# Understanding C++ Coroutines By Example

## Generators (Part 1 of 2)

PAVEL NOVIKOV

Cppcon
The C++ Conference

2022
September 12th-16th

# Understanding C++ coroutines by example part 2: generators

Pavel Novikov

@cpp_ape

# Coroutines at CppCon 2022

Monday 12th September:

- C++20’s Coroutines for Beginners by Andreas Fertig

- Deciphering Coroutines: A Visual Approach by Andreas Weis

Tuesday 13th September:

- Understanding C++ coroutines by example, part 2: generators

you are here

Thursday 15th September:

- C++ Coroutines, from Scratch by Phil Nash

# Goals of this talk

Develop intuition about how generators work:

- coroutine generators in general
- range generators
  + how recursive generators work in principle
- async generators

**Disclaimer**

Code on the slides is intended for educational purposes,

it is somewhat suboptimal and should not be used in production as it is.

# What is a C++ coroutine?

```
Generator<int> foo() {
  co_yield 42;
}
```

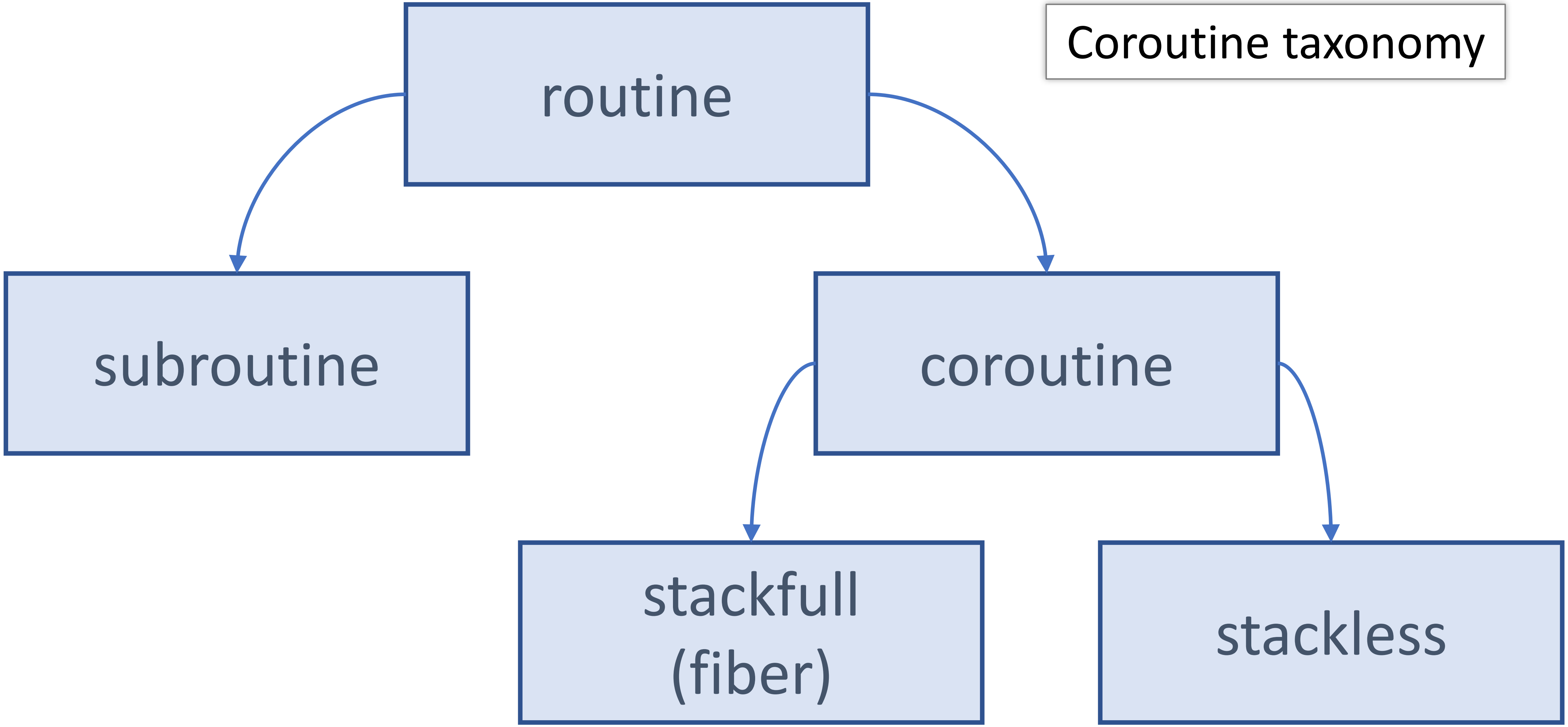
A function is a coroutine if it contains one of these:

`co_return` (coroutine return statement)

`co_await` (await expression)

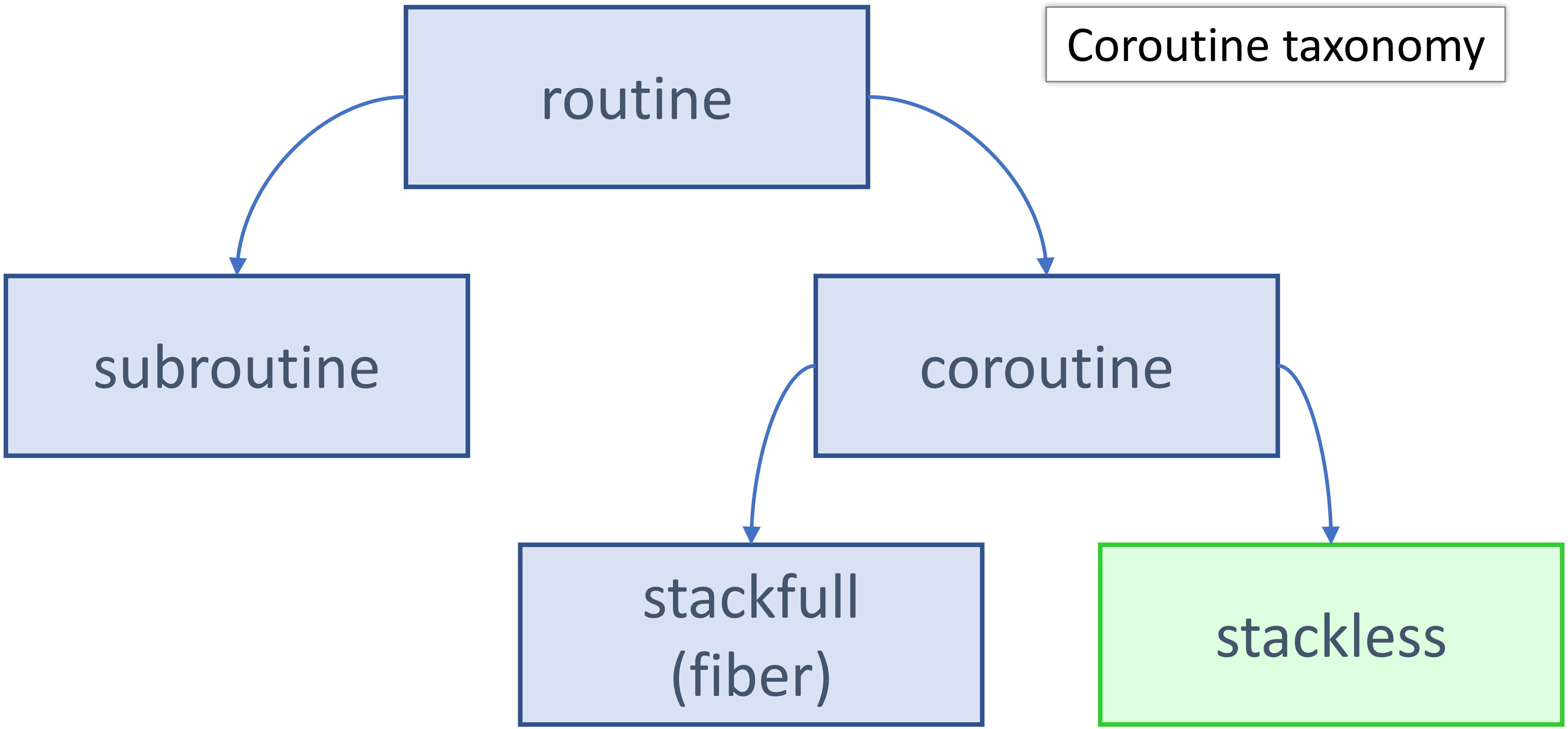
`co_yield` (yield expression)

# What is a C++ coroutine?




Coroutine taxonomy

# What is a C++ coroutine?



# What is a C++ coroutine?

## 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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# What is a C++ coroutine?

```
Generator<int> foo() {
  co_yield 42;
}
```

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

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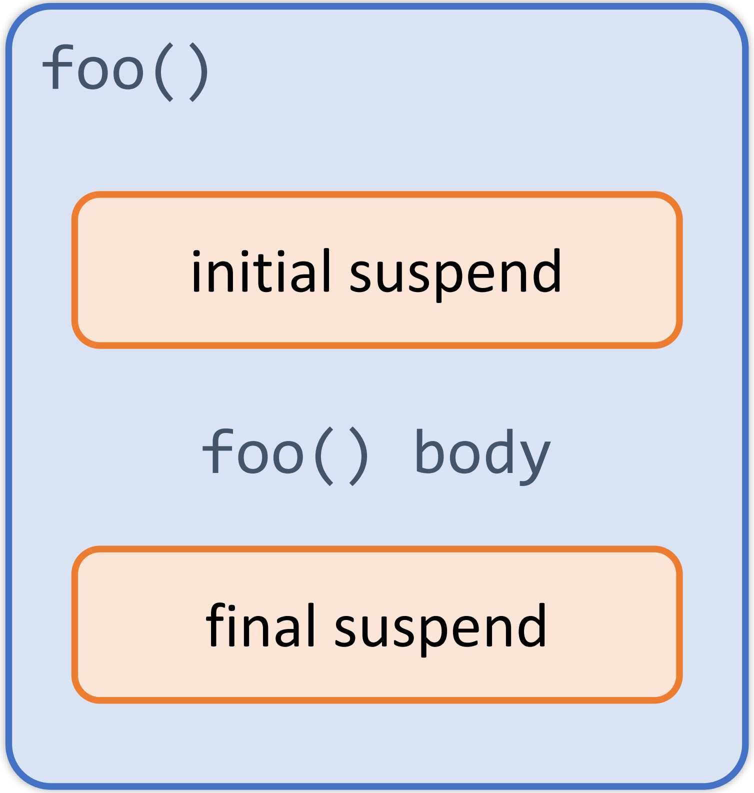


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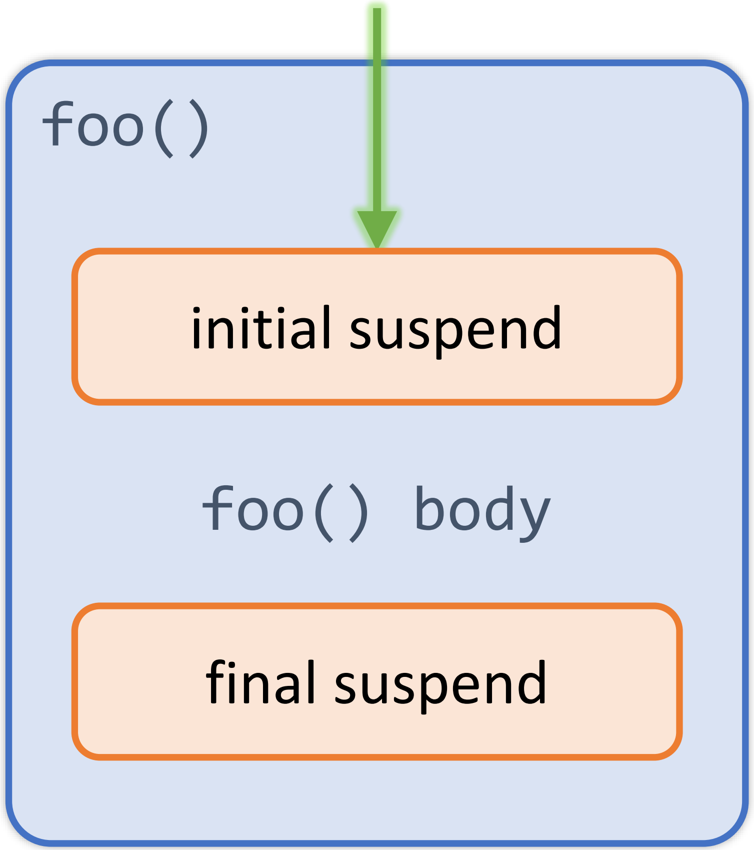


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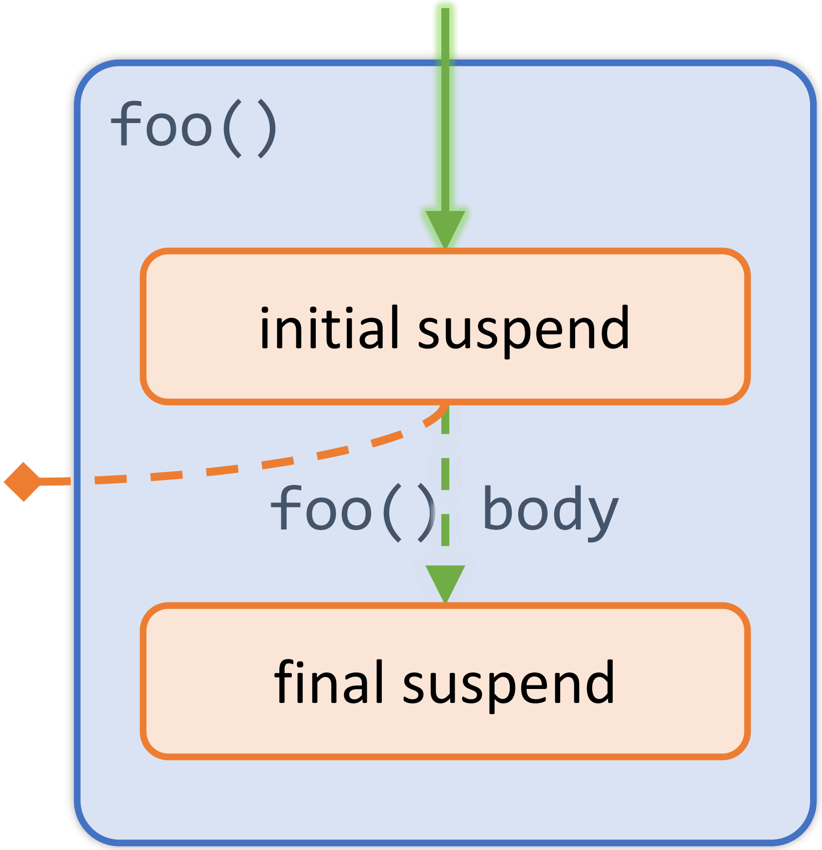


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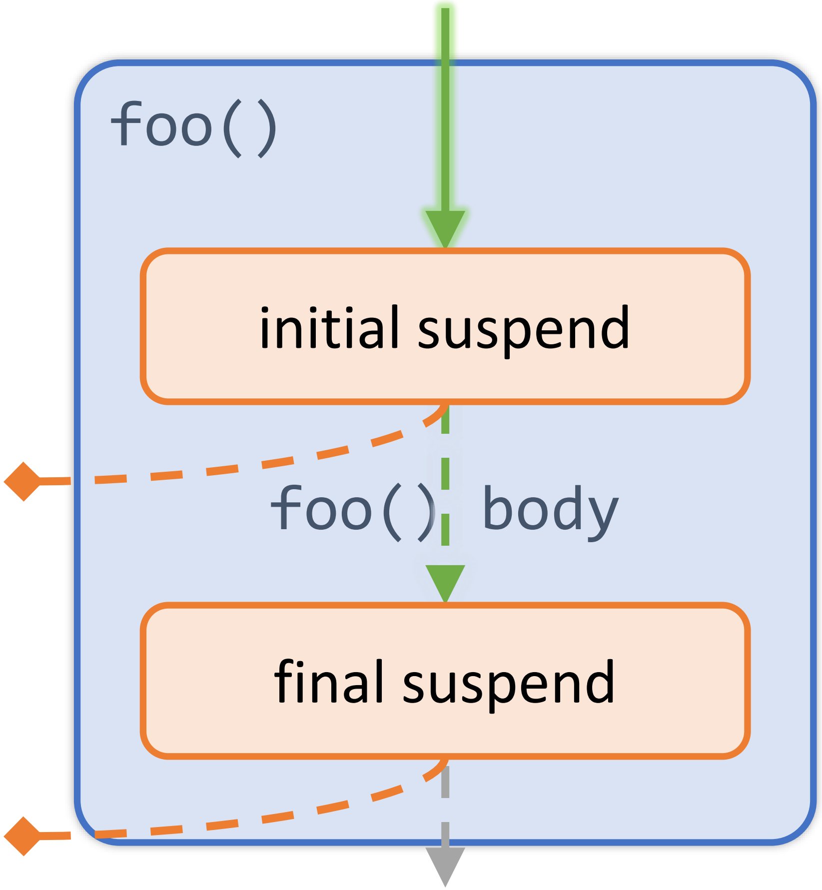


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final-suspend :
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```

# What is a C++ coroutine?

```
co_yield expression
```

⇩

```
co_await promise.yield_value(expression)
```

# What is a C++ coroutine?

```
co_return expression_opt;
```

should be of type `void` in our case

```
{
   expression_opt;
   promise.return_void();
   goto final-suspend;
}
```

# What is a C++ coroutine?

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co_return expression_opt;
```

should be of type void in our case

```
{
  expression_opt;
  promise.return_void();
  goto final-suspend;
}
```

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

# What is a C++ coroutine?

```
co_return expression_opt;
```

```
{
  expression_opt;
  promise.return_void();
  goto final-suspend;
}
```

should be of type `void` in our case

```
Generator<int> foo() {
  co_yield 42;
  // implicit co_return;
}
```

# Best practices so far

- "Lazy" asynchronous tasks which do not start immediately,
  they are suspended at initial suspend point
  (contrast to "eager" tasks)
- Result from asynchronous tasks can be obtained either
  - by `co_await`ing within a coroutine (possibly suspending it), or
  - by synchronously waiting (possibly blocking the thread)

  (unlike `std::future` and co.)

Watch **Lewis Baker**'s talk

*"Structured Concurrency:
Writing safer concurrent code with coroutines and algorithms"*

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

```
const auto f = foo();
std::cout << f() << ' ' << f() << '\n';
```

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**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

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const auto f = foo();
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```

suspends

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const auto f = foo();
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# “Naïve” generator

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Generator<std::string> foo() {
  co_yield "hello";
  
  const auto s = std::string{ "world" };
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}
```

resumes

```
const auto f = foo();
std::cout << f() << ' ' << f() << '\n';
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}
```

**coroutine frame**
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**promise**
tells when and how to suspend and resume

and internal state stuff

lives until f is destroyed

```cpp
const auto f = foo();
std::cout << f() << ' ' << f() << '\n';
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  co_yield s;
}
```

**coroutine frame**
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```
const auto f = foo();
std::cout << f() << ' ' << f() << '\n';
```

outputs
```
hello world
```

# “Naïve” generator

Why *initial suspend*?

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}

{
  const auto g = bar();  // created but not used
}
```

# “Naïve” generator

Why *initial suspend*?

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```

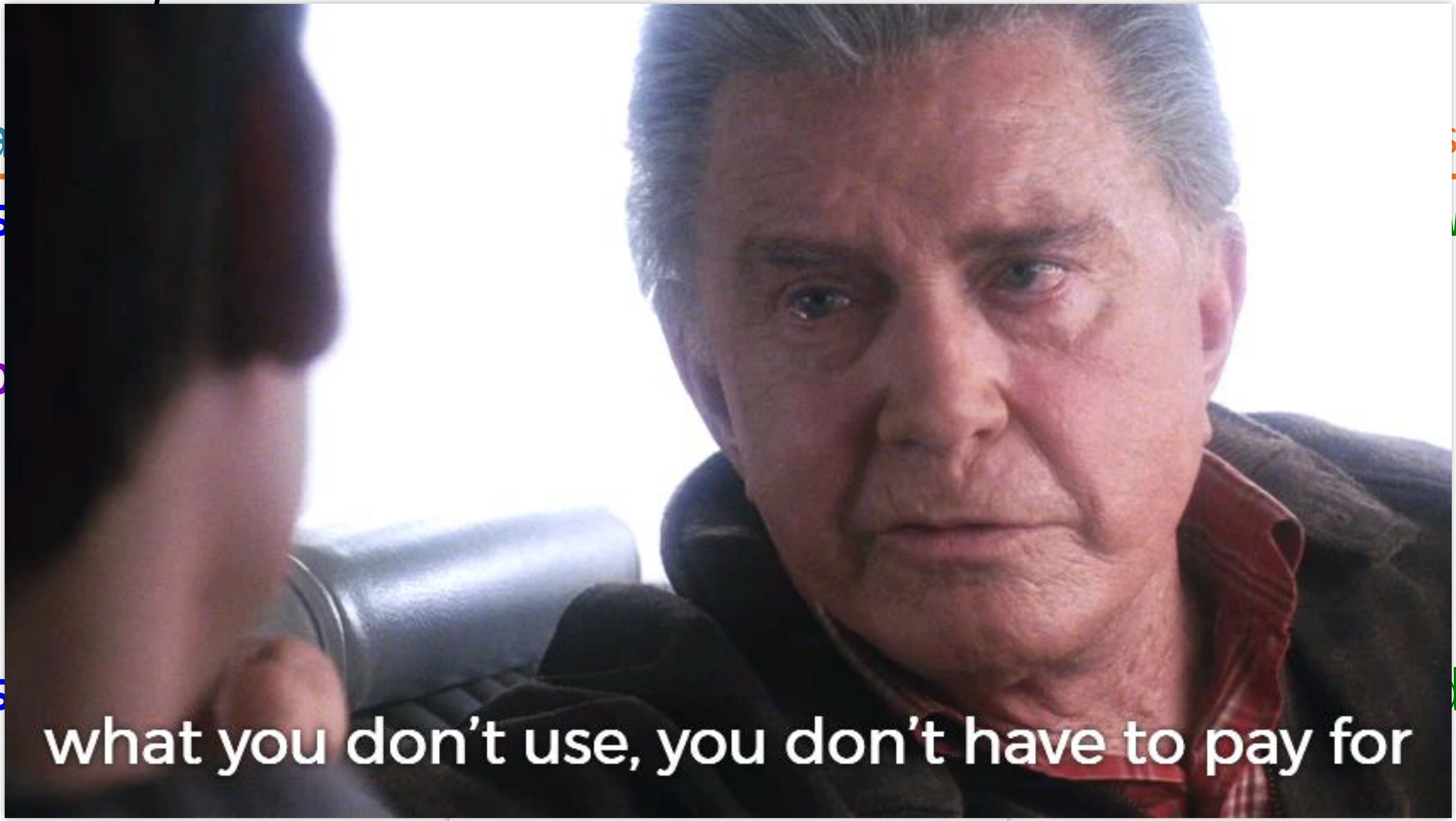
zero overhead principle

# “Naïve” generator

Why *initial suspend*?

```
Genera                                    suspend
   cons
   for
      co
}

{
   cons
}
```




zero overhead principle

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{
  const auto f = foo();
  std::cout << f() << '\n';
} // f is safely destroyed
```

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  co_yield s;
}
```

```cpp
{
  const auto f = foo();
  std::cout << f() << '\n';
} f.~Generator<std::string>()
```

safely* destroys coroutine frame
in suspended state
and frees all associated resources

# “Naïve” generator

```
Generator<std::string> foo(std::string greeting) {
  co_yield greeting;

  const auto s = std::string{ "world" };
  co_yield s;
}
```

```
const auto f = foo("hi");
std::cout << f() << ' ' << f() << '\n';
```

outputs
`hi world`

# “Naïve” generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  auto &operator()() const;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

probably should be `[[nodiscard]]`

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only coroutine handle is stored

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# “Naïve” generator

mandatory

```
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  std::suspend_always final_suspend() const noexcept;

  std::suspend_always yield_value(const T &value) noexcept(std::is_nothrow_copy_constructible_v<T>);

  void return_void() const noexcept {}

  void unhandled_exception() noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  T &getValue();

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

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```

**coroutine frame**
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# “Naïve” generator

```
auto get_return_object() noexcept {
  return Generator{ *this };
}
```

# “Naïve” generator

```
auto get_return_object() noexcept {
  return Generator{ *this };
}
```

```
Generator<std::string> foo();


const auto f = foo();
```

# “Naïve” generator

```
auto get_return_object() noexcept {
  return Generator{ *this };
}
```

```
Generator<std::string> foo();

const auto f = foo();
```

# “Naïve” generator

```
auto get_return_object() noexcept {
  return Generator{ *this };
}
```

```
Generator<std::string> foo();

const auto f = foo();
```

# “Naïve” generator

```
std::suspend_always initial_suspend() const noexcept {
  return {};
}
std::suspend_always final_suspend() const noexcept {
  return {};
}
```

```
Generator<std::string> foo() {                    initial suspend
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;                                       final suspend
}
```

# “Naïve” generator

```
std::suspend_always yield_value(const T &value)
  noexcept(std::is_nothrow_copy_constructible_v<T>) {
  result = value;
  return {};
}
```

# "Naïve" generator

```
std::suspend_always yield_value(const T &value)
  noexcept(std::is_nothrow_copy_constructible_v<T>) {
  result = value;
  return {};
}
```

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

# “Naïve” generator

```
std::suspend_always yield_value(const T &value)
  noexcept(std::is_nothrow_copy_constructible_v<T>) {
  result = value;
  return {};
}
```

```
co_yield expression
```

$\Downarrow$

```
co_await promise.yield_value(expression)
```

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

# “Naïve” generator

```
std::suspend_always yield_value(const T &value)
  noexcept(std::is_nothrow_copy_constructible_v<T>) {
  result = value;
  return {};
}
```

```
Generator<std::string> foo() {
  co_yield "hello";                                   suspends

  const auto s = std::string{ "world" };
  co_yield s;
}
```

# “Naïve” generator

```
void return_void() const noexcept {}
```

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
  co_return;
}
```

# “Naïve” generator

```
void return_void() const noexcept {}
```

```
co_return expressionopt;
```

⇩

```
{ expressionopt; promise.return_void(); goto final-suspend; }
```

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
  co_return;
}
```

# “Naïve” generator

```
void return_void() const noexcept {}
```

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
  co_return;
}
```

# “Naïve” generator

```
void return_void() const noexcept {}
```

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;

}
```

# “Naïve” generator

```
void unhandled_exception()
  noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>) {
  result = std::current_exception();
}
```

```
{
  //...
  try {
    //...
    function-body
  }
  catch (...) {
    //...
    promise.unhandled_exception();
  }
  //...
}
```

# “Naïve” generator

```
struct promise_type {
  //...

