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fiber_context - fibers without scheduler

abstract

This paper proposes a minimal API that 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**).

This revision addresses concerns, questions and suggestions from the past meetings. The proposed API supersedes the former proposals N3985,[8] P0099R1,[11] P0534R3[12] and P0876R10.[24]

Because of name clashes with *coroutine* from C++20, *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.

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`.

Revision History

This document supersedes P0876R10.

Changes since P0876R10

- Removed `cancel()` method and the cancellation-function constructor argument. Replaced with the `std::jthread` stop token handling API: `get_stop_source()`, `get_stop_token()` and `request_stop()`. This simplifies examples by eliminating `launch()` and `assert_on_cancel`.
- Added a section exploring the relationship of `std::fiber_context` to the larger C++ ecosystem.
- Reordered some sections to make the paper more accessible for new readers.

Changes since P0876R9

- Removed `resume_from_any_thread()`, `resume_from_any_thread_with()`, `cancel_from_any_thread()` and `can_resume_from_this_thread()`, along with stated support for resuming a suspended fiber on some thread other than the one on which it was launched.

In Belfast, EWG came down strongly against cross-thread fiber resumption. The most emphatic objection was that for a function referencing TLS, multiple compilers cache TLS pointers on the function's stack frame. Resuming a fiber containing that stack frame on some other thread would cause problems. In the best case, the resumed function would merely reference TLS belonging to the wrong thread – but at some point the original thread will terminate, its TLS will be destroyed, and the cached pointers will be left dangling.

With `std::fiber_context`, any opaque function call might possibly suspend – but invalidating cached TLS pointers across every opaque function call is deemed unacceptable overhead.

Changes since P0876R8

- Reinstated cancellation function constructor argument.
- Added `cancel()` and `cancel_from_any_thread()` member functions.
- Re-removed `std::unwind_fiber()`.

SG1 directed P0876R9 to conform to the Cologne 2019 recommendations, with any other changes proposed in a separate paper.

Changes since D0876R7

- Cancellation function removed from `std::fiber_context` constructor.
- `std::unwind_fiber()` re-added, with implementation-defined behaviour.
- Added elaboration of `filament` example to bind cancellation function.

P0876R8 diverged from the recommendations of the second SG1 round in Cologne 2019. It did not introduce `cancel()` or `cancel_from_any_thread()` member functions. In fact it removed the cancellation-function constructor argument.

`std::fiber_context` is intended as the lowest-level stackful context-switching API. Binding a cancellation-function on the fiber stack is a flourish rather than a necessity. It adds overhead in both space (on the fiber stack) and time (to traverse the stack to retrieve the cancellation-function). For this API, it should suffice to pass the desired cancellation-function to `resume_with()`. If it is important to associate a cancellation-function with a particular fiber earlier in the lifespan of the fiber, a struct serves.

A more compelling reason to avoid constructing an explicit fiber with a cancellation-function is that no implicit fiber has any such cancellation-function – and the consuming application cannot tell, a priori, whether a given `std::fiber_context` instance represents an explicit or an implicit fiber. If `*this` represents an implicit fiber, what should the proposed `cancel()` member function do?

Passing a specific cancellation-function to `resume_with()` avoids that problem.

P0876R8 follows SG1 recommendation in making it Undefined Behaviour to destroy (or assign to) a non-empty `std::fiber_context` instance.

`std::unwind_fiber()` was reintroduced with implementation-defined behaviour to allow fiber cleanup leveraging implementation internals. Its use was entirely optional (and auditable).

Changes since P0876R6

- Implicit stack unwinding (by non-C++ exception) removed.
- `std::unwind_fiber()` removed.
- Cancellation function added to `std::fiber_context` constructor.

In Cologne 2019, SG1 took the position that:

- The `fiber_context` facility is not the only C++ feature that requires "special" unwinding (special function exit path).
- Such functionality should be decoupled from `std::fiber_context`. It requires its own proposal that follows its own course through WG21 process.
- Depending on this (yet to be written) proposal would unduly delay the `fiber_context` facility.
- For now, the `fiber_context` facility should adopt a "less is more" approach, removing promises about implicit unwinding, placing the burden on the consumer of the facility instead.
- This leaves the way open for `fiber_context` to integrate with a new, improved unwind facility when such becomes available.

The idea of making `std::fiber_context`'s constructor accept a cancellation function was suggested to permit consumer opt-in to P0876R5 functionality where permissible, or convey to the fiber in question by any suitable means the need to clean up and terminate.

Requiring the cancellation function is partly because it remains unclear what the default should be. This could be one of the questions to be answered by a TS. Moreover, the absence of a default permits specifying later that the default engages the new, improved unwind facility.

Changes since P0876R5

- `std::unwind_exception` removed.
- `fiber_context::can_resume_from_any_thread()` renamed to `can_resume_from_this_thread()`.
- `fiber_context::valid()` renamed to `empty()` with inverted sense.
- Material has been added concerning the top-level wrapper logic governing each fiber.

