Boost Your Program's Health

by Adding Fibers to your Coroutine

CppCon 2017

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Thanks

- Oliver Kowalke:
  Author of Boost Context, Boost Coroutines and Boost Fiber

- Nat Goodspeed:
  Contributor to the libraries and author of proposals to ISO/WG21 for fibers and coroutines and speaker.

Agenda

- Overview of coroutines
- Two implementations: Stackless and Stackful
- Generators
- Asynchronous APIs
- Threads and Fibers
- The Boost Fiber library
- Questions and Summary

More Information

- Presentation and samples at: https://github.com/david-sackstein/CppCon2017
- Boost Fiber documentation
- My email: davids@codeprecise.com

What are Coroutines?

- Coroutines are a generalization of subroutines.
- Coroutines can be suspended and resumed. The resume at the point of suspension with the same state.

Use Cases for Coroutines

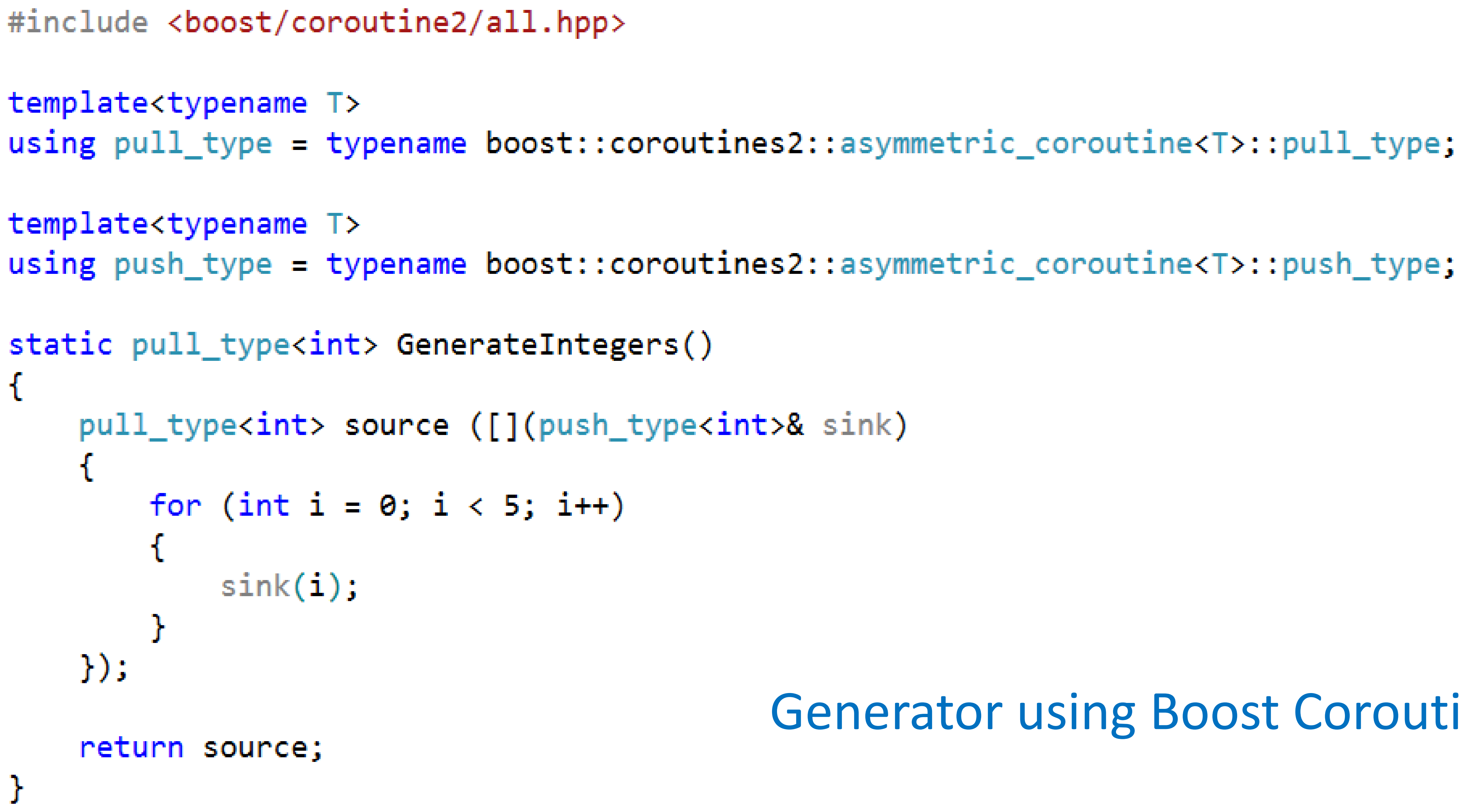
- Generators, Parsers, Pulling from Visitors
- Asynchronous APIs without callbacks
- Combinations of the above: Asynchronous generators
- What is common to all of the above?
  - Coroutines help us “Invert Control”
  - We allow the code that is called in a callback behave as if it were in control

Inversion of Control with Generators

- Both Producer and Consumer want to be in the driver's seat:
  - Producers want to call a function to transfer data
  - Consumers want to call a function to receive data
- With coroutines:
  - The Consumer pulls data. The Producer is the coroutine (inverted):
  - The producer suspends on entry
  - Then pushes data and suspends.
  - Then resumes only when the consumer pulls again.

