fiber_context - fibers without scheduler

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Revision History

This document supersedes P0876R4.

Changes since P0876R4:

abstract

This paper addresses concerns, questions and suggestions from the past meetings. The proposed API supersedes the former proposals N3985, P0099R1, P0534R3, P0876R0 and P0876R2.

Because of name clashes with coroutine from coroutine TS, execution context from executor proposals and continuation used in the context of future::then(), the committee has indicated that fiber is preferable. However, given the foundational, low-level nature of this proposal, we choose fiber_context, leaving the term fiber for a higher-level facility built on top of this one.

A previous revision of this proposal suggested fiber_context, but SG1 felt that use of the term “context” posed potential confusion. The name basic_fiber has also been suggested. Consider that the name is not yet final.
The minimal API enables stackful context switching **without** the need for a scheduler. The API is suitable to act as building-block for high-level constructs such as stackful coroutines as well as cooperative multitasking (aka user-land/green threads that incorporate a scheduling facility).

Informally within this proposal, the term *fiber* is used to denote the lightweight thread of execution launched and represented by the first-class object `std::fiber_context`.

**control transfer mechanism**

According to the literature, 4 coroutine-like control-transfer operations can be distinguished into the concepts of symmetric and asymmetric operations.

**symmetric fiber** A symmetric fiber provides a single control-transfer operation. This single operation requires that the control is passed explicitly between the fibers.

```
1 fiber_context* pf1;
2 fiber_context f4{{&pf1}{
3  pf1->resume();
4  };
5 fiber_context f3{{&f4}{
6    f4.resume();
7  }};
8 fiber_context f2{{&f3}{
9    f3.resume();
10  }};
11 fiber_context f1{{&f2}{
12    f2.resume();
13  };
14  pf1=&f1;
15  f1.resume();
```

In the pseudo-code example above, a chain of fibers is created. Control is transferred to fiber `f1` at line 15 and the lambda passed to constructor of `f1` is entered. Control is transferred from fiber `f1` to `f2` at line 12 and from `f2` to `f3` (line 9) and so on. Fiber `f4` itself transfers control directly back to fiber `f1` at line 3.

**asymmetric fiber** Two control-transfer operations are part of asymmetric fiber’s interface: one operation for resuming (`resume()`) and one for suspending (`suspend()`) the fiber. The suspending operation returns control back to the calling fiber.

```
1 fiber_context f4{{} {
2    self::suspend();
3  };
4 fiber_context f3{{&f4}{
5    f4.resume();
6    self::suspend();
7  };
8 fiber_context f2{{&f3}{
9    f3.resume();
10    self::suspend();
11  };
12 fiber_context f1{{&f2}{
13    f2.resume();
14    self::suspend();
15  };
16  f1.resume();
```
In the pseudo code above execution control is transferred to fiber f1 at line 16. Fiber f1 resumes fiber f2 at line 13 and so on. At line 2 fiber f4 calls its suspend operation self::suspend(). Fiber f4 is suspended and f3 resumed. Inside the lambda, f3 returns from f4.resume() and calls self::suspend() (line 6). Fiber f3 gets suspended while f2 will be resumed and so on ...

The asymmetric version needs N-1 more fiber switches than the variant using symmetric fibers.

| While asymmetric fibers establish a caller-callee relationship (strongly coupled), symmetric fibers operate as siblings (loosely coupled). |

Symmetric fibers represent independent units of execution, making symmetric fibers a suitable mechanism for concurrent programming. Additionally, constructs that produce sequences of values (generators) are easily constructed out of two symmetric fibers (one represents the caller, the other the callee).

Asymmetric fibers incorporate additional fiber switches as shown in the pseudo code above. It is obvious that for a broad range of use cases, asymmetric fibers are less efficient than their symmetric counterparts. Additionally, the calling fiber must be kept alive until the called fiber terminates. Otherwise the call of suspend() will be undefined behaviour (where to transfer execution control to?).

| Symmetric fibers are more efficient, have fewer restrictions (no caller-callee relationship) and can be used to create a wider set of applications (generators, cooperative multitasking, backtracking ...). |

**std::fiber_context as a first-class object**

Because the symmetric control-transfer operation requires explicitly passing control between fibers, fibers must be expressed as first-class objects.

Fibers exposed as first-class objects can be passed to and returned from functions, assigned to variables or stored into containers. With fibers as first-class objects, a program can explicitly control the flow of execution by suspending and resuming fibers, enabling control to pass into a function at exactly the point where it previously suspended.

| Symmetric control-transfer operations require fibers to be first-class objects. First-class objects can be returned from functions, assigned to variables or stored into containers. |

**encapsulating the stack**

Each fiber is associated with a stack and is responsible for managing the lifespan of its stack (allocation at construction, deallocation when fiber terminates). The RAII-pattern* should apply.

*resource acquisition is initialisation
Copying a \texttt{std::fiber\_context} must not be permitted!
If a \texttt{std::fiber\_context} were copyable, then its stack with all the objects allocated on it must be copied too. That presents two implementation choices.

- One approach would be to capture sufficient metadata to permit object-by-object copying of stack contents. That would require dramatically more runtime information than is presently available – and would take considerably more overhead than a coder might expect. Naturally, any one move-only object on the stack would prohibit copying the entire stack.
- The other approach would be a bytewise copy of the memory occupied by the stack. That would force undefined behaviour if any stack objects were RAII-classes (managing a resource via RAII pattern). When the first of the fiber copies terminates (unwinds its stack), the RAII class destructors will release their managed resources. When the second copy terminates, the same destructors will try to doubly-release the same resources, leading to undefined behavior.

\begin{itemize}
  \item encapsulate the stack
  \item manage lifespan of an explicitly-allocated stack: the stack gets deallocated when \texttt{std::fiber\_context} goes out of scope
  \item prevent accidentally copying the stack
\end{itemize}

\texttt{Class \texttt{std::fiber\_context}} must be \texttt{moveable-only}.

\subsection*{invalidation at resumption}

The framework must prevent the resumption of an already running or terminated (computation has finished) fiber. Resuming an already running fiber will cause overwriting and corrupting the stack frames (note, the stack is not copyable). Resuming a terminated fiber will cause undefined behaviour because the stack might already be unwound (objects allocated on the stack were destroyed or the memory used as stack was already deallocated).

As a consequence each call of \texttt{resume()} will invalidate the \texttt{std::fiber\_context} instance, i.e. no valid instance of \texttt{std::fiber\_context} represents the currently-running fiber.

Whether a \texttt{std::fiber\_context} is valid or not can be tested with member function \texttt{operator bool()}. To make this more explicit, functions \texttt{resume()}, \texttt{resume\_with()}, \texttt{resume\_from\_any\_thread()} and \texttt{resume\_from\_any\_thread\_with()} are \texttt{rvalue-reference} qualified.