`std::unwind_exception` was removed in response to deep discussions in Kona 2019 of the surprisingly numerous problems surfaced by using an ordinary C++ exception for that purpose.

Problems resolved by discarding `std::unwind_exception`:

- When unwinding a fiber stack, it is essential to know the subsequent fiber to resume. `std::unwind_exception` therefore bound a `std::fiber_context`. `std::fiber_context` is move-only. But C++ exceptions must be copyable.
- It was possible to catch and discard `std::unwind_exception`, with problematic consequences for its bound `std::fiber_context`.
- Similarly, it was possible to catch `std::unwind_exception` but not rethrow it.
- If we attempted to address the problem above by introducing a `std::unwind_exception` operation to extract the bound `std::fiber_context`, it became possible to rethrow the exception with an empty (moved-from) `std::fiber_context` instance.
- Throwing a C++ exception during C++ exception unwinding terminates the program. It was possible for an exception implementation based on `thread_local` to become confused by exceptions on different fibers on the same thread.
- It was possible to capture `std::unwind_exception` with `std::exception_ptr` and migrate it to a different fiber – or a different thread.

`std::fiber_context` and the larger C++ ecosystem

higher-level libraries `std::fiber_context` as building block for higher-level frameworks enumerates a number of higher-level abstraction libraries built upon the *Boost.Context* implementation of the API proposed in this paper. This is not an exhaustive list, but it suffices to illustrate that there is widespread interest in this functionality.

The most significant point about this proposal is that, given `std::fiber_context`, all those libraries can be written in standard C++. They need not themselves be integrated into the Standard.

Because it creates and switches between different function call stacks, though, the `std::fiber_context` facility cannot be written in portable C++. There is real value to integrating this library into the Standard.

Boost.Context is maintained by one individual to support the specific set of processors and operating systems to which he has access. The `std::fiber_context` facility will ensure support in every implementation of the C++ runtime, extending into the future.

Given the lively ecosystem of open-source libraries, it's possible that standardizing `fiber_context` could suffice. It is not essential that WG21 must standardize additional higher-level libraries before the facility would become useful. The uptake of *Boost.Context* illustrates that the community can make good use of `fiber_context`.

However, the evolution of this proposal and the WG21 discussions thereof have surfaced a number of interesting adjacencies.

cancellation Given C++ support for concurrency, in various forms, within a program, cancellation of an asynchronous task remains a topic of widespread interest. It has been much discussed, e.g. in P1677R2,[25] P1820R0[26] and P2175R0.[27]

Previous revisions of this paper have proposed canceling a suspended fiber by injecting an exception, e.g. using `std::fiber_context::resume_with()`. A comparable approach was rejected for `std::jthread`, although it's worth noting that cooperative fibers differ in a very significant respect: every fiber suspends at a well-defined point, namely a call to `resume_with()`.*

Evolution of the exception mechanism itself[14] may affect the viability of using exceptions for cancellation.

That said, this paper proposes that `std::fiber_context` adopt `std::stop_source`, `std::stop_token` from the Standard,[9] section 33.3.

modules and optimizations Before modules, the only information the compiler could know about a function in an external translation unit was what a human coder stated in the relevant header file. But since the information in a module is prepared by the compiler itself, a subsequent compile of a translation unit that imports that module can know as much about each module function as it would if the function's source code was found within the current translation unit.

This permits the compiler to infer and propagate attributes. If a function neither contains a throw statement nor calls other functions, the compiler can conclude that it doesn't throw. It can encode this information in the module produced for that translation unit, so that subsequent compiles can make use of the knowledge. If another function contains no throw statement and calls only functions known not to throw, it too can be implicitly marked nothrow.

Similarly, when compiling a function that can never return, the compiler can so indicate in the output module. Any caller whose code path leads unconditionally to any such function can also be known never to return.

In much the same way, the module describing the library's `std::fiber_context::resume_with()` method can mark it as *can-suspend*. Then any caller of `resume_with()` will also be marked *can-suspend*, and so forth. The compiler can use this to improve its optimization tactics around any call to a *can-suspend* function.

(The *can-suspend* characteristic of a `co_await` coroutine function is just as pervasive, but in that case the coder must manually propagate it.)

synchronization primitives The Standard[9] provides an assortment of primitives for synchronizing work between threads, e.g. sections 33.6, 33.7, 33.8, 33.9, 33.10. An essential behaviour of many such synchronization primitives is to pause, or suspend, execution of the current thread until some external condition is satisfied.

Such suspension is very different from fiber suspension as proposed in this paper. This proposal neither requires nor implies a scheduler. A fiber suspends by explicitly designating the next fiber to resume, either by passing its `std::fiber_context` to `resume_with()` or by returning that `std::fiber_context` from its entry-function.

* Although exception-based cancellation is not implicitly supported, a consumer of `std::fiber_context` may still explicitly pass to `resume_with()` an invocable that raises an exception in the suspended fiber.