Two Coroutine Implementations

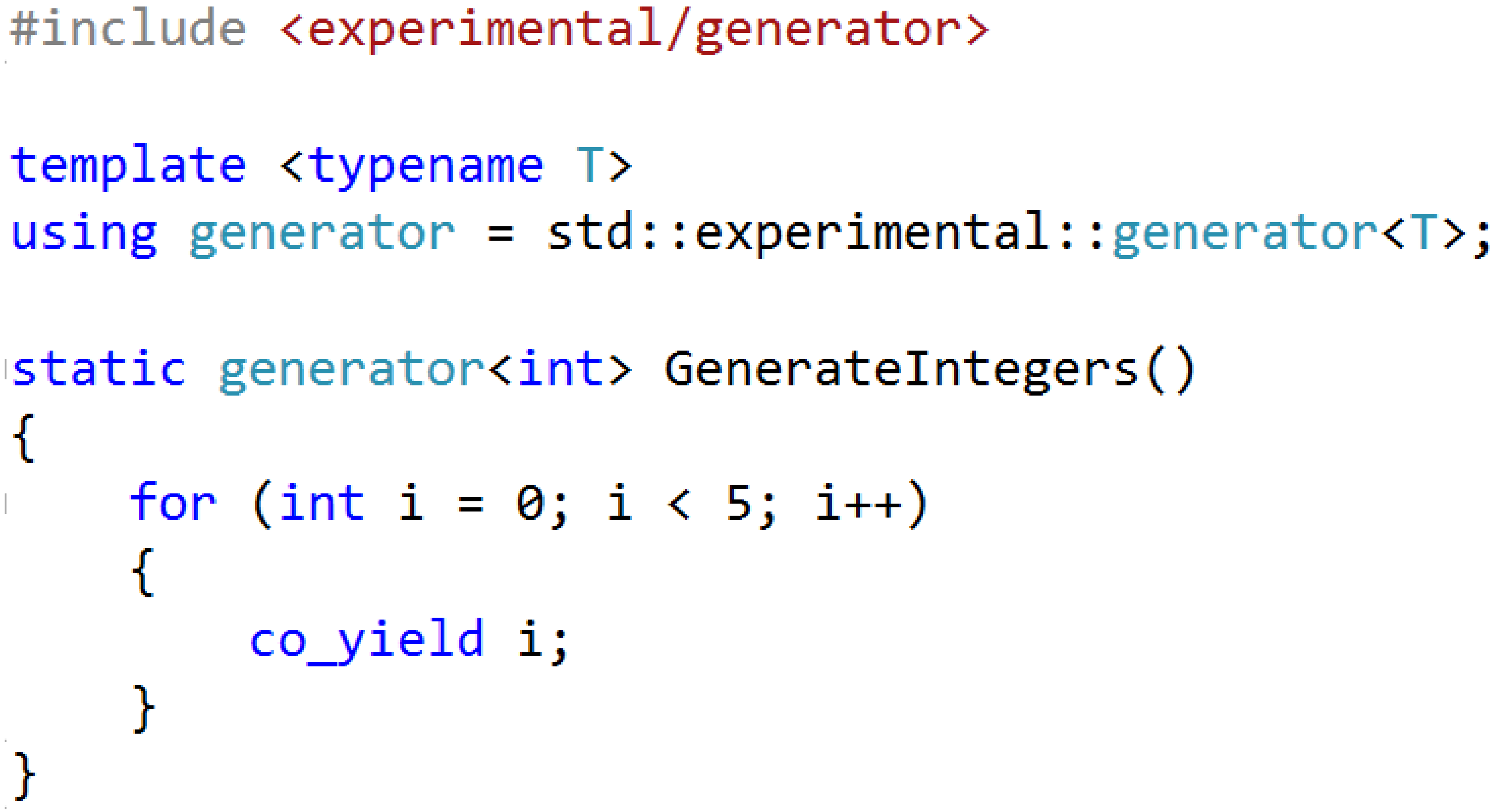
- Coroutines TS:
  - Stackless
  - Suspend by return
- Boost Coroutine2
  - Stackful
  - Suspend by call



```cpp
#include <boost/coroutine2/all.hpp>

template<typename T>
using pull_type = typename boost::coroutines2::asymmetric_coroutine<T>::pull_type;

template<typename T>
using push_type = typename boost::coroutines2::asymmetric_coroutine<T>::push_type;

static pull_type<int> GenerateIntegers()
{
    pull_type<int> source ([](push_type<int>& sink)
    {
        for (int i = 0; i < 5; i++)
        {
            sink(i);
        }
    });

    return source;
}
```

Generator using Boost Coroutine2

Generator using Coroutine TS

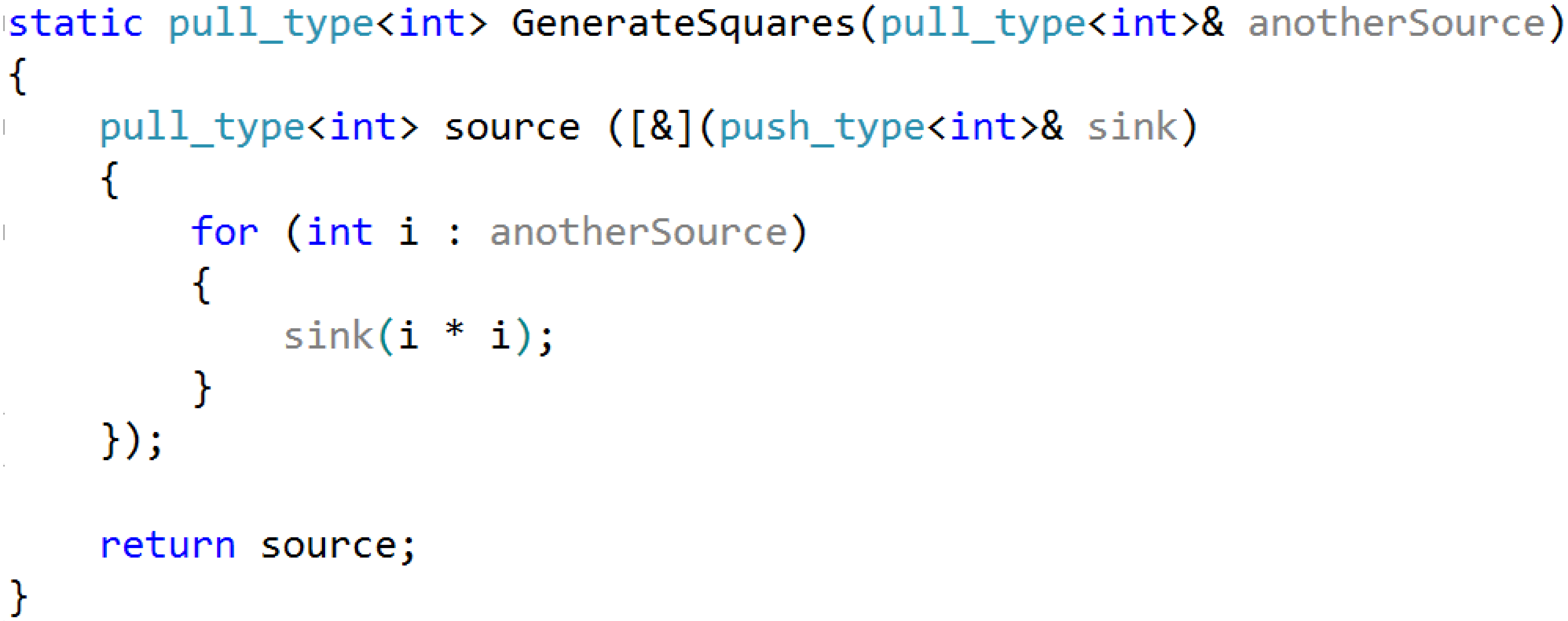


```
#include <experimental/generator>

template <typename T>
using generator = std::experimental::generator<T>;

static generator<int> GenerateIntegers()
{
    for (int i = 0; i < 5; i++)
    {
        co_yield i;
    }
}
```

First class objects?