The essential points:

\begin{itemize}
  \item regardless of the number of \texttt{std::fiber\_context} declarations, exactly one \texttt{std::fiber\_context} instance represents each suspended fiber
  \item no \texttt{std::fiber\_context} instance represents the currently-running fiber
\end{itemize}

Section \texttt{solution: avoiding non-const global variables and undefined behaviour} describes how an instance of \texttt{std::fiber\_context} is synthesized from the active fiber that suspends.

\begin{itemize}
  \item prevent accidentally resuming a running fiber
  \item prevent accidentally resuming a terminated (computation has finished) fiber
  \item \texttt{resume()}, \texttt{resume\_with()}, \texttt{resume\_from\_any\_thread()} and \texttt{resume\_from\_any\_thread\_with()} are \texttt{rvalue-reference} qualified to bind on \texttt{rvalues} only
\end{itemize}

\subsection*{problem: avoiding non-const global variables and undefined behaviour}

According to C++ core guidelines, non-const global variables should be avoided: they hide dependencies and make the dependencies subject to unpredictable changes.

Global variables can be changed by assigning them indirectly using a pointer or by a function call. As a consequence, the compiler can’t cache the value of a global variable in a register, degrading performance (unnecessary loads and stores to
global memory especially in performance critical loops).
Accessing a register is one to three orders of magnitude faster than accessing memory (depending on whether the cache line is in cache and not invalidated by another core; and depending on whether the page is in the TLB).
The order of initialisation (and thus destruction) of static global variables is not defined, introducing additional problems with static global variables.

A library designed to be used as building block by other higher-level frameworks should avoid introducing global variables. If this API were specified in terms of internal global variables, no higher level layer could undo that: it would be stuck with the global variables.

**switch back to main() by returning**  Switching back to main() by returning from the fiber function has two drawbacks: it requires an internal global variable pointing to the suspended main() and restricts the valid use cases.

```cpp
int main() {
    fiber_context f[]{
        ... // switch to `main()` only by returning
    };  
    f.resume(); // resume `f`
    return 0;
}
```

For instance the generator pattern is impossible because the only way for a fiber to transfer execution control back to main() is to terminate. But this means that no way exists to transfer data (sequence of values) back and forth between a fiber and main().

**Switching to main() only by returning is impractical because it limits the applicability of fibers and requires an internal global variable pointing to main().**

**static member function returns active std::fiber_context**  P0099R0 introduced a static member function (execution_context::current()) that returned an instance of the active fiber. This allows passing the active fiber m (for instance representing main()) into the fiber l via lambda capture. This mechanism enables switching back and forth between the fiber and main(), enabling a rich set of applications (for instance generators).

```cpp
int main(){
    int a;
    fiber_context m=fiber_context::current(); // get active fiber
    fiber_context f[]{
        a=0;
        int b=1;
        for(;;){
            m=m.resume(); // switch to `main()`
            int next=a+b;
            a=b;
            b=next;
        }
    };
    for(int j=0; j<10; ++j) {
        f=f.resume(); // resume `f`
        std::cout << a << " ";
    }
    return 0;
}
```

But this solution requires an internal global variable pointing to the active fiber and some kind of reference counting. Reference counting is needed because fiber_context::current() necessarily requires multiple instances of std::fiber_context for the active fiber. Only when the last reference goes out of scope can the fiber be destroyed and its stack deallocated.
fiber_context f1=fiber_context::current();
fiber_context f2=fiber_context::current();
assert(f1==f2); // f1 and f2 point to the same (active) fiber

Additionally a static member function returning an instance of the active fiber would violate the protection requirements of sections encapsulating the stack and invalidation at resumption. For instance you could accidentally attempt to resume the active fiber by invoking resume().

fiber_context m=fiber_context::current();
m.resume(); // tries to resume active fiber == UB

A static member function returning the active fiber requires a reference counted global variable and does not prevent accidentally attempting to resume the active fiber.

solution: avoiding non-const global variables and undefined behaviour

The avoid non-const global variables guideline has an important impact on the design of the std::fiber_context API!

synthesizing the suspended fiber The problem of global variables or the need for a static member function returning the active fiber can be avoided by synthesizing the suspended fiber and passing it into the resumed fiber (as parameter when the fiber is first started, or returned from resume()).

```cpp
void foo(){
    fiber_context f{[](fiber_context&& m){
        m=std::move(m).resume(); // switch to 'foo'
        m=std::move(m).resume(); // switch to 'foo'
        ...
    });

    f=std::move(f).resume(); // start 'f'
    f=std::move(f).resume(); // resume 'f'
}
```

In the pseudo-code above the fiber f is started by invoking its member function resume() at line 7. This operation suspends foo, invalidates instance f and synthesizes a new std::fiber_context m that is passed as parameter to the lambda of f (line 2). Invoking m.resume() (line 3) suspends the lambda, invalidates m and synthesizes a std::fiber_context that is returned by f.resume() at line 7. The synthesized std::fiber_context is assigned to f. Instance f now represents the suspended fiber running the lambda (suspended at line 3). Control is transferred from line 3 (lambda) to line 7 (foo()). Call f.resume() at line 8 invalidates f and suspends foo() again. A std::fiber_context representing the suspended foo() is synthesized, returned from m.resume() and assigned to m at line 3. Control is transferred back to the lambda and instance m represents the suspended foo(). Function foo() is resumed at line 4 by executing m.resume() so that control returns at line 8 and so on...

Class symmetric_coroutine<>::yield_type from N3985 is not equivalent to the synthesized std::fiber_context. symmetric_coroutine<>::yield_type does not represent the suspended context, instead it is a special representation of the same coroutine. Thus main() or the current thread’s entry-function can not be represented by yield_type (see next section representing main() and thread’s entry-function as fiber).

Because symmetric_coroutine<>::yield_type yields back to the starting point, i.e. invocation of symmetric_coroutine<>::call_type::operator()(), both instances (call_type as well as yield_type) must be preserved. Additionally the caller must be kept alive until the called coroutine terminates or UB happens at resumption.

This API is specified in terms of passing the suspended std::fiber_context. A higher level layer can hide that by using private variables.
representing main() and thread’s entry-function as fiber

As shown in the previous section a synthesized fiber is created and passed into the resumed fiber as an instance of std::fiber_context.

```cpp
int main()
    fiber_context f([](fiber_context&& m)
        m=std::move(m).resume(); // switch to 'main'
        ...
    });
f=std::move(f).resume(); // resume 'f'
    return 0;
}
```

The mechanism presented in this proposal describes switching between stacks: each fiber has its own stack. The stacks of main() and explicitly-launched threads are not excluded; these can be used as targets too.

Thus every program can be considered to consist of fibers – some created by the OS (main() stack; each thread’s initial stack) and some created explicitly by the code.

This is a nice feature because it allows (the stacks of) main() and each thread’s entry-function to be represented as fibers. A std::fiber_context representing main() or a thread’s entry-function can be handled like an explicitly created std::fiber_context: it can passed to and returned from functions or stored in a container. When called on such an instance, \texttt{can_resume_from_any_thread()} indicates whether it is valid to call \texttt{resume_from_any_thread()} or \texttt{resume_from_any_thread_with()} on that instance.

