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Author: Oliver Kowalke (oliver.kowalke@gmail.com)

# A unified syntax for stackless and stackful coroutines

## Abstract

This paper proposes a *unified syntax* for stackless and stackful coroutines. The syntax is based on the evaluation of N4397.[?]

The most important features are:

- first-class object that can be stored in variables or containers
- introduction of new keyword `resumable` together with a lambda-like expression
- symmetric transfer of execution control, e.g. suspend-by-call - enables a richer set of control flows than asymmetric transfer of control
- ordinary function calls and returns not affected

## Background

At the meeting in Urbana the committee decided to pursue both kinds of coroutines and encouraged the community to propose a unified syntax.
This paper proposes a syntax suitable for stackless and stackful coroutines based on the ideas of proposal N4397.[?]

## Introduction

Traditionally C++ code is compiled for a linear stack, that means that the activation records are allocated in strict *last-in-first-out*-order. This stack model allocates activation records on function call/return by incrementing/decrementing the stack pointer.
Coroutines enable a more advanced control flow. That requires, that a coroutine outlives the context in which it was created (the activation record of a suspended coroutine **must not** be **removed**)! Additionally, if the activation record of a suspended coroutine remains on the linear processor stack and other code uses the stack in the meanwhile, then all stack frames allocated after suspending the coroutine might have been corrupted (overwritten).
Traditional stack management is inadequate for coroutines.

N4397[?] describes the *first-class* construct `std::execution_context`, representing a execution state. A program contains at least one execution context. As explained in N4397, `std::execution_context` can be used to implement stackful coroutines as proposed in N3985[?] or might be the building block of *oneshot shift/reset*-operators.
In the remaining chapters the proposal describes under which constraints `std::execution_context` can be used for stackless and stackful context switching.

## Definitions

This proposal uses the wording (definitions) of N4397.[?]

## Discussion

N4397? describes `std::execution_context` as a mechanism to implement stackful context switching (for instance coroutines). Each context owns its own side context.
How can this formalism be used to express *stackless* as well *stackful* execution contexts? The answer is the concept of *suspend-by-calling*.

**Calling convention** A calling convention is a scheme, part of the ABI*, that describes how a subroutine has to be called. This includes parameter list, return address, *stack layout* and cleanup.
Some calling conventions (for instance x86 architecture) require that data like *parameter list* as well as *return address* are stored on the callers stack before the subroutine is invoked. Other calling conventions of other architectures (for instance ARM's AAPCS) do not have this restriction †, e.g. using the stack is minimized‡
The proposed syntax for stackless and stackful context switching requires that the stack is clean, e.g. no parameter list and no return address, remain on the callers stack if a context switch happens. This is a guarantee of the requirement that a coroutien can outlive the context is was created in.
In other words, that parts that would remain on the callers stack must be preserved and restored by a context switch (member function `std::execution_context::operator()()`). This also a consequence by the *suspend-by-calling* concept. Previous proposals like N4134? describe a *suspend-by-returning* mechanism, e.g. the coroutine is suspended by calling `yield` etc. (for resumable functions a return value transformation happens, e.g. return value is substituted by a future-like object).

**Suspend-by-calling** A *suspend-by-calling* requires a symmetric transfer of execution control as well as first-class objects in order to specify the next context to be resumed.
This enables an arbitrary flow of context switches providing a broad range of control flows (for instance *shift/reset*-continuations).
As a consequence the part, belonging to the called function, on the caller stack must be poped and preserved in the callers *capture record*. The caller context becoems suspended by calling
`std::execution_context::operator()()` of another execution context. Other execution context's are able to use the stack in the meanwhile. If the suspended context is resumed, the preserved data are pushed to the stack and execution returns from `std::execution_context::operator()()`.

**Prologue** The prologue of `std::execution_context::operator()()` updates the capture record (CPU registers) and popes some parts (part of callee's stack frame) from callers stack and preserves the data into callers capture record too.

**Epilogue** If the context (caller context from above) is resumed, the *epilogue* of
`std::execution_context::operator()()` loads the capture record and pushes callee's partial stack frame on callers stack. The calling convention remains intact and the code, which as called
`std::execution_context::operator()()`, can not distinguish between an ordinary function and a context switch. It's completely transparent for the caller.