- The generator is a first class object
  - Therefore generators can be chained together.
  - This is true for both coroutine implementations

Chained Generator using Boost Coroutine2



```
static pull_type<int> GenerateSquares(pull_type<int>& anotherSource)
{
    pull_type<int> source ([&](push_type<int>& sink)
    {
        for (int i : anotherSource)
        {
            sink(i * i);
        }
    });

    return source;
}
```

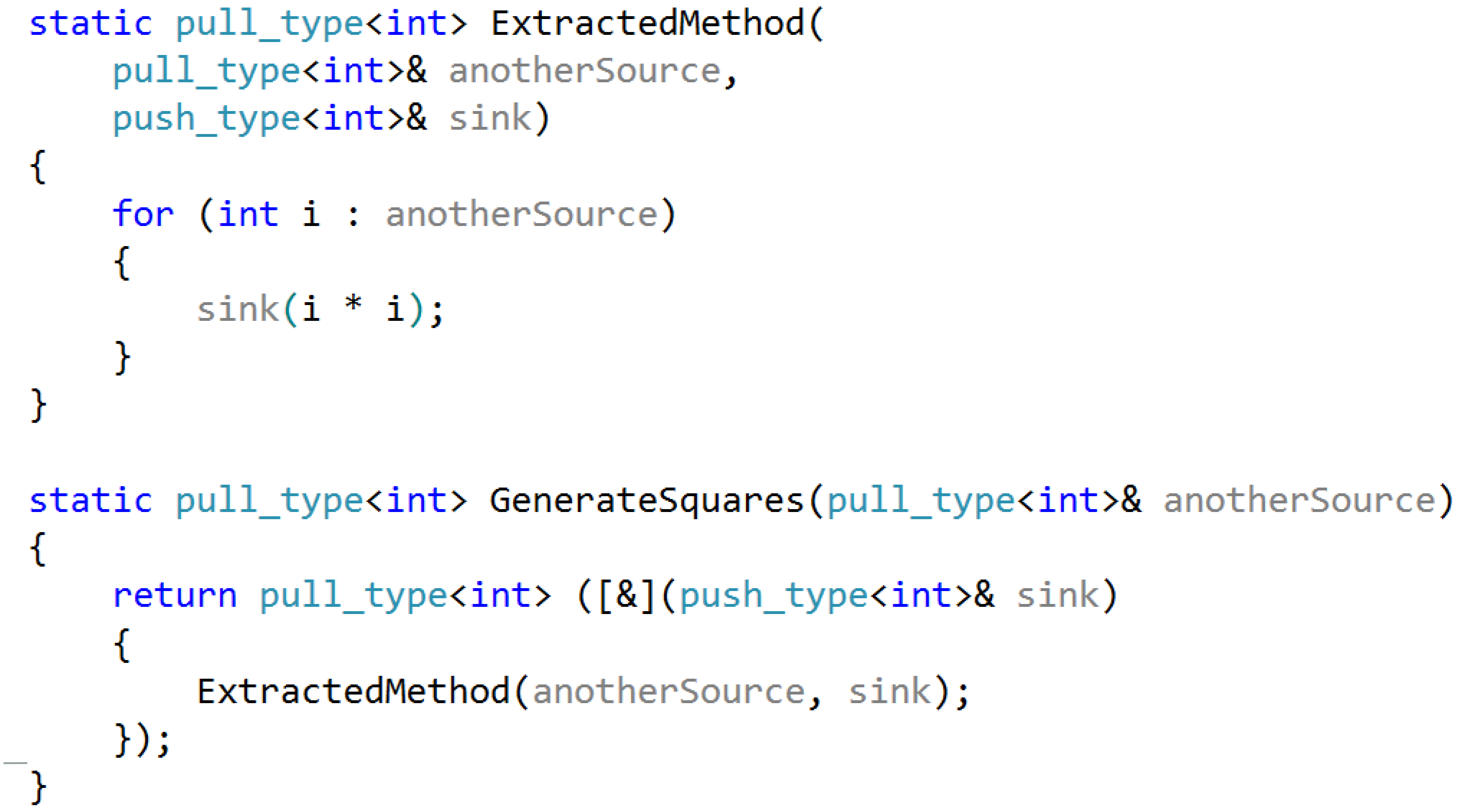
Chained Generator using Coroutines TS

```
static generator<int> GenerateSquares(generator<int>& anotherSource)
{
    for (int i : anotherSource)
    {
        co_yield i * i;
    }
}
```

First class objects?

- The generator is a first class object
  - Therefore generators can be chained together.
  - This is true for both coroutine implementations
- What about the push capability? Can that be passed around?
  - In Boost Coroutine2 the push_type can be passed around.
  - But in Coroutines TS we do not have access to a push object – the coroutine invokes a key word (co_yield) not an callable object.

Nested Generation with Boost Coroutine2



```
static pull_type<int> ExtractedMethod(
    pull_type<int>& anotherSource,
    push_type<int>& sink)
{
    for (int i : anotherSource)
    {
        sink(i * i);
    }
}

static pull_type<int> GenerateSquares(pull_type<int>& anotherSource)
{
    return pull_type<int> ([&](push_type<int>& sink)
    {
        ExtractedMethod(anotherSource, sink);
    });
}
```

Implications of Stacklessness

- Resumable functions require less memory on initial call and in some cases, the heap allocation can be elided and the code inlined
- However
  - Where generators are nested, nested iterations are required
  - As they suspend by return all functions that invoke a coroutine must be aware that the callee may suspend.

