C++20 Coroutines

What's next?

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Introduction

Agenda

Quick refresh about the coroutines.

Asynchronous RAII

RVO for the co_await

return_value or/and return_void

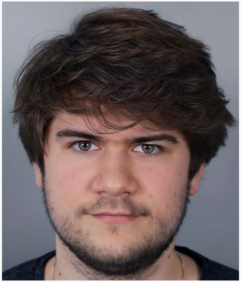
Questions...

Time is rather tight.
Please hold your questions till the end.

Who am I?

Dawid Pilarski

- Senior Software Developer in TomTom
- Member of the ISO/JTC1/SC22/WG21
- Member of the PKN KT (programming languages)
- C++ blog writer



Quick refresh about the coroutines.

What are the coroutines?

Subroutine Is a sequence of program instructions that perform a specific task, packaged as a unit.

Function Is a subroutine

Coroutine Is generalization of the function.

What are the coroutines?

Function can be:

- called
- returned from

What are the coroutines?

Coroutine can be:

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- returned from
- suspended

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Coroutine can be:

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Coroutine can be:

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- returned from
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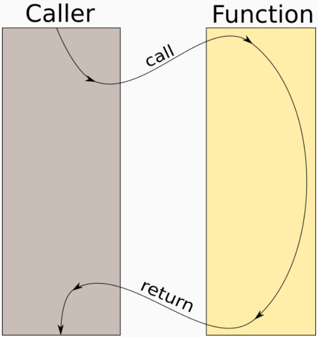
- destroyed

Coroutine flowchart

Function's flow:



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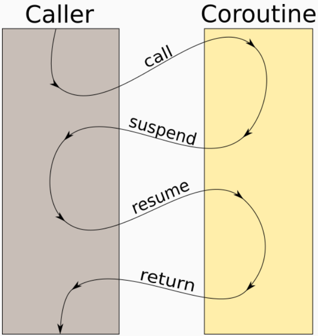

How to implement custom coroutine types.

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This means:

- Implementation of promise_type (~6 functions)
- Implementation of the co_await keyword (~3 functions)

You need to remember to implement on minimum 9 functions.

Coroutine declaration

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// returned-type   name       arguments
//|-------------| |-------| |---------------|
   generator<int> fibonacci (int from_value);
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- Compiler knows the function is a coroutine by presence of keywords `co_await`, `co_return`, `co_yield`
- If function is a coroutine it's return type must support coroutines.

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Type supports coroutines if it has promise_type.

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- member of the specialization of the coroutine_traits<returned_type>

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- `awaitable final_suspend();`
- `return_type get_return_object();`
- `void unhandled_exception();`

- suspension at the beginning
- suspension at the end
- how to create return_type
- handling unhandled exception

Keywords and promise_type

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- `co_return;`
- `co_yield V;`

- `p.return_value(V);`
- `p.return_void();`
- `co_await p.yield_value();`

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        - another `coroutine_handle`
    - `T await_resume()`

Resuming coroutine with coroutine_handle

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template<> struct coroutine_handle<void> {
  constexpr coroutine_handle() noexcept;
  constexpr coroutine_handle(nullptr_t) noexcept;
  coroutine_handle& operator=(nullptr_t) noexcept;

  constexpr void* address() const noexcept;
  constexpr static coroutine_handle from_address(void* addr);

  constexpr explicit operator bool() const noexcept;
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  void operator()() const; void resume() const;

  void destroy() const;
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And how do I get the coroutine_handle object?

`coroutine_handles` are specialized for `promise_type`

```
template<class Promise>
struct coroutine_handle : coroutine_handle<>
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  using coroutine_handle<>::coroutine_handle;
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Why is that useful?

We can:

- hide asynchronous code
- delegate state management to the compiler

Asynchronous RAII

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RAII - Resource Acquisition Is Initialization.

RAII vs. coroutines

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Possible leak when async_read throws

Consider following scenario:

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generator<std::string> lines(const path& file_path) {
  ifstream stream(file_path.string());
  std::string line;
  while(getline(stream, line)){
    co_yield line;
  }
  // stream closes file
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generator example usage

```
for(const auto& line : lines("myfile.txt")){
  if(starts_with(line, "string I am looking for"))
    break;
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generator example usage

```cpp
for(const auto& line : lines("myfile.txt")){
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- at the `break;` we are destroying coroutine
- not all lines from file might be consumed
- proper cleanup needs to be performed anyway on `coroutine_handle::destroy()`

No issue for the given synchronous coroutine

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on destroy

on loop finished

~ifstream()

asynchronous generators

