Working Draft, C++ Extensions for Coroutines

Note: this is an early draft. It’s known to be incomplet and incorrekt, and it has lots of bad formatting.
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1 Scope

This document describes extensions to the C++ Programming Language (Clause 2) that enable definition of
coroutines. These extensions include new syntactic forms and modifications to existing language semantics.

The International Standard, ISO/IEC 14882:2017, provides important context and specification for this
document. This document is written as a set of changes against that specification. Instructions to modify
or add paragraphs are written as explicit instructions. Modifications made directly to existing text from the
International Standard use underlining to represent added text and strikethrough to represent deleted text.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes
requirements of this document. For dated references, only the edition cited applies. For undated references,
the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 14882:2017, Programming Languages – C++

ISO/IEC 14882:2017 is hereafter called the C++ Standard. Beginning with Clause 5, all clause and subclause
numbers, titles, and symbolic references in [brackets] refer to the corresponding elements of the C++ Stan-
dard. Clauses 1 through 4 of this document are unrelated to the similarly-numbered clauses and subclauses
of the C++ Standard.

3 Terms and definitions

No terms and definitions are listed in this document. ISO and IEC maintain terminological databases for
use in standardization at the following addresses:

ISO Online browsing platform: available at http://www.iso.org/obp

4 General

4.1 Implementation compliance
Conformance requirements for this specification shall be the same as those defined in subclause 1.4 of the C++ Standard. [Note: Conformance is defined in terms of the behavior of programs. — end note]

4.2 Feature testing
An implementation that provides support for this document shall define the feature test macro in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Header</th>
</tr>
</thead>
<tbody>
<tr>
<td>__cpp_coroutines</td>
<td>201803</td>
<td>predeclared</td>
</tr>
</tbody>
</table>

4.3 Program execution
In subclause 4.6 of the C++ Standard modify paragraph 6 to read:

7 An instance of each object with automatic storage duration (6.7.3) is associated with each entry into its block. Such an object exists and retains its last-stored value during the execution of the block and while the block is suspended (by a call of a function, suspension of a coroutine (8.3.8), or receipt of a signal).

5 Lexical conventions

5.11 Keywords
Add the keywords co_await, co_yield, and co_return to Table 5 "Keywords".
6 Basic concepts

6.6.1 Main function

Add underlined text to paragraph 3.

3 The function main shall not be used within a program. The linkage (6.5) of main is implementation-defined. A program that defines main as deleted or that declares main to be inline, static, or constexpr is ill-formed. The function main shall not be a coroutine (11.4.4). ...  

6.7.4.1 Allocation functions

Modify paragraph 4 as follows:

4 A global allocation function is only called as the result of a new expression (8.3.4), or called directly using the function call syntax (8.2.2), or called indirectly to allocate storage for a coroutine frame (11.4.4), or called indirectly through calls to the functions in the C++ standard library. [Note: In particular, a global allocation function is not called to allocate storage for objects with static storage duration (6.7.1), for objects or references with thread storage duration (6.7.2), for objects of type std::type_info (8.2.8), or for an exception object (18.1). — end note]

7 Standard Conversions

No changes are made to Clause 7 of the C++ Standard.
8 Expressions

8.3 Unary expressions

Add `await-expression` to the grammar production `unary-expression`:

```
unary-expression:
  postfix-expression
  ++ cast-expression
  -- cast-expression
  await-expression
  unary-operator cast-expression
  sizeof unary-expression
  sizeof ( type-id )
  sizeof ... ( identifier )
  alignof ( type-id )
  noexcept-expression
  new-expression
  delete-expression
```

8.3.8 Await

Add this subclause to 8.3.

1 The `co_await` expression is used to suspend evaluation of a coroutine (11.4.4) while awaiting completion of the computation represented by the operand expression.

```
await-expression:
  co_await cast-expression
```

2 An `await-expression` shall appear only in a potentially-evaluated expression within the `compound-statement` of a `function-body` outside of a `handler` (Clause 18). In a `declaration-statement` or in the `simple-declaration` (if any) of a `for-init-statement`, an `await-expression` shall appear only in an `initializer` of that `declaration-statement` or `simple-declaration`. An `await-expression` shall not appear in a default argument (11.3.6). A context within a function where an `await-expression` can appear is called a `suspension context` of the function.

