Coroutines

Mittwoch, 15. März 2023 13:32

Author: Damir Ljubic
e-mail: damirlj@yahoo.com

Intro

When we define a task in programming language, we define it from the two aspects:

- Execution context (single thread, sub-tasks divided and hosted on multiple threads, thread pool, etc.)
- Execution flow (synchronous, asynchronous)

Coroutines stands for **cooperative** routines, that can be **voluntarily** (explicitly) **suspended** - passing the control flow to the caller (even another coroutine): the one that can **resume** it.
In C++ we already have std::async call - that represents the asynchronous task that can be executed either deferred on the same thread, or launched on a different thread, at which point the caller and the task running concurrently, competing for the same computational resources (CPUs).
This mechanism involves the OS (kernel), in terms of the Scheduler: **preempting** one thread in favorite of another, based on some scheme (usually, thread priorities).

⇒ More on that: https://github.com/damirlj/modern_cpp_tutorials/blob/main/docs/Thread__Attributes.pdf

Coroutines offer overall better utilization of system resources, passing the control flow back and forth - without need for nested callbacks and continuation-passing style code: chained operations.
Coroutines provide the sequential (linear) code flow for the asynchronous tasks - which also results in more intuitive syntax that is easier to write and read - and therefore maintain.
This also makes the integration with legacy code easier, since it can be done iterative, gradually replacing the existing callbacks, or std::async tasks: but only if there is a reason for that.

What are coroutines?

Technically speaking, coroutines are functional blocks that have
- **Result type**: a type that will be returned by the coroutine, as control object
- Any of the keywords: **co_yield**, **co_await**, **co_return**

Under the hood, compiler will generate the **state-machine**, that allows transition from initial suspension point, to the final state, at which point the coroutine will be destroyed.
The mental model could be

```
{
    co_await promise.initial_suspend();// check initial suspension: outside of try/catch block
    try
    {
        <body-statements>

        co_return promise.return_void();// or promise.return_value(val);
        goto Finalize;
    }
    catch(...)
    {
        promise.unhandled_exception();// exception handling
    }
Finalize:
    co_await promise.final_suspend();// check final suspension: outside of try/catch block

}
```

@Hint: You can use CompilerExplorer/Insight tool from Andreas Fertig to inspect how the generated code actually looks like.
For that, you need to enable: "*show coroutine transformation*"

Result type

The coroutine's return type is a wrapper around usually internally implemented interface that must be named or aliased as **promise_type.**
This interface describes the machinery behind the coroutine:

== Creation ==

The very first call is *get_return_object()* which creates the coroutine's control type.
In order to support suspend/resume mechanism, coroutines are **stackless** - they are created on the heap,

which is known as coroutine frame.
The return type of coroutine is nothing but wrapper around the coroutine frame: *std::coroutine_handle*

```
template <typename T>
class [[nodiscard]] ResultType final
{
   public:
       class promise_type;
       using coroutine_handle =std::coroutine_handle<promise_type>;

        /**
           Required nested promise_type entity
        */
        struct promise_type {

           ResultType get_return_object() {
               return ResultType{this};
           }
           // the rest of the interface
           …
        };

     explicit ResultType(promise_type* promise) noexcept:
     _handle(coroutine_handle::from_promise(*promise))
     {}

     operator std::coroutine_handle<> () const {
         return handle_;
     }

   private:
        coroutine_handle handle_;
};
```

The alternative is to use concept: ***std::coroutine_traits***, to attach the required *promise_type*
to some entity that is this way turned into eligible coroutine's return type

```
class Socket final
{
    public:
        explicit Socket(int fd) noexcept: fd_(fd) {}
        ~Socket() { ::close(fd_);}

        using data_type = std::vector<std::byte>;
        ...
};

using domain_type = enum class DomainType {ipv4 = AF_INET,ipv6 = AF_INET6, unix = AF_UNIX};
using socket_type = enum class SocketType {stream = SOCK_STREAM, datagram = SOCK_DGRAM};

template <domain_type domain, socket_type socket>
struct SocketCreator
{
   int make_socket() const {
     return ::socket((int)domain, (int)socket, 0);
   }

};

struct socket_as_coroutine {}; // std template specialization requires at least one user-defined type

template<>
struct std::coroutine_traits<Socket, socket_as_coroutine>
{
    template <domain_type domain,socket_type socket>
    struct promise_type : SocketCreator<domain, socket>
    {
        Socket get_return_object() {return Socket{this->make_socket()}; }
        std::suspend_never initial_suspend() const noexcept { return{}; }
        std::suspend_always final_suspend() const noexcept  { return{}; }
        void return_void() {}
        void unhandled_exception() {}
    };
};
```

At which point the caller receives the coroutine's control object - as return type?