  T &getValue() {
    if (std::holds_alternative<std::exception_ptr>(result))
      std::rethrow_exception(std::get<std::exception_ptr>(result));
    return std::get<T>(result);
  }

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

# “Naïve” generator

```
struct promise_type {
  //...

  T &getValue() {
    if (std::holds_alternative<std::exception_ptr>(result))
      std::rethrow_exception(std::get<std::exception_ptr>(result));
    return std::get<T>(result);
  }

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

precondition:
we must have result or exception

# “Naïve” generator

mandatory

```
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  std::suspend_always final_suspend() const noexcept;

  std::suspend_always yield_value(const T &value) noexcept(std::is_nothrow_copy_constructible_v<T>);

  void return_void() const noexcept {}

  void unhandled_exception() noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  T &getValue();

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

# “Naïve” generator

mandatory

```
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  std::suspend_always final_suspend() const noexcept;

  std::suspend_always yield_value(const T &value) noexcept(std::is_r

  void return_void() const noexcept {}

  void unhandled_exception() noexcept(std::is_nothrow_copy_constructi

  T &getValue();

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

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

# “Naïve” generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  auto &operator()() const;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# “Naïve” generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  auto &operator()() const;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

only coroutine handle is stored

# “Naïve” generator

```
Generator(Generator &&other) noexcept :
  coro{ std::exchange(other.coro, nullptr) }
{}

Generator &operator=(Generator &&other) noexcept {
  if (coro)
    coro.destroy();
  coro = std::exchange(other.coro, nullptr);
}

~Generator() {
  if (coro)
    coro.destroy();
}
```

# "Naïve" generator

```
Generator(Generator &&other) noexcept :
  coro{ std::exchange(other.coro, nullptr) }
{}

Generator &operator=(Generator &&other) noexcept {
  if (coro)
    coro.destroy();
  coro = std::exchange(other.coro, nullptr);
}

~Generator() {
  if (coro)
    coro.destroy();
}
```

# “Naïve” generator

```
Generator(Generator &&other) noexcept :
  coro{ std::exchange(other.coro, nullptr) }
{}

Generator &operator=(Generator &&other) noexcept {
  if (coro)
    coro.destroy();
  coro = std::exchange(other.coro, nullptr);
}

~Generator() {
  if (coro)
    coro.destroy();
}
```

# “Naïve” generator

```
auto &operator()() const {
  coro();  // same as 'coro.resume()'
  return coro.promise().getValue();
}
```

# “Naïve” generator

```
auto &operator()() const {
  coro();  // same as 'coro.resume()'
  return coro.promise().getValue();
}
```

```
struct promise_type {
  //...

  T &getValue() {
    if (std::holds_alternative<std::exception_ptr>(result))
      std::rethrow_exception(std::get<std::exception_ptr>(result));
    return std::get<T>(result);
  }

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

# “Naïve” generator

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

private:
  explicit Generator(promise_type &promise) noexcept :
    coro{ std::coroutine_handle<promise_type>::from_promise(promise) }
  {}

  std::coroutine_handle<promise_type> coro;
};
```

```
struct promise_type {
  auto get_return_object() noexcept {
    return Generator{ *this };
  }
  //...
};
```

# “Naïve” generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  auto &operator()() const;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

only coroutine handle is stored

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
   co_yield "hello";

   const auto s = std::string{ "world" };
   co_yield s;
}
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

```
auto get_return_object() noexcept {
  return Generator{ *this };
}
```

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

**coroutine frame**
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# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```cpp
Generator<std::string> foo() {
  co_yield "hello";
```

suspends

**coroutine frame**
contains

**promise**
tells when and how to
me

and internal state stuff

```cpp
std::suspend_always initial_suspend() const noexcept {
  return {};
}
```

```cpp
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
   co_yield "hello";

   const auto s = std::string{ "world" };
   co_yield s;
}


const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

**coroutine frame**
contains

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and internal state stuff

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";
```

```
auto &Generator::operator()() const {
  coro();  // same as 'coro.resume()'
  return coro.promise().getValue();
}
```

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

**coroutine frame**

contains

**promise**

tells when and how to suspend and resume

and internal state stuff

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";
}
```

resumes

```
auto &Generator::operator()() const {
  coro();  // same as 'coro.resume()'
  return coro.promise().getValue();
}
```

**coroutine frame**

contains

**promise**

tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";                resumes

  const auto s = std::string{ "world" };
  co_yield s;
}


const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

# “Naïve” generator

```cpp
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}


const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";
```

```
std::suspend_always yield_value(const T &value)
  noexcept(std::is_nothrow_copy_constructible_v<T>) {
  result = value;
  return {};
}
```

**coroutine frame**

contains

**promise**

en and how to

d and resume

rnal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";
```

suspends

```
std::suspend_always yield_value(const T &value)
  noexcept(std::is_nothrow_copy_constructible_v<T>) {
  result = value;
  return {};
}
```

**coroutine frame**

contains

**promise**

...en and how to

...d and resume

...rnal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
   co_yield "hello";

   const auto s = std::string{ "world" };
   co_yield s;
}
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
   co_yield "hello";
```

```
auto &Generator::operator()() const {
   coro();  // same as 'coro.resume()'
   return coro.promise().getValue();
}
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```cpp
Generator<std::string> foo() {
  co_yield "hello";
```

```cpp
auto &Generator::operator()() const {
  coro();  // same as 'coro.resume()'
  return coro.promise().getValue();
}
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```cpp
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# "Naïve" generator

```
Generator<std::string> foo() {
  co_yield "hello";
```

```
auto &Generator::operator()() const {
  coro();  // same as 'coro.resume()'
  return coro.promise().getValue();
}
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```
T &getValue() {
  if (std::holds_alternative<std::exception_ptr>(result))
    std::rethrow_exception(std::get<std::exception_ptr>(result));
  return std::get<T>(result);
}
```

# “Naïve” generator

```
Generator<std::string> foo() {
   co_yield "hello";

   const auto s = std::string{ "world" };
   co_yield s;
}
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
   co_yield "hello";

   const auto s = std::string{ "world" };
   co_yield s;
}
```

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```cpp
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

resumes

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```cpp
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
   co_yield "hello";

   const auto s = std::string{ "world" };
   co_yield s;
}
```

**coroutine frame**

contains

**promise**

tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

suspends

**coroutine frame**
contains

**promise**
tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
   co_yield "hello";

   const auto s = std::string{ "world" };
   co_yield s;
}
```

**coroutine frame**

contains

**promise**

tells when and how to suspend and resume

and internal state stuff

```
const auto f = foo();
std::cout << f() << ' '
          << f() << '\n';
```

# “Naïve” generator

- can’t know if there are more values
- perfect for infinite sequences
  though

# “Naïve” generator

- can’t know if there are more values
- perfect for infinite sequences though

```
Generator<int>
```

```
() {
  int prev = 1, next = 1;
  for (;;) {
    co_yield next;
    std::swap(prev, next);
    next += prev;
  }
}

const auto f =
```

```
();
for (size_t i = 0; i != 5; ++i)
  std::cout << f() << '\n';
```

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

```
const auto f = foo();
std::cout << f() << ' '    // yields "hello"
          << f() << '\n';  // yields "world"
```

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

```
const auto f = foo();
std::cout << f() << ' '    // yields "hello"
          << f() << '\n';  // yields "world"
```

# “Naïve” generator

```
Generator<std::string> foo() {
  co_yield "hello";

  const auto s = std::string{ "world" };
  co_yield s;
}
```

```
const auto f = foo();
std::cout << f() << ' '    // yields "hello"
          << f() << '\n';  // yields "world"
std::cout << f();          // ???
```

# “Naïve” generator

- unnecessary extra copy

```
Generator<std::string> foo() {
  co_yield "hello";
  //...
}
```

T = std::string

```
std::suspend_always yield_value(const T &value)
  noexcept(std::is_nothrow_copy_constructible_v<T>) {
  result = value;
  return {};
}
```

copies value into `result`

# “Naïve” generator

```
const auto s = std::string{ "world" };
co_yield s;
```

```
co_await promise.yield_value(s);
```

# “Naïve” generator

```
const auto s = std::string{ "world" };
co_yield s;
```

```
co_await promise.yield_value(s);
```

suspends

# “Naïve” generator

```
const auto s = std::string{ "world" };
co_yield s;
```

```
co_await promise.yield_value(s);
```

variable is still accessible during suspension

# “Naïve” generator

```
co_yield "hello";
```

```
co_await promise.yield_value("hello");
```

# “Naïve” generator

```
co_yield "hello";
```

```
std::string t{ "hello" }
```

```
co_await promise.yield_value(   t   );
```

# “Naïve” generator

```
co_yield "hello";
```

```
std::string t{ "hello" }
```

```
co_await promise.yield_value( t );
```

suspends

# “Naïve” generator

```
co_yield "hello";
```

```
std::string t{ "hello" }
```

```
co_await promise.yield_value(   t   );
```

# “Naïve” generator

```
co_yield "hello";
```

```
std::string t{ "hello" }
```

```
co_await promise.yield_value(   t   );
```

resumes

# “Naïve” generator

```
co_yield "hello";
```

```
std::string t{ "hello" }
```

```
co_await promise.yield_value(   t   );
```

```
t.~std::string()
```

resumes

# “Naïve” generator

```
co_yield "hello";
```

```
std::string t{ "hello" }
```

```
co_await promise.yield_value(    t    );
```

```
t.~std::string()
```

resumes

```
std::suspend_always yield_value(const T &value)
  noexcept(std::is_nothrow_copy_constructible_v<T>) {
  result = value;
  return {};
}
```

reference is valid during suspension
(until destruction of coroutine frame)

# “Naïve” generator

At this point you know almost everything you need to know about how generators work.

The rest is just interface design and making design decisions.

# Simple generator

```
const auto g = bar();
while (g.hasValue())
  std::cout << g() << '\n';
```

# Simple generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  bool hasValue() const noexcept;  //has value or exception
  auto &operator()() const;

private:
  explicit Generator(promise_type &promise) noexcept;

  void getNextValue() const noexcept;

  std::coroutine_handle<promise_type> coro;
  mutable bool gotValue = false;
};
```

# Simple generator

```
const auto g = bar();
std::cout << g() << '\n'; // we _know_ it has a value
```

compared to

has to get the next value

```
if (g.hasValue())
  std::cout << g() << '\n';
```

# Simple generator

```
const auto g = bar();
while (g.hasValue())
  std::cout << g() << '\n';
```

# Simple generator

```
const auto g = bar();
while (g.hasValue())
  std::cout << g() << '\n';
```

UGLY

# Simple generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  bool advance() const noexcept;
  auto &getValue() const;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# Simple generator

```
const auto g = bar();
while (g.advance())
  std::cout << g.getValue() << '\n';
```

# Simple generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  bool advance() const noexcept;
  auto &getValue() const;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# Simple generator

```
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  std::suspend_always final_suspend() const noexcept;

  std::suspend_always yield_value(const T &value) noexcept(std::is_nothrow_copy_constructible_v<T>);

  void return_void() const noexcept {}

  void unhandled_exception() noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  bool hasException() const noexcept;
  T &getValue();

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

# Simple generator

```
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  std::suspend_always final_suspend() const noexcept;

  std::suspend_always yield_value(const T &value) noexcept(std::is_nothrow_copy_constructible_v<T>);

  void return_void() const noexcept {}

  void unhandled_exception() noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  bool hasException() const noexcept;
  T &getValue();

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

# Simple generator

```
struct promise_type {
  //...
  std::suspend_always yield_value(const T &value)
    noexcept(std::is_nothrow_copy_constructible_v<T>) {
    result = value;
    return {};
  }



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

copies value into result

# Simple generator

```
struct promise_type {
  //...
  std::suspend_always yield_value(const T &value)
    noexcept(std::is_nothrow_copy_constructible_v<T>) {
    result = value;
    return {};
  }
  std::suspend_always yield_value(T &&value) noexcept {
    result = std::addressof(value);
    return {};
  }
  //...
private:
  std::variant<std::monostate, T, T*, std::exception_ptr> result;
};
```

copies value into result

# Simple generator

```
struct promise_type {
  //...
  bool hasException() const noexcept {
    return std::holds_alternative<std::exception_ptr>(result);
  }
  T &getValue() {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));

    return std::holds_alternative<T>(result) ? std::get<T>(result) :
                                               *std::get<T*>(result);
  }
  //...
private:
  std::variant<std::monostate, T, T*, std::exception_ptr> result;
};
```

# Simple generator

```
struct promise_type {
  //...
  bool hasException() const noexcept {
    return std::holds_alternative<std::exception_ptr>(result);
  }
  T &getValue() {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));

    return std::holds_alternative<T>(result) ? std::get<T>(result) :
                                                *std::get<T*>(result);
  }
  //...
private:
  std::variant<std::monostate, T, T*, std::exception_ptr> result;
};
```

# Simple generator

```cpp
struct promise_type {
  //...
  bool hasException() const noexcept {
    return std::holds_alternative<std::exception_ptr>(result);
  }
  T &getValue() {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));

    return std::holds_alternative<T>(result) ? std::get<T>(result) :
                                               *std::get<T*>(result);
  }
  //...
private:
  std::variant<std::monostate, T, T*, std::exception_ptr> result;
};
```

precondition:
we must have result or exception

# Simple generator

```
const auto f = foo();
std::vector<std::string> values;
while (f.advance())
  values.push_back(std::move(f.getValue()));
```

# Simple generator

```
const auto f = foo();
std::vector<std::string> values;
while (f.advance())
  values.push_back(std::move(f.getValue()));
```

value is returned by non-const reference and can be moved from

# Simple generator

```
const auto f = foo();
std::vector<std::string> values;
while (f.advance())
  values.push_back(std::move(f.getValue());
```

value is returned by non-const reference and can be moved from

What if we want to yield values only by `const` reference?

# Simple generator

```
const
std::
while
   val
```


What if we want to yield values only by `const` reference?

```cpp
struct promise_type {
  //...
  std::suspend_always yield_value(const T &value) noexcept {
    result = std::addressof(value);
    return {};
  }
  //...
  const T &getValue() {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));

    return *std::get<const T*>(result);
  }
  //...
private:
  std::variant<std::monostate, const T*, std::exception_ptr> result;
};
```

```cpp
struct promise_type {
  //...
  std::suspend_always yield_value(const T &value) noexcept {
    result = std::addressof(value);
    return {};
  }
  //...
  const T &getValue() {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));

    return *std::get<const T*>(result);
  }
  //...
private:
  std::variant<std::monostate, const T*, std::exception_ptr> result;
};
```

```
struct promise_type {
  //...
  std::suspend_always yield_value(const T &value) noexcept {
    result = std::addressof(value);
    return {};
  }
  //...
  const T &getValue() {
    if (hasException())
      std::rethrow_exception(std::get<std::

    return *std::get<const T*>(result);
  }
  //...
private:
  std::variant<std::monostate, const T*, std::exception_ptr> result;
};
```

```
template<typename T>
struct Generator<const T> {
  struct promise_type;

  //...

  auto &getValue() const;

  //...
};
```

# Simple generator

```
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  std::suspend_always final_suspend() const noexcept;

  std::suspend_always yield_value(const T &value) noexcept(std::is_nothrow_copy_constructible_v<T>);
  std::suspend_always yield_value(T &&value) noexcept;

  void return_void() const noexcept {}

  void unhandled_exception() noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  bool hasException() const noexcept;
  T &getValue();

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

# Simple generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  bool advance() const noexcept;
  auto &getValue() const;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# Simple generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  bool advance() const noexcept;
  auto &getValue() const;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# Simple generator

```
template<typename T>
struct Generator {
  //...
  bool advance() const noexcept {
    coro();
    return !coro.done() || coro.promise().hasException();
  }
  auto &getValue() const {
    return coro.promise().getValue();
  }

  //...
};
```

# Simple generator

```
template<typename T>
struct Generator {
  //...
  bool advance() const noexcept {
    coro();
    return !coro.done() || coro.promise().hasException();
  }
  auto &getValue() const {
    return coro.promise().getValue();
  }

  //...
};
```

# Simple generator

```
template<typename T>
struct Generator {
  //...
  bool advance() const noexcept {
    coro();
    return !coro.done() || coro.promise().hasException();
  }
  auto &getValue() const {
    return coro.promise().getValue();
  }

  //...
};
```

precondition:
`advance()` must be called and return `true`

# Simple generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}

const auto g = bar();
try {
  while (g.advance())
    std::cout << g.getValue() << '\n';
}
catch (const std::exception &e) {
  std::cout << "exception: " << e.what() << '\n';
}
```

# Simple generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}

const auto g = bar();
try {
  while (g.advance())
    std::cout << g.getValue() << '\n';
}
catch (const std::exception &e) {
  std::cout << "exception: " << e.what() << '\n';
}
```

may throw exception
from within the coroutine

# Simple generator

```
const auto g = bar();
//...
try {
  if (g.advance())                  // has exception, not value
    std::cout << g.getValue() << '\n';  // throws
}
catch (const std::exception &e) {
  std::cout << "exception: " << e.what() << '\n';
}

std::cout << g.getValue() << '\n'; // still has exception
                                    // and throws
```

# Simple generator

```
const auto g = bar();
//...
try {
  if (g.advance())                  // has exception, not value
    std::cout << g.getValue() << '\n';  // throws
}
catch (const std::exception &e) {
  std::cout << "exception: " << e.what() << '\n';
}

std::cout << g.getValue() << '\n'; // still has exception
                                   // and throws
```

# Simple generator

```
const auto g = bar();
//...
try {
  if (g.advance())                  // has exception, not value
    std::cout << g.getValue() << '\n';  // throws
}
catch (const std::exception &e) {
  std::cout << "exception: " << e.what() << '\n';
}

std::cout << g.getValue() << '\n'; // still has exception
                                   // and throws
```

# Simple generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  bool advance() const noexcept;
  auto &getValue() const;
  bool hasException() const noexcept;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# Simple generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  bool advance() const noexcept;
  auto &getValue() const;
  bool hasException() const n

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

```
bool hasException() const noexcept {
  return coro.promise().hasException();
}
```

# Simple generator

```
const auto g = bar();
while (g.advance()) {
  if (g.hasException()) {
    // handle exception
  }

  std::cout << g.getValue() << '\n';
}
```

# Simple generator

```
const auto g = bar();
while (g.advance()) {
  if (g.hasException()) {
    // handle exception
  }

  std::cout << g.getValue() << '\n';
}
```

UGLY

# What we want to have

Required operations:

- check if there are values
- get a value
- advance to the next value

# What we want to have

Required operations:

- check if there are values
- get a value
- advance to the next value

Iterators and ranges:

```
auto i = r.begin()
if (i != r.end()) {   // check
  auto x = *i;        // get
  ++i;                // advance
}
```

# What we want to have

```
const auto f = foo();
auto i = f.begin();
std::cout << *i << ' ' << *(++i) << '\n';
```

```
const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

# What we want to have

```
const auto f = foo();
auto i = f.begin();
std::cout << *i << ' ' << *(++i) << '\n';
```

```
const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

# Range generator

```
template<typename T>
struct Generator {
  struct promise_type;
  struct Iterator;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  Iterator begin() const;
  Iterator end() const noexcept;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

```cpp
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  std::suspend_always final_suspend() const noexcept;

  std::suspend_always yield_value(const T &value)
    noexcept(std::is_nothrow_copy_constructible_v<T>);
  std::suspend_always yield_value(T &&value) noexcept;

  void return_void() const noexcept {}

  void unhandled_exception()
    noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  bool isValueInitialized() const noexcept;
  T &getValue() noexcept;
  bool hasException() const noexcept;
  void throwIfException() const;

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

```cpp
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  std::suspend_always final_suspend() const noexcept;

  std::suspend_always yield_value(const T &value)
    noexcept(std::is_nothrow_copy_constructible_v<T>);
  std::suspend_always yield_value(T &&value) noexcept;

  void return_void() const noexcept {}

  void unhandled_exception()
    noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  bool isValueInitialized() const noexcept;
  T &getValue() noexcept;
  bool hasException() const noexcept;
  void throwIfException() const;

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

```
struct promise_type {
//...
  bool isValueInitialized() const noexcept {
    return !std::holds_alternative<std::monostate>(result);
  }
  T &getValue() noexcept {
    return std::holds_alternative<T>(result) ? std::get<T>(result) :
                                                *std::get<T*>(result);
  }
  bool hasException() const noexcept {
    return std::holds_alternative<std::exception_ptr>(result);
  }
  void throwIfException() const {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));
  }
//...
};
```

```cpp
struct promise_type {
//...
  bool isValueInitialized() const noexcept {
    return !std::holds_alternative<std::monostate>(result);
  }
  T &getValue() noexcept {
    return std::holds_alternative<T>(result) ? std::get<T>(result) :
                                                *std::get<T*>(result);
  }
  bool hasException() const noexcept {
    return std::holds_alternative<std::exception_ptr>(result);
  }
  void throwIfException() const {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));
  }
//...
};
```

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struct promise_type {
//...
  bool isValueInitialized() const noexcept {
    return !std::holds_alternative<std::monostate>(result);
  }
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    return std::holds_alternative<T>(result) ? std::get<T>(result) :
                                               *std::get<T*>(result);
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    return std::holds_alternative<std::exception_ptr>(result);
  }
  void throwIfException() const {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));
  }
//...
};
```

```
struct promise_type {
//...
  bool isValueInitialized() const noexcept {
    return !std::holds_alternative<std::monostate>(result);
  }
  T &getValue() noexcept {
    return std::holds_alternative<T>(result) ? std::get<T>(result) :
                                                *std::get<T*>(result);
  }
  bool hasException() const noexcept {
    return std::holds_alternative<std::exception_ptr>(result);
  }
  void throwIfException() const {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));
  }
//...
};
```

# Range generator

```
struct Iterator {
  // iterator boilerplate

  Iterator() noexcept = default;
  explicit Iterator(const std::coroutine_handle<promise_type> &coro) noexcept;

  friend bool operator==(const Iterator&, const Iterator&) noexcept = default;
  friend bool operator!=(const Iterator&, const Iterator&) noexcept = default;

  Iterator &operator++();
  auto &operator*() const noexcept;

private:
  const std::coroutine_handle<promise_type> *coro = nullptr;
};
```

# Range generator

```
struct Iterator {
  using iterator_category = std::input_iterator_tag;
  using difference_type = std::ptrdiff_t;  // doesn't make sense for input iterator
  using value_type = T;
  using reference = T&;
  using pointer = T*;

  Iterator() noexcept = default;
  explicit Iterator(const std::coroutine_handle<promise_type> &coro) noexcept :
    coro{ &coro }
  {}

  friend bool operator==(const Iterator&, const Iterator&) noexcept = default;
  friend bool operator!=(const Iterator&, const Iterator&) noexcept = default;
  //...
};
```

# Range generator

```
struct Iterator {
  using iterator_category = std::input_iterator_tag;
  using difference_type = std::ptrdiff_t;  // doesn't make sense for input iterator
  using value_type = T;
  using reference = T&;
  using pointer = T*;

  Iterator() noexcept = default;
  explicit Iterator(const std::coroutine_handle<promise_type> &coro) noexcept :
    coro{ &coro }
  {}

  friend bool operator==(const Iterator&, const Iterator&) noexcept = default;
  friend bool operator!=(const Iterator&, const Iterator&) noexcept = default;
  //...
};
```

# Range generator