3 Evaluation of an `await-expression` involves the following auxiliary types, expressions, and objects:

   (3.1) `p` is an lvalue naming the promise object (8.4.4) of the enclosing coroutine and `P` is the type of that object.

   (3.2) `a` is the `cast-expression` if the `await-expression` was implicitly produced by a `yield-expression` (8.20), an initial suspend point, or a final suspend point (11.4.4). Otherwise, the `unqualified-id await_transform` is looked up within the scope of `P` by class member access lookup (6.4.5), and if this lookup finds at least one declaration, then `a` is `p.await_transform(cast-expression)`; otherwise, `a` is the `cast-expression`.

   (3.3) `o` is determined by enumerating the applicable `operator co_await` functions for an argument `a` (16.3.1.2), and choosing the best one through overload resolution (16.3). If overload resolution is ambiguous, the program is ill-formed. If no viable functions are found, `o` is `a`. Otherwise, `o` is a call to the selected function.

   (3.4) `e` is a temporary object copy-initialized from `o` if `o` is a prvalue; otherwise `e` is an lvalue referring to the result of evaluating `o`.

§ 8.3.8
— $h$ is an object of type `std::experimental::coroutine_handle<p>` referring to the enclosing coroutine.

— `await-ready` is the expression $e.await_ready()$, contextually converted to `bool`.

— `await-suspend` is the expression $e.await_suspend(h)$, which shall be a prvalue of type `void`, `bool`, or `std::experimental::coroutine_handle<z>` for some type `Z`.

— `await-resume` is the expression $e.await_resume()$.

The `await-expression` has the same type and value category as the `await-resume` expression.

The `await-expression` evaluates the `await-ready` expression, then:

— If the result is `false`, the coroutine is considered suspended. Then, the `await-suspend` expression is evaluated. If that expression has type `std::experimental::coroutine_handle<z>` and evaluates to a value $s$, the coroutine referred to by $s$ is resumed as if by a call $s.resume()$. 

[Note: Any number of coroutines may be successively resumed in this fashion, eventually returning control flow to the current coroutine caller or resumer (11.4.4). — end note]

If that expression has type `bool` and evaluates to `false`, the coroutine is resumed. If that expression exits via an exception, the exception is caught, the coroutine is resumed, and the exception is immediately re-thrown (18.1). Otherwise, control flow returns to the current coroutine caller or resumer (11.4.4) without exiting any scopes (9.6).

— If the result is `true`, or when the coroutine is resumed, the `await-resume` expression is evaluated, and its result is the result of the `await-expression`.

[Example:

```cpp
template <typename T>
struct my_future {
    ...
    bool await_ready();
    void await_suspend(std::experimental::coroutine_handle<>);
    T await_resume();
};

template <class Rep, class Period>
auto operator co_await(std::chrono::duration<Rep, Period> d) {
    struct awiter {
        std::chrono::system_clock::duration duration;
        ...
        awiter(std::chrono::system_clock::duration d) : duration(d){}
        bool await_ready() const { return duration.count() <= 0; }  // 18.1
        void await_resume() {}
        void await_suspend(std::experimental::coroutine_handle<> h){...}
    };
    return awiter(d);
}

using namespace std::chrono;

my_future<int> h();

my_future<void> g() {  // § 8.3.8
    std::cout << "just about go to sleep...\n";
    co_await 10ms;
    std::cout << "resumed\n";
    co_await h();
}
auto f(int x = co_await h());  // error: await-expression outside of function suspension context
int a[] = { co_await h() };  // error: await-expression outside of function suspension context

— end example]

8.17 Assignment and compound assignment operators
Add yield-expression to the grammar production assignment-expression.

`assignment-expression:
  conditional-expression
  logical-or-expression assignment-operator initializer-clause
  throw-expression
  yield-expression`

8.19 Constant expressions
Add bullets prohibiting await-expression and yield-expression to paragraph 2.

— an await-expression (8.3.8);
— a yield-expression (8.20);

8.20 Yield
Add a new subclause to Clause 8.

`yield-expression:
  co_yield assignment-expression
  co_yield braced-init-list`

A yield-expression shall appear only within a suspension context of a function (8.3.8). Let e be the operand of the yield-expression and p be an lvalue naming the promise object of the enclosing coroutine (11.4.4), then the yield-expression is equivalent to the expression co_await p.yield_value(e).

[Example:

```cpp
template <typename T>
struct my_generator {
    struct promise_type {
        T current_value;
        ...
        auto yield_value(T v) {
            current_value = std::move(v);
            return std::experimental::suspend_always{};
        }
    };  
    struct iterator { ... };
    iterator begin();
    iterator end();
};

my_generator<pair<int,int>> g1() {
    for (int i = i; i < 10; ++i) co_yield {i,i};
}
my_generator<pair<int,int>> g2() {
    for (int i = i; i < 10; ++i) co_yield make_pair(i,i);
}
```
auto f(int x = co_yield 5); // error: yield-expression outside of function suspension context
int a[] = { co_yield 1 }; // error: yield-expression outside of function suspension context

int main() {
    auto r1 = g1();
    auto r2 = g2();
    assert(std::equal(r1.begin(), r1.end(), r2.begin(), r2.end()));
}
—end example]

9 Statements

9.5 Iteration statements

Add the underlined text to paragraph 1.

1 Iteration statements specify looping.

iteration-statement:

while ( condition ) statement
do statement while ( expression );
for ( for-init-statement conditionopt; expressionopt ) statement
for co_awaitopt ( for-range-declaration : for-range-initializer ) statement

9.5.4 The range-based for statement

Add the underlined text to paragraph 1.

1 For a range-based for statement of the form
for co_awaitopt ( for-range-declaration : for-range-initializer ) statement

is equivalent to

{ auto &&__range = for-range-initializer ;
  auto __begin = co_awaitopt begin-expr ;
  auto __end = end-expr ;
  for ( ; __begin != __end; co_awaitopt ++__begin ) {
    for-range-declaration = *__begin;
    statement
  }
}

Insert a new bullet after paragraph 1 bullet 1.

(1.1) — if the for-range-initializer is an expression, it is regarded as if it were surrounded by parentheses (so that a comma operator cannot be reinterpreted as delimiting two init-declarators);
(1.2) — co_await is present if and only if it appears immediately after the for keyword;
(1.3) — __range, __begin, and __end are variables defined for exposition only; and ...

Add the following paragraph after paragraph 2.

3 A range-based for statement with co_await shall appear only within a suspension context of a function (8.3.8).
9.6 Jump statements

Add coroutine-return-statement to the grammar production jump-statement:

\[
\text{jump-statement:} \\
\text{break ;} \\
\text{continue ;} \\
\text{return expr-braced-init-listopt ;} \\
\text{coroutine-return-statement} \\
\text{goto identifier ;}
\]

Add the underlined text to paragraph 2:

2 On exit from a scope (however accomplished), objects with automatic storage duration (6.7.3) that have been constructed in that scope are destroyed in the reverse order of their construction.

[Note: A suspension of a coroutine (8.3.8) is not considered to be an exit from a scope. —end note] ...

9.6.3 The return statement

Add the underlined text to paragraph 2:

... Flowing off the end of a constructor, a destructor, or a function that is not a coroutine with a cv void return type is equivalent to a return with no operand. Otherwise, flowing off the end of a function other than main (6.6.1) or a coroutine (11.4.4) results in undefined behavior.

9.6.3.1 The co_return statement

Add this subclause to 9.6.3.

\[
\text{coroutine-return-statement:} \\
\text{co_return expr-or-braced-init-listopt ;}
\]

1 A coroutine returns to its caller or resumer (11.4.4) by the co_return statement or when suspended (8.3.8). A coroutine shall not return to its caller or resumer by a return statement (9.6.3).

2 The expr-braced-init-list of a co_return statement is called its operand. Let \( p \) be an lvalue naming the coroutine promise object (11.4.4) and \( P \) be the type of that object, then a co_-return statement is equivalent to:

\[
\{ \; S; \text{goto final_suspend; } \}
\]

where final_suspend is as defined in 11.4.4 and \( S \) is defined as follows:

(2.1) \( S \) is \( p.return_value(expr-or-braced-init-list) \), if the operand is a braced-init-list or an expression of non-void type;

(2.2) \( S \) is \( \{ \text{expression}_{\text{opt}} ; p.return_void(); \} \), otherwise;

\( S \) shall be a prvalue of type void.

3 If \( p.return_void() \) is a valid expression, flowing off the end of a coroutine is equivalent to a co_return with no operand; otherwise flowing off the end of a coroutine results in undefined behavior.
10 Declarations

10.1 Specifiers

10.1.5 The constexpr specifier

Insert a new bullet after paragraph 3 bullet 1.

3 The definition of a constexpr function shall satisfy the following constraints:
   (3.1) it shall not be virtual (13.3);
   (3.2) it shall not be a coroutine (11.4.4);
   (3.3) ...

10.1.6.4 auto specifier

Add the following paragraph.

15 A function declared with a return type that uses a placeholder type shall not be a coroutine (11.4.4).

11 Declarators

11.4 Function definitions

11.4.4 Coroutines

Add this subclause to 11.4.

1 A function is a coroutine if it contains a coroutine-return-statement (9.6.3.1), an await-expression (8.3.8), a yield-expression (8.20), or a range-based for (9.5.4) with co_await. The parameter-declaration-clause of the coroutine shall not terminate with an ellipsis that is not part of a parameter-declaration.

2 [Example:

```cpp
task<int> f();

task<void> g1() {
    int i = co_await f();
    std::cout << "f() => " << i << std::endl;
}

template <typename... Args>
task<void> g2(Args&&...) { // OK: ellipsis is a pack expansion
    int i = co_await f();
    std::cout << "f() => " << i << std::endl;
}

task<void> g3(int a, ...) { // error: variable parameter list not allowed
    int i = co_await f();
    std::cout << "f() => " << i << std::endl;
}
```

§ 11.4.4
For a coroutine \( f \) that is a non-static member function, let \( P_1 \) denote the type of the implicit object parameter (16.3.1) and \( P_2 \ldots P_n \) be the types of the function parameters; otherwise let \( P_1 \ldots P_n \) be the types of the function parameters. Let \( p_1 \ldots p_n \) be lvalues denoting those objects. Let \( R \) be the return type and \( F \) be the function-body of \( f \). \( T \) be the type \( \text{std:}:\text{experimental::coroutine_traits}<R,P_1,\ldots,P_n> \), and \( P \) be the class type denoted by \( T::\text{promise_type} \). Then, the coroutine behaves as if its body were:

\[
\{ \\
\quad P\ p\ \text{promise-constructor-arguments} ; \\
\quad \text{co\_await \ } p.\text{initial\_suspend}(); \quad // \text{initial suspend point} \\
\quad \text{try \{} \ F \ \text{catch(...) \{} \ p.\text{unhandled\_exception}(); \} \\
\quad \text{final\_suspend:} \\
\quad \quad \text{co\_await \ } p.\text{final\_suspend}(); \quad // \text{final suspend point} \\
\}
\]

where an object denoted as \( p \) is the promise object of the coroutine and its type \( P \) is the promise type of the coroutine, and promise-constructor-arguments is determined as follows: overload resolution is performed on a promise constructor call created by assembling an argument list with lvalues \( p_1 \ldots p_n \). If a viable constructor is found (16.3.2), then promise-constructor-arguments is \((p_1,\ldots,p_n)\), otherwise promise-constructor-arguments is empty.

The unqualified-ids return_void and return_value are looked up in the scope of class \( P \). If both are found, the program is ill-formed. If the unqualified-id return_void is found, flowing off the end of a coroutine is equivalent to a \text{co\_return} with no operand. Otherwise, flowing off the end of a coroutine results in undefined behavior.

When a coroutine returns to its caller, the return value is produced by a call to \( p.\text{get\_return\_object}() \). A call to a get_return_object is sequenced before the call to initial_suspend and is invoked at most once.

A suspended coroutine can be resumed to continue execution by invoking a resumption member function (21.11.2.4) of an object of type \text{coroutine\_handle<\( P \)>} associated with this instance of the coroutine. The function that invoked a resumption member function is called resumer. Invoking a resumption member function for a coroutine that is not suspended results in undefined behavior.

An implementation may need to allocate additional storage for a coroutine. This storage is known as the coroutine state and is obtained by calling a non-array allocation function (6.7.4.1). The allocation function’s name is looked up in the scope of \( P \). If this lookup fails, the allocation function’s name is looked up in the global scope. If the lookup finds an allocation function in the scope of \( P \), overload resolution is performed on a function call created by assembling an argument list. The first argument is the amount of space requested, and has type \text{std:}:\text{size\_t}. The lvalues \( p_1 \ldots p_n \) are the succeeding arguments. If no viable function is found (16.3.2), overload resolution is performed again on a function call created by passing just the amount of space required as an argument of type \text{std:}:\text{size\_t}.

The unqualified-id get_return_object_on_allocation_failure is looked up in the scope of class \( P \) by class member access lookup (6.4.5). If a declaration is found, then the result of a call to an allocation function used to obtain storage for the coroutine state is assumed to return nullptr if it fails to obtain storage, and if a global allocation function is selected, the ::operator new(size_t, noexcept_t) form shall be used. If an allocation function returns nullptr, the coroutine returns control to the caller of the coroutine and the return value is obtained by a call to \( P::\text{get\_return\_object\_on\_allocation\_failure}() \). The allocation function used in this case must have a non-throwing noexcept-specification.
Example:

```cpp
#include <iostream>
#include <experimental/coroutine>

// ::operator new(size_t, nothrow_t) will be used if allocation is needed
struct generator {
    struct promise_type {
        int current_value;
        static auto get_return_object_on_allocation_failure() { return generator{nullptr}; }
        auto get_return_object() { return generator{handle::from_promise(*this)}; }
        auto initial_suspend() { return std::experimental::suspend_always{}; }
        auto final_suspend() { return std::experimental::suspend_always{}; }
        void unhandled_exception() { std::terminate(); }
        void return_void() {}
        auto yield_value(int value) {
            current_value = value;
            return std::experimental::suspend_always{};
        }
    };
    bool move_next() { return coro ? (coro.resume(), !coro.done()) : false; }
    int current_value() { return coro.promise().current_value; }
    generator(generator const&) = delete;
    generator(generator && rhs) : coro(rhs.coro) { rhs.coro = nullptr; }
    ~generator() { if (coro) coro.destroy(); }
    private:
        generator(handle h) : coro(h) {}
        handle coro;
    };
    generator f() { co_yield 1; co_yield 2; }
    int main() {
        auto g = f();
        while (g.move_next()) std::cout << g.current_value() << std::endl;
    }
}
```

The coroutine state is destroyed when control flows off the end of the coroutine or the `destroy` member function (21.11.2.4) of an object of type `std::experimental::coroutine_handle<P>` associated with this coroutine is invoked. In the latter case objects with automatic storage duration that are in scope at the suspend point are destroyed in the reverse order of the construction. The storage for the coroutine state is released by calling a non-array deallocation function (6.7.4.2). If `destroy` is called for a coroutine that is not suspended, the program has undefined behavior.

The deallocation function’s name is looked up in the scope of `P`. If this lookup fails, the deallocation function’s name is looked up in the global scope. If deallocation function lookup finds both a usual deallocation function with only a pointer parameter and a usual deallocation function with both a pointer parameter and a size parameter, then the selected deallocation function shall be the one with two parameters. Otherwise, the selected deallocation function shall be the function with one parameter. If no usual deallocation function is found, the program is ill-formed. The selected deallocation function shall be called with the address of the block of storage to be reclaimed as its first argument. If a deallocation function with a parameter of type `std::size_t` is used, the size of the block is passed as the corresponding argument.

§ 11.4.4
When a coroutine is invoked, a copy is created for each coroutine parameter. Each such copy is an object with automatic storage duration that is direct-initialized from an lvalue referring to the corresponding parameter if the parameter is an lvalue reference, and from an xvalue referring to it otherwise. A reference to a parameter in the function-body of the coroutine and in the call to the coroutine promise constructor is replaced by a reference to its copy. The initialization and destruction of each parameter copy occurs in the context of the called coroutine. Initializations of parameter copies are sequenced before the call to the coroutine promise constructor and indeterminately sequenced with respect to each other. The lifetime of parameter copies ends immediately after the lifetime of the coroutine promise object ends. [Note: If a coroutine has a parameter passed by reference, resuming the coroutine after the lifetime of the entity referred to by that parameter has ended is likely to result in undefined behavior. — end note]

12 Classes

No changes are made to Clause 12 of the C++ Standard.

13 Derived classes

No changes are made to Clause 13 of the C++ Standard.

14 Member Access Control

No changes are made to Clause 14 of the C++ Standard.

15 Special member functions

15.1 Constructors

Add new paragraph after paragraph 5.

A constructor shall not be a coroutine.

15.4 Destructors

Add new paragraph after paragraph 16.

A destructor shall not be a coroutine.
15.8 Copying and moving class objects

15.8.3 Copy/move elision

Add a bullet to paragraph 1:

— in a coroutine (11.4.4), a copy of a coroutine parameter can be omitted and references to that copy replaced with references to the corresponding parameter if the meaning of the program will be unchanged except for the execution of a constructor and destructor for the parameter copy object

Modify paragraph 3 as follows:

3 In the following copy-initialization contexts, a move operation might be used instead of a copy operation:

(3.1) If the expression in a return or co_return statement (9.6.3) is a (possibly parenthesized) id-expression that names an object with automatic storage duration declared in the body or parameter-declaration-clause of the innermost enclosing function or lambda-expression, or