The proposed fiber API allows representing and handling main() and the current thread’s entry-function by an instance of std::fiber_context in the same way as explicitly created fibers.

fiber returns (terminates)

When a fiber returns (terminates), what should happen next? Which fiber should be resumed next? The only way to avoid internal global variables that point to main() is to explicitly return a valid std::fiber_context instance that will be resumed after the active fiber terminates.

```cpp
int main()
    fiber_context f([](fiber_context&& m)
        return std::move(m); // resume 'main()' by returning 'm'
    });
    std::move(f).resume(); // resume 'f'
    return 0;
}
```

In line 5 the fiber is started by invoking \texttt{resume()} on instance \texttt{f}. main() is suspended and an instance of type std::fiber_context is synthesized and passed as parameter \texttt{m} to the lambda at line 2. The fiber terminates by returning \texttt{m}. Control is transferred to main() (returning from \texttt{f.resume()} at line 5) while fiber \texttt{f} is destroyed.

In a more advanced example another std::fiber_context is used as return value instead of the passed in synthesized fiber.

```cpp
int main()
    fiber_context m;
    fiber_context f1([&]{fiber_context&& f)
        std::cout << "f1: entered first time" << std::endl;
        assert(!f);
        return std::move(m); // resume (main-)fiber that has started 'f2'
    });
    fiber_context f2([&]{fiber_context&& f)
        std::cout << "f2: entered first time" << std::endl;
        m=std::move(f);
        // preserve 'f' (= suspended main())
        return std::move(f1);
    });
```
std::move(f2).resume();
std::cout << "main: done" << std::endl;
return 0;
}
output:
f2: entered first time
f1: entered first time
main: done

At line 13 fiber f2 is resumed and the lambda is entered at line 8. The synthesized `std::fiber_context f` (representing suspended `main()`) is passed as a parameter f and stored in m (captured by the lambda) at line 10. This is necessary in order to prevent destructing f when the lambda returns. Fiber f2 uses f1, that was also captured by the lambda, as return value. Fiber f2 terminates while fiber f1 is resumed (entered the first time). The synthesized `std::fiber_context f` passed into the lambda at line 3 represents the terminated fiber f2 (e.g. the calling fiber). Thus instance f is invalid as the assert statement verifies at line 5. Fiber f1 uses the captured `std::fiber_context m` as return value (line 6). Control is returned to `main()`, returning from `f2.resume()` at line 13.

The function passed to `std::fiber_context`’s constructor must have signature ‘`fiber_context(fiber_context&&)`’. Using `std::fiber_context` as the return value from such a function avoids global variables.

**returning synthesized `std::fiber_context` instance from `resume()`** An instance of `std::fiber_context` remains invalid after return from `resume()`, `resume_with()`, `resume_from_any_thread()` or `resume_from_any_thread_with()`—the synthesized fiber is returned, instead of implicitly updating the `std::fiber_context` instance on which `resume()` was called.

If the `std::fiber_context` object were implicitly updated, the fiber would change its identity because each fiber is associated with a stack. Each stack contains a chain of function calls (call stack). If this association were implicitly modified, unexpected behaviour happens.

The example below demonstrates the problem:

```cpp
int main(){
    fiber_context f1,f2,f3;
    f3=fiber_context{[&]{fiber_context&& f)->fiber_context{
        f2=std::move(f);
        for(;;){
            std::cout << "f3 ";
            std::move(f1).resume();
        }
        return ();
    }};
    f2=fiber_context{[&]{fiber_context&& f)->fiber_context{
        f1=std::move(f);
        for(;;){
            std::cout << "f2 ";
            std::move(f3).resume();
        }
        return ();
    }};
    f1=fiber_context{[&]{fiber_context&& /*main*/->fiber_context{
        for(;;){
            std::cout << "f1 ";
            std::move(f2).resume();
        }
        return ();
    }};
    std::move(f1).resume();
    return 0;
}
```

In this pseudo-code the std::fiber_context object is implicitly updated. The example creates a circle of fibers: each fiber prints its name and resumes the next fiber (f1 -> f2 -> f3 -> f1 -> ...). Fiber f1 is started at line 26. The synthesized std::fiber_context main passed to the resumed fiber is not used (control flow cycles through the three fibers). The for-loop prints the name f1 and resumes fiber f2. Inside f2’s for-loop the name is printed and f3 is resumed. Fiber f3 resumes fiber f1 at line 7. Inside f1 control returns from f2.resume(). f1 loops, prints out the name and invokes f2.resume(). But this time fiber f3 instead of f2 is resumed. This is caused by the fact the instance f2 gets the synthesized std::fiber_context of f3 implicitly assigned. Remember that at line 7 fiber f3 gets suspended while f1 is resumed through f1.resume().

This problem can be solved by returning the synthesized std::fiber_context from resume(), resume_with(), resume_from_any_thread() or resume_from_any_thread_with().

```cpp
int main(){
    fiber_context f1,f2,f3;
    f3=fiber_context{[&](fiber_context&& f)->fiber_context{
        f2=std::move(f);
        for(;;){
            std::cout << "f3 ";
            f2=std::move(f1).resume();
        }
        return {};
    }};
    f2=fiber_context{[&](fiber_context&& f)->fiber_context{
        f1=std::move(f);
        for(;;){
            std::cout << "f2 ";
            f1=std::move(f3).resume();
        }
        return {};
    }};
    f1=fiber_context{[&](fiber_context&& /*main*/)->fiber_context{
        for(;;){
            std::cout << "f1 ";
            f3=std::move(f2).resume();
        }
        return {};
    }};
    std::move(f1).resume();
    return 0;
}
```

In the example above the synthesized std::fiber_context returned by resume() is move-assigned to the invoking std::fiber_context instance (that has resumed the current fiber).

The synthesized std::fiber_context must be returned from resume(), resume_with(), resume_from_any_thread() and resume_from_any_thread_with() in order to prevent changing the identity of the fiber.

If the overall control flow isn’t known, member functions resume_with() or resume_from_any_thread_with() (see section inject function into suspended fiber) can be used to assign the synthesized std::fiber_context to the correct std::fiber_context instance (the caller).

*The operating-system stack provided for main() or the current thread’s entry-function is not destroyed when the corresponding std::fiber_context instance is destroyed.
class filament{
private:
    fiber_context f_;  
public:
    ...
    void resume_next(fila& fila){
        std::move(fila.f_).resume_with([this](fiber_context&& f)->fiber_context{
            f_=std::move(f);
            return {};
        });
    }
};

Picture a higher-level framework in which every fiber can find its associated filament instance, as well as others. Every context switch must be mediated by passing the target filament instance to the running fiber's resume_next() method. 

Running fiber A has an associated filament instance filamentA, whose std::fiber_context f_ is invalid – because fiber A is running.

Desiring to switch to suspended fiber B (with associated filament filamentB), running fiber A calls filamentA.resume_next(filamentB).

resume_next() calls filamentB.f_.resume_with(<lambda>). This invalidates filamentB.f_ – because fiber B is now running.

The lambda binds filamentA as this. Running on fiber B, it receives a std::fiber_context instance representing the newly-suspended fiber A as its parameter f. It moves that std::fiber_context instance to filamentA.f_.

The lambda then returns a default-constructed (therefore invalid) std::fiber_context instance. That invalid instance is returned by the previously-suspended resume_with() call in filamentB.resume_next() – which is fine because resume_next() drops it on the floor anyway.