```
struct Iterator {
  using iterator_category = std::input_iterator_tag;
  using difference_type = std::ptrdiff_t;  // doesn't make sense for input iterator
  using value_type = T;
  using reference = T&;
  using pointer = T*;

  Iterator() noexcept = default;
  explicit Iterator(const std::coroutine_handle<promise_type> &coro) noexcept :
    coro{ &coro }
  {}

  friend bool operator==(const Iterator&, const Iterator&) noexcept = default;
  friend bool operator!=(const Iterator&, const Iterator&) noexcept = default;
  //...
};
```

# Range generator

```
struct Iterator {
  //...
  Iterator &operator++() {
    assert(coro != nullptr);
    assert(!coro->done());

    coro->resume();
    if (coro->done()) {
      auto coroHandle = std::exchange(coro, nullptr);
      coroHandle->promise().throwIfException();
    }
    return *this;
  }
  //...
};
```

precondition:
can increment
`++i`
only if
`i != end()`
and coroutine is not finished

# Range generator

```
struct Iterator {
  //...
  Iterator &operator++() {
    assert(coro != nullptr);
    assert(!coro->done());

    coro->resume();
    if (coro->done()) {
      auto coroHandle = std::exchange(coro, nullptr);
      coroHandle->promise().throwIfException();
    }
    return *this;
  }
  //...
};
```

# Range generator

```
struct Iterator {
  //...
  Iterator &operator++() {
    assert(coro != nullptr);
    assert(!coro->done());

    coro->resume();
    if (coro->done()) {
      auto coroHandle = std::exchange(coro, nullptr);
      coroHandle->promise().throwIfException();
    }
    return *this;
  }
  //...
};
```

# Range generator

```
struct Iterator {
  //...
  Iterator &operator++() {
    assert(coro != nullptr);
    assert(!coro->done());

    coro->resume();
    if (coro->done()) {
      auto coroHandle = std::exchange(coro, nullptr);
      coroHandle->promise().throwIfException();
    }
    return *this;
  }
  //...
};
```

# Range generator

```
struct Iterator {
  //...
  Iterator &operator++() {
    assert(coro != nullptr);
    assert(!coro->done());

    coro->resume();
    if (coro->done()) {
      auto coroHandle = std::exchange(coro, nullptr);
      coroHandle->promise().throwIfException();
    }
    return *this;
  }
  //...
};
```

# Range generator

```
struct Iterator {
  //...
  Iterator &operator++() {
    assert(coro != nullptr);
    assert(!coro->done());

    coro->resume();
    if (coro->done()) {
      auto coroHandle = std::exchange(coro, nullptr);
      coroHandle->promise().throwIfException();
    }
    return *this;
  }
  //...
};
```

# Range generator

```
const auto g = bar();
auto k = g.begin();

auto i = k;  // 'i' and 'k' both refer to 'g.begin()'
while (i != g.end())
  ++i;

assert(i == g.end());
// 'k' is invalid
```

Iterators are invalidated when generator coroutine finishes.

(Except the `end()` sentinel iterator.)

# Range generator

```
struct Iterator {
  //...
  auto &operator*() const noexcept {
    assert(coro != nullptr);
    assert(!coro->done());

    return coro->promise().getValue();
  }

private:
  const std::coroutine_handle<promise_type> *coro = nullptr;
};
```

# Range generator

```
template<typename T>
struct Generator {
  struct promise_type;
  struct Iterator;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  Iterator begin() const;
  Iterator end() const noexcept;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# Range generator

```
template<typename T>
struct Generator {
  struct promise_type;
  struct Iterator;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  Iterator begin() const;
  Iterator end() const noexcept;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# Range generator

```
Iterator begin() const {
  if (coro.done())
    return end();

  auto i = Iterator{ coro };
  if (!coro.promise().isValueInitialized())
    ++i;  // can throw, or become '*this == end()'
  return i;
}

Iterator end() const noexcept {
  return {};
}
```

# Range generator

```
Iterator begin() const {
  if (coro.done())
    return end();

  auto i = Iterator{ coro };
  if (!coro.promise().isValueInitialized())
    ++i;  // can throw, or become '*this == end()'
  return i;
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Iterator end() const noexcept {
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# Range generator

```
Iterator begin() const {
  if (coro.done())
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  auto i = Iterator{ coro };
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}

Iterator end() const noexcept {
  return {};
}
```

# Range generator

```
Iterator begin() const
  if (coro.done())
    return end();

  auto i = Iterator{ coro };
  if (!coro.promise().isValueInitialized())
    ++i;  // can throw, or become '*this == end()'
  return i;
}

Iterator end() const noexcept {
  return {};
}
```

```
const auto g = bar();
if (g.begin() == g.end())
  //...

for (auto &i : g)  // 'g.begin()' called
  std::cout << i << '\n';
```

# Range generator

```
Iterator begin() const {
  if (coro.done())
    return end();

  auto i = Iterator{ coro };
  if (!coro.promise().isValueInitialized())
    ++i;  // can throw, or become '*this == end()'
  return i;
}

Iterator end() const noexcept {
  return {};
}
```

# Range generator

```
Iterator begin() const {
  if (coro.done())
    return end();

  auto i = Iterator{ coro };
  if (!coro.promise().isValueInitialized())
    ++i;  // can throw, or become '*this == end()'
  return i;
}

Iterator end() const noexcept {
  return {};
}
```

# Range generator

```
template<typename T>
struct Generator {
  struct promise_type;
  struct Iterator;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  Iterator begin() const;
  Iterator end() const noexcept;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}
```

# Range generator

```
const auto g = bar();
try {
  for (auto &i : g)
    std::cout << i << '\n';
}
catch (const std::exception &e) {
  std::cout << "exception: " << e.what() << '\n';
}
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}
```

```
const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
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# Range generator

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Generator<int> bar() {
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const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
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  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
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  std::cout << i << '\n';
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n
}



const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n
}   co_return;
```

```
const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}   co_return;
```

```
{
  promise.return_void();
  goto final-suspend;
}
```

```
const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}
```

```
struct promise_type {
//...
  std::suspend_always final_suspend() const noexcept;
//...
};
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}
```

final suspend

```
struct promise_type {
//...
  std::suspend_always final_suspend() const noexcept;
//...
};
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}
```

final suspend

```
const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

# Range generator

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Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
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final suspend

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const auto g = bar();
for (auto &i : g)
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# Range generator

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Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
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}
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final suspend

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const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
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# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // throws
  for (auto n : values)
    co_yield n;
}


const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // throws
  for (au
    co_yi
}

const aut
for (auto
  std::co
```

```
{
  //...
  try {
    //...
    function-body
  }
  catch (...) {
    //...
    promise.unhandled_exception();
  }
final-suspend:
  //...
}
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // throws
  for (auto n : values)
    co_yield n;
}


const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // throws
  for (auto n : values)
    co_yield n;
}
```

```
struct promise_type {
//...
  std::suspend_always final_suspend() const noexcept;
//...
};
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // throws
  for (auto n : values)
    co_yield n;
}
```

final suspend

```
struct promise_type {
//...
  std::suspend_always final_suspend() const noexcept;
//...
};
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // throws
  for (auto n : values)
    co_yield n;
}
```

final suspend

```
const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // throws
  for (auto n : values)
    co_yield n;
}
```

final suspend

```
const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // throws
  for (auto n : values)
    co_yield n;
}

const auto g = bar();
for (auto &i : g)
  std::cout << i << '\n';
```

final suspend

`g.begin()` or `++it`
rethrow the exception

# Range generator

At *this* point you know *almost everything* you need to know about how generators work.

For real this time.

# Understanding C++ coroutines by example part 2: generators

Pavel Novikov

@cpp_ape

Thanks to Phil Nash for feedback.

Slides: bit.ly/3wr5vxW

# Understanding C++ Coroutines By Example

## Generators (Part 2 of 2)

PAVEL NOVIKOV

Cppcon
The C++ Conference

2022
September 12th-16th

# Range generator

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}
```

# Range generator

```
const auto g = bar();
for (auto i = g.begin();   // may throw
     i != g.end();
     ++i) {                // may throw
    std::cout <<
      *i                   // never throws
      << '\n';
}
```

```cpp
struct LazyIterator {
  // iterator boilerplate

  LazyIterator() noexcept = default;
  explicit LazyIterator(const std::coroutine_handle<promise_type> &coro) noexcept;

  friend bool operator==(const LazyIterator&, const LazyIterator&) noexcept = default;
  friend bool operator!=(const LazyIterator&, const LazyIterator&) noexcept = default;

  LazyIterator &operator++() noexcept;
  auto &operator*() const;
  friend bool hasException(const LazyIterator &i) noexcept;

private:
  const std::coroutine_handle<promise_type> *coro = nullptr;
};
```

```cpp
struct LazyIterator {
  // iterator boilerplate

  LazyIterator() noexcept = default;
  explicit LazyIterator(const std::coroutine_handle<promise_type> &coro) noexcept;

  friend bool operator==(const LazyIterator&, const LazyIterator&) noexcept = default;
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  LazyIterator &operator++() noexcept;
  auto &operator*() const;
  friend bool hasException(const LazyIterator &i) noexcept;

private:
  const std::coroutine_handle<promise_type> *coro = nullptr;
};
```

```
struct LazyIterator {
  // iterator boilerplate

  LazyIterator() noexcept = default;
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  friend bool operator==(const LazyIterator&, const LazyIterator&) noexcept = default;
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  LazyIterator &operator++() noexcept;
  auto &operator*() const;
  friend bool hasException(const LazyIterator &i) noexcept;

private:
  const std::coroutine_handle<promise_type> *coro = nullptr;
};
```

# Range generator

```
template<typename T>
struct Generator {
  struct promise_type;
  struct LazyIterator;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  LazyIterator begin() const noexcept;
  LazyIterator end() const noexcept;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

does not throw

# Range generator

```
const auto g = bar();
for (auto i = g.begin();  // does
     i != g.end();        // not
     ++i) {               // throw
  if (hasException(i))
    break;
  std::cout << *i << '\n';
}
```

# Range generator

```
const auto g = bar();
for (auto i = g.begin();   // does
     i != g.end();         // not
     ++i) {                // throw
  if (hasException(i))
    break;
  std::cout << *i << '\n';
}
```

```
const auto g = bar();
for (auto i = g.begin(); i != g.end(); ++i) {
  if (hasException(i)) {
    try {
      *i;  // throws
    }
    catch (...) {
    }
    try {
      *i;  // throws
    }
    catch (...) {
    }
    break;
  }
  std::cout << *i << '\n';
}
```

# Yielding from nested generators

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}

Generator<int> baz() {
  co_yield 1;
  co_yield 2;
  co_yield 3;

  for (auto n : bar())  // 'bar()' is resumed and suspended
    co_yield n;  // yields and suspends, then resumes
}
```

# Yielding from nested generators

```
Generator<int> bar() {
  const auto values = getValues();  // may throw
  for (auto n : values)
    co_yield n;
}

Generator<int> baz() {
  co_yield 1;
  co_yield 2;
  co_yield 3;

  for (auto n : bar())  // 'bar()' is resumed and suspended
    co_yield n;  // yields and suspends, then resumes
}
```

# Yielding from nested generators

```
Generator<int> qux() {
  const auto g
  if (auto i =                          ()) {
    co_yield *
    ++i;
  }
  for (auto i
    co_yield i;  // yield the rest
}
```

# Yielding from nested generators

```
Generator<int> qux() {
  const auto g = baz();
  if (auto i = g.begin(); i != g.end()) {
    co_yield *i * 33;
    ++i;
  }
  for (auto i : g)
    co_yield i;  // yield the rest
}
```

# Yielding from nested generators

```
Generator<int> qux() {
  const auto g = baz();
  if (auto i = g.begin(); i != g.end()) {
    co_yield *i * 33;
    ++i;
  }
  for (auto i : g)
    co_yield i;  // yield the rest
}
```

up to three resumes & suspends per yielded value!

```
const auto h = qux();
for (auto &i : h)
  std::cout << i << '\n';
```

# Recursive generator

```
RecursiveGenerator<int> bar() {
  for (auto n : getValues())
    co_yield n;
}

RecursiveGenerator<int> baz() {
  co_yield 1;
  co_yield 2;
  co_yield 3;

  co_yield bar();  // yield the _whole_ thing
}
```

# Recursive generator

```
RecursiveGenerator<int> bar() {
  for (auto n : getValues())
    co_yield n;
}

RecursiveGenerator<int> baz() {
  co_yield 1;
  co_yield 2;
  co_yield 3;

  co_yield bar();  // yield the _whole_ thing
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```

# Recursive generator

```
RecursiveGenerator<int> qux() {
  const auto g = baz();
  if (auto i = g.begin(); i != g.end()) {
    co_yield *i * 33;
    ++i;
  }
  co_yield g;  // yield the rest
}
```

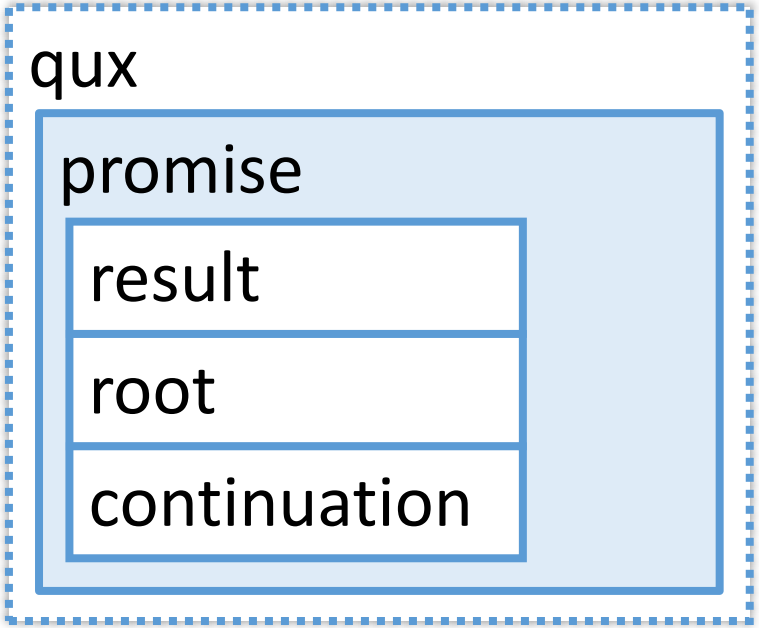
# Recursive generator

```
RecursiveGenerator<int> qux() {
  const auto g = baz();
  if (auto i = g.begin(); i != g.end()) {
    co_yield *i * 33;
    ++i;
  }
  co_yield g;  // yield the rest
}
```

```cpp
const auto h = qux();
for (auto &i : h)
  std::cout << i << '\n';
```

```
const auto h = qux();
for (auto &i : h)
  std::cout << i << '\n';
```

```cpp
const auto h = qux();
for (auto &i : h)
  std::cout << i << '\n';
```



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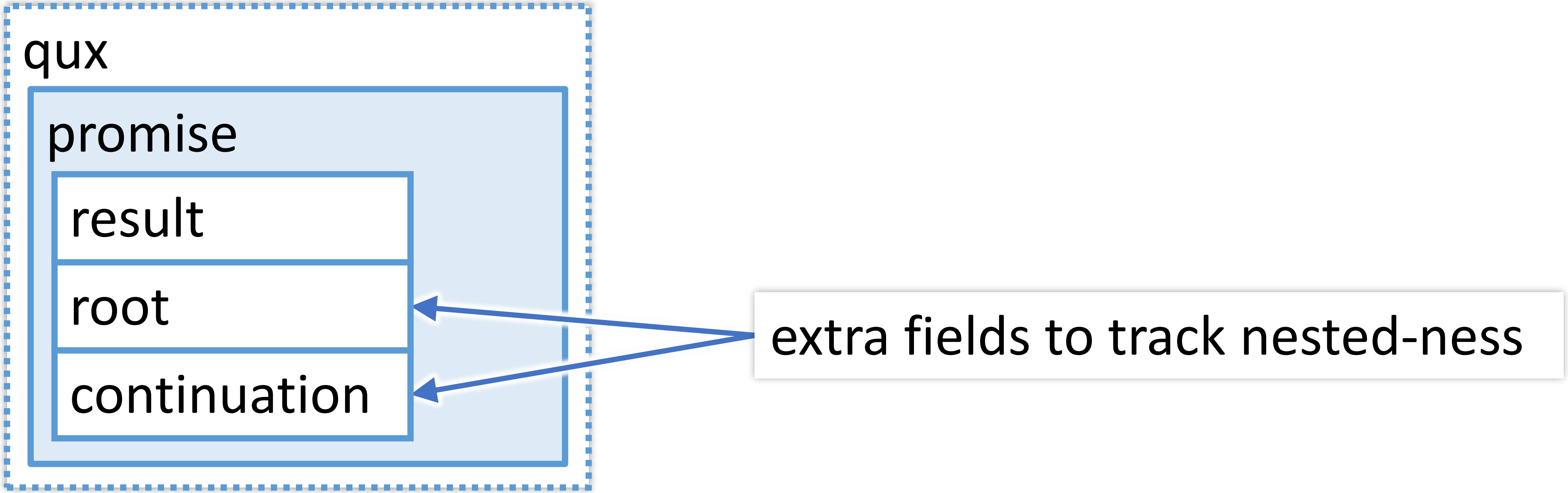
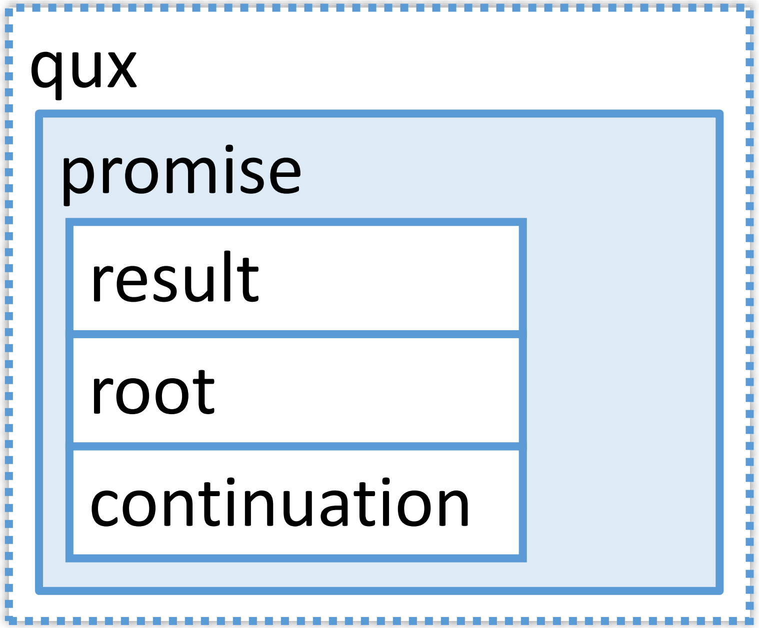
const auto h = qux();
for (auto &i : h)
  std::cout << i << '\n';
```