(3.2) if the operand of a throw-expression is the name of a non-volatile automatic object (other than a function or catch-clause parameter) whose scope does not extend beyond the end of the innermost enclosing try-block (if there is one),

overload resolution to select the constructor for the copy or the return_value overload to call is first performed as if the object were designated by an rvalue. If the first overload resolution fails or was not performed, or if the type of the first parameter of the selected constructor or return_value overload is not an rvalue reference to the object’s type (possibly cv-qualified), overload resolution is performed again, considering the object as an lvalue. Remark: This two-stage overload resolution must be performed regardless of whether copy elision will occur. It determines the constructor or return_value overload to be called if elision is not performed, and the selected constructor or return_value overload must be accessible even if the call is elided.

16 Overloading

16.5 Overloaded operators

Add co_await to the list of operators in paragraph 1 before operators () and [].

Add the following paragraph after paragraph 5.

6 The co_await operator is described completely in 8.3.8. The attributes and restrictions found in the rest of this subclause do not apply to it unless explicitly stated in 8.3.8.
17 Templates

No changes are made to Clause 17 of the C++ Standard.

18 Exception handling

No changes are made to Clause 18 of the C++ Standard.

19 Preprocessing directives

No changes are made to Clause 19 of the C++ Standard.
20 Library introduction

20.6.1.3 Freestanding implementations

Add a row to Table 19 for coroutine support header `<experimental/coroutine>`.

Table 19 — C++ headers for freestanding implementations

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21 Language support library
[language.support]

21.1 General
[support.general]
Add a row to Table 32 for coroutine support header <experimental/coroutine>.

Table 32 — Language support library summary

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21.10 Other runtime support
[support.runtime]
Add underlined text to paragraph 4.

The function signature longjmp(jmp_buf jbuf, int val) has more restricted behavior in this International Standard. A setjmp/longjmp call pair has undefined behavior if replacing the setjmp and longjmp by catch and throw would invoke any non-trivial destructors for any automatic objects. A call to setjmp or longjmp has undefined behavior if invoked in a suspension context of a coroutine (8.3.8).

See also: ISO C 7.10.4, 7.8, 7.6, 7.12.

21.11 Coroutines support library
[support.coroutine]
Add this subclause to Clause 21.

The header <experimental/coroutine> defines several types providing compile and run-time support for coroutines in a C++ program.

Header <experimental/coroutine> synopsis
namespace std {
namespace experimental {
inline namespace coroutines_v1 {

// 21.11.1 coroutine traits
template <class R, class... ArgTypes>
struct coroutine_traits;

// 21.11.2 coroutine handle
template <class Promise = void>
struct coroutine_handle;

// 21.11.3 noop coroutine promise
struct noop_coroutine_promise;
template <> struct coroutine_handle<noop_coroutine_promise>;
// noop coroutine handle
using noop_coroutine_handle = coroutine_handle<noop_coroutine_promise>;

// 21.11.4 noop coroutine
noop_coroutine_handle noop_coroutine() noexcept;

// 21.11.2.6 comparison operators:
constexpr bool operator==(coroutine_handle<> x, coroutine_handle<> y) noexcept;
constexpr bool operator!=(coroutine_handle<> x, coroutine_handle<> y) noexcept;
constexpr bool operator<(coroutine_handle<> x, coroutine_handle<> y) noexcept;
constexpr bool operator>(coroutine_handle<> x, coroutine_handle<> y) noexcept;
constexpr bool operator<=(coroutine_handle<> x, coroutine_handle<> y) noexcept;
constexpr bool operator>=(coroutine_handle<> x, coroutine_handle<> y) noexcept;

// 21.11.5 trivial awaitables
struct suspend_never;
struct suspend_always;
}
} // namespace experimental

// 21.11.2.7 hash support:
template <class T> struct hash;
template <class P> struct hash<experimental::coroutine_handle<P>>;
}
} // namespace std

21.11.1 Coroutine traits [coroutine.traits]
This subclause defines requirements on classes representing coroutine traits, and defines the class template coroutine_traits that satisfies those requirements.

21.11.1.1 Class template coroutine_traits [coroutine.traits.primary]
The header <experimental/coroutine> defines the primary template coroutine_traits such that if ArgTypes is a parameter pack of types and if the qualified-id R::promise_type is valid and denotes a type (17.9.2), then coroutine_traits<R,ArgTypes...> has the following publicly accessible member:

using promise_type = typename R::promise_type;

§ 21.11.1
Otherwise, `coroutine_traits<R,ArgTypes...>` has no members.

Program defined specializations of this template shall define a publicly accessible nested type named `promise_type`.

## 21.11.2 Class template coroutine_handle