Thus, the running fiber's associated filament::f_ is always invalid, whereas the filament associated with each suspended fiber is continually updated with the std::fiber_context instance representing that fiber.*

---

It is not necessary to know the overall control flow. It is sufficient to pass a reference/pointer of the caller (fiber that gets suspended) to the resumed fiber that move-assigns the synthesized std::fiber_context to caller (updating the instance).

inject function into suspended fiber

Sometimes it is useful to inject a new function (for instance, to throw an exception or assign the synthesized fiber to the caller as described in returning synthesized std::fiber_context instance from resume()) into a suspended fiber. For this purpose resume_with(Fn&& fn) (or resume_from_any_thread_with()) may be called, passing the function fn() to execute.

    fiber_context fn(fiber_context&& caller){
        // ...
        std::move(caller).resume();
        // ...
    }

* Boost.Fiber uses this pattern for resuming user-land threads.
The `resume_with()` call at line 11 injects function `fn()` into fiber `f` as if the `resume()` call at line 3 had directly called `fn()`.

Like an *entry-function* passed to `std::fiber_context, fn()` must accept `std::fiber_context&&` and return `std::fiber_context`. The `std::fiber_context` instance returned by `fn()` will, in turn, be returned to `f`'s lambda by the `resume()` at line 3.

Suppose that code running on the program’s main fiber calls `resume()` (line 12 below), thereby entering the first lambda shown below. This is the point at which `m` is synthesized and passed into the lambda at line 2.

Suppose further that after doing some work (line 4), the lambda calls `m.resume()`, thereby switching back to the main fiber. The lambda remains suspended in the call to `m.resume()` at line 5.

At line 18 the main fiber calls `f.resume_with()` where the passed lambda accepts `fiber_context &&`. That new lambda is called on the fiber of the suspended lambda. It is as if the `m.resume()` call at line 8 directly called the second lambda.

The function passed to `resume_with()` has almost the same range of possibilities as any function called on the fiber represented by `f`. Its special invocation matters when control leaves it in either of two ways:

1. If it throws an exception, that exception unwinds all previous stack entries in that fiber (such as the first lambda’s) as well, back to a matching `catch` clause.*

2. If the function returns, the returned `std::fiber_context` instance is returned by the suspended `m.resume()` (or `resume_with()`), or `resume_from_any_thread()`, or `resume_from_any_thread_with()`) call.

```cpp
int data = 0;
fiber_context f{[&data](fiber_context&& m){
    std::cout << "f1: entered first time: " << data << std::endl;
    data+=1;
    m=std::move(m).resume();
    std::cout << "f1: entered second time: " << data << std::endl;
    data+=1;
    m=std::move(m).resume();
    std::cout << "f1: entered third time: " << data << std::endl;
    return std::move(m);
}};
f=std::move(f).resume();
std::cout << "f1: returned first time: " << data << std::endl;
data+=1;
f=std::move(f).resume();
std::cout << "f1: returned second time: " << data << std::endl;
data+=1;
f=std::move(f).resume_with{[&data](fiber_context&& m){
    std::cout << "f2: entered: " << data << std::endl;
    data=-1;
    return std::move(m);
}};
std::cout << "f1: returned third time" << std::endl;
```

```
output:
f1: entered first time: 0
f1: returned first time: 1
f1: entered second time: 2
f1: returned second time: 3
f2: entered: 4
f1: entered third time: -1
f1: returned third time
```

*As stated in exceptions, if there is no matching `catch` clause in that fiber, `std::terminate()` is called.
The `f.resume_with(<lambda>)` call at line 18 passes control to the second lambda on the fiber of the first lambda.

As usual, `resume_with()` synthesizes an `std::fiber_context` instance representing the calling fiber, passed into the lambda as `m`. This particular lambda returns `m` unchanged at line 21; thus that `m` instance is returned by the `resume()` call at line 8.

Finally, the first lambda returns at line 10 the `m` variable updated at line 8, switching back to the main fiber.

One case worth pointing out is when you call `resume_with()` (or `resume_from_any_thread_with()`) on a `std::fiber_context` that has not yet been resumed for the first time:

```cpp
1 fiber_context topfunc(fiber_context&& prev);
2 fiber_context injected(fiber_context&& prev);
3
4 fiber_context f(topfunc);
5 // topfunc() has not yet been entered
6 std::move(f).resume_with(injected);
```

In this situation, `injected()` is called with a `std::fiber_context` instance representing the caller of `resume_with()`. When `injected()` eventually returns that (or some other valid) `std::fiber_context` instance, the returned `std::fiber_context` instance is passed into `topfunc()` as its `prev` parameter.

Member functions `resume_with()` and `resume_from_any_thread_with()` allow you to inject a function into a suspended fiber.

**passing data between fibers**

Data can be transferred between two fibers via global pointer, a calling wrapper (like `std::bind`) or lambda capture.

```cpp
1 int i=1;
2 std::fiber_context lambda{[&i](fiber_context&& caller){
3     std::cout << "inside lambda,i==" << i << std::endl;
4     i+=1;
5     caller=std::move(caller).resume();
6     return std::move(caller);
7 }};
8 lambda=std::move(lambda).resume();
9 std::cout << "i==" << i << std::endl;
10 lambda=std::move(lambda).resume();
11
12 output:
13     inside lambda,i=1
14     i=2
```

The `resume()` call at line 8 enters the lambda and passes 1 into the new fiber. The value is incremented by one, as shown at line 4. The expression `caller.resume()` at line 5 resumes the original context (represented within the lambda by `caller`).

The call to `lambda.resume()` at line 10 resumes the lambda, returning from the `caller.resume()` call at line 5. The `std::fiber_context` instance `caller` invalidated by the `resume()` call at line 5 is replaced with the new instance returned by that same `resume()` call.

Finally the lambda returns (the updated) `caller` at line 6, terminating its context.

Since the updated `caller` represents the fiber suspended by the call at line 10, control returns to `main()`.

However, since context `lambda` has now terminated, the updated `lambda` is invalid. Its `operator bool()` returns `false`.

"12"
Using lambda capture is the preferred way to transfer data between two fibers; global pointers or a calling wrapper (such as std::bind) are alternatives.

**termination**

There are a few different ways to terminate a given fiber without terminating the whole process, or engaging undefined behavior.

When a std::fiber_context instance is constructed with an entry-function, its new stack is initialized with the frame of an implicit top-level function that can catch std::unwind_exception. std::unwind_exception binds a std::fiber_context instance; the implicit catch clause returns the bound std::fiber_context from that top-level function.

Therefore, any of the following will gracefully terminate a fiber:

- Cause its entry-function to return a valid std::fiber_context.
- From within the fiber you wish to terminate, call std::unwind_fiber() with a valid std::fiber_context. This throws a std::unwind_exception instance that binds the passed std::fiber_context; that fiber will be resumed when the active fiber terminates.
- From within the fiber you wish to terminate, construct and throw std::unwind_exception, binding the std::fiber_context you intend to resume next. This is what std::unwind_fiber() does internally.
- Call fiber_context::resume_with(unwind_fiber). This is what ~fiber_context() does. Since std::unwind_fiber() accepts a std::fiber_context, and since resume_with() synthesizes a std::fiber_context representing its caller and passes it to the subject function, this terminates the fiber referenced by the original std::fiber_context instance and switches back to the caller.
- Engage ~fiber_context(): switch to some other fiber, which will receive a std::fiber_context instance representing the current fiber. Make that other fiber destroy the received std::fiber_context instance.