```
const auto h = qux();
for (auto &i : h)
  std::cout << i << '\n';
```



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  const auto g = baz();
  if (auto i = g.begin(); i != g.end()) {
    co_yield *i * 33;
    ++i;
  }
  co_yield g;  // yield the rest
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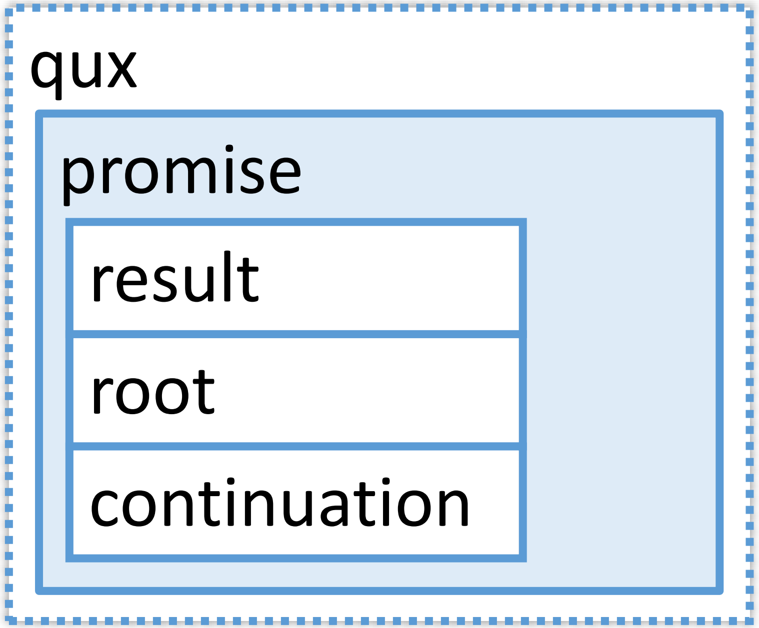

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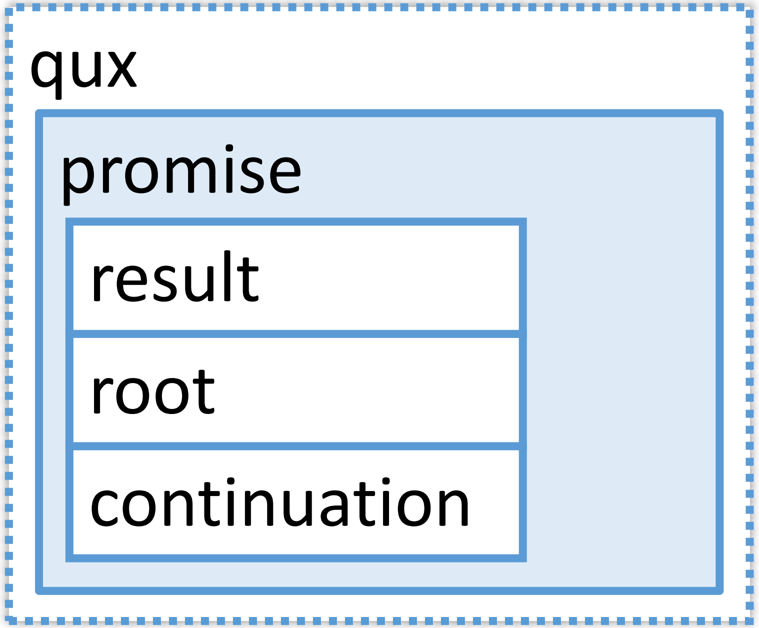

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  const auto g = baz();
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    co_yield *i * 33;
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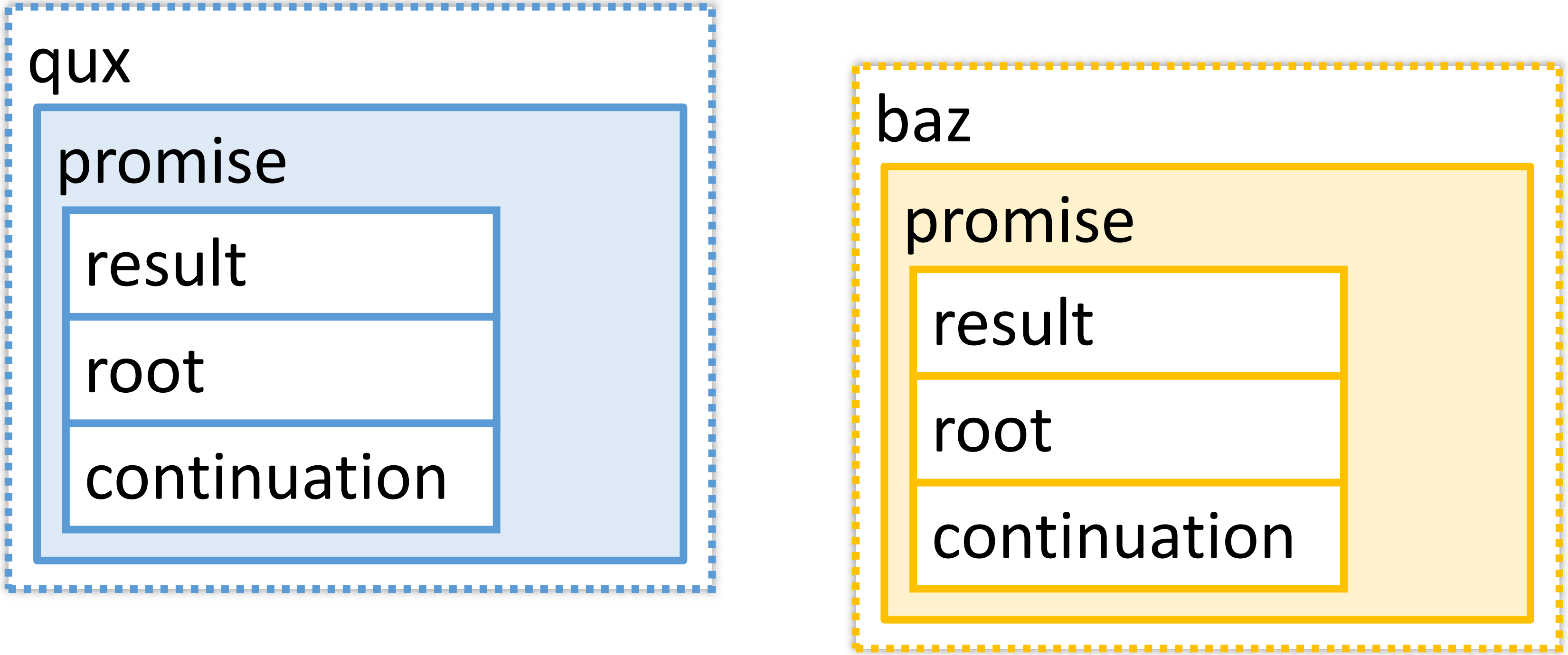

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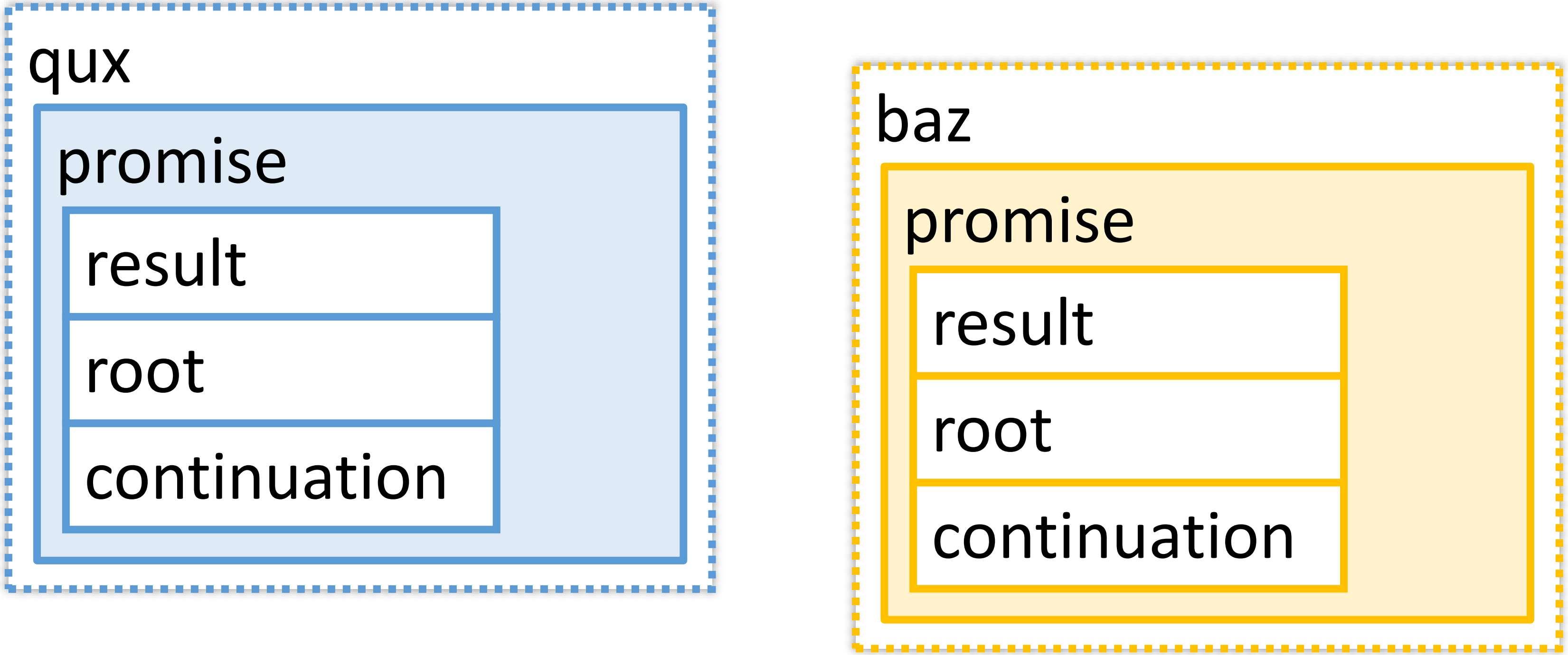
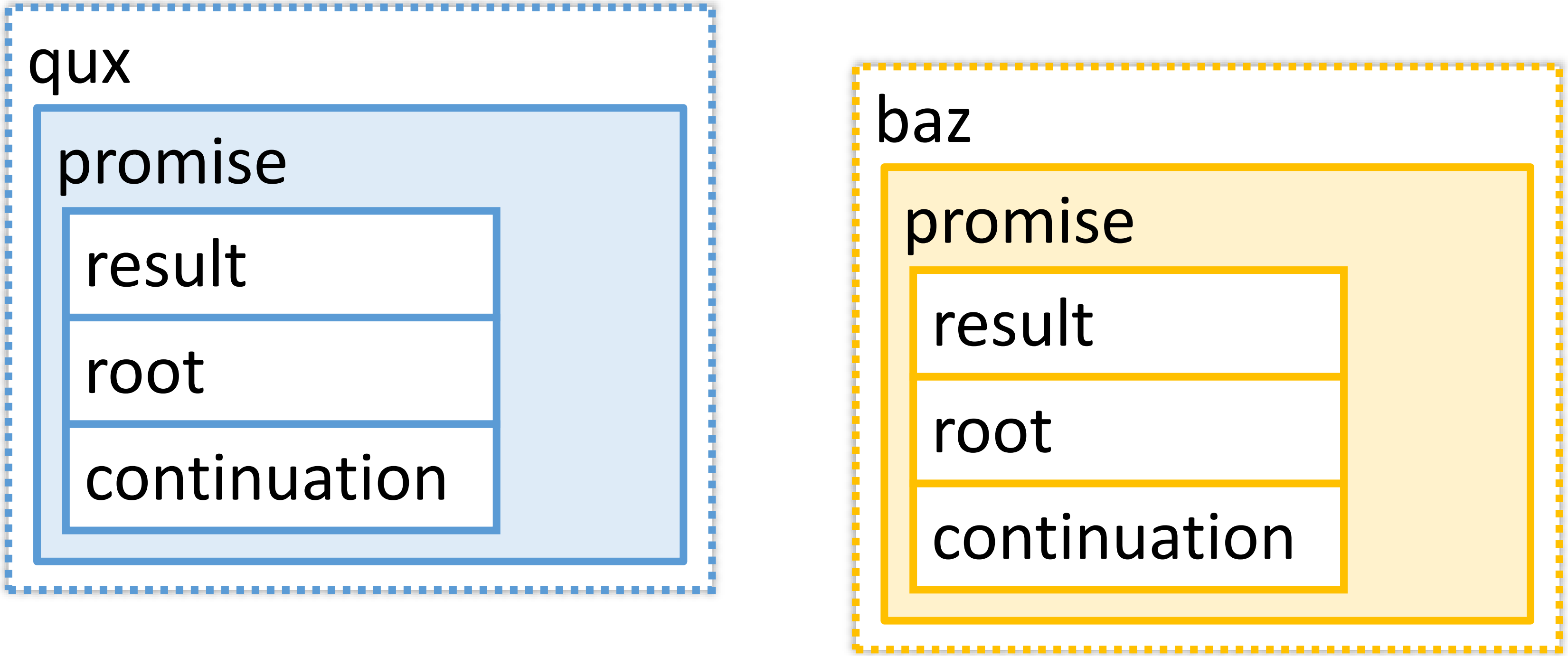
  const auto g = baz();
  if (auto i = g.begin(); i != g.end()) {
    co_yield *i * 33;
    ++i;
  }
  co_yield g;  // yield the rest
}
```



```
RecursiveGenerator<int> baz() {
  co_yield 1;
  co_yield 2;
  co_yield 3;

  co_yield bar();  // yield the _whole_ thing
}
```



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  co_yield 1;
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  co_yield 3;

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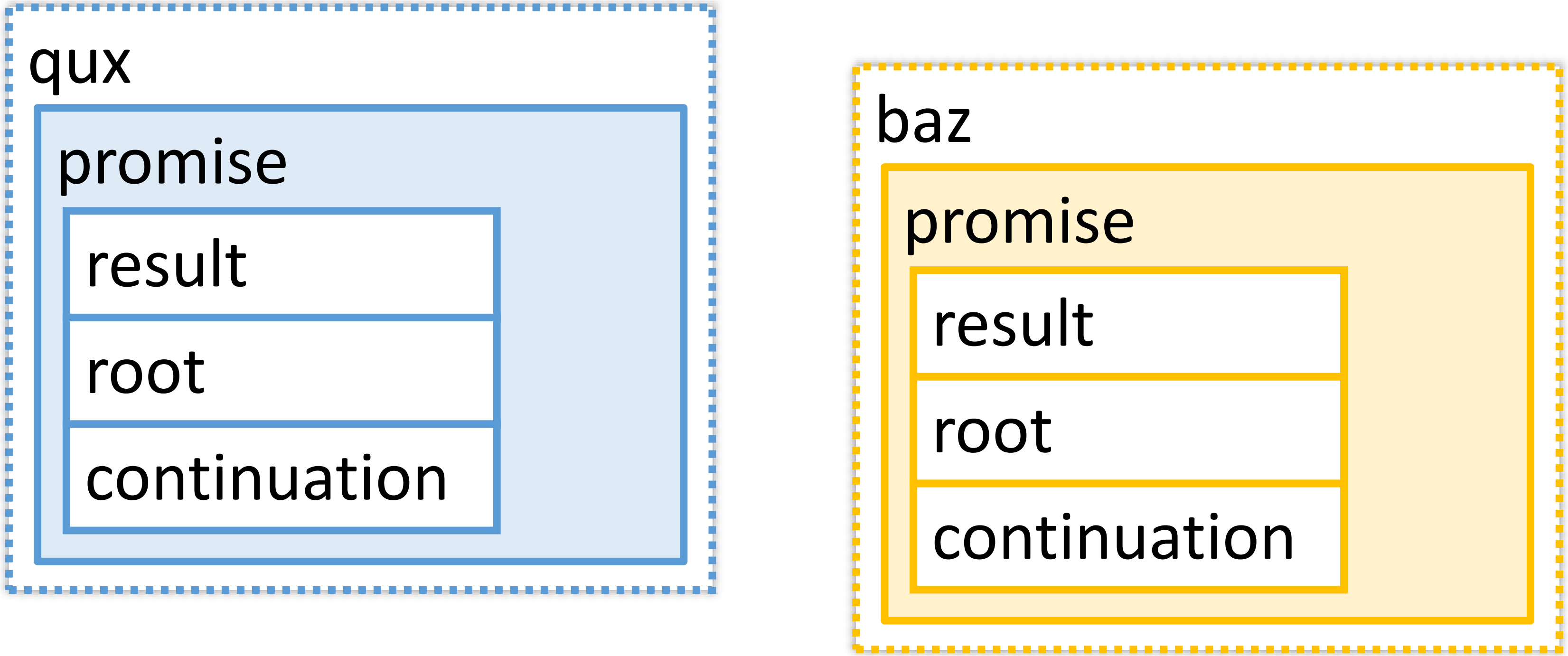

```
RecursiveGenerator<int> qux() {
  const auto g = baz();
  if (auto i = g.begin(); i != g.end()) {
    co_yield *i * 33;
    ++i;
  }
  co_yield g;  // yield the rest
}
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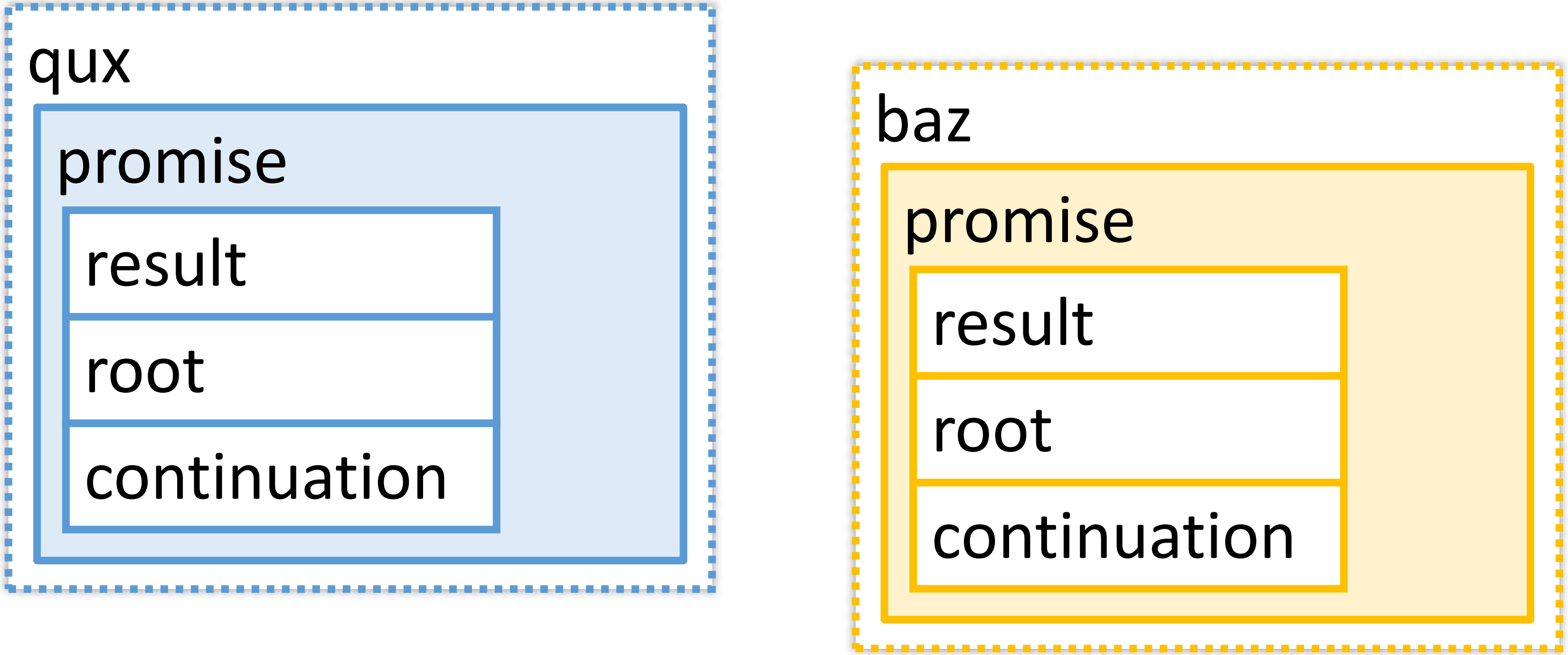
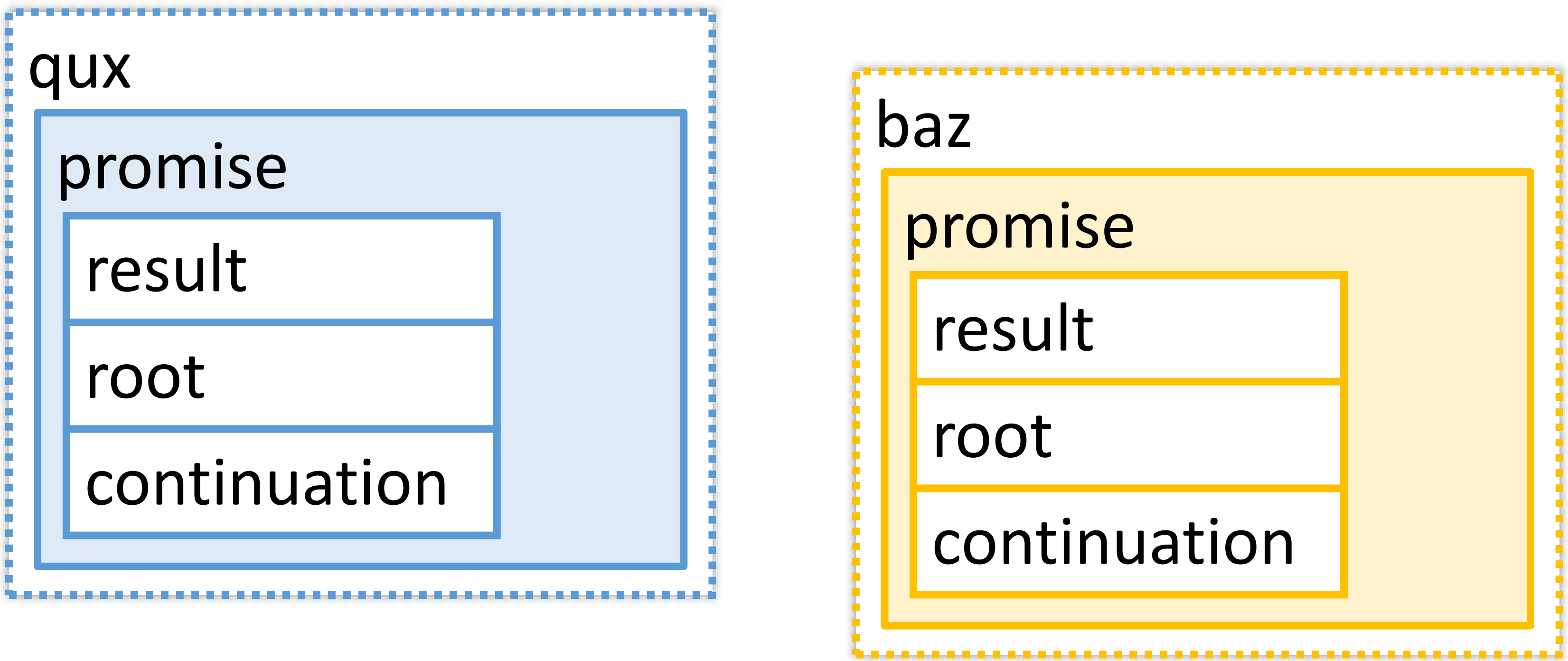


```
const auto h = qux();
for (auto &i : h)
  std::cout << i << '\n';
```



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  const auto g = baz();
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    co_yield *i * 33;
    ++i;
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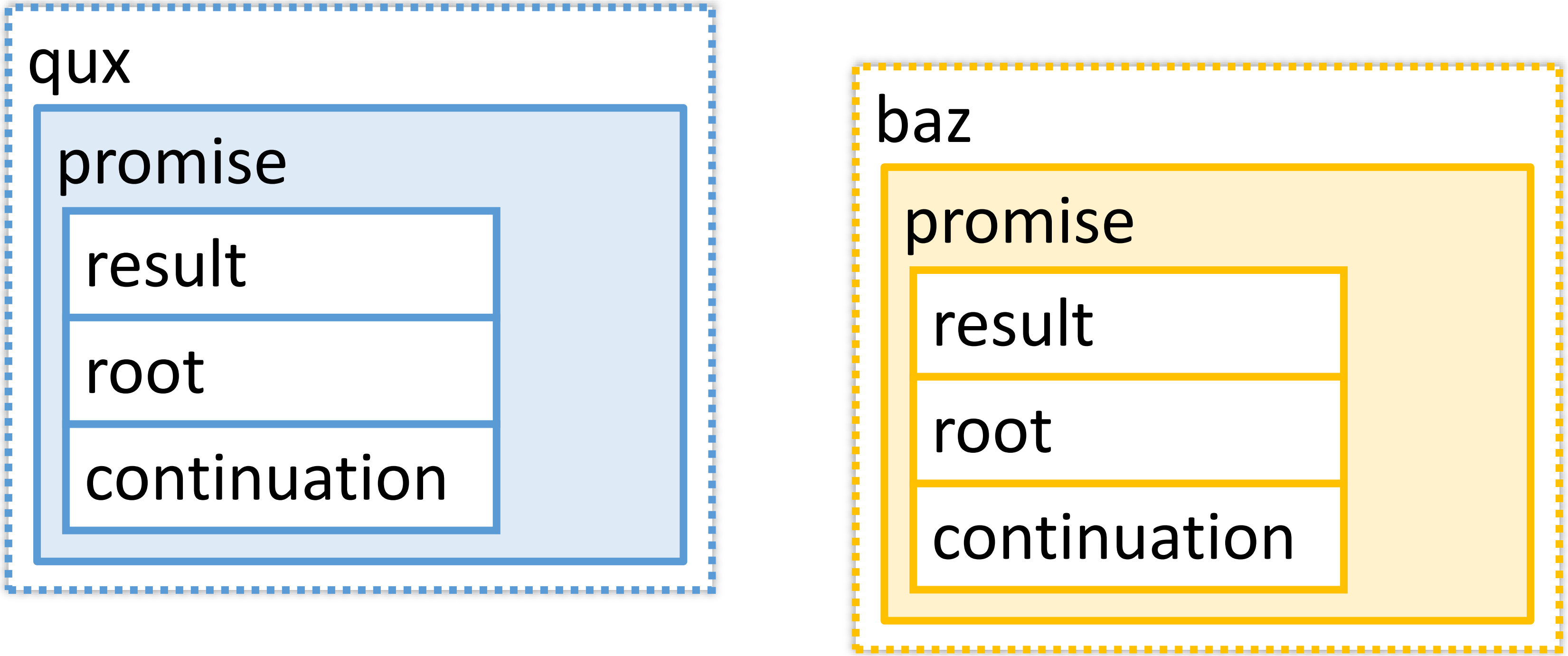
}
```



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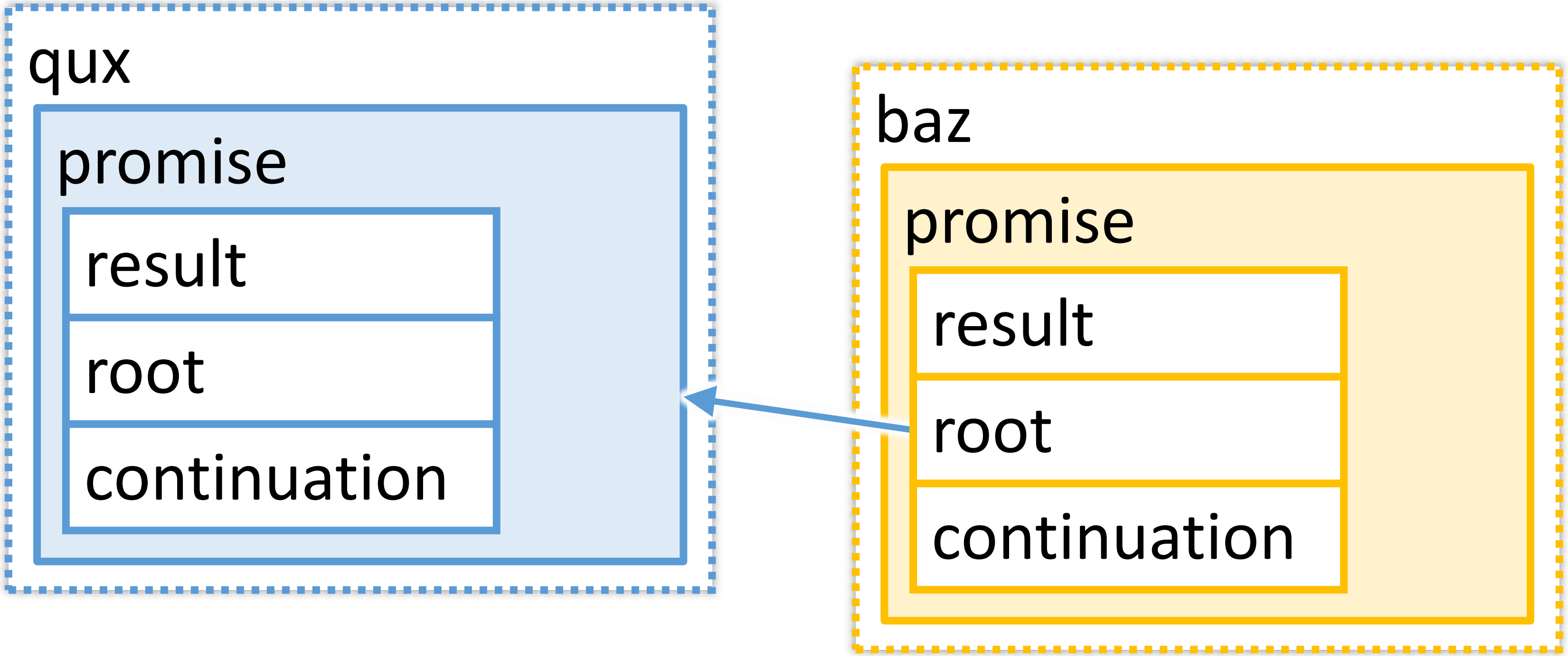