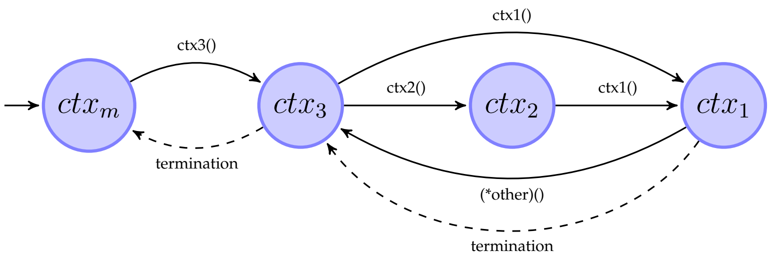
**Flow of control** Because `std::execution_context` uses a symmetric execution control transfer mechanism, the flow of control can be arbitrary.

```
// N4398: stackless execution context
int main(){
    std::execution_context* other=nullptr;
    auto ctx1=[other]() resumable {
        (* other)(); // suspend ctx1, resume other
    };
    auto ctx2=[&ctx1]() resumable {
```

*Application Binary Interfaces; an executable must be conform to, in order to be executable in the specified execution environment
†AAPCS64: parameters in registers R0-R7/V0-V7, return address in link register LR
‡of course a long parameters list requires the stack; but this is negibile as shown in the text

```
        ctx1(); // suspend ctx2; resume ctx1
    };
    auto ctx3=[&ctx1,&ctx2]() resumable {
        ctx2(); // suspend ctx3, resume ctx2
        ctx1(); // suspend ctx3, resume ctx1
    };
    other=&ctx3;
    ctx3(); // suspend main context, resume ctx3
}
```

As shown in the example, the context's of *ctx1*, *ctx2* and *ctx3* form a cycle of flow of control.




The cycle is started by calling `ctx3()` from the main context ($ctx_m$, created on start-up). Context $ctx_3$ starts $ctx_2$ while $ctx_2$ resumes $ctx_1$. Context $ctx_1$ is suspended by resuming $ctx_3$ with `(*other)()`. Function `ctx2()` returns in $ctx_3$ and `ctx1()` resumes $ctx_1$ at next. Context $ctx_1$ terminates after returning from `(*other)()`.
After termination of $ctx_1$, $ctx_3$ is resumed because it has become the parent context of $ctx_1$ (by calling `ctx1()`). As $ctx_3$ terminates, the main context $ctx_m$ is resumed (return from `ctx3()`).

**Stackless and stackful** The compiler allocates for a *stackless context* only one, suitable sized, capture record and for a *stackful context* a side stack (linked stack, e.g. non-contiguous, on demand growing).
In order to decide what kind of context has to be generated, the compiler has to analyse the toplevel context function. Following use cases have to be distinguished:

- no context switch: generate an ordinary function
- context switch at toplevel: create a *stackless* context
- in all other cases: generate a *stackful* context

```
// N4398: stackless execution context
// suspend in body of toplevel context function
#define yield(x) p=x; mctx();
int main(){
    int n=35;
    int p=0;
    auto mctx(std::execution_context::current());
    auto ctx([n,&p,mctx]()mutable resumable{
            int a=0,b=1;
            while(n-->0){
                yield(a);
                auto next=a+b;
                a=b;
                b=next;
            }
        });
    for(int i=0;i<10;++i){
        ctx();
        std::cout<<p<<std::endl;
```

```
    }
}
```

In other words, if `std::execution_context::operator()()` is called inside the body of the toplevel context function (as shown in Fibonacci example above) a *stackless* context is sufficient.

```
// N4398: stackful execution context
// example taken from proposal N4397
int main(){
    std::istringstream is("1+1");
    char c;
    // access current execution context
    auto m=std::execution_context::current();
    // use of linked stack (grows on demand) with initial size of 1KB
    std::execution_context l(
    auto l=[&m,&is,&c]()resumable{
            Parser p(is,
                     // callback, used to signal new symbol
                     [&m,&c](char ch){
                        c=ch;
                        m(); // resume main-context from nested call stack
                     });
            p.run(); // start parsing
        });
    try{
        // inversion of control: user-code pulls parsed data from parser
        while(l){
            l(); // resume parser-context
            std::cout<<"Parsed: "<<c<<std::endl;
        }
    }catch(const std::exception& e){
        std::cerr<<"exception: "<<e.what()<<std::endl;
    }
}
```

Calling a context switch from a nested call stack requires a *stackful* context.

## Design

The design of `std::execution_context` is based on N4397[7] with one modification - the *lambda-like expression* does not have the *hint* attribute.
Instead the compiler desides if one activation records is sufficient (*stackless* or a side stack is required (*stackful*. The compiler makes the decision based on the analysis of the toplevel context function. If the compiler can prove, that context switches are only done at the toplevel function and not from nested call stack (from subroutines), than a *stackless* execution context is created. Otherwise the compiler constructs a `std::execution_context` with a non-contiguous, linked side stack. The initial default stacksize depends on the platform.