(However, since the operating system allocates the stack for main() and for a thread’s entry-function, of course there is no implicit top-level stack frame, no implicit catch (std::unwind_exception). In a conforming implementation, returning from a thread’s entry-function may terminate all fibers on that thread. Returning from main() may terminate the whole process.)

The above are all equivalent: stack variables are properly destroyed, since the stack is unwound by throwing an exception. (See stack destruction.)

In an environment that forbids exceptions, every std::fiber_context you launch must terminate gracefully, by returning from its top-level function. You may not call std::unwind_fiber(). You may not call ~fiber_context(), explicitly or implicitly, on a valid std::fiber_context instance.

When an explicitly-launched fiber’s entry-function returns a valid std::fiber_context instance, that fiber is terminated. Control switches to the fiber indicated by the returned std::fiber_context instance. The entry-function may return (switch to) any reachable valid std::fiber_context instance — it need not be the instance originally passed in, or an instance returned from any of the resume() family of methods.

Returning an invalid std::fiber_context instance (operator bool() returns false) invokes undefined behavior.

Calling resume() means: “Please switch to the indicated fiber; I am suspending; please resume me later.”

Returning a particular std::fiber_context means: “Please switch to the indicated fiber; and by the way, I am done.”
exceptions

In general, if an uncaught exception escapes from the _entry-function_, `std::terminate` is called. There is one exception: `std::unwind_exception`. The `std::fiber_context` facility internally uses `std::unwind_exception` to clean up the stack of a suspended context being destroyed. This exception must be allowed to propagate out of an _entry-function_.

A correct _entry-function_ try/catch block looks like this:

```cpp
try{
    // ... body of fiber logic ...
} catch(const std::unwind_exception&){
    // do not swallow unwind_exception
    throw;
} catch(...){
    // ... log, or whatever ...
}
```

Of course, no try/catch block is needed if neither _entry-function_ nor anything it calls throws exceptions.

stack destruction

On construction of a `std::fiber_context` a stack is allocated. If the _entry-function_ returns, the stack will be destroyed. If the function has not yet returned and the ?? of the `std::fiber_context` instance representing that context is called, the stack will be unwound and destroyed.

Consider a running fiber `f2` that destroys the `std::fiber_context` instance representing `f1`.

`f1`'s destructor, running on `f2`, implicitly calls member-function `resume_with()`, passing `std::unwind_fiber()` as argument. Fiber `f1` will be temporarily resumed and `std::unwind_fiber()` is invoked. Function `std::unwind_fiber()` binds an instance of `std::fiber_context` that represents `f2`, then throws exception `std::unwind_exception`, which unwinds `f1`'s stack (walking the stack and destroying automatic variables in reverse order of construction). The first frame on `f1`'s stack, the one created by `std::fiber_context`'s constructor, catches the exception, extracts the bound `std::fiber_context` representing `f2` and terminates `f1` by returning `f2`. Control is returned to `f2` and `f1`'s stack gets deallocated.

The stack on which `main()` is executed, as well as the stack implicitly created by `std::thread`'s constructor, is allocated by the operating system. Such stacks are recognized by `std::fiber_context`, and are not deallocated by its destructor.

`std::fiber_context` as building block for higher-level frameworks

A low-level API enables a rich set of higher-level frameworks that provide specific syntaxes/semantics suitable for specific domains. As an example, the following four frameworks are based on the low-level fiber switching API of _Boost.Context_14 (implements the API of this proposal).

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[BoostCoroutine2](#) implements asymmetric coroutines `coroutine<>::push_type` and `coroutine<>::pull_type`, providing a unidirectional transfer of data. These stackful coroutines are only used in pairs. When `coroutine<>::push_type` is explicitly instantiated, `coroutine<>::pull_type` is synthesized and passed as parameter into the coroutine function. In the example below, `coroutine<>::push_type` (variable `writer`) provides the resume operation, while `coroutine<>::pull_type` (variable `in`) represents the suspend operation. Inside the lambda, `in.get()` pulls strings provided by `coroutine<>::push_type`'s output iterator support.

```cpp
struct FinalEOL{ ~FinalEOL(){ std::cout << std::endl; } };
std::vector<std::string> words{
    "peas", "porridge", "hot", "peas",
    "porridge", "cold", "peas", "porridge",
    "in", "the", "pot", "nine",
};
```
"days", "old" );
int num=5,width=15;
boost::coroutines2::coroutine<std::string>::push_type writer{
  [&](boost::coroutines2::coroutine<std::string>::pull_type& in){
    FinalEOL eol;
    for (;;) {
      for (int i=0; i<num; ++i){
        if (!in) {
          return;
        }
        std::cout << std::setw(width) << in.get();
        in();
      }
      std::cout << std::endl;
    }
  };
  std::copy(std::begin(words), std::end(words), std::begin(writer));
}

Synca\textsuperscript{20} (by Grigory Demchenko) is a small, efficient library to perform asynchronous operations in synchronous manner. The main features are a GO-like syntax, support for transferring execution context explicitly between different thread pools or schedulers (portals/teleports) and asynchronous network support.

```cpp
int fibo(int v) {
  if (v<2) return v;
  int v1,v2;
  Waiter()
    .go([v,&v1]{ v1=fibo(v-1); })
    .go([v,&v2]{ v2=fibo(v-2); })
    .wait();
  return v1+v2;
}
```

The code itself looks like synchronous invocations while internally it uses asynchronous scheduling.

\textit{Boost.Fiber}\textsuperscript{16} implements user-land threads and combines fibers with schedulers (scheduler-algorithms are customization points). The API is modelled after the \texttt{std::thread}-API and contains objects like \texttt{future}, \texttt{mutex}, \texttt{condition_variable}...

```cpp
boost::fibers::unbuffered_channel<unsigned int> chan;
boost::fibers::fiber f1[&chan]{
  chan.push(1);
  chan.push(1);
  chan.push(2);
  chan.push(3);
  chan.push(5);
  chan.push(8);
  chan.push(12);
  chan.close();
};
boost::fibers::fiber f2[&chan]{
  for (unsigned int value: chan) {
    std::cout << value << " ";
  }
  std::cout << std::endl;
};
f1.join();
f2.join();
```
Facebook’s folly::fibers\textsuperscript{19} is an asynchronous C++ framework using user-land threads for parallelism. In contrast to Boost.Fiber, folly::fibers exposes the scheduler and permits integration with various event dispatching libraries.

```cpp
std::EventBase ev_base;
auto& fiber_manager=folly::fibers::getFiberManager(ev_base);
folly::fibers::Baton baton;
fiber_manager.addTask([&]{
    std::cout << "task 1: start" << std::endl;
    baton.wait();
    std::cout << "task 1: after baton.wait()" << std::endl;
});
fiber_manager.addTask([&]{
    std::cout << "task 2: start" << std::endl;
    baton.post();
    std::cout << "task 2: after baton.post()" << std::endl;
});
ev_base.loop();
```

folly::fibers is used in many critical applications at Facebook for instance in mcrouter\textsuperscript{17} and some other Facebook services/libraries like ServiceRouter (routing framework for Thrift\textsuperscript{18}), Node API (graph ORM API for graph databases) ...