```
namespace std {
    namespace experimental {
        inline namespace coroutines_v1 {

            template <>
            struct coroutine_handle<void> {

                // 21.11.2.1 construct/reset
                constexpr coroutine_handle() noexcept;
                constexpr coroutine_handle(nullptr_t) noexcept;
                coroutine_handle& operator=(nullptr_t) noexcept;

                // 21.11.2.2 export/import
                constexpr void* address() const noexcept;
                constexpr static coroutine_handle from_address(void* addr);

                // 21.11.2.3 observers
                constexpr explicit operator bool() const noexcept;
                bool done() const;

                // 21.11.2.4 resumption
                void operator()() const;
                void resume() const;
                void destroy() const;

                private:
                    void* ptr; // exposition only
            };

            template <class Promise>
            struct coroutine_handle : coroutine_handle<> {

                // 21.11.2.1 construct/reset
                using coroutine_handle<>::coroutine_handle;
                static coroutine_handle from_promise(Promise&);
                coroutine_handle& operator=(nullptr_t) noexcept;

                // 21.11.2.2 export/import
                constexpr static coroutine_handle from_address(void* addr);

                // 21.11.2.5 promise access
                Promise& promise() const;
            };

            template <> struct coroutine_handle<noop_coroutine_promise> : coroutine_handle<> {

                // 21.11.2.8 noop observers
                constexpr explicit operator bool() const noexcept;
                constexpr bool done() const noexcept;
            }

```

§ 21.11.2
Let $P$ be the promise type of a coroutine (11.4.4). An object of type `coroutine_handle<\textit{P}>` is called a coroutine handle and can be used to refer to a suspended or executing coroutine. A default constructed `coroutine_handle` object does not refer to any coroutine.

If a program declares an explicit or partial specialization of `coroutine_handle`, the behavior is undefined.

### 21.11.2.1 coroutine_handle construct/reset

```cpp
constexpr coroutine_handle() noexcept;
constexpr coroutine_handle(nullptr_t) noexcept;
```

**Postconditions:**
- `address() == nullptr`.

```cpp
static coroutine_handle from_promise(Promise& p);
```

**Requires:**
- $p$ is a reference to a promise object of a coroutine.

**Returns:**
- A coroutine handle $h$ referring to the coroutine.

**Postconditions:**
- `addressof(h.promise()) == addressof(p)`.

```cpp
coroutine_handle& operator=(nullptr_t) noexcept;
```

**Postconditions:**
- `address() == nullptr`.

**Returns:**
- `*this`.

### 21.11.2.2 coroutine_handle export/import

```cpp
constexpr void* address() const noexcept;
```

**Returns:**
- `ptr`.