```
async_generator<std::string> lines(const path& file_path) {
  auto opened_file = co_await async_open(file_path);
  std::optional<std::string> opt_line;
  while(opt_line = co_await
                   async_read_line(opened_file)){
    co_yield *opt_line;
  }

  co_await async_close(opened_file);
}
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                  async_read_line(opened_file)){
    co_yield *opt_line;
  }      on early destroy - no cleanup

  co_await async_close(opened_file);
}                                     on loop finished
                      cleanup
```

Current solution to the problem

```
async_generator<std::string> lines(const path& file_path) {
  auto opened_file = co_await async_open(file_path);
  std::optional<std::string> opt_line;
  while(opt_line = co_await
                   async_read_line(opened_file)){
    // remember to resume the coroutine before destroying
    auto cancellation_token = co_yield *opt_line;
    if(cancellation_token) break;
  }

  co_await async_close(opened_file);
}
```

Current solution to the problem

```cpp
async_generator<std::string> lines(const path& file_path) {
  auto opened_file = co_await async_open(file_path);
  std::optional<std::string> opt_line;
  while(opt_line = co_await
                   async_read_line(opened_file)){
    // remember to resume the coroutine before destroying
    auto cancellation_token = co_yield *opt_line;
    if(cancellation_token) break;
  }

  co_await async_close(opened_file);
}
```

Current solution to the problem

```
async_generator<std::string> lines(const path& file_path) {
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- `~operator co_await` gets co-awaited at the end of the scope
- instead of `destroy()` you will invoke `set_done()`

Example

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    - coroutine bodies
    - coroutine type, because we cannot simply destroy the coroutine
- In the space of asynchronous operations we have got no RAII idiom
- With adoption of the proposal it will get better

RVO for the co_await

What is RVO?

RVO - Return Value Optimization.

Allows to avoid unnecessary copy or move construction of the values returned from the function.

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RVO - Return Value Optimization.

Allows to avoid unnecessary copy or move construction of the values returned from the function.
For example:

```
std::vector<int> foo(){
  return {1,2,3,4,5};
}

// no copy or move construction
// invoked
auto _ = foo();
```

RVO on regular functions

regular function

```
std::vector<int> foo(){
  return {1,2,3,4,5};
}
```

transformed by compiler into:

```
void foo(std::vector<int>* ptr){
  new(ptr) std::vector<int>
           {1,2,3,4,5};
}
```

Why RVO is not possible with co_await

expression

```
co_await event;
```

transformed by compiler into:

```
{
  auto&& awaiter = transform(event);
  if(!awaiter.await_ready()){
    <coroutine suspend>
    awaiter.await_suspend();
    <coroutine resume>;
  }
  awaiter.await_resume();
}
```

Why RVO is not possible with co_await

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1. On await_suspend coroutine gets executed

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Why RVO is not possible with co_await

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```

How to resolve the issue [P1663R0]

1. Remove await_resume function.

```
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  auto&& awaiter = transform(event);
  if(!awaiter.await_ready()){
    <coroutine suspend>
    awaiter.await_suspend();
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  }
  awaiter.await_resume();
}
```

How to resolve the issue [P1663R0]

1. Remove await_resume function.
2. await_suspend will create return result

```
{
  auto&& awaiter = transform(event);
  if(!awaiter.await_ready()){
    <coroutine suspend>
    [redacted]
    <coroutine resume>;
  }
  awaiter.await_resume();
}
```

How to resolve the issue [P1663R0]

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2. await_suspend will create return result
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{
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Extensions to the coroutine_handle

Two additional functions in the coroutine_handle are needed.

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Two additional functions in the coroutine_handle are needed.

- set_value(T)
- set_value_from(std::in_place_construct<Arg&&...>)
- set_exception(exception_ptr)

On coroutine resumption the compiler will generate code to check whether the exception was saved with set_exception and will rethrow it when needed.

Example of the yield_value

```
template <typename T> class task<T>::promise_type{
// ....

  template <typename U> requires ConvertibleTo<U, T>
  void return_value(U&& value){
    handle.set_value<T>(std::forward<U>(value));
  }

  template <typename... Args>
            requires Constructible<T, Args...>
  void return_value(std::in_place_construct<Args&&...>
                    ctor_args){
    handle.set_value_from<T>(ctor_args);
  }

};
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                    ctor_args){
    handle.set_value_from<T>(ctor_args);
  }

};
```

How do compiler know the result of the co_await?

With removal of the await_resume the compiler no longer knows about the co_await returned type.

We will need to guide the compiler. The proposal P1663R0 proposes to add member await_result_type to the Awaiter.

RVO summary

pros	cons
• very simplified awaiter concept	

RVO summary

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• very simplified awaiter concept • savings in CPU cycles	

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- very simplified awaiter concept
- savings in CPU cycles
  - Avoiding unnecessary move construction
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  - no temporary variable created

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  - Avoiding unnecessary move construction
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  - no temporary variable created
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- removing await_ready makes co_await always suspend the coroutine (even if not needed)
- a need to support RVO manually (with the help of construct_in_place)
- proposed RVO does not consider synchronous coroutines - only co_await keyword.

return_value or/and return_void

return value [and|or] return void

right now it's not possible to implement both in the same scope.