Implications of StackFullness

- Boost Coroutine2 coroutines needs to allocate a stack on the initial call. Still, stack allocation can be customized using the Boost Coroutine2 library.
- Because they suspend by call
  - Suspension is transparent to the caller.
  - This makes it easier to introduce coroutines to legacy code.
  - Nat Goodspeed demonstrates this in his C++Now 2016 talk: Pulling Visitors
  - Another example, a SAX puller

Asynchronous IO

- Not only IO – Any operation that takes time.
- Caller should not block the thread. If it does, an expensive context switch occurs.
- Instead we initiate the IO operation, install a callback and go and do something useful.
- When the operation completes the callback is invoked and we pick up where we were upon suspension.

Problems with callbacks

- Difficult to explain and to maintain
  - The business logic of the class is split up into disjoint functions.
  - State has to be stored and retrieved each time a callback is called.
- Error handling is difficult.
  - In particular exceptions cannot be used
- The problem requires inversion of control.
  - We would like the function and the callback to behave as they were in control.

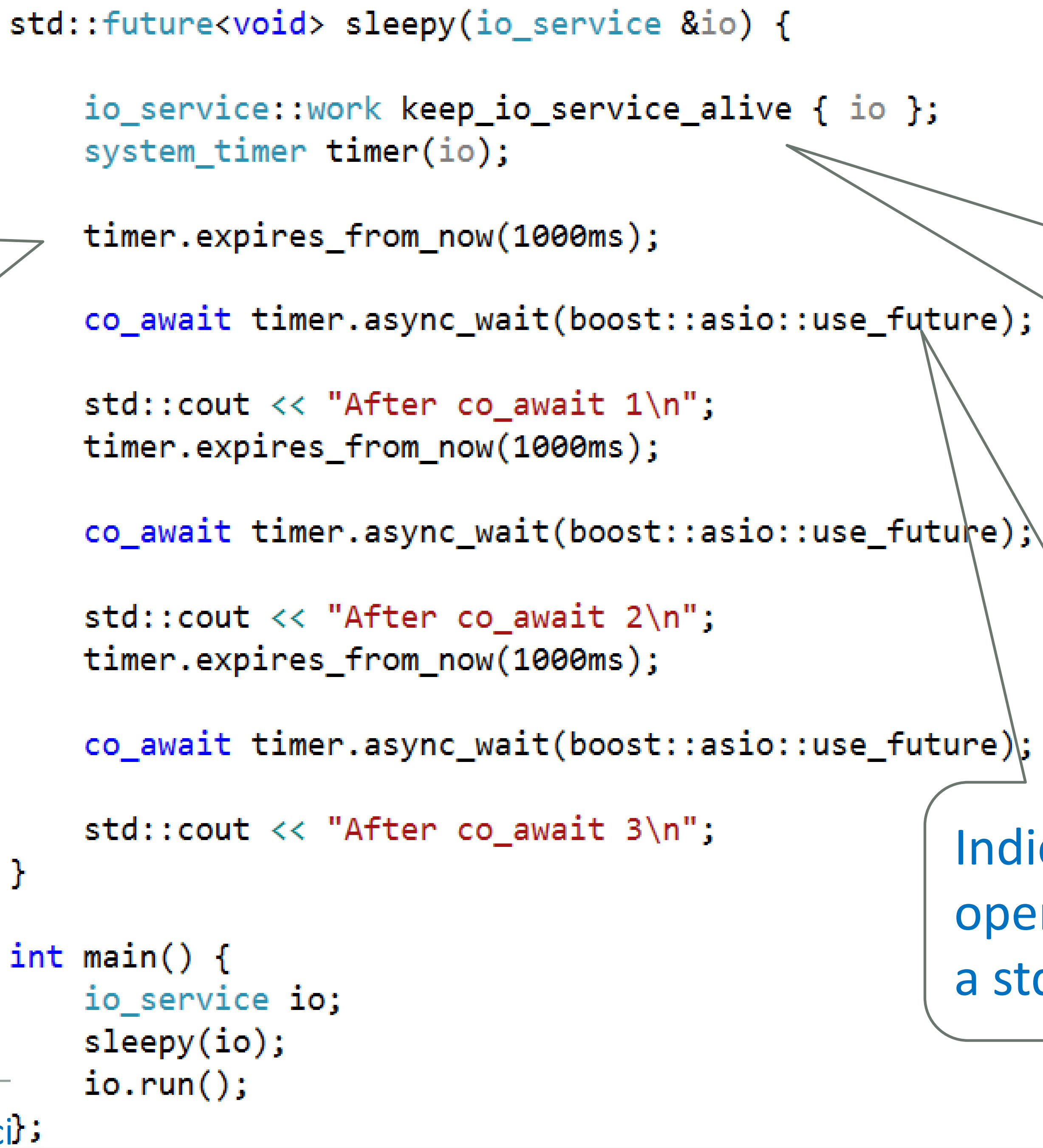
Boost Asio

- Provides a wrapper for synchronous and asynchronous use of sockets (and other OS facilities)
- io_service implements the Proactor Pattern for asynchronous IO.
- Christopher Kohlhoff, the author of the library, provides a generalized way to invoke asynchronous operations.
- Callable objects are only one method of completion. The compiler can deduce different return types from handler types for coroutines, futures and more.

Coroutines and Boost Asio

- The code shows how a boost asio system timer that is invoked asynchronously can be awaited upon.

Coroutine TS implemented coroutine_traits <future<void>, _ArgTypes...>



```
std::future<void> sleepy(io_service &io) {

    io_service::work keep_io_service_alive { io };
    system_timer timer(io);

    timer.expires_from_now(1000ms);

    co_await timer.async_wait(boost::asio::use_future);

    std::cout << "After co_await 1\n";
    timer.expires_from_now(1000ms);

    co_await timer.async_wait(boost::asio::use_future);

    std::cout << "After co_await 2\n";
    timer.expires_from_now(1000ms);

    co_await timer.async_wait(boost::asio::use_future);

    std::cout << "After co_await 3\n";
}

int main() {
    io_service io;
    sleepy(io);
    io.run();
};
```

Keeps io_service busy so it exits only after coroutine ends

Indicates to asio that the operation should return a std::future object.