C++ threads, in contrast, assume a thread scheduler, usually provided by the operating system. Suspending a thread means passing control to the scheduler, which reallocates CPU resources to other pending threads. At some future time, the scheduler is responsible for directing some CPU core to resume the suspended thread.

Fiber suspension as implemented by `std::fiber_context` is independent of thread suspension. Suspending the running fiber simply means directing the thread to run a different fiber; the thread continues running. Conversely, suspending the host thread (e.g. by invoking a synchronization primitive) means that *no* fiber is running on that thread.

A higher-level fiber-based library that emulates the `std::thread` API, such as *Boost.Fiber*,[32] necessarily implements a fiber scheduler, permitting implicit fiber suspension. Standardizing such a library would raise the interesting question of how to present fiber-aware synchronization primitives.

A straightforward approach is to present a suite of fiber-aware synchronization primitives distinct from, but analogous to, the thread-based synchronization primitives.* A program running multiple fibers within a thread would use fiber-aware synchronization primitives rather than thread-based synchronization primitives. Evaluating a thread-based synchronization primitive would suspend the entire thread, as usual, halting all fibers within that thread.

It is tempting to contemplate modifying the semantics of the present suite of synchronization primitives to make them fiber-aware. Naturally this is a matter of some concern.

For purposes of this `std::fiber_context` proposal, though, it is entirely moot.

Execution Agent Local Storage A similar question arises concerning variable storage duration. Should the Standard introduce a fiber-specific storage duration, e.g. `fiber_local`, analogous to `thread_local`[9]? (section 6.7.5.3 **Thread storage duration**)

The Standard defines the general term *execution agent* (section 33.2.5.1) to allow for multiple kinds of parallelism. It seems reasonable to assume that over time, new types of execution agents will be defined. Will we want the Standard to present a new `xyz_local` storage duration for each new "xyz" execution agent type?

P0772R1[15] notes that library code should not have to care what kind of execution agent is running it. Already it's important to ensure that library code avoids `static` variables because any such variable prohibits calling that library from more than one thread. P0772R1 suggests a generalized variable storage duration dynamically local to the innermost current execution agent.

(The same consideration about library code impacts the above question about presenting fiber-aware synchronization primitives.)

It's true that if:

- a particular function relies on a `thread_local` variable
- the function calls a function that resumes a different fiber
- the other fiber makes a different call to that same function, or to another function that modifies the same `thread_local` variable

then on resumption of the original fiber, the function will observe the new value for the `thread_local` variable.

This is analogous to use of a `static` variable by multiple threads in the same program – though not as bad, since it doesn't produce race-related Undefined Behaviour on top of correctness problems.

`std::thread` was introduced despite this problem because it's *useful.*

Multiple C++ implementations cache a pointer to thread-local storage in the stack frame of a function referencing TLS. If a suspended fiber were resumed by a thread other than the one on which it previously ran, such cached TLS pointers would point to TLS for the wrong thread. This is why such cross-thread resumption is forbidden.

(This is the only optimization that has yet been surfaced by implementers as a potentially problematic interaction with fibers.)

tooling One particularly valuable consequence of adding `std::fiber_context` to the Standard will be to add fiber awareness to debuggers, performance analyzers and other tools that inspect a running C++ program.

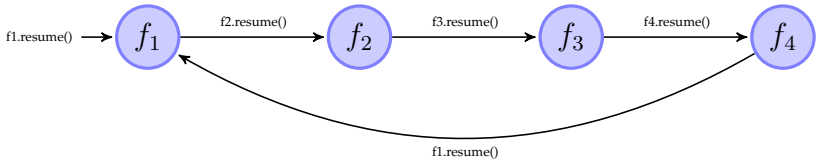
Such tools need only be aware of `std::fiber_context`. They would *not* need to be further adapted to support higher-level libraries built on the `fiber_context` facility.

*This is the approach taken by *Boost.Fiber*.

control transfer mechanism

According to the literature,[7] 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.

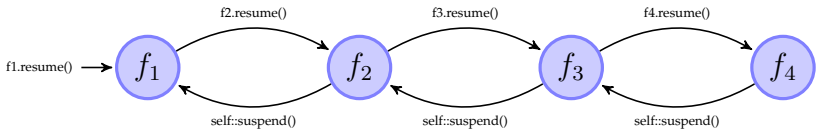



```
1  fiber_context* pf1;
2  fiber_context f4{[&pf1]{
3      pf1->resume();
4  }};
5  fiber_context f3{[&f4]{
6      f4.resume();
7  }};
8  fiber_context f2{[&f3]{
9      f3.resume();
10 }};
11 fiber_context f1{[&f2]{
12     f2.resume();
13 }};
14 pf1=&f1;
15 f1.resume();
```

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  // hypothetical API
2  fiber_context f4{[]{
3      self::suspend();
4  }};
5  fiber_context f3{[&f4]{
6      f4.resume();
7      self::suspend();
8  }};
9  fiber_context f2{[&f3]{
10     f3.resume();
11     self::suspend();
12 }};
13 fiber_context f1{[&f2]{
14     f2.resume();
15     self::suspend();
16 }};
```

```
17  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 threads 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 function call stack and is responsible for managing the lifespan of its stack (allocation at construction, deallocation when fiber terminates). The RAII-pattern* should apply.