As shown in this section a low-level API can act as building block for a rich set of high-level frameworks designed for specific application domains that require different aspects of design, semantics and syntax.

### interaction with STL algorithms

In the following example STL algorithm std::generator and fiber g generate a sequence of Fibonacci numbers and store them into std::vector v.

```cpp
int a;
std::fiber_context g{([&a]{std::fiber_context&& m){
        a=0;
        int b=1;
        for(;;){
            m=std::move(m).resume();
            int next=a+b;
            a=b;
            b=next;
            return std::move(m);
        }}};
std::vector<int> v(10);
std::generate(v.begin(), v.end(), [&a,&g](){
    g=std::move(g).resume();
    return a;
});
std::cout << "v: ";
for (auto i : v) {
    std::cout << i << " ";
}
std::cout << "\n";
```

```
output: v: 0 1 1 2 3 5 8 13 21 34
```

The proposed fiber API does not require modifications of the STL and can be used together with existing STL algorithms.
possible implementation strategies

This proposal does NOT seek to standardize any particular implementation or impose any specific calling convention!

Modern micro-processors are register machines; the content of processor registers represent the execution context of the program at a given point in time. Operating systems maintain for each process all relevant data (execution context, other hardware registers etc.) in the process table. The operating system’s CPU scheduler periodically suspends and resumes processes in order to share CPU time between multiple processes. When a process is suspended, its execution context (processor registers, instruction pointer, stack pointer, ...) is stored in the associated process table entry. On resumption, the CPU scheduler loads the execution context into the CPU and the process continues execution. The CPU scheduler does a full context switch. Besides preserving the execution context (complete CPU state), the cache must be invalidated and the memory map modified. A kernel-level context switch is several orders of magnitude slower than a context switch at user-level.

hypothetical fiber preserving complete CPU state  This strategy tries to preserve the complete CPU state, e.g. all CPU registers. This requires that the implementation identifies the concrete micro-processor type and supported processor features. For instance the x86-architecture has several flavours of extensions such as MMX, SSE1-4, AVX1-2, AVX-512. Depending on the detected processor features, implementations of certain functionality must be switched on or off. The CPU scheduler in the operating system uses such information for context switching between processes. A fiber implementation using this strategy requires such a detection mechanism too (equivalent to swapper/system_32() in the Linux kernel). Aside from the complexity of such detection mechanisms, preserving the complete CPU state for each fiber switch is expensive.

A context switch facility that preserves the complete CPU state like an operating system is possible but impractical for user-land.

fiber switch using the calling convention  For std::fiber_context, not all registers need be preserved because the context switch is effected by a visible function call. It need not be completely transparent like an operating-system context switch; it only needs to be as transparent as a call to any other function. The calling convention – the part of the ABI that specifies how a function’s arguments and return values are passed – determines which subset of micro-processor registers must be preserved by the called subroutine.

The calling convention of SYSV ABI for x86_64 architecture determines that general purpose registers R12, R13, R14, R15, RBX and RBP must be preserved by the sub-routine - the first arguments are passed to functions via RDI, RSI, RDX, RCX, R8 and R9 and return values are stored in RAX, RDX. So on that platform, the resume() implementation preserves the general purpose registers (R12-R15, RBX and RBP) specified by the calling convention. In addition, the stack pointer and instruction pointer are preserved and exchanged too – thus, from the point of view of calling code, resume() behaves like an ordinary function call. In other words, resume() acts on the level of a simple function invocation – with the same performance characteristics (in terms of CPU cycles).

This technique is used in Boost.Context which acts as building block for folly::fibers. The folly::fibers framework itself is the basis of many critical applications at Facebook, such as microuter and some other Facebook services/libraries like ServiceRouter (routing framework for Thrift), Node API (graph ORM API for graph databases) ...

in-place substitution at compile time  During code generation, a compiler-based implementation could inject the assembler code responsible for the fiber switch directly into each function that calls resume(). That would save an extra indirection (JMP + PUSH/MOV of certain registers used to invoke resume()).

CPU state at the stack  Because each fiber must preserve CPU registers at suspension and load those registers at resumption, some storage is required. Instead of allocating extra memory for each fiber, an implementation can use the stack by simply advancing the stack
pointer at suspension and pushing the CPU registers (CPU state) onto the stack owned by the suspending fiber. When the
fiber is resumed, the values are popped from the stack and loaded into the appropriate registers.

This strategy works because only a running fiber creates new stack frames (moving the stack pointer). While a fiber is
suspended, it is safe to keep the CPU state on its stack.

Using the stack as storage for the CPU state has the additional advantage that std::fiber_context must only contain
a pointer to the stack location: its memory footprint can be that of a pointer. Section synthesizing the suspended fiber describes how global variables are avoided by synthesizing a std::fiber_context from the active fiber (execution context) and passing this synthesized std::fiber_context (representing the now-suspended fiber) into the resumed fiber. Using the stack as storage makes this mechanism very easy to implement. Inside
resume() the code pushes the relevant CPU registers onto the stack, and from the resulting stack address creates a new
std::fiber_context. This instance is then passed (or returned) into the resumed fiber (see synthesizing the suspended
fiber).

Using the active fiber’s stack as storage for the CPU state is efficient because no additional allocations or dealloca-
tions are required.

fiber switch on architectures with register window

The implementation of fiber switch is possible – many libc implementations still provide the ucontext-API (swapcontext ()
and related functions) for architectures using a register window (such as SPARC). The implementation of swapcontext ()
could be used as blueprint for a fiber implementation.

how fast is a fiber switch

A fiber switch takes 11 CPU cycles on a x86_64-Linux system using an implementation based on the strategy described in
fiber switch using the calling convention (implemented in Boost.Context, branch fiber).

interaction with accelerators

For many core devices several programming models, such as OpenACC, CUDA, OpenCL etc., have been developed
targeting host-directed execution using an attached or integrated accelerator. The CPU executes the main program while
controlling the activity of the accelerator. Accelerator devices typically provide capabilities for efficient vector processing. Usually the host-directed execution uses computation offloading that permits executing computationally intensive work on a separate device (accelerator). For instance CUDA devices use a command buffer to establish communication between host and device. The host puts commands (op-codes) into the command buffer and the device process them asynchronously. It is obvious that a fiber switch does not interact with host-directed device-offloading. A fiber switch works like a function call (see fiber switch using the calling convention).

multi-threading environment

Member function can_resume_from_any_thread() returns false if the stack used by the std::fiber_context instance was created by the operating system (main application or thread stack), and the caller is running on a different thread. When the stack represented by the std::fiber_context instance was created by std::fiber_context’s

*The implementation of Boost.Context utilizes this technique.
†ucontext was removed from POSIX standard by POSIX.1-2008
‡Intel XEON E5 2620v4 2.2GHz
§warp on CUDA devices, wavefront on AMD GPUs, 512-bit SIMD on Intel Xeon Phi
constructor, can_resume_from_any_thread() returns true.* You must not attempt to resume an instance representing a stack provided by the operating system on some other thread!

can_resume() can be called to determine whether a given std::fiber_context instance might safely be resumed on a particular thread by calling resume() or resume_with().

std::fiber_context is TLS-agnostic - best practices related to TLS apply to fibers too (see P0772R0.)

