_type;

  template<typename E>
  void onEvent(E e);

  ~StateMachine() { coro.destroy(); }
  StateMachine(const StateMachine &) = delete;
  StateMachine &operator=(const StateMachine &) = delete;

private:
  StateMachine(std::coroutine_handle<promise_type> coro) : coro{ coro } {}
  std::coroutine_handle<promise_type> coro;
};
```

State machine using coroutines

```
struct promise_type {
  using CoroHandle = std::coroutine_handle<promise_type>;
  StateMachine get_return_object() noexcept {
    return { CoroHandle::from_promise(*this) };
  }
  std::suspend_never initial_suspend() const noexcept { return {}; }
  std::suspend_always final_suspend() const noexcept { return {}; }
  template<typename... E>
  auto await_transform(Event<E...>) noexcept;
  void return_void() noexcept {}
  void unhandled_exception() noexcept {}

  std::any currentEvent;
  bool (*isWantedEvent)(const std::type_info&) = nullptr;
};
```

StateMachine::promise_type

```
template<typename... E>
auto await_transform(Event<E...>) noexcept {
  isWantedEvent = [](const std::type_info &type)->bool {
    return ((type == typeid(E)) || ...);
  };

  struct Awaitable { /*...*/ };
  return Awaitable{ &currentEvent };
}
```

StateMachine::promise_type

```
struct Awaitable {
  bool await_ready() const noexcept { return false; }
  void await_suspend(CoroHandle) noexcept {}
  std::variant<E...> await_resume() const {
    std::variant<E...> event;
    (void)((
      currentEvent->type() == typeid(E) ?
        (event = std::move(*std::any_cast<E>(currentEvent)), true) :
        false
    ) || ...);
    return event;
  }
  const std::any *currentEvent;
};
```

State machine using coroutines

```
struct StateMachine {
  //...
  template<typename E>
  void onEvent(E &&e) {
    auto &promise = coro.promise();
    if (promise.isWantedEvent(typeid(E))) {
      promise.currentEvent = std::forward<E>(e);
      coro();
    }
  }
  //...
};
```

State machine using coroutines

```
auto door = getDoor();
door.onEvent(Open{});  // Closed -> Open
door.onEvent(Close{}); // Open -> Closed
door.onEvent(Knock{});
door.onEvent(Close{}); // Closed -> Closed
```

output:

```
Come in, it's open!
```

State machine using coroutines

```
StateMachine getDoor(std::string answer) {
closed:
  for (;;) {
    auto e = co_await Event<Open, Knock>{};
    if (std::holds_alternative<Knock>(e)) {
      shout(answer);
    }
    else if (std::holds_alternative<Open>(e)) {
      goto open;
    }
  }
open:
  co_await Event<Close>{};
  goto closed;
}
```

State machine using coroutines

```
auto door = getDoor("Occupied!");
door.onEvent(Open{});  // Closed -> Open
door.onEvent(Close{}); // Open -> Closed
door.onEvent(Knock{});
door.onEvent(Close{}); // Closed -> Closed
```

output:

```
Occupied!
```