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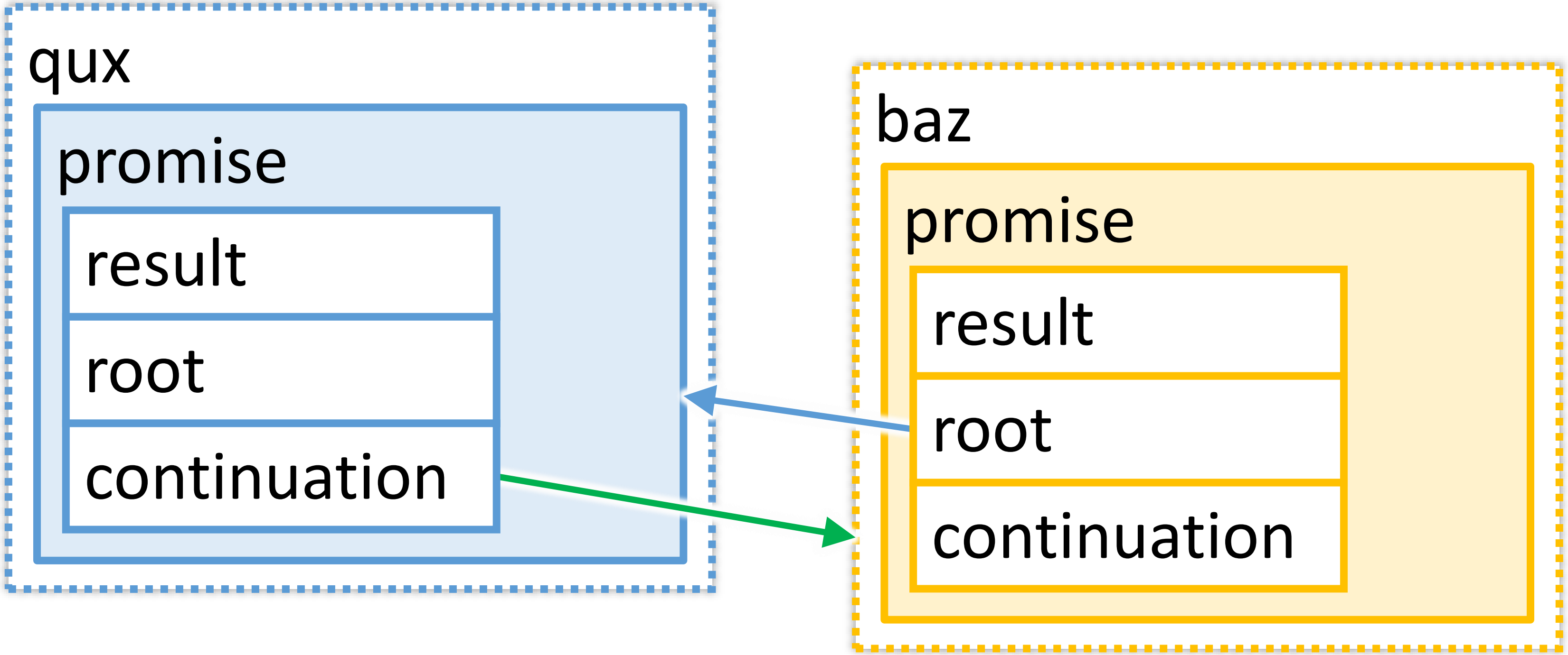

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RecursiveGenerator<int> baz() {
  co_yield 1;
  co_yield 2;
  co_yield 3;

  co_yield bar();  // yield the _whole_ thing
}
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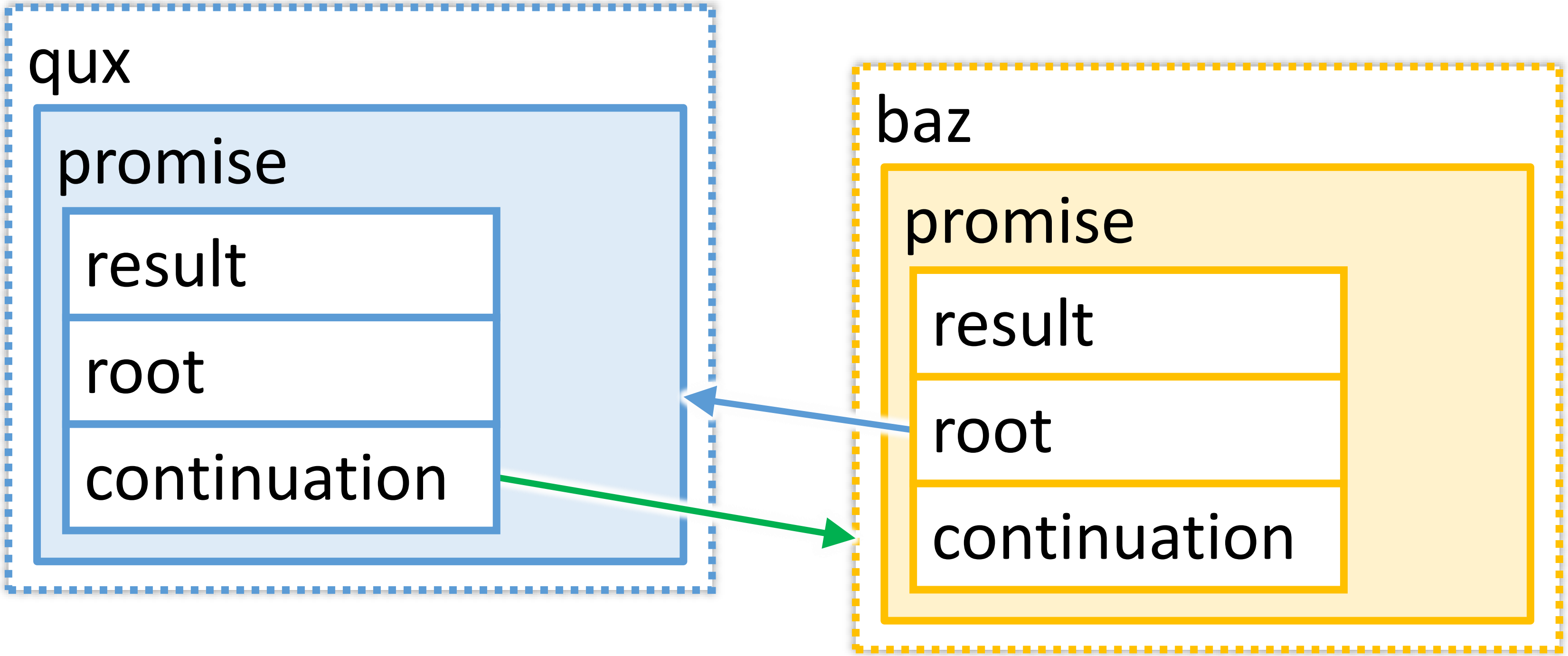
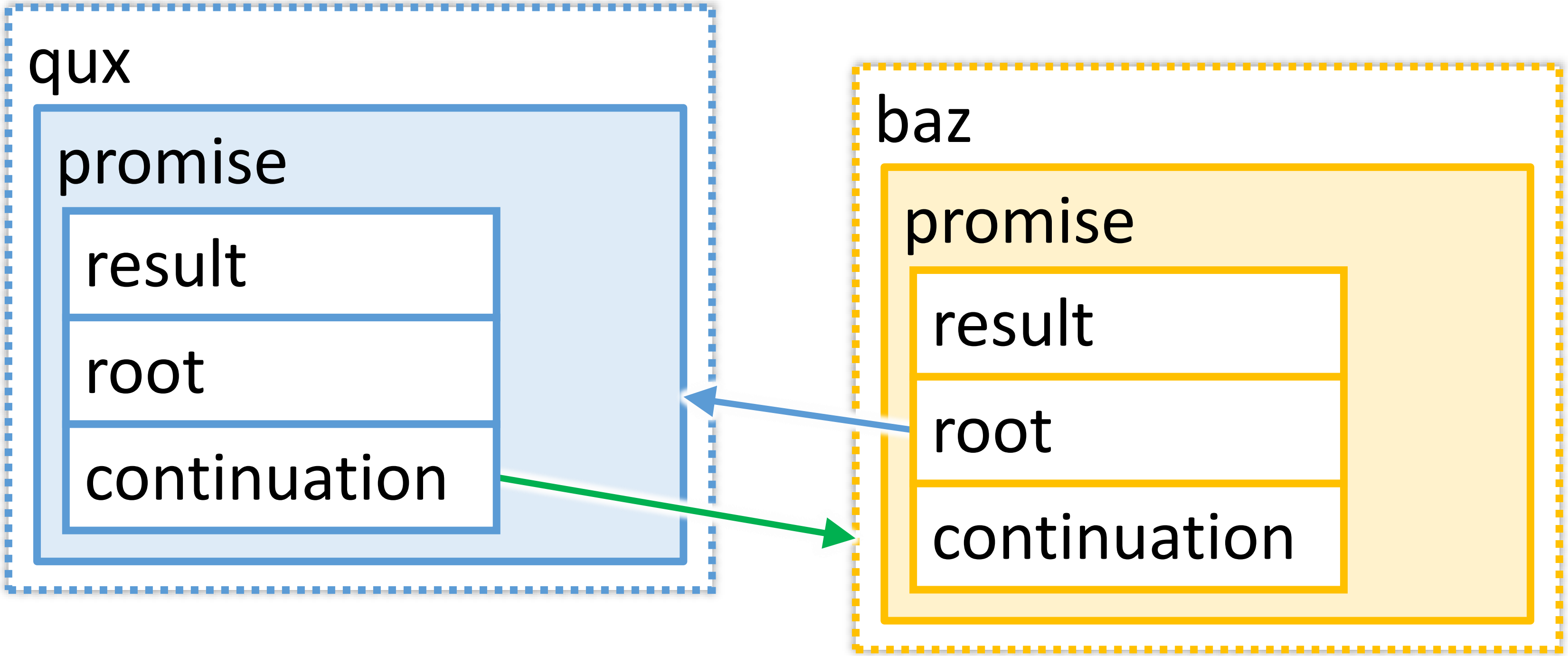


```
const auto h = qux();
for (auto &i : h)
  std::cout << i << '\n';
```



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  co_yield 1;
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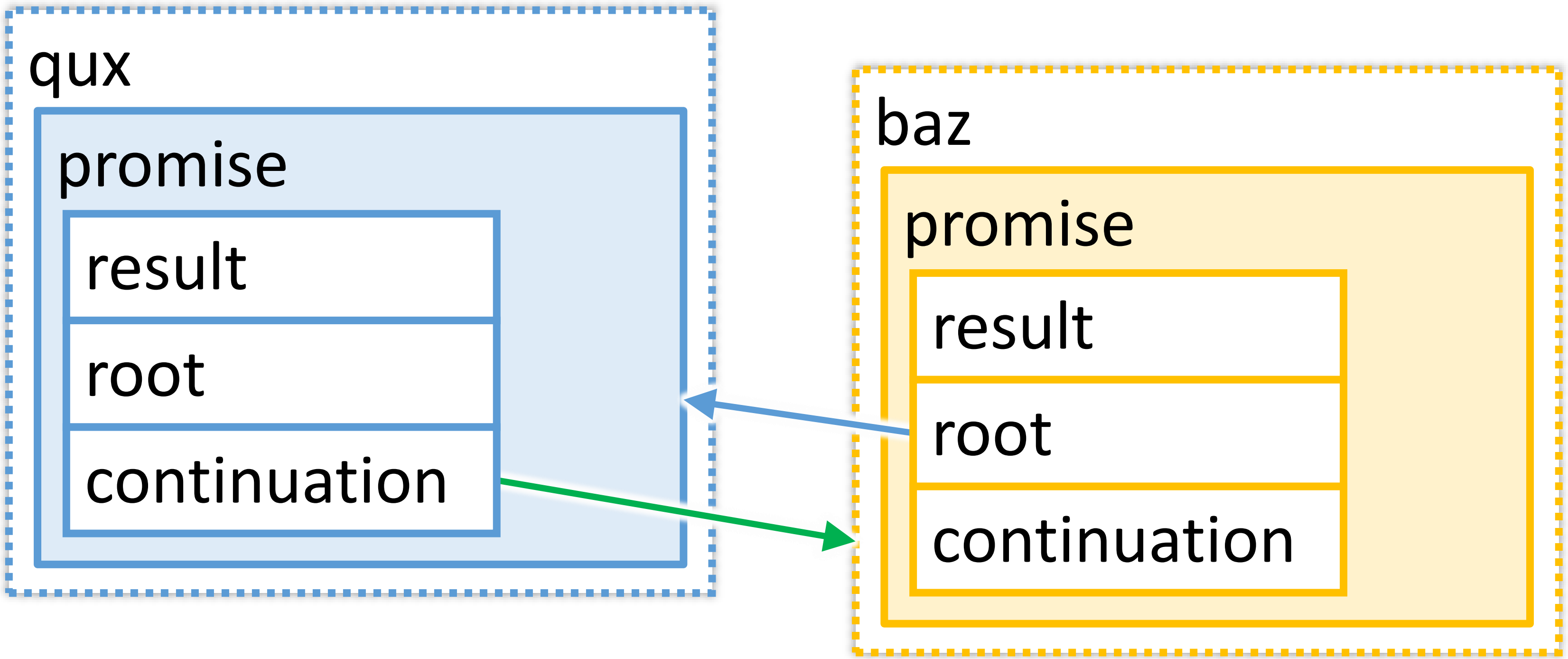
  co_yield 3;

  co_yield bar();  // yield the _whole_ thing
}
```



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RecursiveGenerator<int> baz() {
  co_yield 1;
  co_yield 2;
  co_yield 3;

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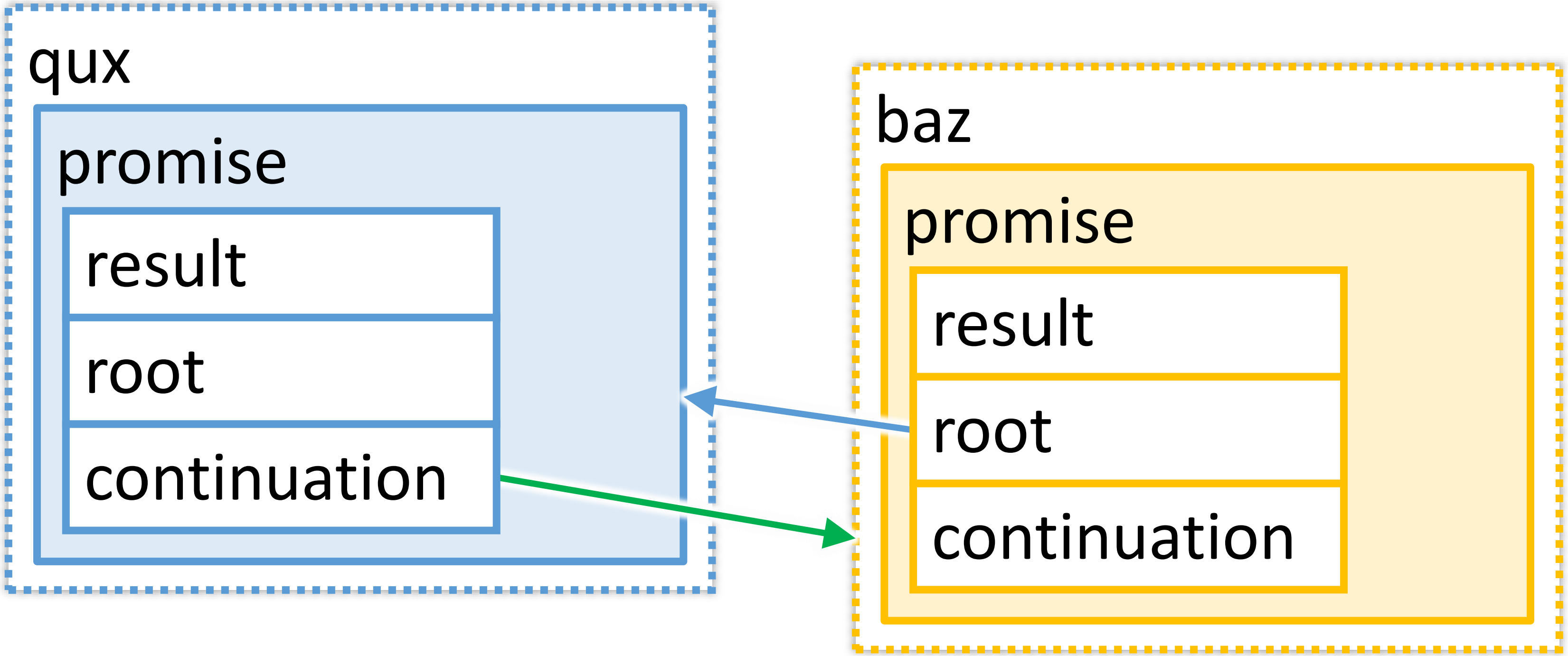
}
```



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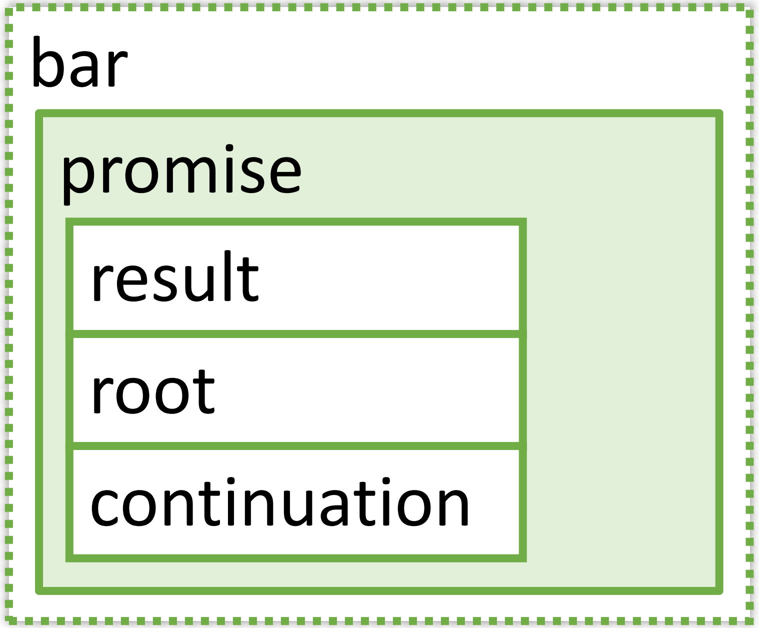
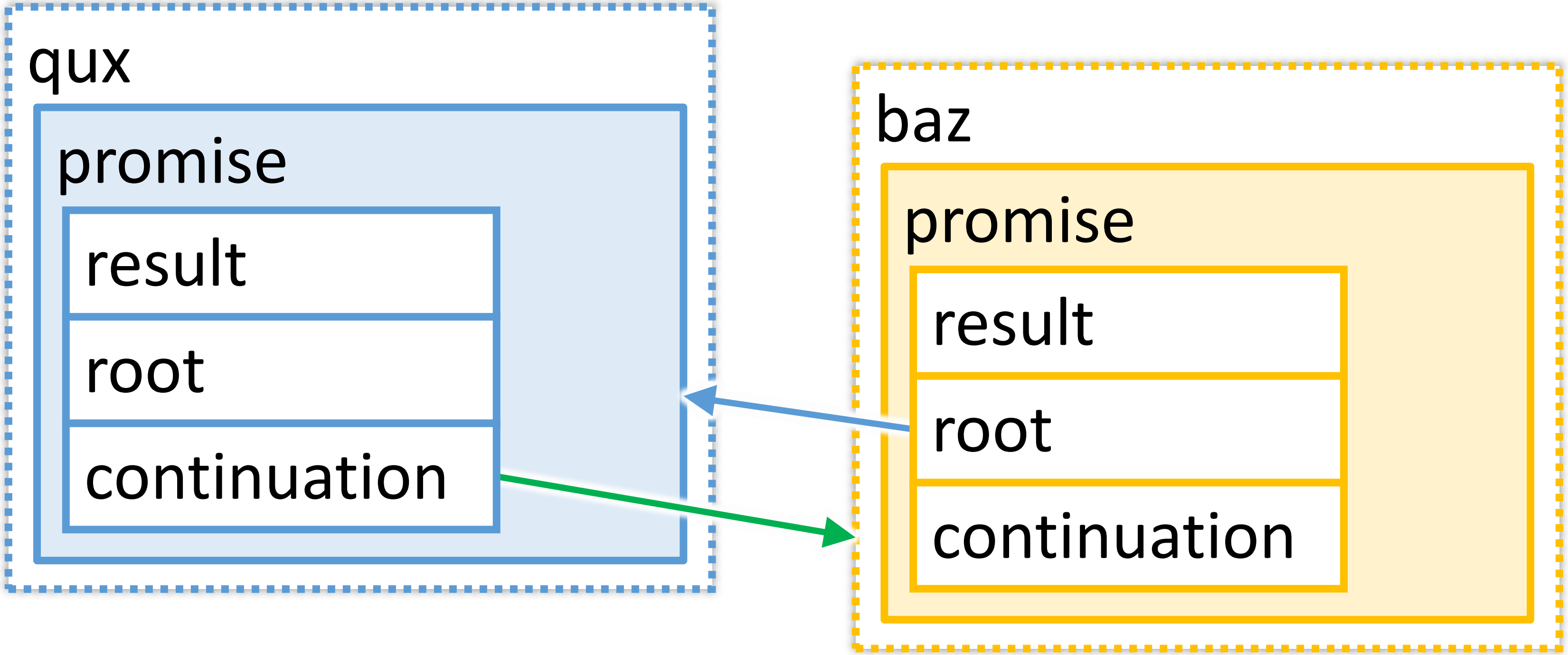
RecursiveGenerator<int> baz() {
  co_yield 1;
  co_yield 2;
  co_yield 3;

  co_yield bar();  // yield the _whole_
}
```



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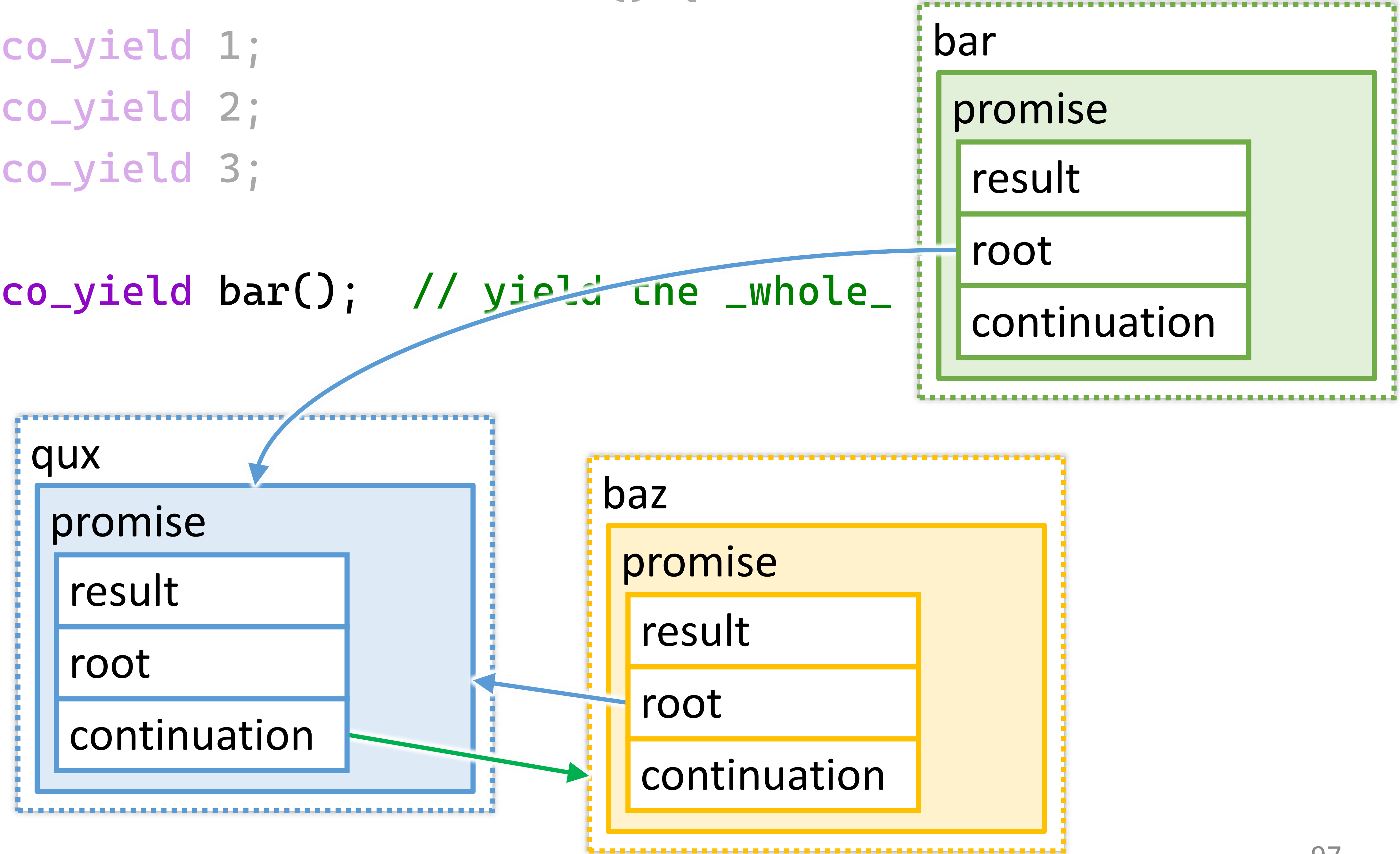
  co_yield bar();  // yield the _whole_
}
```