- `return_value()`
- `return_void()`

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- `return_value()`
- `return_void()`

Why would we even need that?

Motivating example: implementation simplifications

```
task<int> foo(){
  co_return 42;
}

task<void> start(){
  std::cout << (co_await foo()) << std::endl;
  // implicit co_return;
}
```

Motivating example: implementation simplifications

```
task<int> foo(){
  co_return 42;←—— return_value(42);
}

task<void> start(){
  std::cout << (co_await foo()) << std::endl;
  // implicit co_return;
}
```

Motivating example: implementation simplifications

```
task<int> foo(){
  co_return 42;
}

task<void> start(){
  std::cout << (co_await foo()) << std::endl;
  // implicit co_return;
}
```

return_value(42);

return_void()

How implementors would like to implement it

```
template <typename T>
struct task<T>::promise_type{
  // ...
  void return_void()
    requires std::is_same<T, void>{}

  template <typename U>
  void return_value(U&& val)
    requires not std::is_same<T, void>{}
}
```

How implementors would like to implement it

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template <typename T>
struct task<T>::promise_type{
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}
```

But that's not the way it works.

How implementors have to implement it?

```
template <typename T>
struct task<T>::promise_type{
  //...
  template <typename T>
  void return_value(T&&){
    //...
  }
};
```

How implementors have to implement it?

```
template <typename T>
struct task<T>::promise_type{
  //...
  template <typename T>
  void return_value(T&&){
    //...
  }
};
```

```
template <>
struct task<void>::promise_type{
  //...
  void return_void(){
    //...
  }
};
```

What are tail recursive coroutines?

Tail recursive coroutines

What are tail recursive coroutines?

```
task<int> bar(){
  co_return 42;
}

task<int> foo(){
  co_return co_await bar();
}
```

What are tail recursive coroutines?

Find a difference in the pictures

```
task<int> bar(){
  co_return 42;
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task<int> foo(){
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Tail recursive coroutines