From Threads to Coroutines To Fibers

- The Echo Server Project
- Four Parts
  - A. AsioSyncThreads
  - B. AsioAsyncCallbacks
  - C. AsioAsyncCoroutines
  - D. AsioAsyncFibers

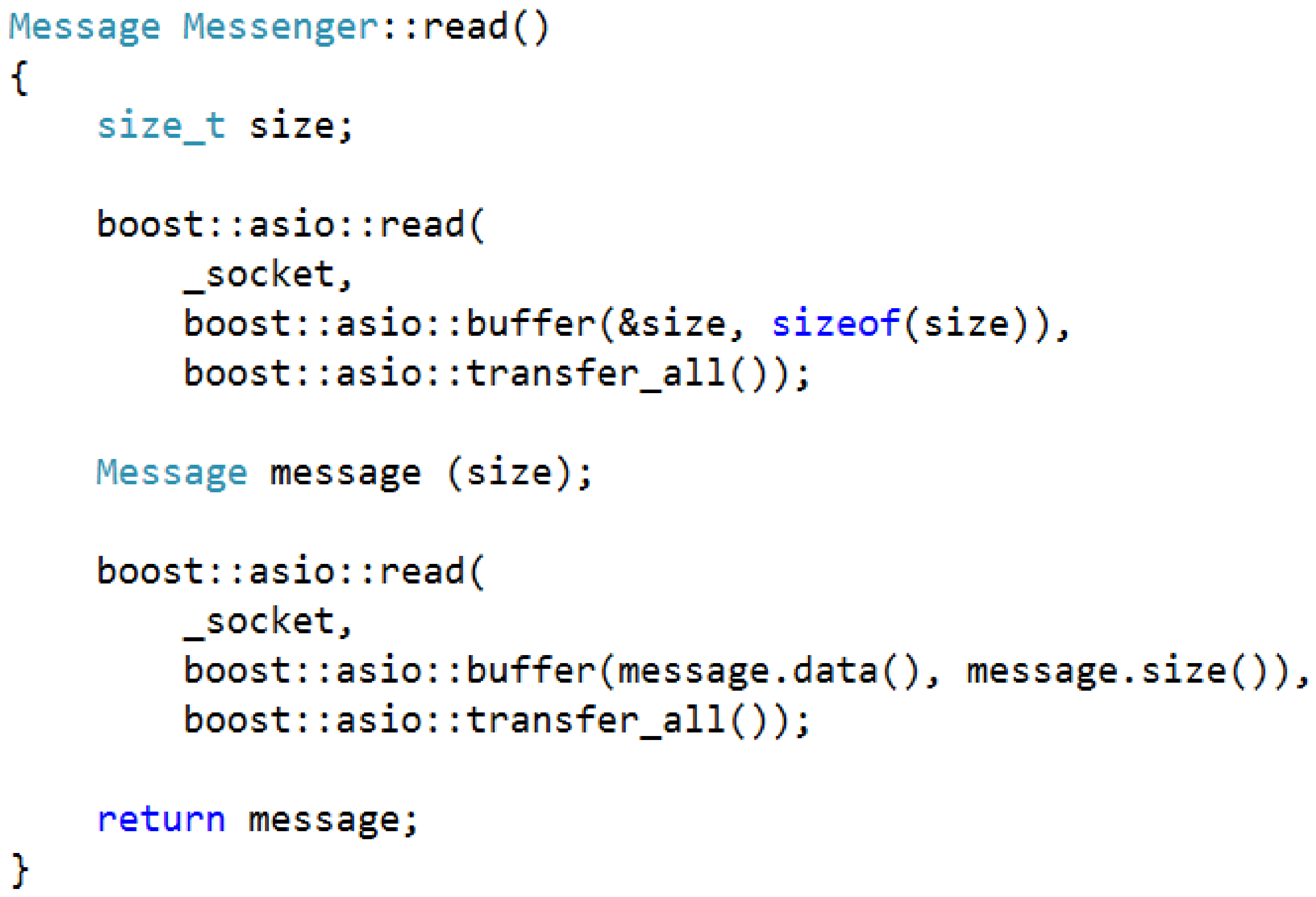
The Echo Server Project

- Implemented an EchoServer and a few EchoClients
- Clients send a message, Server responds with the same message, Clients send the message they received and so on.
- A Message is defined as a header indicating size and data of the specified size.
- Writing a Message requires to writes and reading a message requires two reads.
- We will zoom in on the Messenger object which reads and writes messages.