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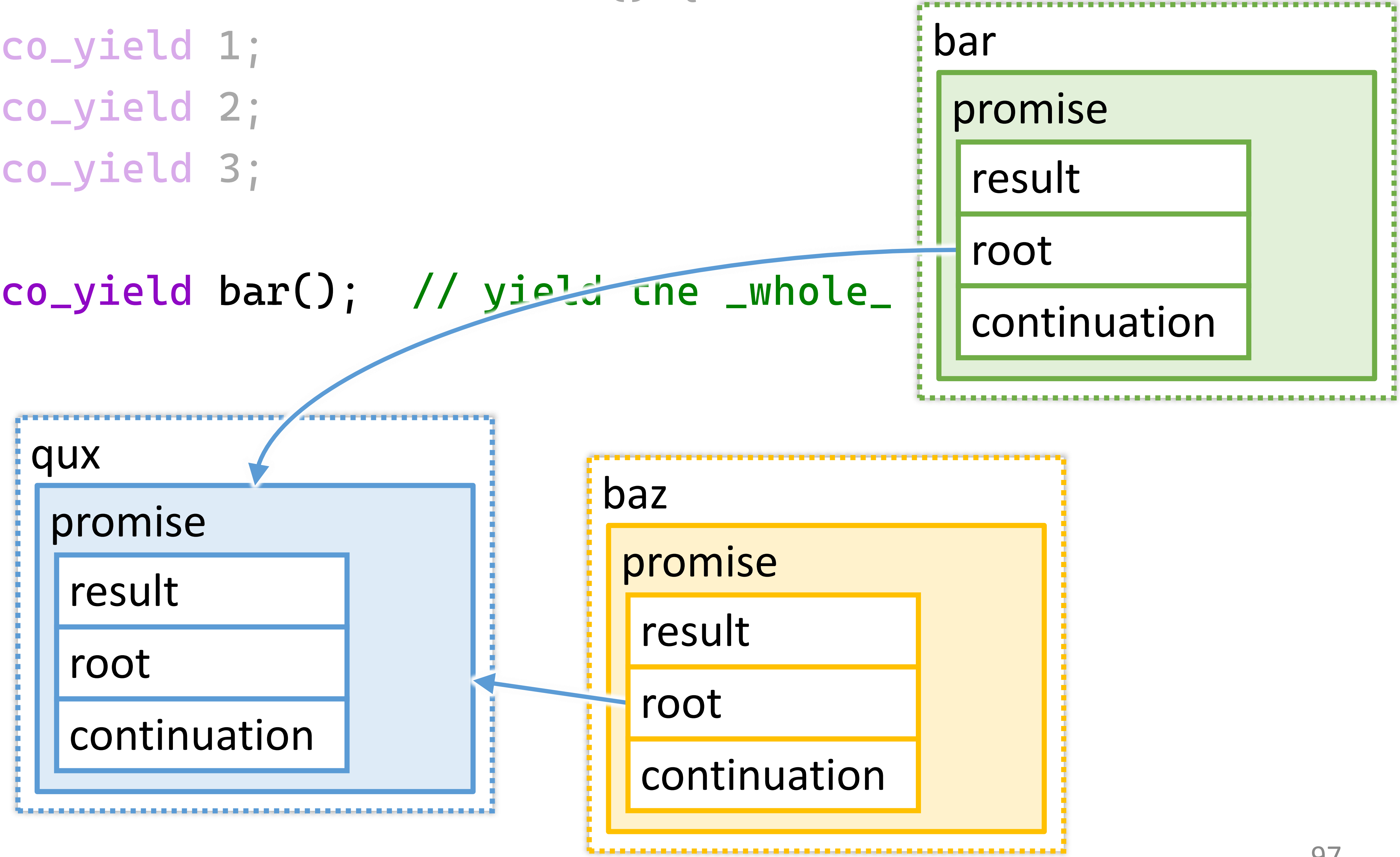

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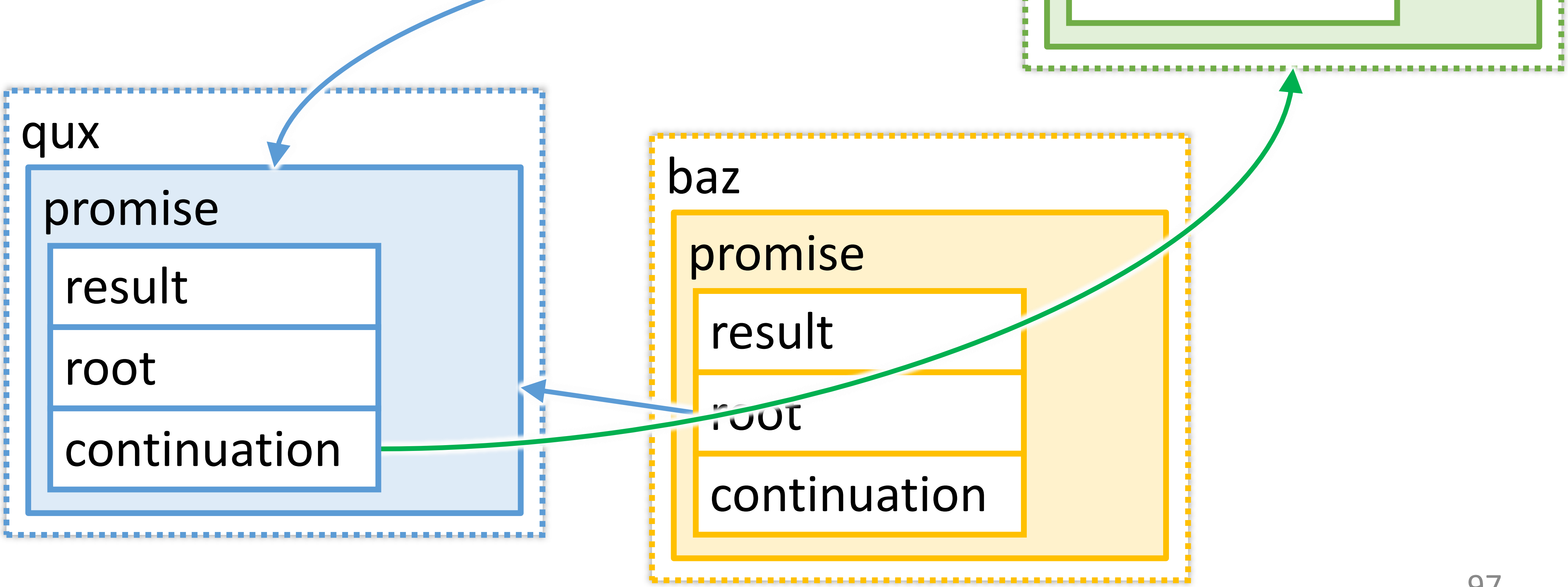
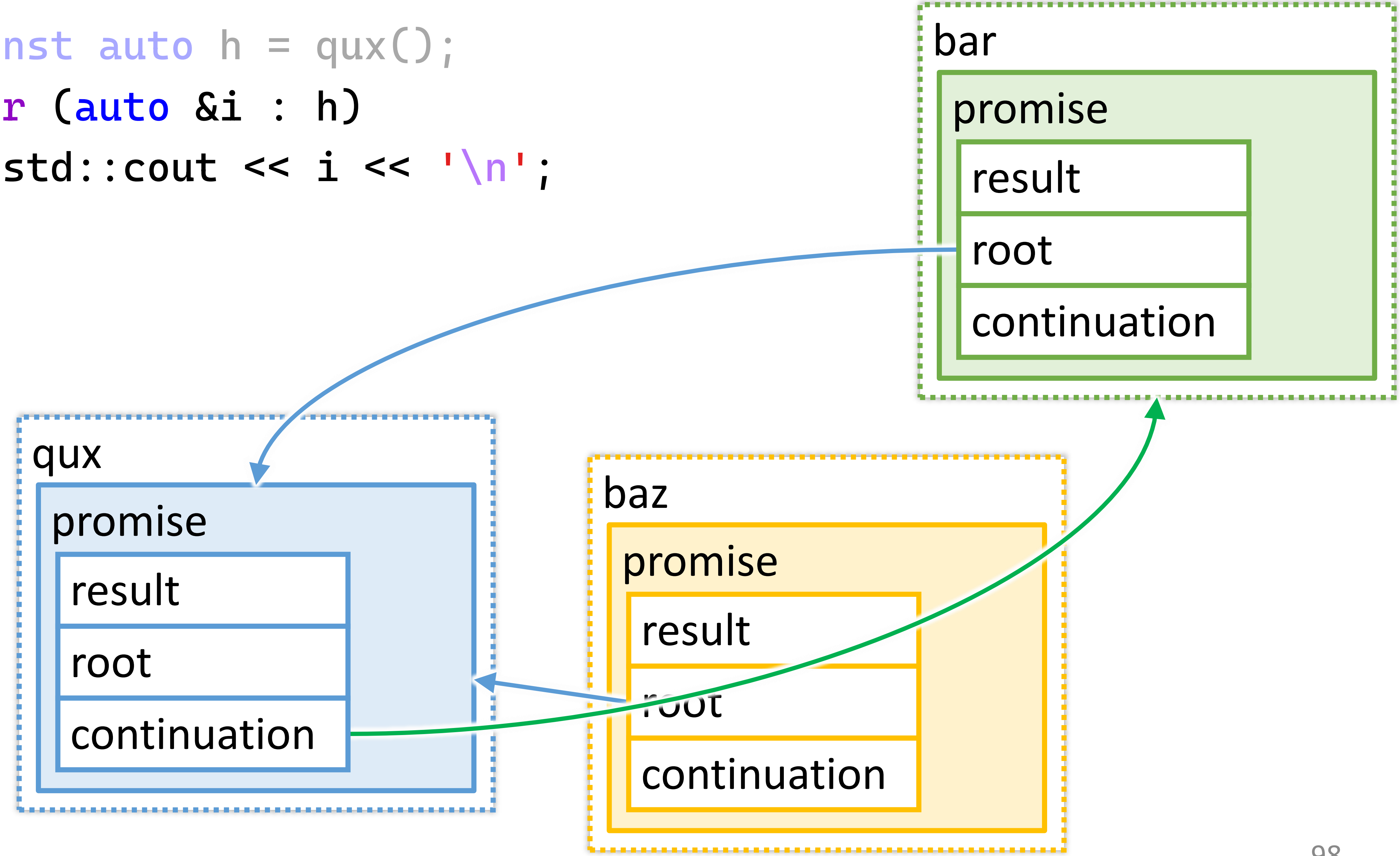
}
```



```
const auto h = qux();
for (auto &i : h)
  std::cout << i << '\n';
```



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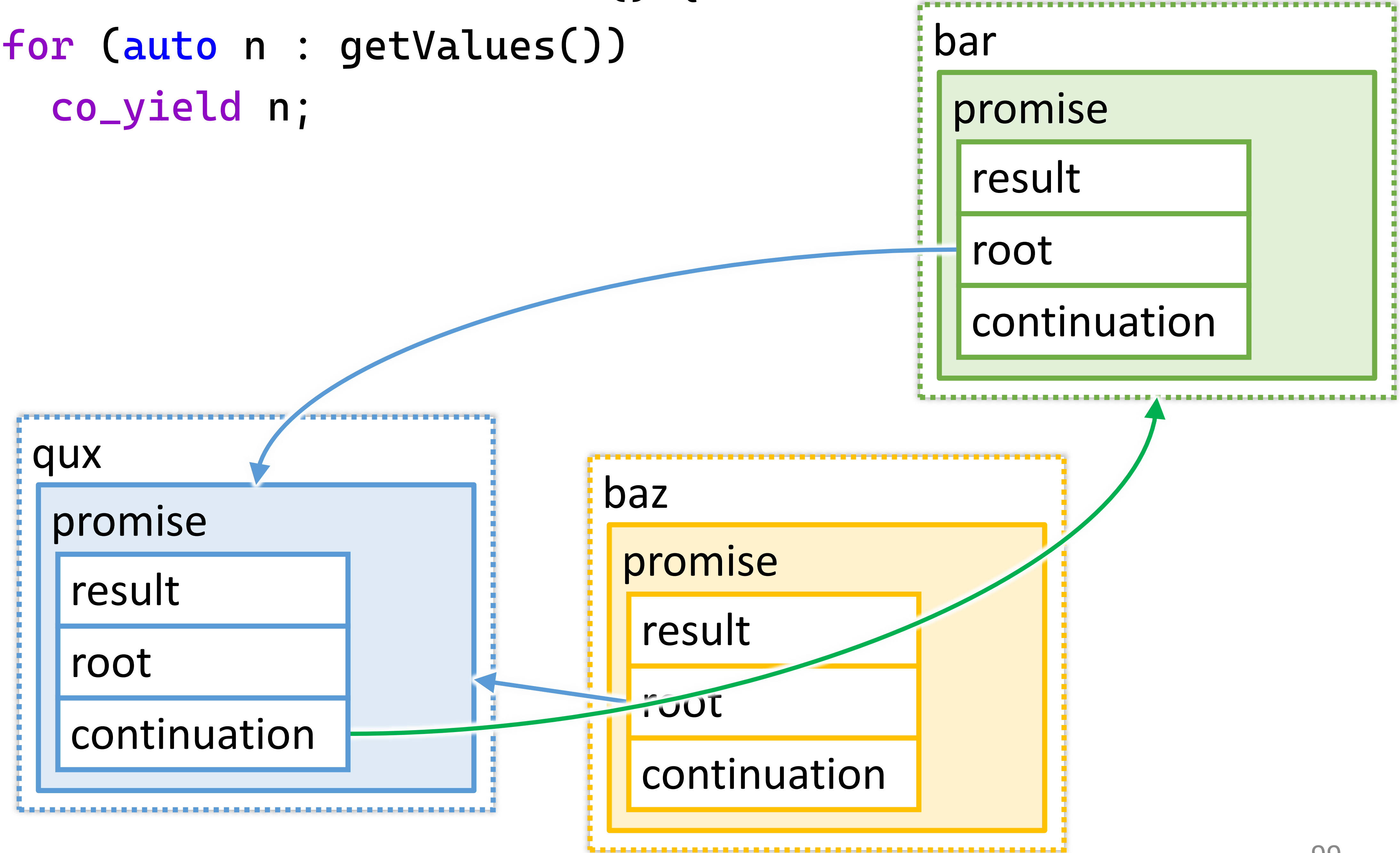
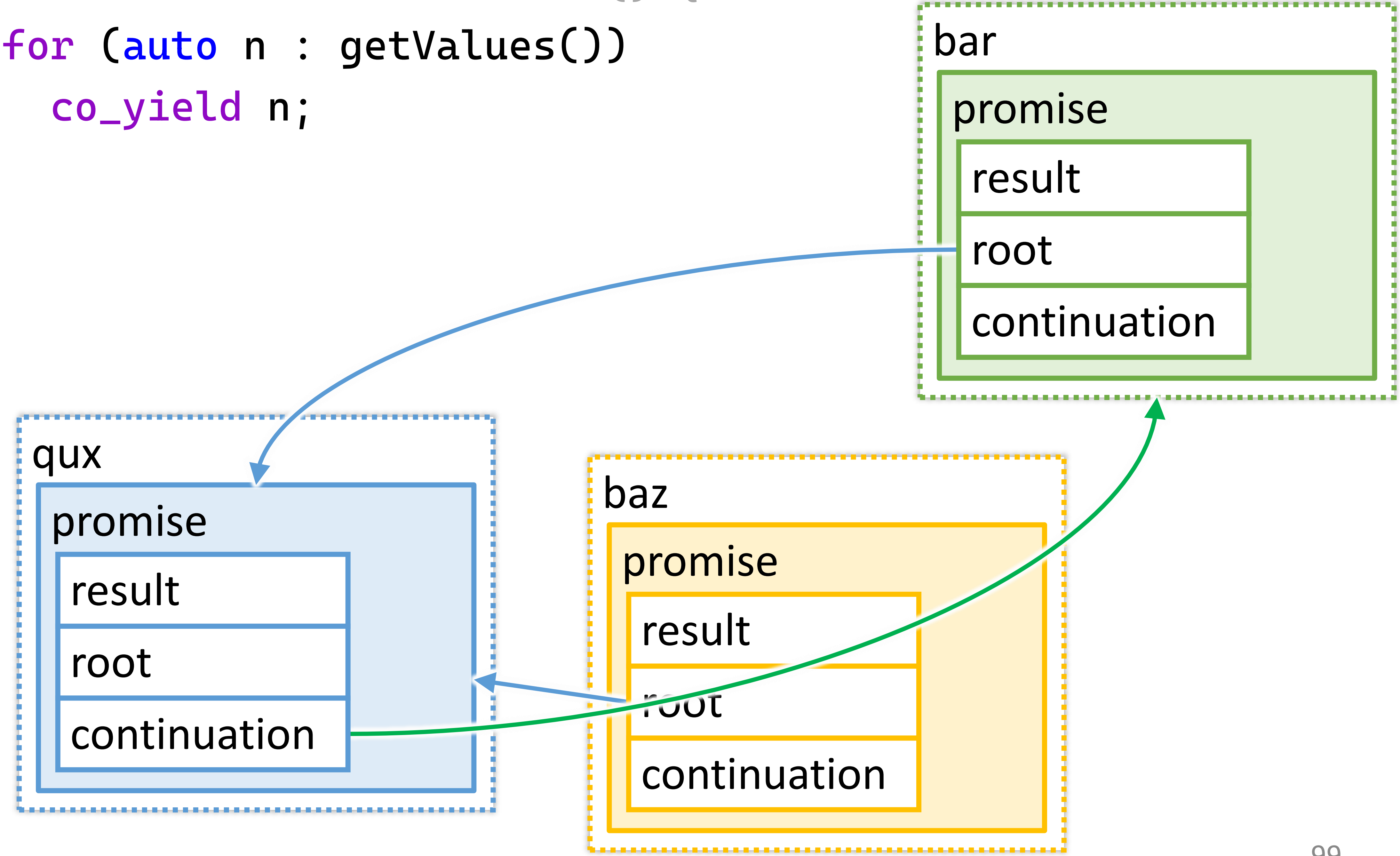
RecursiveGenerator<int> bar() {
  for (auto n : getValues())
    co_yield n;
}
```

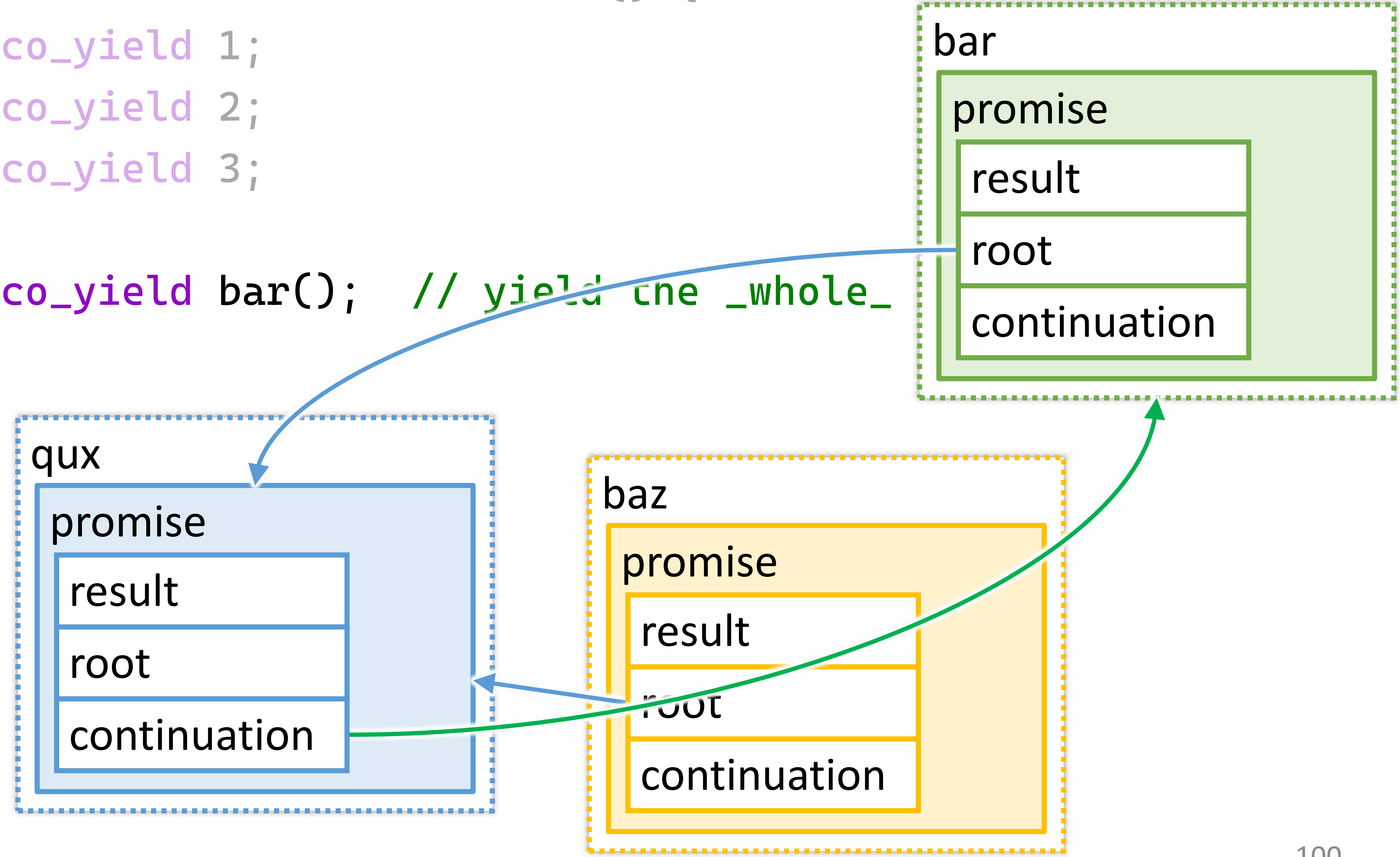


```
RecursiveGenerator<int> bar() {
  for (auto n : getValues())
    co_yield n;
}
```



```
RecursiveGenerator<int> baz() {
  co_yield 1;
  co_yield 2;
  co_yield 3;

  co_yield bar();  // yield _the _whole_
}
```



```
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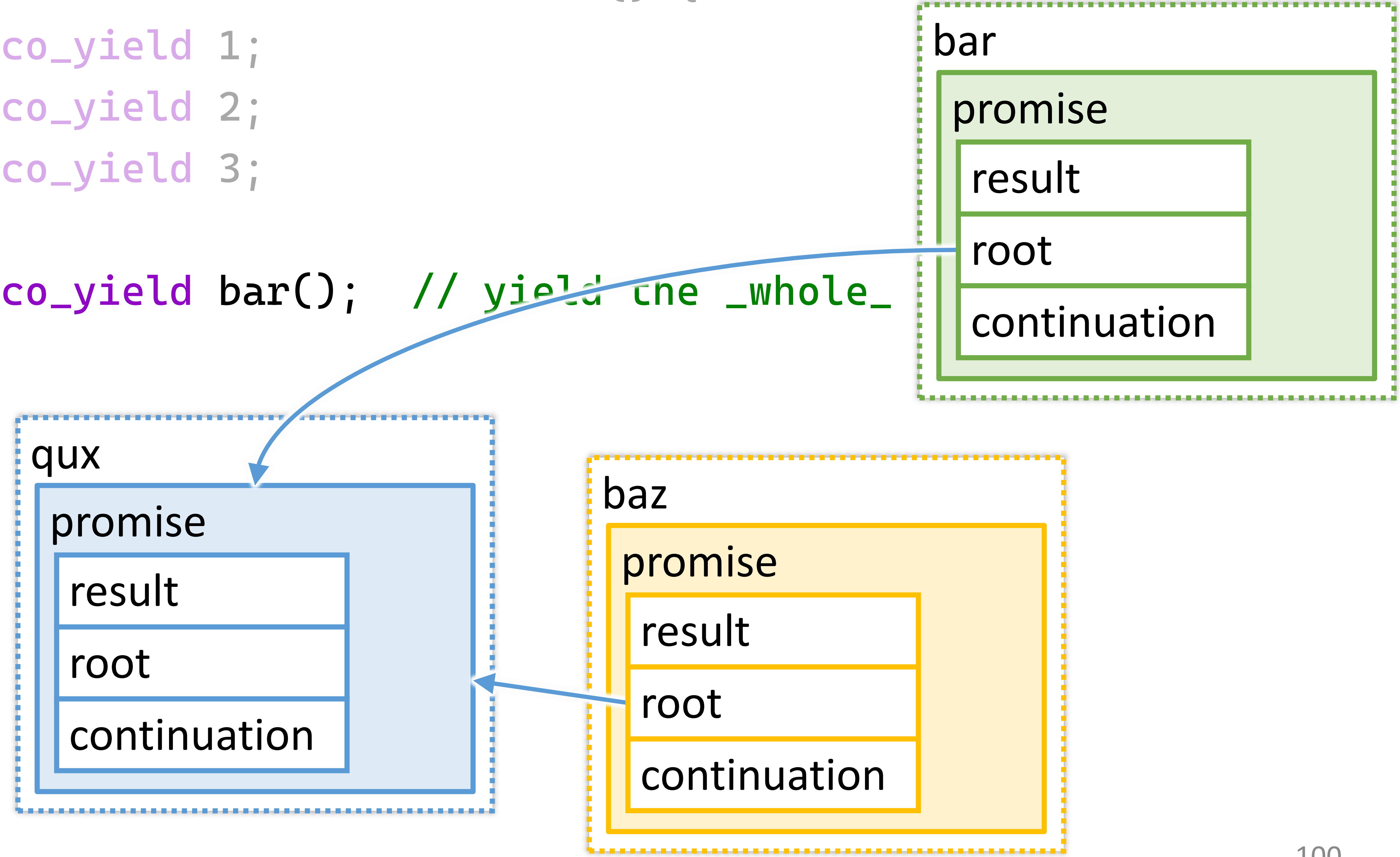
  co_yield 1;
  co_yield 2;
  co_yield 3;

  co_yield bar();  // yield the _whole_
}
```