Copying a `std::fiber_context` must not be permitted!

If a `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 behaviour.

*resource acquisition is initialisation

A fiber API must:

- **encapsulate the stack**
- **manage lifespan of an explicitly-allocated stack: the stack gets deallocated when `std::fiber_context` goes out of scope**
- **prevent accidentally copying the stack**

Class `std::fiber_context` must be *move-only*.

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 `resume()` will empty the `std::fiber_context` instance.

Whether or not a `std::fiber_context` is empty can be tested with member function `operator bool()`.

To make this more explicit, functions `resume()` and `resume_with()` are rvalue-reference qualified.

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

Section solution: avoiding non-const global variables and undefined behaviour describes how an instance of `std::fiber_context` is synthesized from the active fiber that suspends.

A fiber API must:

- **prevent accidentally resuming a running fiber**
- **prevent accidentally resuming a terminated fiber**
- **`resume()` and `resume_with()` are rvalue-reference qualified**

problem: avoiding non-const global variables and undefined behaviour

According to C++ *core guidelines*,[28] 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.

```
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[10] 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 `f` via lambda capture. This mechanism enables switching back and forth between the fiber and `main()`, enabling a rich set of applications (for instance generators).

```
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()`).

```
1  void foo(){
2      fiber_context f{[](fiber_context&& m){
3          m=std::move(m).resume(); // switch to 'foo()'
4          m=std::move(m).resume(); // switch to 'foo()'
5          ...
6      }};
7      f=std::move(f).resume(); // start 'f'
8      f=std::move(f).resume(); // resume 'f'
9      ...
10 }
```

In the pseudo-code above the fiber `f` is started by invoking its member function `resume()` at line 7. This operation suspends `foo`, empties 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, empties `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 empties `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[8] 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 instance of `std::fiber_context` is passed into the resumed fiber.

```
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.

In the code snippet above the suspended `main()` is represented by instance `m` and could be stored in containers or managed just like `f` by a scheduling algorithm.

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 non-empty `std::fiber_context` instance that will be resumed after the active fiber terminates.

```
1  int main(){
2      fiber_context f{[](fiber_context&& m){
3          return std::move(m); // resume `main()` by returning `m`
4      }};
5      f = std::move(f).resume(); // resume `f`
6      assert(f.empty());
7      return 0;
8  }
```

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

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

```
1  int main(){
2      fiber_context m;
3      fiber_context f1{[&](fiber_context&& f){
4          std::cout << "f1: entered first time" << std::endl;
5          assert(!f);
6          return std::move(m); // resume (main-)fiber that has started `f2`
7      }};
8      fiber_context f2{[&](fiber_context&& f){
9          std::cout << "f2: entered first time" << std::endl;
10         m=std::move(f); // preserve `f` (== suspended main())
11         return std::move(f1);
12     }};
13     std::move(f2).resume();
14     std::cout << "main: done" << std::endl;
15     return 0;
16 }
17
18 output:
19 f2: entered first time
20 f1: entered first time
21 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 empty 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 entry-function passed to `std::fiber_context`'s constructor must have signature '`fiber_context(fiber_context&&)` ' or '`fiber_context(stop_token, 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 empty 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:

```
1  int main(){
2      fiber_context m,f1,f2,f3;
3      f3=fiber_context{[&](fiber_context&& f)->fiber_context{
4          f2=std::move(f);
5          for(;;){
6              std::cout << "f3 ";
7              std::move(f1).resume();
8          }
9          return {};
10     }};
11     f2=fiber_context{[&](fiber_context&& f)->fiber_context{
12         f1=std::move(f);
13         for(;;){
14             std::cout << "f2 ";
15             std::move(f3).resume();
16         }
17         return {};
18     }};
19     f1=fiber_context{[&](fiber_context&& f)->fiber_context{
20         m=std::move(f);
21         for(;;){
22             std::cout << "f1 ";
23             std::move(f2).resume();
24         }
25         return {};
26     }};
27     std::move(f1).resume();
28     return 0;
29 }
30
31 output:
32 f1 f2 f3 f1 f3 f1 f3 f1 f3 ...
```

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 27. The synthesized `std::fiber_context` `main` passed to the resumed fiber is stored but 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()` or `resume_with()`.

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

output:
f1 f2 f3 f1 f2 f3 f1 f2 f3 ...
```

In the example above the synthesized `std::fiber_context` returned by each `resume()` call is specifically move-assigned to a `std::fiber_context` instance other than the one on which `resume()` was called, to properly track the three fibers. (Of course this particular example depends on static knowledge of the overall control flow. But the API does not, in general, require that.)

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

If the overall control flow isn't known, member function `resume_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 (held by the caller).

```
class filament{
private:
    fiber_context       f_;

public:
    ...
    void resume_next( filament& 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()`.