```cpp
constexpr static coroutine_handle<> coroutine_handle<>::from_address(void* addr);
constexpr static coroutine_handle<Promise> coroutine_handle<Promise>::from_address(void* addr);
```

**Requires:**
- `addr` was obtained via a prior call to `address`.

**Postconditions:**
- `from_address(address()) == *this`.

### 21.11.2.3 coroutine_handle observers

```cpp
constexpr explicit operator bool() const noexcept;
```

**Returns:**
- `address() != nullptr`.
bool done() const;
   Requires: *this refers to a suspended coroutine.
   Returns: true if the coroutine is suspended at its final suspend point, otherwise false.

21.11.2.4 coroutine_handle resumption [coroutine.handle.resumption]

void operator()() const;
void resume() const;
   Requires: *this refers to a suspended coroutine.
   Effects: Resumes the execution of the coroutine. If the coroutine was suspended at its final
   suspend point, behavior is undefined.
   [Note: A concurrent resumption of the coroutine via resume, operator(), or destroy may
   result in a data race. — end note]

void destroy() const;
   Requires: *this refers to a suspended coroutine.
   Effects: Destroys the coroutine (11.4.4).
   [Note: A concurrent resumption of the coroutine via resume, operator(), or destroy may
   result in a data race.

21.11.2.5 coroutine_handle promise access [coroutine.handle.promise]

Promise& promise() const;
   Requires: *this refers to a coroutine.
   Returns: A reference to the promise of the coroutine.

21.11.2.6 Comparison operators [coroutine.handle.compare]

constexpr bool operator==(coroutine_handle<> x, coroutine_handle<> y) noexcept;
   Returns: x.address() == y.address().
constexpr bool operator!=(coroutine_handle<> x, coroutine_handle<> y) noexcept;
   Returns: !(x == y).
constexpr bool operator<(coroutine_handle<> x, coroutine_handle<> y) noexcept;
   Returns: less<>()(x.address(), y.address()).
constexpr bool operator>(coroutine_handle<> x, coroutine_handle<> y) noexcept;
   Returns: (y < x).
constexpr bool operator<=(coroutine_handle<> x, coroutine_handle<> y) noexcept;
   Returns: !(x > y).
constexpr bool operator>=(coroutine_handle<> x, coroutine_handle<> y) noexcept;
   Returns: !(x < y).

21.11.2.7 Hash support [coroutine.handle.hash]

template <class P> struct hash<experimental::coroutine_handle<P>>;
   The specialization is enabled (23.14.15).
21.11.2.8 *noop_coroutine_handle* observers

```cpp
constexpr explicit operator bool() const noexcept;
    Returns: true.
constexpr bool done() const noexcept;
    Returns: false.
```

21.11.2.9 *noop_coroutine_handle* resumption

```cpp
constexpr void operator()() const noexcept;
constexpr void resume() const noexcept;
constexpr void destroy() const noexcept;
    Effects: None.
    Remarks: If *noop_coroutine_handle* is converted to *coroutine_handle<>*, calls to operator(), resume and destroy on that handle will also have no observable effects.
```

21.11.2.10 *noop_coroutine_handle* promise access

```cpp
noop_coroutine_promise& promise() const noexcept;
    Returns: A reference to the promise object associated with this coroutine handle.
```

21.11.2.11 *noop_coroutine_handle* address

```cpp
constexpr void* address() const noexcept;
    Returns: ptr.
    Remarks: A *noop_coroutine_handle*’s ptr is always a non-null pointer value.
```

21.11.3 Class *noop_coroutine_promise*

```cpp
struct noop_coroutine_promise {};
```

The class *noop_coroutine_promise* defines the promise type for the coroutine referred to by *noop_coroutine_handle* (21.11).

21.11.4 Function *noop_coroutine*

```cpp
noop_coroutine_handle noop_coroutine() noexcept;
    Returns: A handle to a coroutine that has no observable effects when resumed or destroyed.
    Remarks: A handle returned from *noop_coroutine* may or may not compare equal to a handle returned from another invocation of *noop_coroutine*.
```

21.11.5 Trivial awaitables

The header `<experimental/coroutine>` defines *suspend_never* and *suspend_always* as follows.

```cpp
namespace std {
    namespace experimental {
        inline namespace coroutines_v1 {

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

} // namespace coroutines_v1
} // namespace experimental
} // namespace std