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```

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task<int> foo(){
  co_return bar();
}
```

tail call / no tail call

How does regular/tail call work?

First, how does regular call work?

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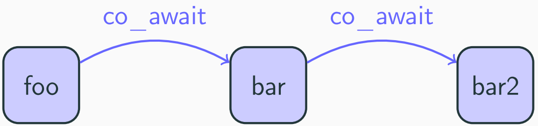

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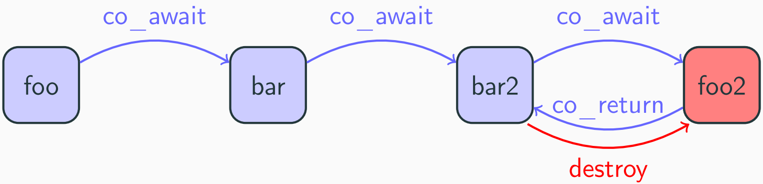

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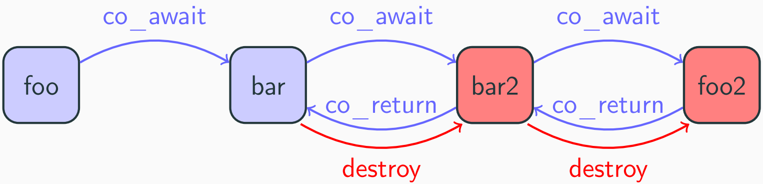

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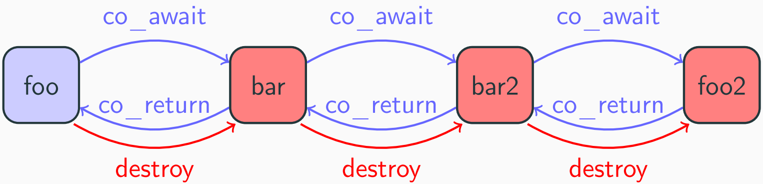

Conclusion:

- At peak 4 coroutine frames had to be allocated
- Only after returning to the caller coroutine, called one can be destroyed

How does non tail-call work?

In case of non tail-call we first destroy the coroutine and then call another one.

At most 2 frames were allocated.

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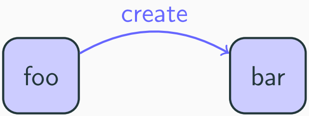

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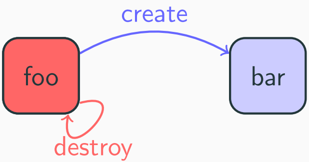

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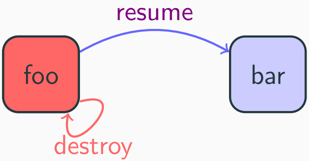

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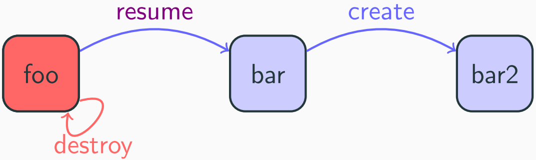

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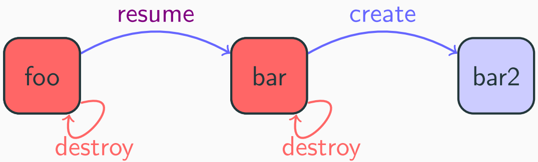

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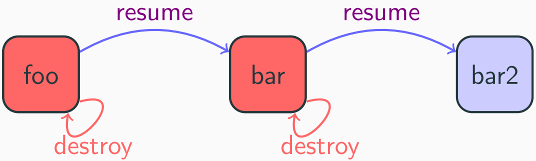

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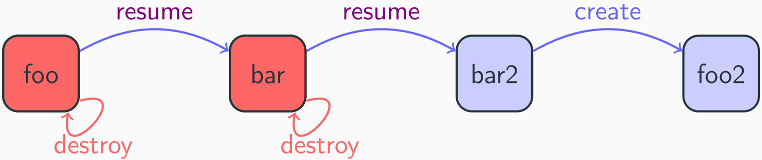

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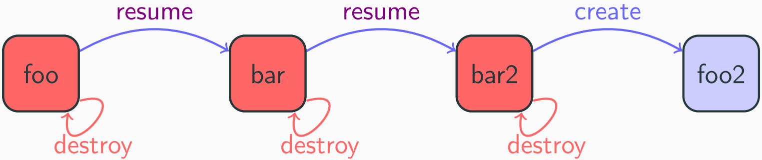

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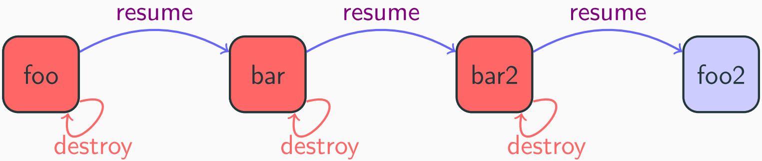

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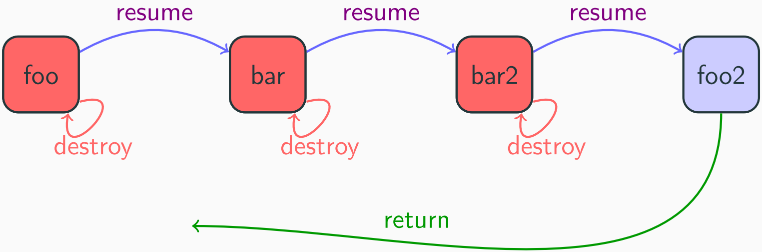

At most 2 frames were allocated.

Tail call is implementable.

But only for non-void returning types.

Why it's not implementable for task<void> types.

```
task<void> display_text(string text){
  // ...
  // implicit co_return;
}

task<void> display_file(path file){
  auto content = co_await read_file(file);
  co_return display_text(content);
}
```

Why it's not implementable for task<void> types.

```
task<void> display_text(string text){
  // ...
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}

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}
```

p.return_value(display_text(content))

Why it's not implementable for task<void> types.

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template <>
struct task<void>::promise_type{
  //...

  void return_void(){}




};
```

Why it's not implementable for task<void> types.

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struct task<void>::promise_type{
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  void return_value(task<void>&&){
    // ...
  }
};
```

Why it’s not implementable for task<void> types.

```
template <>
struct task<void>::promise_type{
  //...

  void return_void(){}

  void return_value(task<void>&&){
    // ...
  }
};
```

Both cannot apear in the same scope!

Summary

After accepting this change we will able to:

- simplify implementations of `promise_types` for some cases.

Summary

After accepting this change we will able to:

- simplify implementations of `promise_types` for some cases.
- make it possible for some type to support non tail coroutines calls

Thank you for your attention!

Special thank you! goes to:

- Gor Nishanov
- Lewiss Baker

for creating C++ coroutines

Summary

Bibliography and further reading

- Lewiss Baker's Assymetric transfer blog
- newest C++ draft
- My blog - blog.panicsoftware.com
- James McNellis - "Introduction to the C++ Coroutines"
- Gor Nishanov - any video about the coroutines
- Toby Allsopp - "Coroutines: what can't they do?"

Questions?

blog	blog.panicsoftware.com
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