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  co_yield 1;
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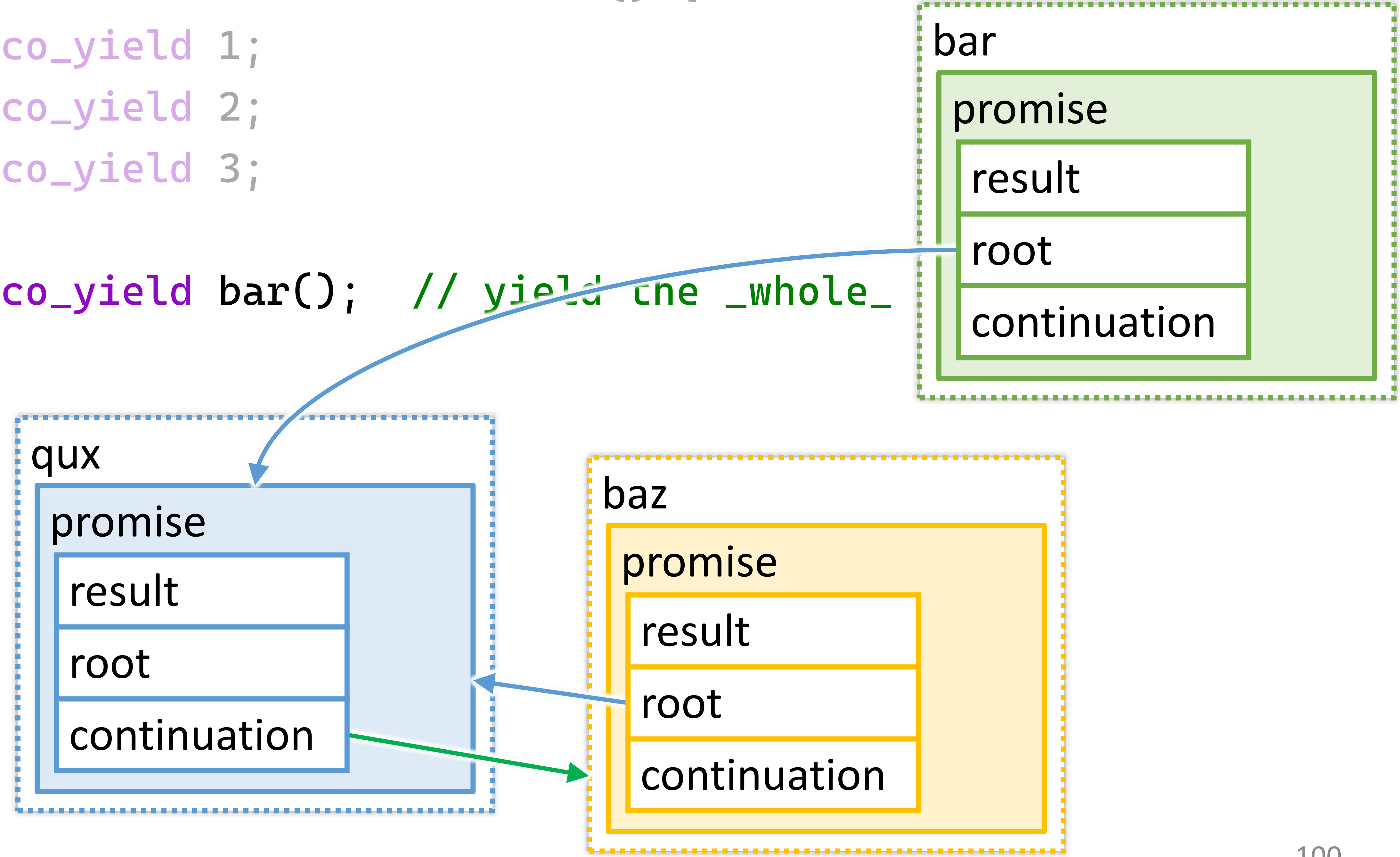
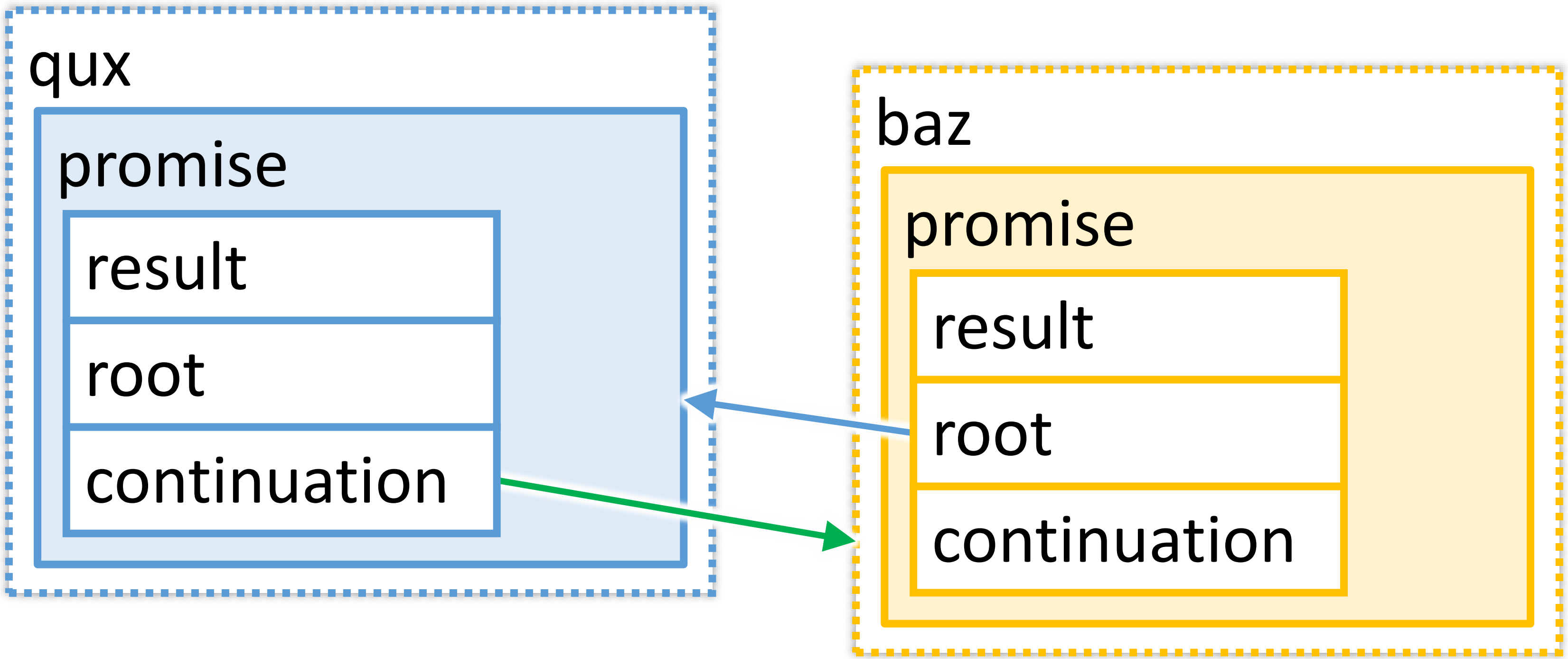
  co_yield 3;

  co_yield bar();  // yield the _whole_
}
```

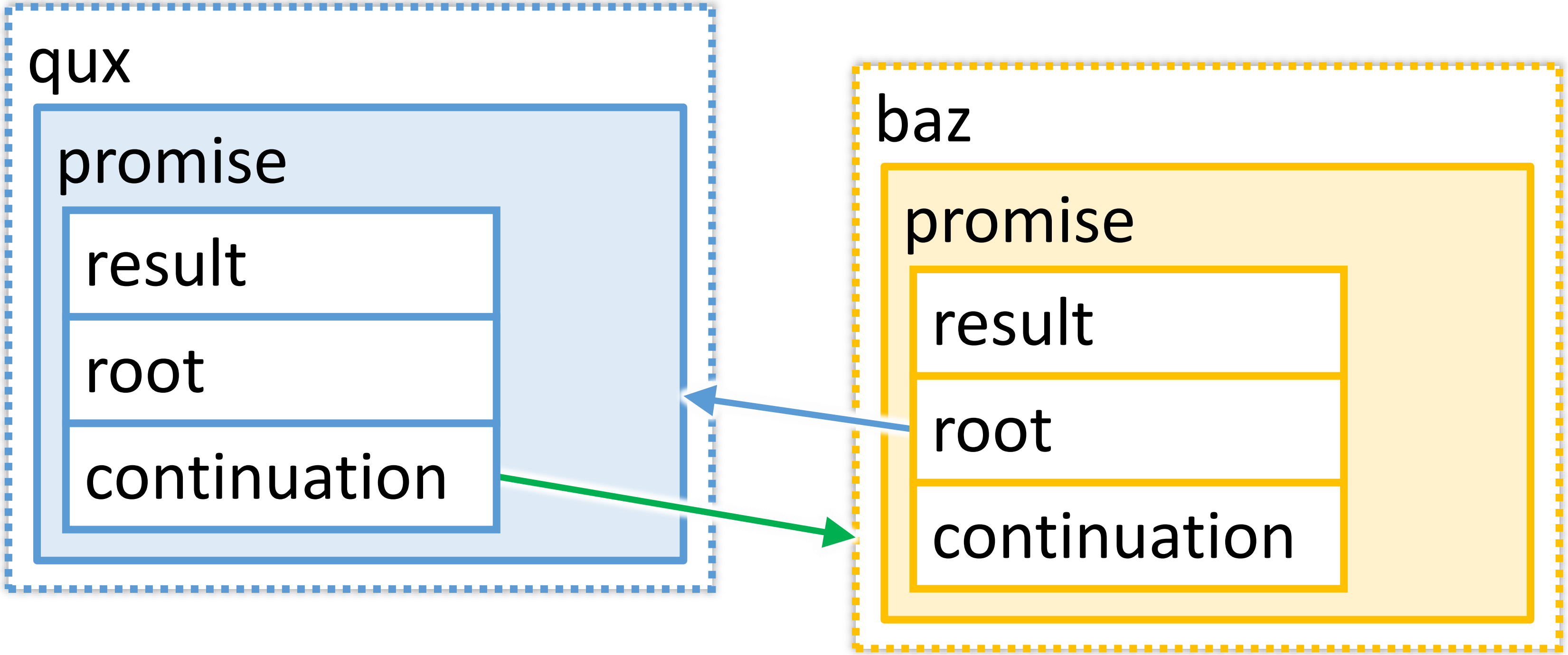


```
RecursiveGenerator<int> baz() {
  co_yield 1;
  co_yield 2;
  co_yield 3;

  co_yield bar();  // yield the _whole_ thing
}
```



```
RecursiveGenerator<int> qux() {
  const auto g = baz();
  if (auto i = g.begin(); i != g.end()) {
    co_yield *i * 33;
    ++i;
  }
  co_yield g;  // yield the rest
}
```



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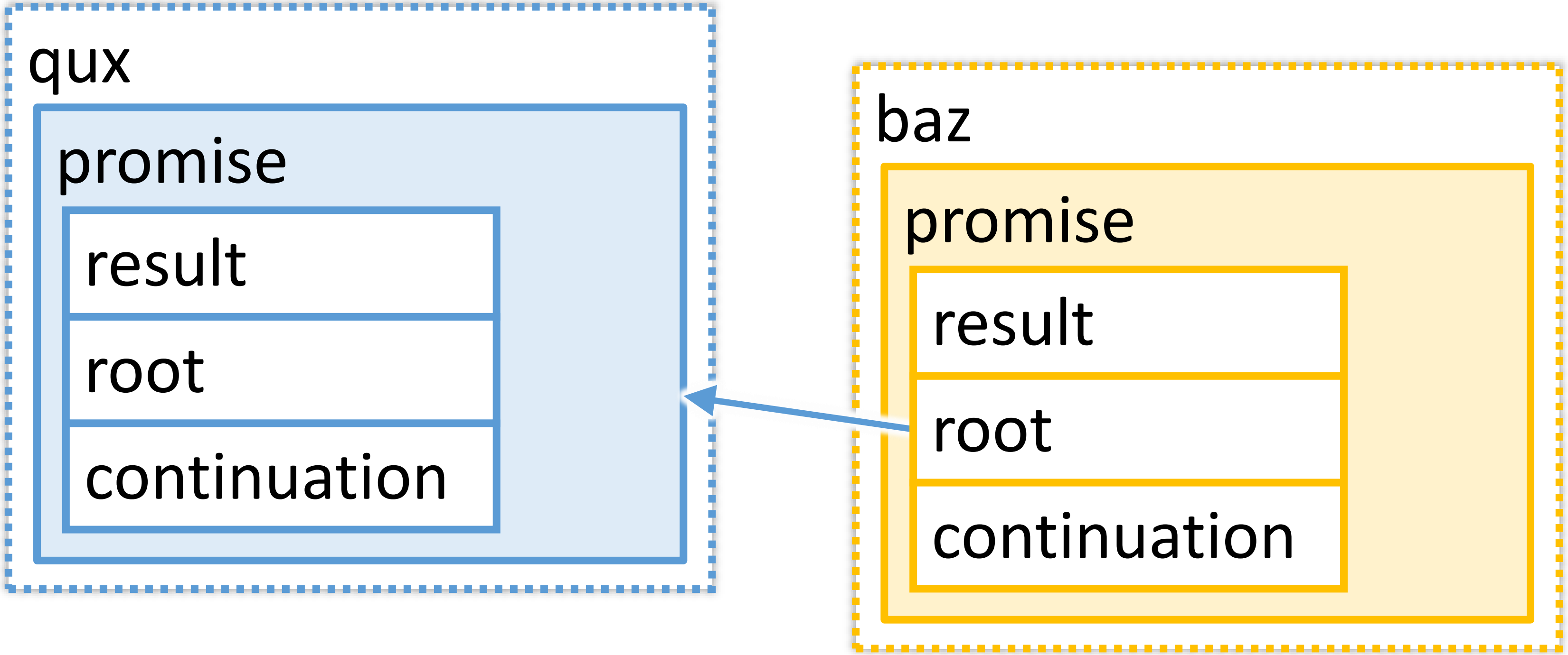

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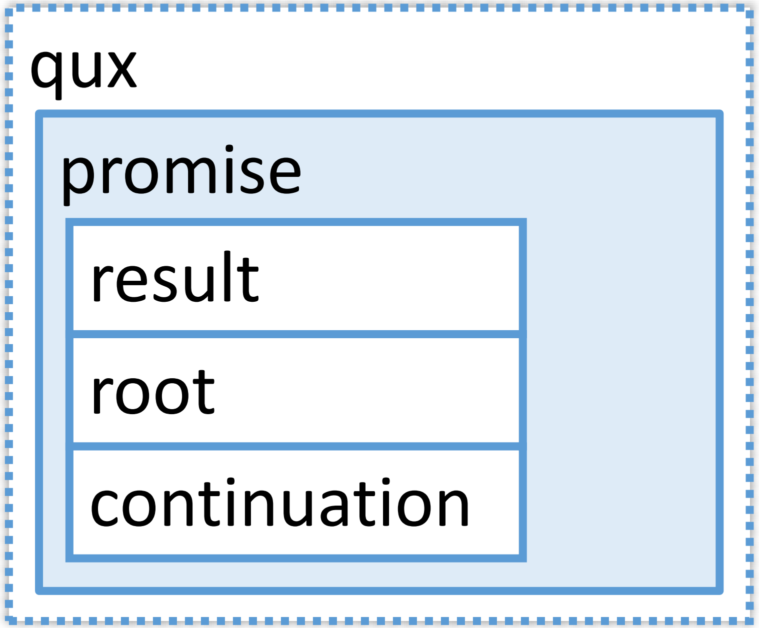

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const auto h = qux();
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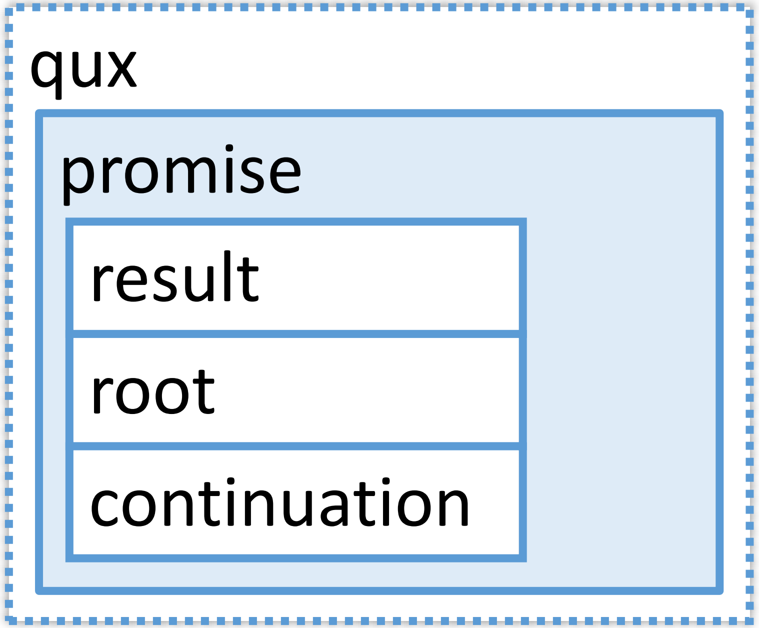

# Recursive generator

In this presentation `Generator` and `RecursiveGenerator` are different because the latter needs additional fields to track nested-ness, which is an overhead (though a reasonably small one).

# Recursive generator

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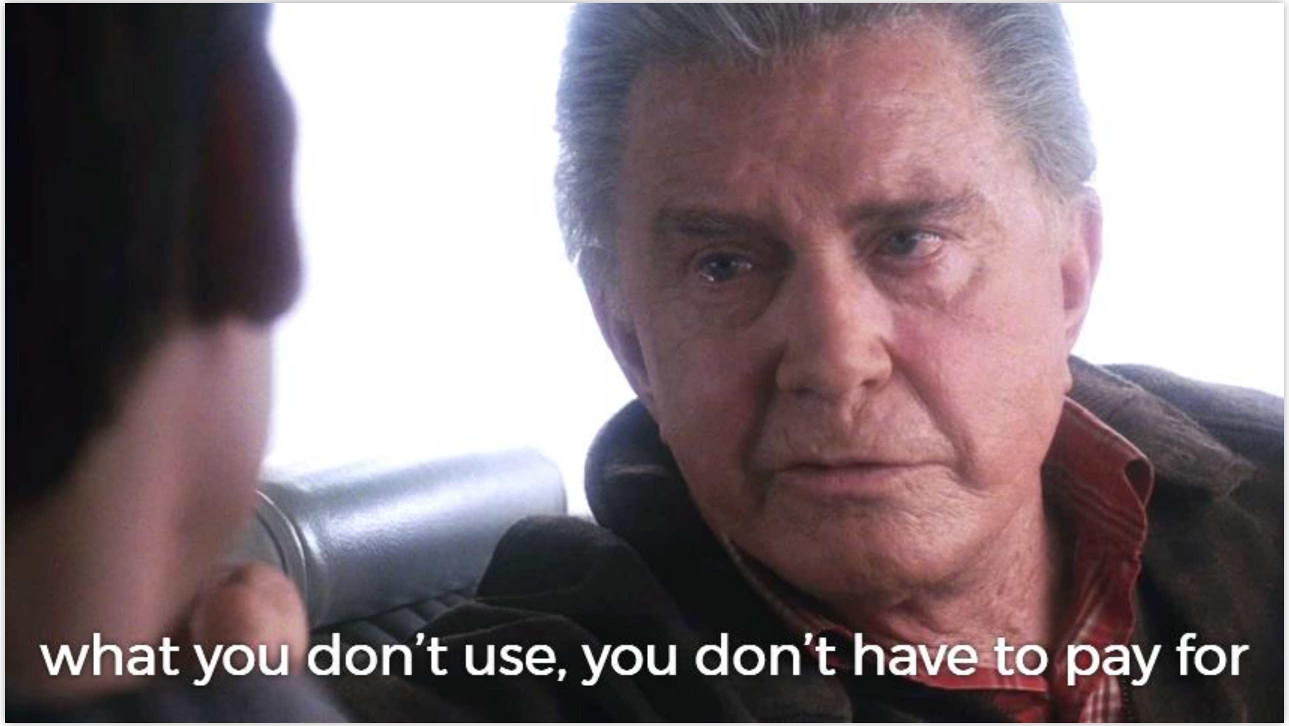

# `std::generator`

- **P2502**: `std::generator`: Synchronous Coroutine Generator for Ranges by Casey Carter http://wg21.link/p2502
- accepted into C++23
- works very much like `RecursiveGenerator`

```cpp
namespace std {
  template<class R, class V = void, class Allocator = void>
  class generator {
  public:
    using yielded =
      conditional_t<is_reference_v<reference>, reference, const reference&>;
    class promise_type;

    generator(const generator&) = delete;
    generator(generator&&) noexcept;
    ~generator();
    generator &operator=(const generator&) = delete;
    generator &operator=(generator&&) noexcept;
    iterator begin();
    default_sentinel_t end() const noexcept;
  };

  template<class R, class V, class Allocator>
  constexpr bool ranges::enable_view<generator<R, V, Allocator>> = true;
}
```

[[nodiscard]]?

# `std::generator`

Members [generator.members]

`iterator begin();`

*Preconditions:* *`coroutine_`* refers to a coroutine suspended at its initial suspend-point.

*Effects:* Equivalent to:

```
coroutine_.resume();
return iterator(coroutine_);
```

*Remarks:* This function pushes *`coroutine_`* onto the `generator`'s empty stack of associated coroutines.

[ *Note:* A program that calls `begin` more than once on the same generator has undefined behavior. — *end note* ]

# std::generator

Members [generator.members]

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*Remarks:* This function pushes *`coroutine_`* onto the `generator`'s empty stack of associated coroutines.

[ *Note:* A program that calls `begin` more than once on the same generator has undefined behavior. — *end note* ]

# std::generator

```
std::generator<int> qux() {
  const auto g = baz();
  if (auto i = g.begin(); i != g.end()) {
    co_yield *i * 33;
    ++i;
  }
  for (auto i : g)  // UB: 'g.begin()' is called
    co_yield i;  // yield the rest
}
```

changes observable state
(that we can't observe)

# std::generator

```
std::generator<int> qux() {
  const auto g = baz();
  for (auto i : g | std::views::take(1))
    co_yield i * 33;


  for (auto i : g)  // UB: 'g.begin()' is called
    co_yield i;  // yield the rest
}
```

# std::generator

```
std::generator<int> qux() {
  const auto g = baz();
  for (auto i : g | std::views::take(1))
    co_yield i * 33;



  co_yield std::ranges::elements_of{ g };  // UB?
}
```

# std::generator

```
std::generator<int> qux() {
  auto g = baz();
  for (auto i : g | std::views::take(1))
    co_yield i * 33;

  // pointless: calling 'begin()' is UB
  processValues(std::move(g));
}
```

# std::generator

```
std::istringstream s{ "hello world ..." };
for (auto i = std::istream_iterator<std::string>{ s };
     i != std::istream_iterator<std::string>{};
     ++i) {
  std::cout << *i << '\n';
  //...
  if (someCondition)
    break;
}
for (auto i = std::istream_iterator<std::string>{ s };
     i != std::istream_iterator<std::string>{};
     ++i) {
  // do something else with the rest of the data
}
```

# std::generator

```
std::istringstream s{ "hello world ..." };
for (auto i = std::istream_iterator<std::string>{ s };
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  std::cout << *i << '\n';
  //...
  if (someCondition)
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}
for (auto i = std::istream_iterator<std::string>{ s };
     i != std::istream_iterator<std::string>{};
     ++i) {
  // do something else with the rest of the data
}
```

`istream_iterator`'s ctor reads from `s`, i.e. changes its observable state

iteration can be safely restarted/continued

# `std::generator`

- generator type in the standard library

  Yay!

- recursive — always has (reasonably small) overhead when you don't yield nested generators

- can't restart/continue iteration after `begin()` is already called once

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  whatever…

- can't restart/continue iteration after `begin()` is already called once

  (╯°□°）╯︵ ┻━┻

# Async generator

```
Task<std::vector<int>> getValuesAsync();

AsyncGenerator<int> generateValuesAsync() {
  const auto values = co_await getValuesAsync();
  for (auto &v : values) {
    if (isValueValid(v))
      co_yield v;
  }
}
```

# Async generator

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AsyncGenerator<int> generateValuesAsync() {
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  }
}
```

# Async generator

```
Task<int> getPrettiestValue() {
  auto g = generateValuesAsync();
  //...
  for (auto i = g.begin();
       i != g.end();
       i = co_await i.next()) {
    //...
  }
  //...
}
```

# Async generator

```
Task<int> getPrettiestValue() {
  auto g = generateValuesAsync();
  //...
  for (auto i = g.begin();
       i != g.end();
       i = co_await i.next()) {
    //...
  }
  //...
}
```

# Async generator

```
Task<int> getPrettiestValue() {
  auto g = generateValuesAsync();
  int prettiest = -37;
  int prettinessLevel = 0;

  while (auto next = co_await g.next()) {
    const auto p = getPrettinessLevel(*next);
    if (prettinessLevel < p ||
        prettinessLevel == p && prettiest < *next) {
      prettiest = *next;
      prettinessLevel = p;
    }
  }

  co_return prettiest;
}
```

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Task<int> getPrettiestValue() {
  auto g = generateValuesAsync();
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  while (auto next = co_await g.next()) {
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    if (prettinessLevel < p ||
        prettinessLevel == p && prettiest < *next) {
      prettiest = *next;
      prettinessLevel = p;
    }
  }

  co_return prettiest;
}
```

# Async generator

```
try {
  const auto value = syncWait(getPrettiestValue());
  std::cout << value << '\n';
}
catch (const std::exception &e) {
  std::cout << "exception: " << e.what() << '\n';
}
```

# Async generator

```
Task<int> getPrettiestValue() {
  auto g = generateValuesAsync();
  //...
  while (auto next = co_await g.next()) {
    //...
  }
  //...
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  auto g = generateValuesAsync();
  //...
  while (auto next = co_await g.next()) {
    //...
  }
  //...
}
```

this coroutine is suspended and set as continuation for g

# Async generator

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Task<int> getPrettiestValue() {
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this coroutine is resumed
as a continuation of g
and optional result is returned

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# Async generator

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Task<int> getPrettiestValue() {
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   while (auto next = co_await g.next()) {
      //...
   }
   //...
}
```

this coroutine is resumed
as a continuation of g
and optional result is returned

# Async generator

What lies ahead
is separated by an even thinner veil
from nonsense.