A. AsioSyncThreads

- Blocking IO on a thread per connection

Reading a message synchronously



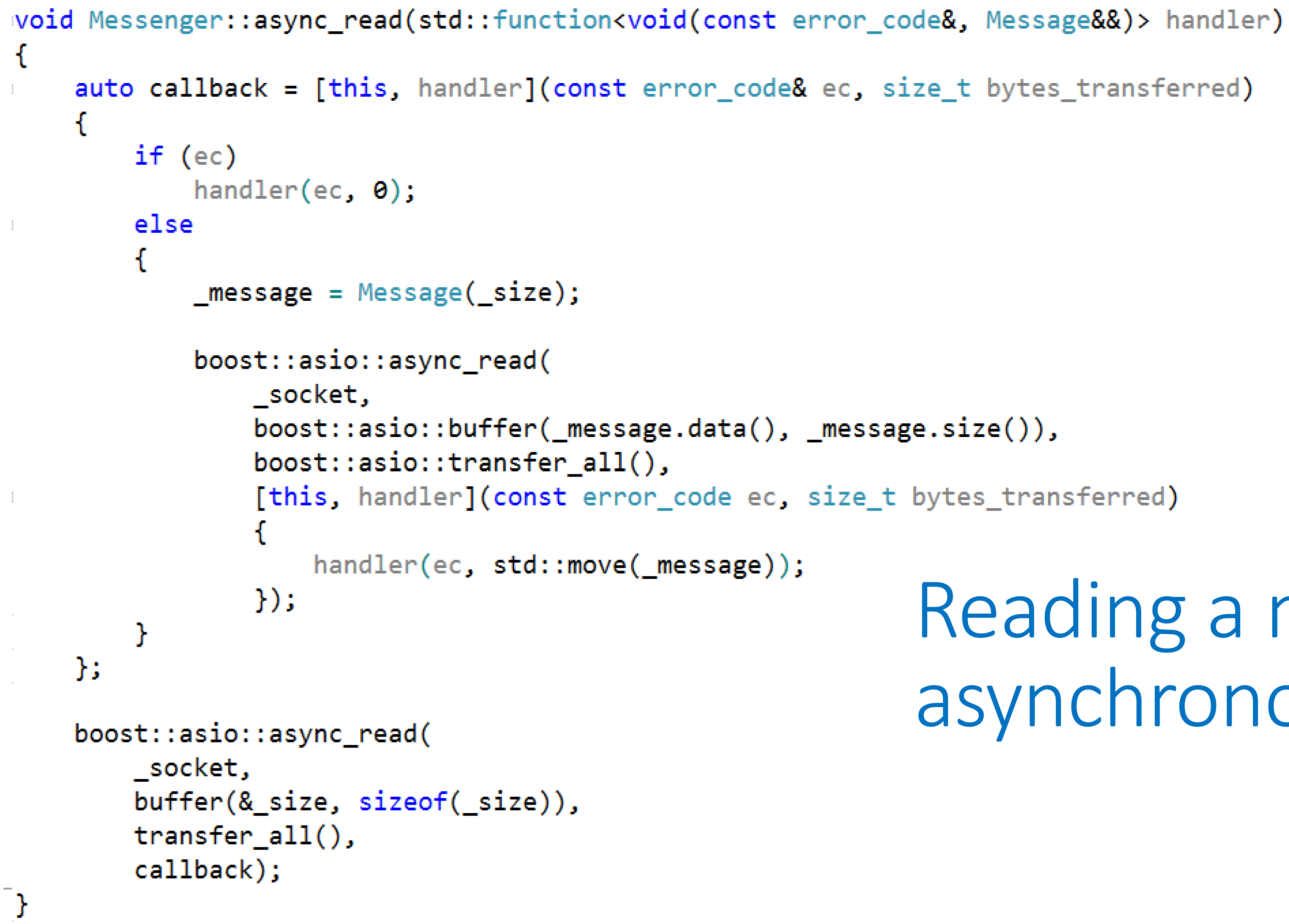
```
Message Messenger::read()
{
    size_t size;

    boost::asio::read(
        _socket,
        boost::asio::buffer(&size, sizeof(size)),
        boost::asio::transfer_all());

    Message message (size);

    boost::asio::read(
        _socket,
        boost::asio::buffer(message.data(), message.size()),
        boost::asio::transfer_all());

    return message;
}
```

A. AsioSyncThreads

- Blocking IO on a thread per connection
- The Good:
  - Main thread listening for connections remains responsive
- The Bad
  - Threads are expensive. Will not scale to thousands.
  - Context switching takes time and will dominate the server for large scales.

B. AsioAsyncCallbacks

- Asynchronous IO using Boost Asio serviced by three threads (arbitrary number). The completion handlers are callback lambdas.



```
void Messenger::async_read(std::function<void(const error_code&, Message&&)> handler)
{
    auto callback = [this, handler](const error_code& ec, size_t bytes_transferred)
    {
        if (ec)
            handler(ec, 0);
        else
        {
            _message = Message(_size);

            boost::asio::async_read(
                _socket,
                boost::asio::buffer(_message.data(), _message.size()),
                boost::asio::transfer_all(),
                [this, handler](const error_code ec, size_t bytes_transferred)
                {
                    handler(ec, std::move(_message));
                });
        }
    };

    boost::asio::async_read(
        _socket,
        buffer(&_size, sizeof(_size)),
        transfer_all(),
        callback);
}
```

Reading a message asynchronously

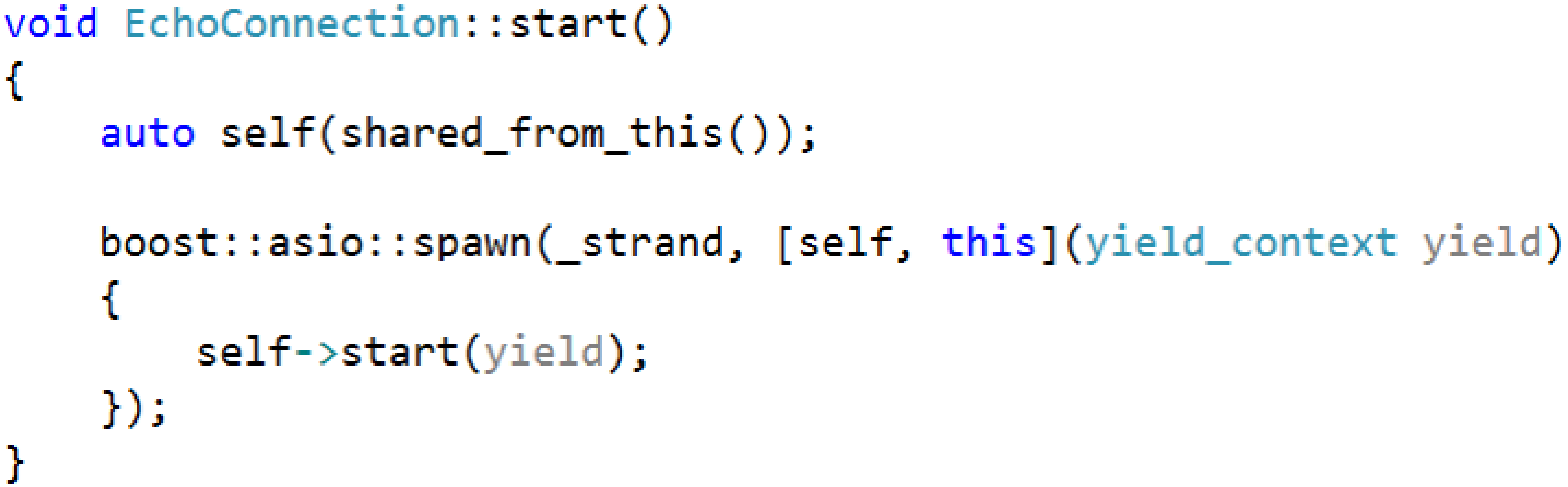
B. AsioAsyncCallbacks

- Asynchronous IO using Boost Asio serviced by three threads (arbitrary number). The completion handlers are callback lambdas.
- The Good
  - Main thread listening for connections remains responsive
  - Scales well. The number of threads does not depend on the number of connections.
- The Bad
  - Call back code is difficult to debug. Error handling is difficult