When the coroutine is for the first time suspended, or - if there is no suspension point, when the coroutine is destroyed (which is not quite useful).

== Suspension/Resumption ==

Promise interface describes the initial and final suspension points of a coroutine.
As you can see in the mental model, they are outside of the try/catch block - so it's important that they do not throw exception.
If initial suspension point is actively set (using predefined *std::suspend_always*), the coroutine is created with laziness in mind, returning immediately control to the caller.
The caller is responsible to resume it.
Final suspension point gives the possibility to make the last snapshot of the coroutine frame, delaying it's destruction - giving control back to the caller. To caller can inspect - query the state, or preserved value of coroutine at the point when finalization is reached.
And the caller is responsible to destroy it.
To avoid memory leaking, we can ensure proper cleanup, by capturing the finalization in the control object destructor (RAII)

```
~ResultType(){
   if(_handle) {
       _handle.destroy();
   }
}
```

== Exception handling ==

The coroutine's error handling is based on catching the exceptions, in try/catch block around the coroutines body statements.
The *promise_type* gives the callback entry that can be implemented as user-specific error handling.
There are different kind of strategies:

- Call *std::terminate* to terminate the application, indicating non-recoverable error.
  Not recommendable for the real applications, especially in embedded domain.
- Similar to *std::promise<T>*, capture either value or exception within *std::variant<std::monostate, T, std::exception_ptr>*, or *std::expected<T, std::error_code>* in C++23 library
- We can just rethrow, delegating responsibility (what we like the most) to the caller

```
void unhandled_exception() {
    std::rethrow_exception(std::current_exception());
}
```

- The most relaxed one: completely ignore the exception (UB)

```
void unhandled_exception() {}
```

Suspending coroutines

**** co_await****

In case that we **wait on the result of asynchronous task**, i.e. having the pseudo-code like

```
auto result = co_await Awaitable<Task, Result>{};
```

our *Awaitable* type could look something like this

```
template <typename Task, typename Result =std::invoke_result_t<Task>>
struct Awaitable: std::suspend_always {
    using co_handle = promise_type::co_handle; // Awaitable as coroutine!

    /*
        We're passing at suspension point: co_await,
        the handle of the suspended coroutine - other, which
        waits on the result of the asynchronous task.

    */
    co_handle await_suspend(std::coroutine_handle<> other) {
        coro_.promise().continuation_ = other; // so that we can resume caller
         // Execute hosted task
         result_ = task_();

        return coro_; //so that we can be resumed implicitly
    }

    /*
       In this particular case, returning the co_handle of callee,
       the Awaitable will be resumed automatically (implicitly) by the compiler on exiting
       await_suspend(), since caller is waiting on (asynchronous) task result
```

```
     */
     Result&& await_resume() {

          return std::move(result_);
     }
};
```

This would mean that *Awaitable* interface can be part of the coroutine wrapper type itself, since *await_suspend*() returns a handle of the enclosing coroutine type, so that it can be implicitly resumed by the compiler.

The another possibility would be that *await_suspend*() returns **boolean flag**, as indication whether the suspended coroutine should be resumed explicitly ("*false*"): on its preserved handle, or implicitly ("*true*"): by the compiler - in which case the *await_resume*() will be executed immediately upon exiting the *await_suspend*().
In case that the caller - suspended coroutine is waiting on the result, the usual design decision would be to return "*true*", unless there are reasons not to.

In this example, Awaitable type is just an asynchronous task - a callable, that produces result on which caller - coroutine is synchronized: will be implicitly resumed.

<**Example1**>: https://godbolt.org/z/Yqcx8KG9c

Finally, if task doesn't produce the result, both *await_suspend()*, and later on *await_resume*() will return **void.**
In that case, the caller - the suspended coroutine, needs to be explicitly resumed

```
void CoResultType::resume() {
     if (not coro_.promise().continuation_.done()) {
          coro_.promise().continuation_.resume();
     }
}
```

Since coroutines guarantee the "happens before" relationship – unlike the threads for which we either need to use synchronization primitives, or for lock-free programming: memory barriers to prevent compiler of doing optimization, but also to ensure that all threads, synchronized on the same atomic variable, observe the same order of write/read operations
⇒ https://github.com/damirlj/modern_cpp_tutorials/blob/main/docs/Lock-free%20programming%2C%20part%201.pdf
we can

- write asynchronous code in a procedural – sequential way
- pass the local variable in the scope of coroutine by reference