**First-class object** As first-class object the execution context can be stored in a variable or container.

**Capture record** Each instance of `std::execution_context` owns a toplevel activation record, the capture record. The capture record is a special activation record that stores additional data like stack pointer, instruction pointer and a link to its parent execution context. That means that during a execution context switch, the execution state of the running context is captured and stored in the capture record while the content of the resumed execution context is loaded (into CPU registers etc.).

**Parent context** The pointer to its *parent* execution context allows to traverse the chain of ancestor context's, e.g. the execution context which has resumed (`std::execution_context::operator()()` called) the running context.

**Active context** Static member function `std::execution_context::current()` returns a `std::execution_context` pointing to the current capture record (e.g. execution context). The current active capture record is stored in an internal, thread local pointer.

**Toplevel capture records** At entering `main()` as well as the *thread-function* of a thread, a execution context (capture record) is created and stored in the internally. `std::execution_context::current()`.

**Termination** If the body of the toplevel context function reaches its end, the parent execution context (pointer in the capture record) is resumed. That means that in the parent context the function `std::execution_context::operator()()` returns. For this purpose the *epilogue* loads the capture record (instruction pointer, stack pointer etc.) of the parent context, so that it is resumed.

**Exceptions** A exception thrown inside the execution context is catched, the parent execution context is resumed and the exception is re-thrown inside the parent context (e.g. the exception is emitted by `std::execution_context::operator()()`).

### member functions

**(constructor)** constructs new execution context

| | |
|---|---|
| `[captures](params) mutable resumable exceptions attrs -> ret {body}` | (1) |
| `execution_context(const execution_context& other)=default` | (2) |
| `execution_context(execution_context&& other)=default` | (3) |

**1)** the constructor does not take a lambda as argument, instead the compiler evaluates the lambda-like syntax and constructs a `std::execution_context` directly

**captures** list of captures

**params** only empty parameter-list allowed

**mutable** allows to modify parameters captured by copy

**resumable** identify resumable context

**exceptions** only `noexcept` allowed; emitted exceptions trigger `std::terminate()`

**attrs** attributes for `operator()`

**ret** only `void` allowed; resumable lambda returns nothing (use of capture list instead)

**body** function body

**2)** copies `std::execution_context`, e.g. underlying control block is shared

**3)** moves underlying control block to new `std::execution_context`

**(destructor)** destroys a execution context

| | |
|---|---|
| `~execution_context()` | (1) |

**1)** destroys a `std::execution_context`. If associated with a context of execution and holds the last reference to the internal control block, then the context of execution is destroyed too. Specifically, the stack is unwound.

**operator=** copies/moves the coroutine object

| | |
|---|---|
| `execution_context& operator=(execution_context&& other)` | (1) |
| `execution_context& operator=(const execution_context& other)` | (2) |

**1)** assigns the state of *other* to **this* using move semantics

**2)** copies the state of *other* to **this*, state (control block) is shared

**Parameters**

**other** another execution context to assign to this object

**Return value**

***this**

**operator()** jump context of execution

| | |
|---|---|
| `execution_context& operator()()` | (1) |

**1)** resumes the execution context

**Exceptions**

**1)** re-throws the exception of the resumed context in the parent context

**Notes**
The *prologue* preserves the execution context of the calling context as well as stack parts like *parameter list* and *return address* [§]. Those data are restored by the *epilogue* if the calling context is resumed.
A exception thrown inside execution context is catched, the parent execution context is resumed and the exception is re-throw in the parent context (out of `std::execution_context::operator()()`).
If the toplevel context function terminates (reaches end), the parent context is resumed (return of `std::execution_context::operator()()` in the parent execution context).
The behaviour is undefined if `operator()` is called while `current()` returns **this* (e.g. resuming an already running context).

**explicit bool operator** test if context has not reached its end

| | |
|---|---|
| `explicit bool operator() noexcept` | (1) |

**1)** returns *true* if context is not terminated

**Exceptions**

**1)** noexcept specification: `noexcept`

[§]required only by some x86 ABIs

**operator!** test if context has reached its end

| | |
|---|---|
| `bool operator!() noexcept` | (1) |

**1)** returns *true* if context is terminated

### Exceptions

**1)** noexcept specification: `noexcept`

**current** accesses the current active execution context

| | |
|---|---|
| `static execution_context current()` | (1) |

**1)** construct a instance of `std::execution_context` pointing to the capture record of the current, active execution context

### Notes

The current active execution context is thread-specific, e.g. for each thread (including `main()`) a execution context is created at start-up.

## Acknowledgement

I'd like to thank Nat Goodspeed for reviewing earlier drafts of this proposal.

# References

[1] N4134: Resumable Functions v.2

[2] N4397: A low-level API for stackful coroutines

[3] Library *boost.context*: git repo, documentation