C. AsioAsyncCoroutines

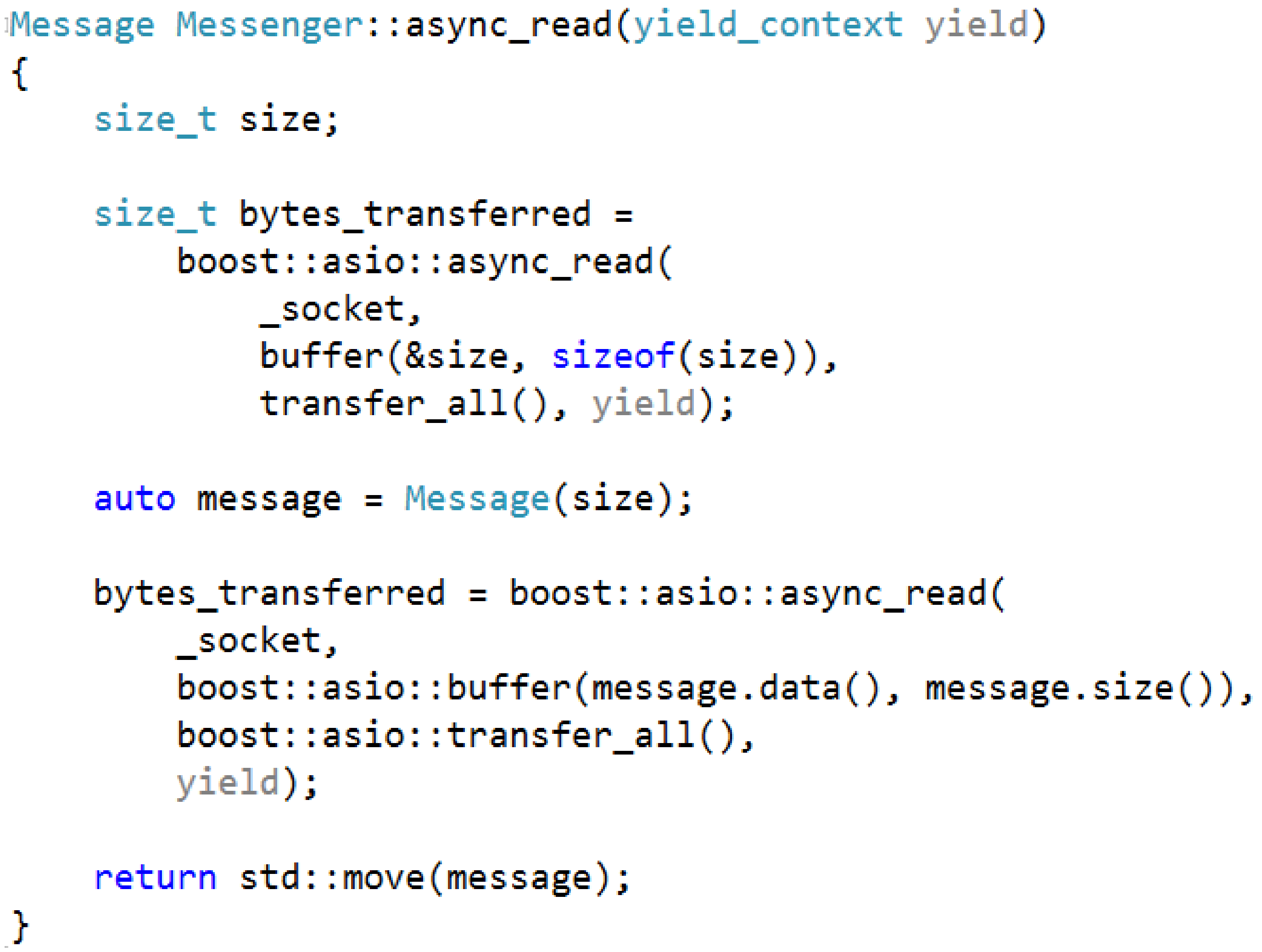
- Like B only asynchronous IO has been made to look like synchronous IO due to the use of coroutines.

Asynchronously with Coroutine



```
void EchoConnection::start()
{
    auto self(shared_from_this());

    boost::asio::spawn(_strand, [self, this](yield_context yield)
    {
        self->start(yield);
    });
}
```