Running fiber A has an associated `filament` instance `filamentA`, whose `std::fiber_context filament::f_` is empty – 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 empties `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 empty) `std::fiber_context` instance. That empty 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 empty, 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()` may be called, passing the function `fn()` to execute.

```
1  fiber_context f([](fiber_context&& caller){
2      // ...
3      std::move(caller).resume();
4      // ...
5  });
6
7  fiber_context fn(fiber_context&&);
8
9  f = std::move(f).resume();
10 // ...
11 std::move(f).resume_with(fn);
```

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.

In the example below, suppose that code running on the program's main fiber calls `resume()` (line 12), thereby entering the first lambda. 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.†

* *Boost.Fiber*[32] uses this pattern for resuming user-land threads.
† As stated in exceptions, if there is no matching `catch` clause in that fiber, `std::terminate()` is called.

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

```
1  int data = 0;
2  fiber_context f{[&data](fiber_context&& m){
3      std::cout << "f1: entered first time: " << data  << std::endl;
4      data+=1;
5      m=std::move(m).resume();
6      std::cout << "f1: entered second time: " << data  << std::endl;
7      data+=1;
8      m=std::move(m).resume();
9      std::cout << "f1: entered third time: " << data << std::endl;
10     return std::move(m);
11 }};
12 f=std::move(f).resume();
13 std::cout << "f1: returned first time: " << data << std::endl;
14 data+=1;
15 f=std::move(f).resume();
16 std::cout << "f1: returned second time: " << data << std::endl;
17 data+=1;
18 f=std::move(f).resume_with([&data](fiber_context&& m){
19     std::cout << "f2: entered: " << data << std::endl;
20     data=-1;
21     return std::move(m);
22 });
23 std::cout << "f1: returned third time" << std::endl;
24
25 output:
26     f1: entered first time: 0
27     f1: returned first time: 1
28     f1: entered second time: 2
29     f1: returned second time: 3
30     f2: entered: 4
31     f1: entered third time: -1
32     f1: returned third time
```

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 a `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()` on a `std::fiber_context` that has not yet been resumed for the first time:

```
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) `std::fiber_context` instance, the returned `std::fiber_context` instance is passed into `topfunc()` as its `prev` parameter.

Member function `resume_with()` allows 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.

```
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` emptied 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 fiber `lambda` has now terminated, the updated `lambda` is empty. Its `operator bool()` returns `false`.

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

Every `std::fiber_context` you launch must terminate gracefully by returning from its entry-function.

When an explicitly-launched fiber's entry-function returns a non-empty `std::fiber_context` instance, the running 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 non-empty `std::fiber_context` instance – it need not be the instance originally passed in, or an instance returned from the `resume()` family of methods.

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."

The `get_stop_source()` / `get_stop_token()` / `request_stop()` mechanism provides a way for consuming code to attempt to communicate to a suspended fiber the desire that it should terminate. The intention is that the program may call `request_stop()` before destroying a `std::fiber_context` instance that might not be empty, or is known not to be empty.

The interaction between `request_stop()` and any particular entry-function is the responsibility of the program. Use of `request_stop()` does not terminate the subject fiber, or guarantee that the fiber will terminate. The fiber must be resumed *after* the `request_stop()` call before it could observe `stop_requested()`. Even then, the entry-function might not immediately return.

One tactic would be to call `request_stop()`, then loop over `resume()` or `resume_with()` calls until the returned `std::fiber_context` is `empty()`. However, that information is ambiguous.

Suppose we have a `std::fiber_context` instance `f1` representing suspended fiber F. The running fiber M calls `f1.request_stop()`, then `f1.resume()`, which returns another `std::fiber_context` instance `f2`.

`f2` has various possible values.

- `f2` might be empty. This might mean that fiber F did in fact terminate.
- Alternatively, it might mean that fiber F, instead of terminating, resumed fiber G, which terminated by resuming fiber M.
- Or fiber F might have terminated by resuming fiber G, which might have terminated by resuming fiber M.
- In other words, if `f2` is empty, fiber M cannot know the present state of fiber F.
- `f2` might not be empty. That might mean that fiber F did not terminate before resuming fiber M. `f2` would represent fiber F.
- Or it might mean that fiber F terminated by resuming fiber G, which might have resumed fiber M. `f2` would represent fiber G.
- Or it might mean that fiber F, instead of terminating, resumed fiber G, which resumed fiber M. `f2` would (again) represent fiber G.
- In other words, if `f2` is not empty, fiber M cannot know the present state of fiber F.

The `autocancel` class introduced in Appendix A: support code for examples illustrates a possible way to use the `request_stop()` mechanism, subject to the limitations described above.

exceptions

If an uncaught exception escapes from a fiber's entry-function, `std::terminate` is called.

`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 frameworks are based on the low-level fiber switching API of *Boost.Context*[30] (which implements the API proposed here).

Boost.Coroutine2[31] 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.

```
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[39] (by Grigory Demchenko) is a small, efficient library to perform asynchronous operations using source code that resembles synchronous operations. 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.

```
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.