There could potentially be Undefined Behavior if:
- code running on a fiber references thread_local variables
- the compiler/runtime implementation caches a pointer to thread_local storage on the stack
- that fiber is suspended, and
- the suspended fiber is resumed on a different thread.

The cached TLS pointer is now pointing to storage belonging to some other thread. If the original thread terminates before the new thread, the cached TLS pointer is now dangling.

For a runtime that caches TLS pointers in such fashion, an implementation of resume_from_any_thread() or resume_from_any_thread_with() could conceivably walk the suspended stack, patching cached pointers.

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*A possible implementation could mark the first stack frame by creating a special marker (for instance 0xBADCAFFEE etc.) at a specific offset in the first stack frame or use a special function name for the first function and walk the stack searching for these markers.
The extensions proposed here support creation and activation of cooperative user-mode threads, here called fibers.

The term “user-mode” means that a given fiber can be activated without entering the operating-system kernel.

The term “cooperative” means that typically multiple fibers share an underlying execution agent, for example a std::thread. On a given std::thread, only one fiber is running at any given time. Sharing that agent is explicit rather than pre-emptive. The running fiber suspends (or yields) to another fiber. This action launches a new fiber, or resumes a previously-suspended fiber.

Suspending the running fiber in order to resume (or launch) another is called context switching.

The term “thread” here means that even though a given fiber may suspend and later be resumed, it is logically a thread of execution as defined in [intro.multithread].

Every C++ function that has been called, but has neither returned nor suspended, requires some storage for its variables with automatic storage duration [basic.stc.auto]. Typically this storage also contains bookkeeping data such as the location of the function’s most recent caller, to support the return statement [stmt.return]. This storage is called the function’s activation record or activation frame.

Activation frames for active functions are logically kept in a function stack, or simply stack, as discussed in Exceptions [except], particularly sections Constructors and destructors [except.ctor], Handling an exception [except.handle], The std::terminate function [except.terminate] and The std::uncaught_exceptions() function [except.uncaught].

The term “stack” simply means that each function call causes the called function to construct a new activation frame. Return from that function destroys that activation frame, in last-in-first-out fashion. Each recursive call to a function causes a new activation frame to be constructed even though its previous activation frame(s) still exist.

The implementation of such a stack is implementation-dependent.

Launching a fiber logically creates a new stack, which remains associated with that fiber throughout its lifetime. Calling functions on a particular fiber, and returning from them, is independent of function calls and returns on any other fiber.

Context switching can be effected by designating some other fiber’s stack as current, in a manner appropriate to the implementation of function stacks.

33.7.2 Header <experimental/fiber_context> synopsis

```cpp
#include <fiber_context>

#define __cpp_lib_experimental_fiber_context 201902

namespace std { 
namespace experimental {
inline namespace concurrency_v2 {

class fiber_context;

class unwind_exception;

void unwind_fiber(fiber_context&& other);

} // namespace concurrency_v2
} // namespace experimental
} // namespace std
```

33.7.3 Class fiber_context

```cpp
#include <fiber_context>
```
namespace std {
namespace experimental {
inline namespace concurrency_v2 {

class fiber_context {
public:
    fiber_context() noexcept;

    template<typename Fn>
    explicit fiber_context(Fn&& fn);

    fiber_context(fiber_context&& other) noexcept;
    fiber_context& operator=(fiber_context&& other) noexcept;
    fiber_context(const fiber_context& other) noexcept = delete;
    fiber_context& operator=(const fiber_context& other) noexcept = delete;

    fiber_context resume() &&;
    template<typename Fn>
    fiber_context resume_with(Fn&& fn) &&;
    fiber_context resume_from_any_thread() &&;
    template<typename Fn>
    fiber_context resume_from_any_thread_with(Fn&& fn) &&;

    bool can_resume() noexcept;
    bool can_resume_from_any_thread() noexcept;

    explicit operator bool() const noexcept;
    bool valid() const noexcept;
    void swap(fiber_context& other) noexcept;
};
} // namespace concurrency_v2
} // namespace experimental
} // namespace std

// Construc tor

// (constructor) constructs new fiber_context

fiber_context() noexcept

template<typename Fn>
explicit fiber_context(Fn&& fn)

fiber_context(fiber_context&& other) noexcept

fiber_context(const fiber_context& other) noexcept = delete

fiber_context& operator=(const fiber_context& other) noexcept = delete

fiber_context resume() &&

fiber_context resume_with(Fn&& fn) &&

fiber_context resume_from_any_thread() &&

template<typename Fn>
fiber_context resume_from_any_thread_with(Fn&& fn) &&

bool can_resume() noexcept;

bool can_resume_from_any_thread() noexcept;

explicit operator bool() const noexcept;

bool valid() const noexcept;

void swap(fiber_context& other) noexcept;

1) this constructor instantiates an invalid std::fiber_context. Its valid() method returns false.

2) takes a callable object [func.def] as argument. The callable must have signature fiber_context fn(fiber_context&&). This constructor template shall not participate in overload resolution unless Fn is L.value-Callable [func.wrap.func] for the argument type std::fiber_context&& and the return type std::fiber_context. [Note: The entry-function fn is not immediately entered. The stack and any other necessary resources are created on construction, but fn is not entered until resume(), resume_with(), resume_from_any_thread() or resume_from_any_thread_with() is called. — end note] [Note: The entry-function fn passed to std::fiber_context will be passed a synthesized std::fiber_context instance representing the suspended caller of resume(), resume_with(), resume_from_any_thread() or resume_from_any_thread_with(). — end note]

3) moves underlying state to new std::fiber_context

4) copy constructor deleted

~fiber_context()
Effects:
— destroys a std::fiber_context instance. If this instance represents a fiber of execution (valid() returns true), then the fiber of execution is destroyed too. Specifically, the stack is unwound by throwing std::unwind_exception.

Remarks:
— In a program in which exceptions are thrown, it is prudent to code a fiber’s entry-function with a last-ditch catch (...) clause: in general, exceptions must not leak out of the entry-function. However, since stack unwinding is implemented by throwing an exception, a correct entry-function try statement must also catch (std::unwind_exception const&) and rethrow it.

operator=
  moves the std::fiber_context object

fiber_context& operator=(fiber_context&& other) noexcept (1)
fiber_context& operator=(const fiber_context& other)=delete (2)

Effects:
1) assigns the state of other to *this using move semantics
2) copy assignment operator deleted

Parameters:
other another std::fiber_context to assign to this object

Returns:
*this

Postconditions:
— other is invalidated (valid() returns false)

resume()
  resumes a fiber

fiber_context resume() && (1)
template<typename Fn>
fiber_context resume_with(Fn&& fn) && (2)
fiber_context resume_from_any_thread() && (3)
template<typename Fn>
fiber_context resume_from_any_thread_with(Fn&& fn) && (4)

Effects:
1),3) suspends the active fiber, resumes fiber *this
2),4) suspends the active fiber, resumes fiber *this but calls fn() in the resumed fiber (as if called by the suspended function) These member function templates shall not participate in overload resolution unless Fn is Lvalue-Callable [func.wrap.func] for the argument type std::fiber_context&& and the return type std::fiber_context.