This enables us to write "in-place" code like

```
auto doubleTask(int& value)
{

     struct Awaitable : std::suspend_always
     {
          explicit Awaitable(int& value) noexcept: val_(value) {}
          bool await_suspend(std::coroutine_handle<> )
          {
               val_ *= 2;

               return true;
          }
      private:
           int& val_;
     };

     return Awaitable{value};
}
```

There is another, concise way, overriding the *co_await* unary operator

```
auto doubleTask(int& value) {

     struct Awaitable
     {
          explicit Awaitable(int& value) noexcept: val_(value) {}

          std::suspend_always operator co_await()
          {
               val_ *= 2;
```

```
            return {}; // defaulted - parameterless c-tor of the return type
        }
      private:
          int& val_;
      };

      return Awaitable{value};
}
```

We can now write our small unit test

```
// coroutine
MyResultType myCoroutine(int& value) {
    ...
    co_await doubleTask(value);
}

// caller
int value = 10;
auto co  = myCoroutine(value);
co.resume();
assert(value == 20);
```

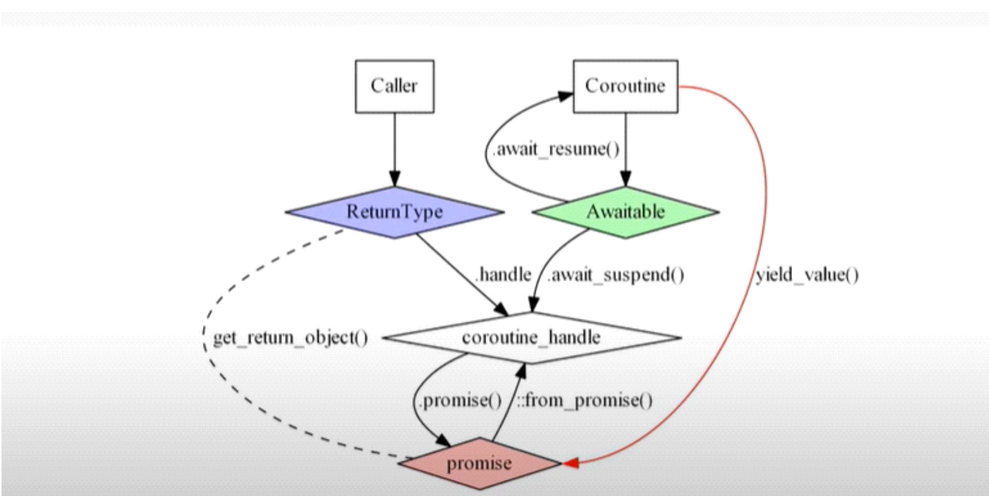
What if our coroutine needs to produce the value, in produce-consumer scenario?
**** co_yield****

In case that coroutine generates the value on which the caller is synchronized, there is a dedicated *co_yield* unary operator, which is shortcut for **co_await promise.yield_value(value)**
In other words, we need to ensure that *promise_type* has implemented yield_value() callback, which basically stores the value inside the promise_type and suspend itself

```
std::suspend_always yield_value(T&& value) noexcept(std::is_nothrow_move_constructible_v<T>){
   value_ = std::move(value);
   return{};// suspend itself
}
```

<Example2>: https://godbolt.org/z/qeKe75v71

At the end, this is a fine overview of the relationships and APIs that are involved around the coroutines, which I borrowed from Andreas Weis talk



Final thought

We do already have reactive libraries that implements the event-based asynchronous communication.
The coroutines can be useful alternative to that, in terms of better utilization on system resources and having structural, deterministic code that simplifies the design solutions.
When it comes to I/O asynchronous data transfer, coroutines can be particularly useful.
They allow you to write code that appears sequential and intuitive, mimicking synchronous operations,

while still benefiting from the asynchronous nature of I/O.
This can result in code that is easier to write, read, and maintain.
This also applies on the network: socket-based communications.
The state-machines are also one example of handling the events and state-machine transitions in efficient way.

Links

Official paper
https://timsong-cpp.github.io/cppwp/n4861/dcl.fct.def.coroutine

Andreas Weis - CppCon 2022
Deciphering C++ Coroutines - A Diagrammatic Coroutine Cheat Sheet - Andreas Weis - CppCon 2022

Andreas Fertig
(34) C++ Insights - Episode 36: Coroutine customization points - YouTube

Lewis Baker: Structured Concurrency
https://www.youtube.com/watch?v=1Wy5sq3s2rg

Pavel Novikov: examples
https://www.youtube.com/watch?v=7sKUAyWXNHA

Šimon Tóth
C++20 Coroutines — Complete* Guide | by Šimon Tóth | ITNEXT