Boost.Fiber[32] implements **user-land threads** and combines fibers with schedulers (the scheduler algorithm is a customization point). The API is modelled after the `std::thread` API and contains objects such as `future`, `mutex`, `condition_variable` ...

```
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***[35] 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.

```
folly::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*[33] and some other Facebook services/libraries like ServiceRouter (routing framework for *Thrift*[34]), Node API (graph ORM API for graph databases) ...

Bloomberg's ***quantum***[36] is a full-featured and powerful C++ framework that allows users to dispatch units of work (a.k.a. tasks) as coroutines and execute them concurrently using the 'reactor' pattern. Its main features are support for streaming futures which allows faster processing of large data sets, task prioritization, fast pre-allocated memory pools and parallel `forEach` and `mapReduce` functions.

```
// Define a coroutine
int getDummyValue(Bloomberg::quantum::CoroContext<int>::Ptr ctx) {
    int value;
    ...           //do some work
    ctx->yield(); //be nice and let other coroutines run (optional cooperation)
    ...           //do more work and calculate 'value'
    return ctx->set(value);
}
// Create a dispatcher
Bloomberg::quantum::Dispatcher dispatcher;
// Dispatch a work item to do some work and return a value
int result = dispatcher.post(getDummyValue)->get();
```

quantum is used in large projects at Bloomberg.

Habanero Extreme Scale Software Research Project[37] provides a task-based parallel programming model via its *HClib*.[38] The runtime provides work-stealing, async-finish,* parallel-for and future-promise parallel programming patterns. The library is not an exascale programming system itself, but it manages intra-node resources and schedules components within an exascale programming system.

Intel's ***TBB***[40] internally uses fibers for long running jobs† as reported by Intel.

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::generate` and fiber `g` generate a sequence of Fibonacci numbers and store them into `std::vector v`.

```
int a;
autocancel consumer, generator;
generator = autocancel{[&a,&consumer,&generator](std::fiber_context&& m){
    a=0;
    int b=1;
    while (! generator.stop_requested()){
        generator.resume(consumer);
        int next=a+b;
        a=b;
        b=next;
    }
    return std::move(m);
}};
consumer = autocancel{[&a,&consumer,&generator](std::fiber_context&& m){
    std::vector<int> v(10);
    std::generate(v.begin(), v.end(), [&a,&consumer,&generator]() mutable {
        consumer.resume(generator);
        return a;
    });
    std::cout << "v: ";
```

*async-finish is a variant of the fork-join model. While a task might fork a group of child tasks, the child tasks might fork even more tasks. All tasks can potentially run in parallel with each other. The model allows a parent task to selectively join a subset of child tasks.
†because of the requirement to support a broad range of architectures `swapcontext()` was used

```
    for (auto i: v) {
        std::cout << i << " ";
    }
    std::cout << "\n";
    return std::move(m);
}};
consumer.resume();

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

(See Appendix A: support code for examples for the definition of `autocancel`.)

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 N O T seek to standardize any particular implementation or impose any specific calling convention!

Modern **micro-processors** are **register machines**; the content of processor registers represents 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.[6]

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**[29] 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*[30] which acts as building block for (e.g.) *folly::fibers* and *quantum*; see section `std::fiber_context` as building block for higher-level frameworks.

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 on 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` need not itself contain the stored CPU state: it need only contain a pointer to the stack location.

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 deallocations 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*,[30] 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§.

*The implementation of *Boost.Context*[30] 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

Usually the host-directed execution uses **computation offloading** that permits executing computationally intensive work on a separate device (accelerator).[4]

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 processes them **asynchronously**.[5]

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

Any thread in a program may be shared by multiple fibers.

A newly-instantiated fiber is not yet associated with any thread. However, once a fiber has been resumed the first time by some thread, it must thereafter be resumed only by that same thread.

There could potentially be Undefined Behaviour if:

- a function running on a fiber references `thread_local` variables
- the compiler/runtime implementation caches a pointer to `thread_local` storage in that function's stack frame
- 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 this reason, it is forbidden to resume a fiber on any thread other than the one on which it was first resumed.

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API

33.11 Cooperative User-Mode Threads [fiber-context]

33.11.1 General [fiber-context.general]

The extensions proposed here support creation and activation of cooperative user-mode threads, here called *fibers*.

A fiber is a thread of execution ([intro.multithread.general]) with weakly parallel forward progress guarantees ([intro.progress] paragraph 11).

The term "user-mode" means that control can be passed from one fiber to another 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 the underlying execution agent, 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*. This is an explicit variant of blocking with forward progress guarantee delegation ([intro.progress] paragraph 14).

Launching a fiber logically creates a new function call 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 existing implementation of function call stacks.

33.11.2 Empty vs. Non-Empty [fiber-context.empty]

A `std::fiber_context` instance may be *empty* or *non-empty*. A default-constructed `std::fiber_context` is empty. A moved-from `std::fiber_context` is empty. A `std::fiber_context` representing a suspended fiber is non-empty.

33.11.3 Explicit Fiber vs. Implicit Fiber [fiber-context.implicit]

The default thread on which the program runs `main()` has an initial *default fiber* whose stack is the stack on which `main()` is entered. [*Note:* Thus, when `main()` instantiates a new `std::fiber_context`, it becomes the second fiber in the program. — *end note*] Similarly, every explicitly-launched `std::thread` or `std::jthread` has an initial default fiber whose stack is the stack on which the function passed to `std::thread` or `std::jthread`'s constructor is entered.

We use the phrase *explicit fiber* or *explicitly-launched fiber* to designate a fiber instantiated by user code; conversely, *implicit fiber* designates the default fiber on any thread. An implicit fiber's *owning thread* is the thread of which that fiber is the default fiber. An explicit fiber has no owning thread. Instead, when necessary, we speak of the thread on which a fiber was first resumed.

A fiber is explicitly instantiated by passing an *entry-function* to `std::fiber_context`'s constructor. This function is not entered until the first call to one of the `fiber_context::resume()` family of methods.

When a fiber is first entered, a synthesized non-empty `std::fiber_context` instance representing the newly-suspended previous fiber is passed as a parameter to its entry-function. Once entered, a fiber may suspend by calling one of the `resume()` family of methods on any available non-empty `std::fiber_context` instance. When the suspended fiber is resumed, that method returns a synthesized `std::fiber_context` instance representing the newly-suspended previous fiber.

The synthesized `std::fiber_context` instance received in either of those ways might represent either an explicit fiber or an implicit fiber.

An explicit fiber terminates by returning from its entry-function. If the entry-function returns a non-empty `std::fiber_context` instance, the fiber represented by that `std::fiber_context` instance is resumed.

If the fiber's entry-function exits via an exception, `std::terminate` is called.

33.11.4 Header <experimental/fiber_context> synopsis [fiber-context.synopsis]