Parameters:
fn callable object injected into resumed fiber

Returns:
fiber_context the returned instance represents the fiber that has been suspended in order to resume the current fiber

Exceptions:
- `resume()`, `resume_with()`, `resume_from_any_thread()` or `resume_from_any_thread_with()` throws `std::unwind_exception` when, while suspended, the `std::fiber_context` instance representing the suspended fiber is destroyed.

- `resume()`, `resume_with()`, `resume_from_any_thread()` or `resume_from_any_thread_with()` can throw any exception if, while suspended:
  - some other fiber calls `resume_with()` or `resume_from_any_thread_with()` to resume this suspended fiber
  - the function `fn` passed to `resume_with()` or `resume_from_any_thread_with()` – or some function called by `fn` – throws an exception

- Any exception thrown by the function `fn` passed to `resume_with()` or `resume_from_any_thread_with()`, or any function called by `fn`, is thrown in the fiber referenced by `*this` rather than in the fiber of the caller of `resume_with()` or `resume_from_any_thread_with()`.

**Requires:**
- `*this` represents a valid fiber (`valid()` returns `true`)
- for `resume()` and `resume_with()`, the calling thread is the same as the thread on which the fiber represented by `*this` was most recently run
- for `resume()`, `resume_with()`, `resume_from_any_thread()` and `resume_from_any_thread_with()`, if `can_resume_from_any_thread()` would return `false`, the calling thread is the same as the thread on which the fiber represented by `*this` was most recently run

**Postconditions:**
- `*this` is invalidated (`valid()` returns `false`)

**Remarks:**
The intent of the distinction between `resume()` and `resume_from_any_thread()`, as between `resume_with()` and `resume_from_any_thread_with()`, is both for validation and for code auditing. If an application only ever calls `resume()` and `resume_with()`, no fiber will ever be resumed on a thread other than the one on which it was initially resumed.

The intent of the names `resume_from_any_thread()` and `resume_from_any_thread_with()` is to clarify the direction in which cross-thread resumption occurs. The calling thread always directly resumes a suspended fiber: control is passed into the suspended fiber, and the currently-running fiber suspends. These method names mean that the fiber represented by `*this` will be resumed whether or not it was last resumed on the calling thread.

`resume()`, `resume_with()`, `resume_from_any_thread()` and `resume_from_any_thread_with()` preserve the execution context of the calling fiber. Those data are restored if the calling fiber is resumed.

A suspended `fiber_context` can be destroyed. Its resources will be cleaned up at that time.

The returned `fiber_context` indicates via `valid()` whether the previous active fiber has terminated (returned from `entry_function`).

Because `resume()`, `resume_with()`, `resume_from_any_thread()` and `resume_from_any_thread_with()` invalidate the instance on which they are called, no valid `std::fiber_context` instance ever represents the currently-running fiber. In order to express the invalidation explicitly, these methods are rvalue-reference qualified.

When calling any of these methods, it is conventional to replace the newly-validated instance – the instance on which the method was was called – with the new instance returned by that call. This helps to avoid subsequent inadvertent attempts to resume the old, invalidated instance.

An injected function `fn()` must have signature `std::fiber_context fn(std::fiber_context&&)`. It will be passed a synthesized `std::fiber_context` instance representing the suspended caller of `resume_with()` or `resume_from_any_thread_with()`. The `std::fiber_context` instance returned by `fn()` is, in turn, used as the return value for the suspended function: `resume()`, `resume_with()`, `resume_from_any_thread()` or `resume_from_any_thread_with()`.

```cpp
bool can_resume_from_any_thread() noexcept
```

**Effects:** query whether the calling thread can resume the suspended `std::fiber_context` instance by calling `resume_from_any_thread()` or `resume_from_any_thread_with()`. The implementation must return `false` if the suspended `std::fiber_context` instance represents a fiber with a
system-provided stack, and the calling thread is not that thread.

Returns:

— fiber_context::can_resume_from_any_thread() returns false if *this does not represent a valid fiber, or if the stack used by the fiber was provided by the operating system, and the calling thread is not that thread; otherwise true.

Remarks:

— When main(), or the entry-function of a std::thread, or any function directly called by these, is suspended, a std::fiber_context instance represents that suspended fiber. You may resume that suspended fiber on the same thread using any of resume(), resume_with(), resume_from_any_thread() or resume_from_any_thread_with(). Attempting to resume that suspended fiber from any other thread is Undefined Behavior.

— can_resume_from_any_thread() returns true if the calling thread is the same as the thread on which the fiber represented by *this was most recently run, or if the std::fiber_context instance represents a fiber explicitly created by std::fiber_context’s constructor.

— can_resume_from_any_thread() is not marked const because in at least one implementation, it requires an internal context switch.

bool can_resume() noexcept

Returns: true if the calling thread is the same as the thread on which the fiber represented by *this was most recently run, or if *this has not yet been resumed. When can_resume() returns true, the std::fiber_context instance may be resumed by resume(), resume_with(), resume_from_any_thread() or resume_from_any_thread_with().

Remarks:

— returns true if *this represents a valid fiber, and the calling thread is the same as the thread on which the fiber represented by *this was most recently run. If the std::fiber_context has not yet run and has therefore never been suspended, returns true as well.

— can_resume() is not marked const because in at least one implementation, it requires an internal context switch.

valid() test whether std::fiber_context is valid

bool valid() const noexcept (1)

explicit operator bool() const noexcept (2)

Returns:

1) returns true if *this represents a fiber of execution, false otherwise.

2) alias for valid()

[Note: A std::fiber_context instance might not represent a valid fiber for any of a number of reasons.

• It might have been default-constructed.
• It might have been moved from.
• It might already have been resumed – calling resume(), resume_with(), resume_from_any_thread() or resume_from_any_thread_with() invalidates the instance.
• The entry-function might have voluntarily terminated the fiber by returning.

The essential points:

• Regardless of the number of std::fiber_context declarations, exactly one std::fiber_context instance represents each suspended fiber.
• No std::fiber_context instance represents the currently-running fiber.
```c++
void swap(fiber_context& other) noexcept

Effects:
— Exchanges the state of *this with other.

33.7.4 Function unwind_fiber()
[[ noreturn ]] void unwind_fiber(fiber_context&& other)

Effects: terminate the current running fiber, switching to the fiber represented by the passed std::fiber_context. This is like returning that std::fiber_context from the entry-function, but may be called from any function on that fiber.

Remarks:
— throws std::unwind_exception, binding the passed std::fiber_context. The running fiber’s first stack entry catches std::unwind_exception, extracts the bound std::fiber_context and terminates the current fiber by returning that std::fiber_context.

Parameters:
other the std::fiber_context to which to switch once the current fiber has terminated

Requires:
— other must be valid (valid() returns true)

Returns:
— None: std::unwind_fiber() does not return

Exceptions:
— throws std::unwind_exception

33.7.5 Class unwind_exception

class unwind_exception

is the exception used to unwind the stack referenced by a std::fiber_context being destroyed. It is thrown by std::unwind_fiber(). std::unwind_exception binds a std::fiber_context referencing the fiber to which control should be passed once the current fiber is unwound and destroyed.
```
References


[5] N3985: A proposal to add coroutines to the C++ standard library

[6] P0099R0: A low-level API for stackful context switching

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[10] P0876R2: fibers without scheduler


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[15] Library BoostCoroutine2

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