# Async generator

```
template<typename T>
struct AsyncGenerator {
  struct promise_type;

  AsyncGenerator(AsyncGenerator &&other) noexcept;
  AsyncGenerator &operator=(AsyncGenerator &&other) noexcept;
  ~AsyncGenerator();

  auto next();

private:
  explicit AsyncGenerator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# Async generator

```
template<typename T>
struct AsyncGenerator {
  struct promise_type;

  AsyncGenerator(AsyncGenerator &&other) noexcept;
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private:
  explicit AsyncGenerator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

# Async generator

```
template<typename T>
struct AsyncGenerator {
  //...
  AsyncGenerator(AsyncGenerator &&other) noexcept :
    coro{ std::exchange(other.coro, nullptr) }
  {}
  AsyncGenerator &operator=(AsyncGenerator &&other) noexcept {
    if (coro)
      coro.destroy();
    coro = std::exchange(other.coro, nullptr);
  }
  ~AsyncGenerator() {
    if (coro)
      coro.destroy();
  }
  //...
};
```

# Async generator

```
template<typename T>
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      coro.destroy();
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  }
  ~AsyncGenerator() {
    if (coro)
      coro.destroy();
  }
  //...
};
```

# Async generator

```
template<typename T>
struct AsyncGenerator {
  //...
  auto next() {
    return typename promise_type::NextAwaitable{ coro };
  }

private:
  explicit AsyncGenerator(promise_type &promise) noexcept :
    coro{ std::coroutine_handle<promise_type>::from_promise(promise) }
  {}

  std::coroutine_handle<promise_type> coro;
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  {}

  std::coroutine_handle<promise_type> coro;
};
```

```cpp
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  auto final_suspend() const noexcept;

  struct YieldAwaitable;
  YieldAwaitable yield_value(T &&value) noexcept;
  YieldAwaitable yield_value(const T &value) noexcept(std::is_nothrow_copy_constructible_v<T>);

  void return_void() const noexcept {}
  void unhandled_exception() noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  T &getValue();
  bool hasException() const noexcept;
  void throwIfException() const;

  struct NextAwaitable;

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

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  void unhandled_exception() noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  T &getValue();
  bool hasException() const noexcept;
  void throwIfException() const;

  struct NextAwaitable;

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

```
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  auto final_suspend() const noexcept;

  struct YieldAwaitable;
  YieldAwaitable yield_value(T &&value) noexcept;
  YieldAwaitable yield_value(const T &value) noexcept(std::is_nothrow_copy_constructible_v<T>);

  void return_void() const noexcept {}
  void unhandled_exception() noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  T &getValue();
  bool hasException() const noexcept;
  void throwIfException() const;

  struct NextAwaitable;

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

# Async generator

```
struct NextAwaitable {
  NextAwaitable(std::coroutine_handle<promise_type> coro) noexcept :
    coro{ coro } {}
  bool await_ready() const noexcept {
    return false;
  }
  auto await_suspend(std::coroutine_handle<> thatCoro) const noexcept {
    coro.promise().continuation = thatCoro;
    return coro;
  }
  std::optional<T> await_resume() const {
    //...
  }
private:
  std::coroutine_handle<promise_type> coro;
};
```

# Async generator

```
struct NextAwaitable {
  NextAwaitable(std::coroutine_handle<promise_type> coro) noexcept :
    coro{ coro } {}
  bool await_ready() const noexcept {
    return false;
  }
  auto await_suspend(std::coroutine_handle<> thatCoro) const noexcept {
    coro.promise().continuation = thatCoro;
    return coro;
  }
  std::optional<T> await_resume() const {
    //...
  }
private:
  std::coroutine_handle<promise_type> coro;
};
```

handle of generator's coroutine

# Async generator

```
struct NextAwaitable {
  NextAwaitable(std::coroutine_handle<promise_type> coro) noexcept :
    coro{ coro } {}
  bool await_ready() const noexcept {
    return false;
  }
  auto await_suspend(std::coroutine_handle<> thatCoro) const noexcept {
    coro.promise().continuation = thatCoro;
    return coro;
  }
  std::optional<T> await_resume() const {
    //...
  }
private:
  std::coroutine_handle<promise_type> coro;
};
```

# Async generator

```
struct NextAwaitable {
  NextAwaitable(std::coroutine_handle<promise_type> coro) noexcept :
    coro{ coro } {}
  bool await_ready() const noexcept {
    return false;
  }
  auto await_suspend(std::coroutine_handle<> thatCoro) const noexcept {
    coro.promise().continuation = thatCoro;
    return coro;
  }
  std::optional<T> await_resume() const {
    //...
  }
private:
  std::coroutine_handle<promise_type> coro;
};
```

symmetric transfer of control

# Async generator

```
struct NextAwaitable {
  //...
  std::optional<T> await_resume() const {
    auto &promise = coro.promise();
    if (coro.done()) {
      promise.throwIfException();
      return {};
    }
    return std::move(promise.getValue());
  }

private:
  std::coroutine_handle<promise_type> coro;
};
```

# Async generator

```
struct NextAwaitable {
  //...
  std::optional<T> await_resume() const {
    auto &promise = coro.promise();
    if (coro.done()) {
      promise.throwIfException();
      return {};
    }
    return std::move(promise.getValue());
  }

private:
  std::coroutine_handle<promise_type> coro;
};
```

# Async generator

```
struct NextAwaitable {
  //...
  std::optional<T> await_resume() const {
    auto &promise = coro.promise();
    if (coro.done()) {
      promise.throwIfException();
      return {};
    }
    return std::move(promise.getValue());
  }

private:
  std::coroutine_handle<promise_type> coro;
};
```

# Async generator

```
struct NextAwaitable {
  //...
  std::optional<T> await_resume() const {
    auto &promise = coro.promise();
    if (coro.done()) {
      promise.throwIfException();
      return {};
    }
    return std::move(promise.getValue());
  }

private:
  std::coroutine_handle<promise_type> coro;
};
```

```cpp
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  auto final_suspend() const noexcept;

  struct YieldAwaitable;
  YieldAwaitable yield_value(T &&value) noexcept;
  YieldAwaitable yield_value(const T &value) noexcept(std::is_nothrow_copy_constructible_v<T>);

  void return_void() const noexcept {}
  void unhandled_exception() noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  T &getValue();
  bool hasException() const noexcept;
  void throwIfException() const;

  struct NextAwaitable;

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

```
struct promise_type {
  auto get_return_object() noexcept;
  std::suspend_always initial_suspend() const noexcept;
  auto final_suspend() const noexcept;

  struct YieldAwaitable;
  YieldAwaitable yield_value(T &&value) noexcept;
  YieldAwaitable yield_value(const T &value) noexcept(std::is_nothrow_copy_constructible_v<T>);

  void return_void() const noexcept {}
  void unhandled_exception() noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>);

  T &getValue();
  bool hasException() const noexcept;
  void throwIfException() const;

  struct NextAwaitable;

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

# Async generator

```
struct promise_type {
  auto get_return_object() noexcept {
    return AsyncGenerator{ *this };
  }
  std::suspend_always initial_suspend() const noexcept {
    return {};
  }
  //...
};
```

# Async generator

```
struct promise_type {
  auto get_return_object() noexcept {
    return AsyncGenerator{ *this };
  }
  std::suspend_always initial_suspend() const noexcept {
    return {};
  }
  //...
};
```

# Async generator

```
struct promise_type {
  //...
  auto final_suspend() const noexcept {
    struct FinalAwaitable {
      //...
    };
    return FinalAwaitable{};
  }
  //...
};
```

# Async generator

```
struct FinalAwaitable {
  bool await_ready() const noexcept {
    return false;
  }
  std::coroutine_handle<>
    await_suspend(std::coroutine_handle<promise_type> thisCoro)
      noexcept {
    auto &promise = thisCoro.promise();

    assert(promise.continuation);

    return promise.continuation;
  }
  void await_resume() const noexcept {}
};
```

# Async generator

```
struct FinalAwaitable {
  bool await_ready() const noexcept {
    return false;
  }
  std::coroutine_handle<>
    await_suspend(std::coroutine_handle<promise_type> thisCoro)
      noexcept {
    auto &promise = thisCoro.promise();

    assert(promise.continuation);

    return promise.continuation;
  }
  void await_resume() const noexcept {}
};
```

# Async generator

```
struct FinalAwaitable {
  bool await_ready() const noexcept {
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  }
  std::coroutine_handle<>
    await_suspend(std::coroutine_handle<promise_type> thisCoro)
      noexcept {
    auto &promise = thisCoro.promise();

    assert(promise.continuation);

    return promise.continuation;
  }
  void await_resume() const noexcept {}
};
```

# Async generator

```
struct FinalAwaitable {
  bool await_ready() const noexcept {
    return false;
  }
  std::coroutine_handle<>
    await_suspend(std::coroutine_handle<promise_type> thisCoro)
      noexcept {
    auto &promise = thisCoro.promise();

    assert(promise.continuation);

    return promise.continuation;
  }
  void await_resume() const noexcept {}
};
```

# Async generator

```
struct FinalAwaitable {
  bool await_ready() const noexcept {
    return false;
  }
  std::coroutine_handle<>
    await_suspend(std::coroutine_handle<promise_type> thisCoro)
      noexcept {
    auto &promise = thisCoro.promise();

    assert(promise.continuation);

    return promise.continuation;
  }
  void await_resume() const noexcept {}
};
```

symmetric transfer of control

# Async generator

```
struct FinalAwaitable {
  bool await_ready() const noexcept {
    return false;
  }
  std::coroutine_handle<>
    await_suspend(std::coroutine_handle<promise_type> thisCoro)
      noexcept {
    auto &promise = thisCoro.promise();

    assert(promise.continuation);

    return promise.continuation;
  }
  void await_resume() const noexcept {}
};
```

```cpp
struct promise_type {
  //...
  struct YieldAwaitable {
    //...
  };

  YieldAwaitable yield_value(T &&value) noexcept {
    result = std::addressof(value);
    return {};
  }
  YieldAwaitable yield_value(const T &value)
    noexcept(std::is_nothrow_copy_constructible_v<T>) {
    result = value;
    return {};
  }
  //...
};
```

```
struct promise_type {
  //...
  struct YieldAwaitable {
    //...
  };

  YieldAwaitable yield_value(T &&value) noexcept {
    result = std::addressof(value);
    return {};
  }
  YieldAwaitable yield_value(const T &value)
    noexcept(std::is_nothrow_copy_constructible_v<T>) {
    result = value;
    return {};
  }
  //...
};
```

```
struct promise_type {
  //...
  struct YieldAwaitable {
    //...
  };

  YieldAwaitable yield_value(T &&value) noexcept {
    result = std::addressof(value);
    return {};
  }
  YieldAwaitable yield_value(const T &value)
    noexcept(std::is_nothrow_copy_constructible_v<T>) {
    result = value;
    return {};
  }
  //...
};
```

# Async generator

```
struct YieldAwaitable {
  bool await_ready() const noexcept {
    return false;
  }
  std::coroutine_handle<>
    await_suspend(std::coroutine_handle<promise_type> thisCoro)
      const noexcept {
    auto &promise = thisCoro.promise();

    assert(promise.continuation);

    return std::exchange(promise.continuation, nullptr);
  }
  void await_resume() const noexcept {}
};
```

# Async generator

```
struct YieldAwaitable {
  bool await_ready() const noexcept {
    return false;
  }
  std::coroutine_handle<>
    await_suspend(std::coroutine_handle<promise_type> thisCoro)
      const noexcept {
    auto &promise = thisCoro.promise();

    assert(promise.continuation);

    return std::exchange(promise.continuation, nullptr);
  }
  void await_resume() const noexcept {}
};
```

# Async generator

```
struct YieldAwaitable {
  bool await_ready() const noexcept {
    return false;
  }
  std::coroutine_handle<>
    await_suspend(std::coroutine_handle<promise_type> thisCoro)
      const noexcept {
    auto &promise = thisCoro.promise();

    assert(promise.continuation);

    return std::exchange(promise.continuation, nullptr);
  }
  void await_resume() const noexcept {}
};
```

symmetric transfer of control

# Async generator

```
struct YieldAwaitable {
  bool await_ready() const noexcept {
    return false;
  }
  std::coroutine_handle<>
    await_suspend(std::coroutine_handle<promise_type> thisCoro)
      const noexcept {
    auto &promise = thisCoro.promise();

    assert(promise.continuation);

    return std::exchange(promise.continuation, nullptr);
  }
  void await_resume() const noexcept {}
};
```

# Async generator

```
AsyncGenerator<int> generateValuesAsync() {
  const auto values = co_await getValuesAsync();
  for (auto &v : values) {
    if (isValueValid(v))
      co_yield v;
  }
}
```

# Async generator

```
AsyncGenerator<int> generateValuesAsync() {
  const auto values = co_await getValuesAsync();
  for (auto &v : values) {
    if (isValueValid(v))
      co_yield v;
  }
}
```

suspend

value is yielded,
this coroutine is suspended
and continuation is resumed
via symmetric transfer of control

# Async generator

```
struct promise_type {
  //...
  void return_void() const noexcept {}

  void unhandled_exception()
    noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>) {
    result = std::current_exception();
  }
  //...
};
```

# Async generator

```
struct promise_type {
  //...
  void return_void() const noexcept {}

  void unhandled_exception()
    noexcept(std::is_nothrow_copy_constructible_v<std::exception_ptr>) {
    result = std::current_exception();
  }
  //...
};
```

# Async generator

```
struct promise_type {
  //...
  T &getValue() {
    return std::holds_alternative<T>(result) ? std::get<T>(result) :
                                               *std::get<T*>(result);
  }
  bool hasException() const noexcept {
    return std::holds_alternative<std::exception_ptr>(result);
  }
  void throwIfException() const {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));
  }
  //...
};
```

# Async generator

```
struct promise_type {
  //...
  T &getValue() {
    return std::holds_alternative<T>(result) ? std::get<T>(result) :
                                               *std::get<T*>(result);
  }
  bool hasException() const noexcept {
    return std::holds_alternative<std::exception_ptr>(result);
  }
  void throwIfException() const {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));
  }
  //...
};
```

# Async generator

```
struct promise_type {
  //...
  T &getValue() {
    return std::holds_alternative<T>(result) ? std::get<T>(result) :
                                               *std::get<T*>(result);
  }
  bool hasException() const noexcept {
    return std::holds_alternative<std::exception_ptr>(result);
  }
  void throwIfException() const {
    if (hasException())
      std::rethrow_exception(std::get<std::exception_ptr>(result));
  }
  //...
};
```

# Async generator

```cpp
struct promise_type {
  //...
  struct NextAwaitable {
    //...
  };

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

# Async generator

```
Task<std::vector<int>> getValuesAsync();

AsyncGenerator<int> generateValuesAsync() {
  const auto values = co_await getValuesAsync();
  for (auto &v : values) {
    if (isValueValid(v))
      co_yield v;
  }
}
```

# Async generator

```
Task<std::vector<int>> getValuesAsync();

AsyncGenerator<int> generateValuesAsync() {
  const auto values = co_await getValuesAsync();
  for (auto &v : values) {
    if (isValueValid(v))
      co_yield v;
  }
}
```

# Async generator

```
Task<std::vector<int>> getValuesAsync();

AsyncGenerator<int> generateValuesAsync() {
  const auto values = co_await getValuesAsync();
  for (auto &v : values) {
    if (isValueValid(v))
      co_yield v;
  }
}
```

# Async generator

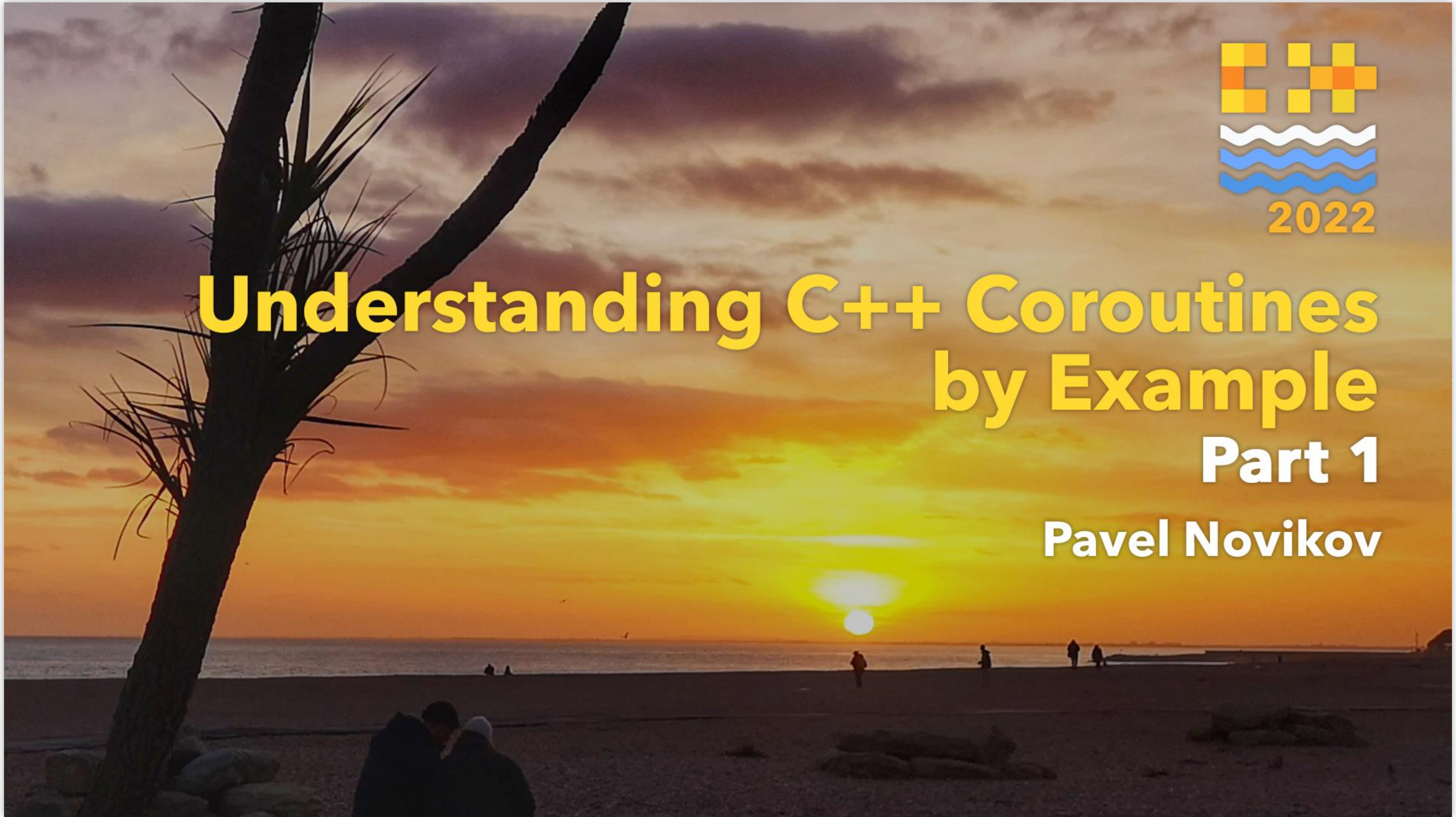
```
Task<int> getPrettiestValue() {
  auto g = generateValuesAsync();
  int prettiest = -37;
  int prettinessLevel = 0;

  while (auto next = co_await g.next()) {
    const auto p = getPrettinessLevel(*next);
    if (prettinessLevel < p ||
        prettinessLevel == p && prettiest < *next) {
      prettiest = *next;
      prettinessLevel = p;
    }
  }

  co_return prettiest;
}
```

# You may want to watch

youtu.be/tj0URCY_A1s



# Thanks for listening!

# Understanding C++ coroutines by example part 2: generators

Pavel Novikov

@cpp_ape

Thanks to Phil Nash for feedback.

Slides: bit.ly/3wr5vxW

# References


- Lewis Baker "Structured Concurrency: Writing safer concurrent code with coroutines and algorithms" https://youtu.be/1Wy5sq3s2rg
- P2502: `std::generator`: Synchronous Coroutine Generator for Ranges http://wg21.link/p2502
- Understanding C++ coroutines by example, part 1 https://youtu.be/tj0URCY_A1s

# Bonus slides

# Ugly simple generator

```
template<typename T>
struct Generator {
  struct promise_type;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  bool hasValue() const noexcept;  //has value or exception
  auto &operator()() const;

private:
  explicit Generator(promise_type &promise) noexcept;

  void getNextValue() const noexcept;

  std::coroutine_handle<promise_type> coro;
  mutable bool gotValue = false;
};
```

# Ugly simple generator

```
template<typename T>
struct Generator {
  //...
private:
  //...
  void getNextValue() const noexcept {
    if (!gotValue && !coro.done()) {
      coro();
      gotValue = !coro.done() || coro.promise().hasException();
    }
  }

  std::coroutine_handle<promise_type> coro;
  mutable bool gotValue = false;
};
```

# Ugly simple generator

```
template<typename T>
struct Generator {
  //...
  bool hasValue() const noexcept {  //has value or exception
    getNextValue();
    return gotValue;
  }

  auto &operator()() const {
    getNextValue();
    gotValue = false;
    return coro.promise().getValue();
  }
  //...
};
```

precondition:

```
  hasValue() == true
```

or, more precisely:

```
  !coro.done() or
  coro.promise().hasException()
```

# Range generator with lazy iterator

```
template<typename T>
struct Generator {
  struct promise_type;
  struct LazyIterator;

  Generator(Generator &&other) noexcept;
  Generator &operator=(Generator &&other) noexcept;
  ~Generator();

  LazyIterator begin() const noexcept;
  LazyIterator end() const noexcept;

private:
  explicit Generator(promise_type &promise) noexcept;

  std::coroutine_handle<promise_type> coro;
};
```

```cpp
struct LazyIterator {
  // iterator boilerplate

  LazyIterator() noexcept = default;
  explicit LazyIterator(const std::coroutine_handle<promise_type> &coro) noexcept;

  friend bool operator==(const LazyIterator&, const LazyIterator&) noexcept = default;
  friend bool operator!=(const LazyIterator&, const LazyIterator&) noexcept = default;

  LazyIterator &operator++() noexcept;
  auto &operator*() const;
  friend bool hasException(const LazyIterator &i) noexcept;

private:
  const std::coroutine_handle<promise_type> *coro = nullptr;
};
```

# Range generator with lazy iterator

```
struct LazyIterator {
  //...
  LazyIterator &operator++() noexcept {
    assert(coro != nullptr);
    assert(!coro->done());

    coro->resume();
    if (coro->done() && !coro->promise().hasException())
      coro = nullptr;
    return *this;
  }
  //...
};
```

# Range generator with lazy iterator

```
struct LazyIterator {
  //...
  auto &operator*() const {
    assert(coro != nullptr);
    coro->promise().throwIfException();
    return coro->promise().getValue();
  }

  friend bool hasException(const LazyIterator &i) noexcept {
    return i.coro && i.coro->promise().hasException();
  }
  //...
};
```

# Range generator with lazy iterator

```
LazyIterator begin() const noexcept {
  if (coro.done())
    return end();

  auto i = LazyIterator{ coro };
  if (!coro.promise().isValueInitialized())
    ++i;
  return i;
}

LazyIterator end() const noexcept {
  return {};
}
```