```
#include <fiber_context>

#define __cpp_lib_experimental_fiber_context 202302

namespace std {
namespace experimental {
inline namespace concurrency_v2 {

class fiber_context;

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

33.11.5 Class fiber_context [fiber-context.class]

```
namespace std {
namespace experimental {
inline namespace concurrency_v2 {

class fiber_context {
public:
    fiber_context() noexcept;

    template<typename F>
    explicit fiber_context(F&& entry);

    ~fiber_context();

    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) &&;

    // stop token handling
    [[nodiscard]] stop_source get_stop_source() noexcept;
    [[nodiscard]] stop_token get_stop_token() const noexcept;
    bool request_stop() noexcept;

    bool can_resume() noexcept;

    explicit operator bool() const noexcept;
    bool empty() const noexcept;
    void swap(fiber_context& other) noexcept;

private:
    stop_source ssource;            // exposition only
};

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

fiber_context() noexcept ;

Effects:

— instantiates an empty `std::fiber_context`.

Ensures:

— `empty()` returns `true`.

— `ssource.stop_possible()` returns `false`.

template<typename F> explicit fiber_context(F&& entry) ;

Constraints:

— `remove_cvref_t<F>` is not the same type as `fiber_context`.

Mandates:

— `is_invocable_v<decay_t<F>, fiber_context&&> || is_invocable_v<decay_t<F>, stop_token, fiber_context&&>`

Effects:

— Initializes `ssource`.

— Instantiates a `std::fiber_context` representing a fiber suspended before entry to `entry`. [*Note:* `entry` is entered only when `resume()` or `resume_with()` is called. —*end note*]

— The stack and any other necessary resources are created.

Ensures:

— `ssource.stop_possible()` returns `true`.

— `empty()` returns `false`.

Throws:

— Any exception resulting from failure to acquire necessary system resources.

fiber_context(fiber_context&& other) noexcept ;

Effects:

— moves underlying state from `other` to new `std::fiber_context`

Ensures:

— `empty()` returns the value previously returned by `other.empty()`

— `other.empty()` returns `true`

~fiber_context() ;

Effects:

— destroys a `std::fiber_context` instance.

Requires:

— `empty()` returns `true`.

[*Note:* If a `std::fiber_context` instance to be destroyed is not yet empty, an application must call `request_stop()`, or otherwise convey to the suspended fiber the need to terminate voluntarily. —*end note*]

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

Requires:

— `empty()` returns `true`.

Effects:

— assigns the state of `other` to `*this`

Returns:

— `*this`

Ensures:

— `empty()` returns the value previously returned by `other.empty()`

— `other.empty()` returns `true`

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

Mandates:

— `is_invocable_v<decay_t<Fn>, fiber_context&&>`

— `empty()` returns `false`

— the calling thread is the same as the thread on which the fiber represented by `*this` was first resumed

Effects:

— Saves the execution context of the calling fiber.

— Suspends the calling fiber.

— Let `caller` be a synthesized `std::fiber_context` instance representing the suspended caller.

— Resumes the fiber represented by `*this`.

— Restores the execution context of the resumed fiber.

— Evaluates `invoke(std::forward<Fn>(fn), std::move(caller))` on the newly-resumed fiber. Let `returned` be the `std::fiber_context` instance returned by `fn`. [*Note:* `returned` may or may not be the same as `caller`. — *end note*] [*Note:* `returned` may be empty. — *end note*]

— If the fiber represented by `*this` has not previously been entered, passes `returned` to its entry-function: executes
`invoke(std::forward<F>(entry), get_stop_token(), std::move(returned))`
if that expression is well-formed, otherwise
`invoke(std::forward<F>(entry), std::move(returned))`

— Otherwise, the fiber represented by `*this` previously suspended itself by calling one of `resume()` or `resume_with()`. Returns `returned` from whichever of the resume functions was called.

Remarks:

— A newly constructed but not yet resumed fiber may be resumed by any thread.

Returns:

— If the previous fiber resumed this one by returning `std::fiber_context`, an empty `std::fiber_context`.

— If the previous fiber resumed this one by calling `resume()`, a `std::fiber_context` representing that previous fiber.

— If the previous fiber resumed this one by passing some `fn` to `resume_with()`, the `std::fiber_context` returned by that `fn`.

Throws:

— Nothing before suspending the calling fiber.

— On resuming:

- If the previous fiber resumed this one by returning `std::fiber_context`, nothing.
- If the previous fiber resumed this one by calling `resume()`, nothing.
- If the previous fiber resumed this one by calling `resume_with()`:
  - If the `fn` passed by the previous fiber to `resume_with()` returned `std::fiber_context`, nothing.
  - If the `fn` passed by the previous fiber to `resume_with()` threw an exception, that exception.

Ensures:

— `empty()` returns `true`

[*Note:* The returned `fiber_context` indicates via `empty()` whether the previous active fiber has terminated (returned from entry-function). — *end note*]

[*Note:* `resume()` or `resume_with()` empties the instance on which it is called. In order to express the state change explicitly, these methods are rvalue-reference qualified. For this reason, no non-empty `std::fiber_context` instance ever represents the currently-running fiber. — *end note*]

fiber_context resume() && ;

Effects: Equivalent to:
```
resume_with([](fiber_context&& caller){ return std::move(caller); })
```

[[nodiscard]] stop_source get_stop_source() noexcept ;

Effects: Equivalent to: `return ssource;`

[[nodiscard]] stop_token get_stop_token() const noexcept ;

Effects: Equivalent to: `return ssource.get_token();`

bool request_stop() noexcept; ;

Effects: Equivalent to: `return ssource.request_stop()`

bool can_resume() noexcept ;

Returns:

— `false` if `*this` is empty, or if the calling thread is not the same as the thread on which the fiber represented by `*this` was first resumed.

[*Note:* When `can_resume()` returns `true`, the `std::fiber_context` instance may be resumed by `resume()` or `resume_with()`. — *end note*]

Remarks:

— `can_resume()` must not be called concurrently from multiple threads.

[*Note:* `can_resume()` is not marked `const` because in at least one implementation, it requires an internal context switch. However, the stack operations are effectively read-only. — *end note*]

bool empty() const noexcept ;

Returns:

— `false` if `*this` represents a fiber of execution, `true` otherwise.

[*Note:* Regardless of the number of `std::fiber_context` declarations, exactly one `std::fiber_context` instance represents each suspended fiber. — *end note*]

explicit operator bool() const noexcept ;

— Equivalent to `(! empty())`

void swap(fiber_context& other) noexcept ;

Effects:

— Exchanges the state of `*this` with `other`.

Appendix A: support code for examples

Destroying a non-empty `std::fiber_context` instance invokes Undefined Behaviour – you must first call `request_stop()` (see termination). To simplify code examples in this paper, we introduce an `autocancel` wrapper class that tracks the sequence of `std::fiber_context` instances representing a particular fiber. When an `autocancel` instance is destroyed, it calls `request_stop()` on the stored `std::fiber_context` and loops until the fiber voluntarily terminates.

```
// autocancel is a wrapper class that, when destroyed, implicitly requests
// stop on its stored fiber_context. It uses the tactic seen in the example
// 'filament' class to continually update the fiber_context representing the
// fiber of interest. (See "returning synthesized std::fiber_context instance
// from resume()")
class autocancel{
private:
    std::fiber_context       f_;

public:
    autocancel() = default;
    template <typename Fn>
    autocancel(Fn&& entry_function):
        f_{std::forward<Fn>(entry_function)}
    {}
    autocancel& operator=(autocancel&& other) = default;

    ~autocancel() {
        f_.request_stop();
        while (f_) {
            resume(*this);
        }
    }

    bool stop_requested() const noexcept {
        return f_.get_stop_source().stop_requested();
    }

    // for initial entry from a plain fiber rather than an autocancel instance
    std::fiber_context resume(){
        return std::move(f_).resume();
    }

    void resume( autocancel& ac){
        std::move(ac.f_).resume_with([this](std::fiber_context&& f)->std::fiber_context{
            f_=std::move(f);
            return {};
        });
    }
};
```

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