Asynchronously with Coroutine



```
Message Messenger::async_read(yield_context yield)
{
    size_t size;

    size_t bytes_transferred =
        boost::asio::async_read(
            _socket,
            buffer(&size, sizeof(size)),
            transfer_all(), yield);

    auto message = Message(size);

    bytes_transferred = boost::asio::async_read(
        _socket,
        boost::asio::buffer(message.data(), message.size()),
        boost::asio::transfer_all(),
        yield);

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

C. AsioAsyncCoroutines

- Like B only asynchronous IO has been made to look like synchronous IO due to the use of coroutines.
- The Good
  - Main thread listening for connections remains responsive
  - Scales well. The number of threads does not depend on the number of connections.
  - The code is now organized like synchronous code.

Introducing the Boost Fiber Library

ARBONNE essentials DAILY FIBER BOOST
FIBER BOOST
BOOST Your HEALTH And TRIM Your WAISTLINE With FIBER
Flipping50 FIBER BOOST
DIGESTIVE HEALTH BOOST
91% felt more full/satiated for an average of 2.9 hours
88% felt it helped improve their regularity
83% felt or looked less bloated
Boost Your Shakeology® Introducing The Fiber.
DAILY FIBER BOOST
Kid Essentials
1.5 FIBER
VANILLA
Shakeology Digestive Health Boost ShakeItUpFitness.com
A quick and easy way to help support regularity and digestive health.
ARBONNE
FIBER BOOST
9 Whole Food FIBER SOURCES That Can BOOST Your HEALTH
Vale DETOX DRINK ENHANCER FIBER Boost
ThinkitDrinkit Fiber Boost
Meta HEALTH BAR
FIBER!
Increase your fiber intake Health tips
BOOST Benefiber

Boost Fiber Library Architecture

- A fiber is a userland thread - a thread of execution that is scheduled cooperatively.
- The library is organized as coroutines plus a manager plus a scheduler.
- Each fiber has its own stack.
- Like Boost Coroutine the library uses Boost Context to allocate and switch between stacks.
- You can choose the stack allocation strategy. The default is fixed size. The size itself is configurable.

Fiber vs Thread

- At most one fiber on a thread can be running
- Therefore a fiber does not need to protect resources from other fibers running on the same thread.
- However, if a fiber on another thread access the resource – protection is required.
- Spawning fibers does not distribute your computation across more hardware cores.
- But fibers do help you manage the division between working and waiting on a thread.

Manager

- A fiber can be in the running, suspended or ready state.
- The running fiber can call the manager to yield or suspend itself.
  - When a fiber yields it moves to the ready state
  - When a fiber suspends it moves to a suspended state.
- In both cases the manager uses a scheduling algorithm to select another ready fiber to run.
- The manager performs a context switch to the selected fiber.
- If there were no ready fibers, the manager blocks the thread.
- Context switching is direct, the manager runs on the source fiber.

Scheduler Algorithm

- There is one scheduler algorithm for all fibers in a thread
- The scheduler’s responsibility is to pick one of the ready fibers that should to run.
- The default is a round robin scheduler among the ready fibers on the thread.
- So, by default a fiber will always be resumed on the thread where it was created.
- A blocked fiber can however be awoken by another thread

Scheduler Algorithm

- The scheduling algorithm is an extension point. You can also implement and install your own.
- You can also install others provided by the library for instance:
  - shared_work: ready fibers from all threads are treated equally
  - work_stealing: local ready fibers are selected if any, otherwise a fiber is stolen from another scheduler
- Note that these algorithms migrate fibers between threads which requires care in protecting shared resources

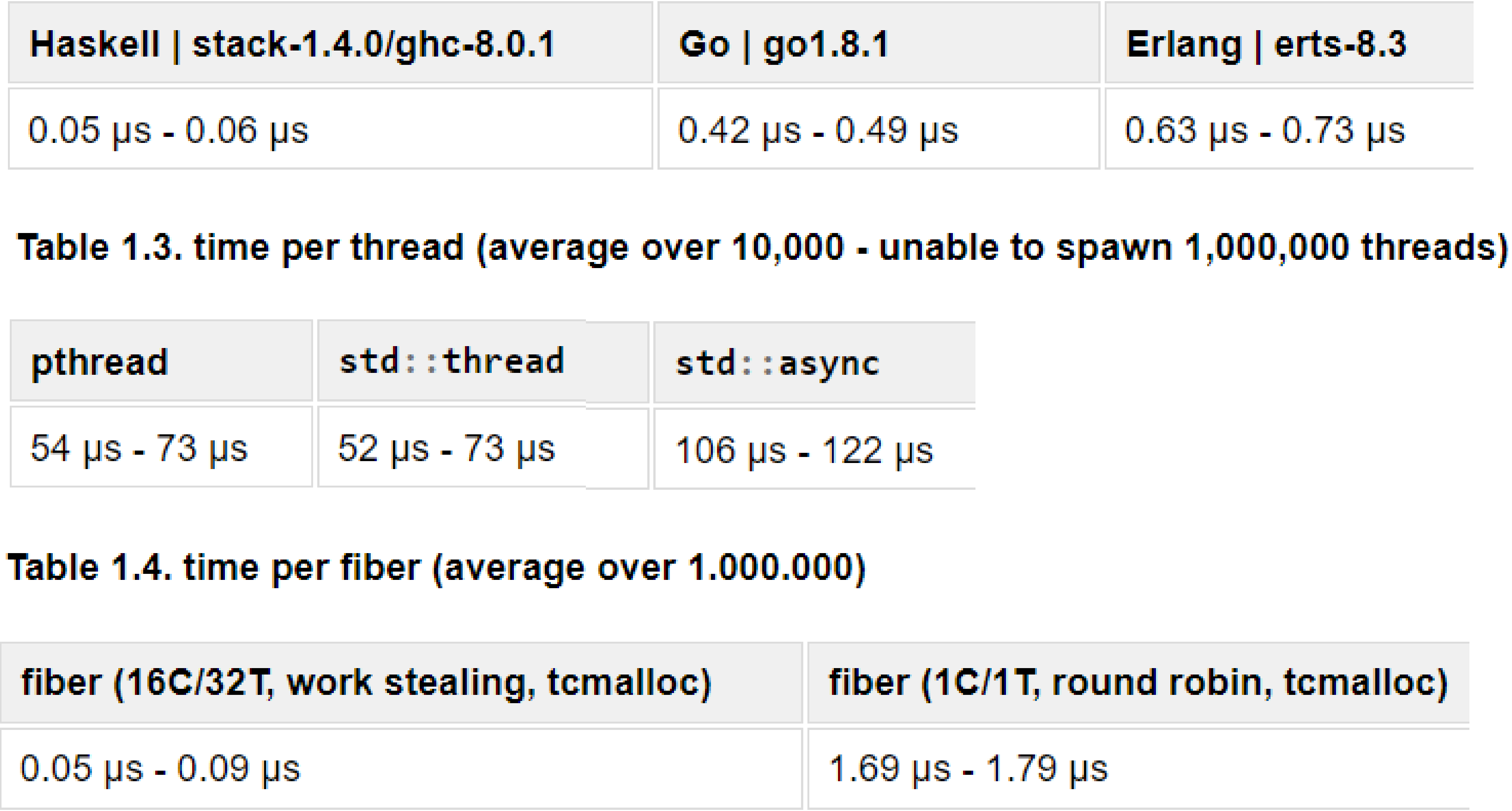
Fiber Suspension

- A fiber can yield itself or it can suspend itself (a.k.a. block) in a number of ways:
  - It can request to sleep (until a time or for a specified duration)
  - Use fiber synchronization objects that are defined in the library.
- The semantics of the synchronization objects are are similar to those in the std::thread library, however:
- The fiber types suspend only the current fiber. They do not block the thread (unless there are no other fibers to run)

Synchronization Object

Type	Comment
boost::fibers::mutex	Can be used with std::unique_lock
boost::fibers::condition_variable	No spurious wake ups
boost::fibers::barrier	Reusable fiber rendez-vous object
boost::fibers::future<T>, boost::fibers::promise<T> boost::fibers::packaged_task<T>	
boost::fibers::buffered_channel<T> boost::fibers::unbuffered_channel<T>	Like a future-promise of a sequence of values

Context switching is fast*



Haskell | stack-1.4.0/ghc-8.0.1	Go | go1.8.1	Erlang | erts-8.3
0.05 µs - 0.06 µs	0.42 µs - 0.49 µs	0.63 µs - 0.73 µs

Table 1.3. time per thread (average over 10,000 - unable to spawn 1,000,000 threads)

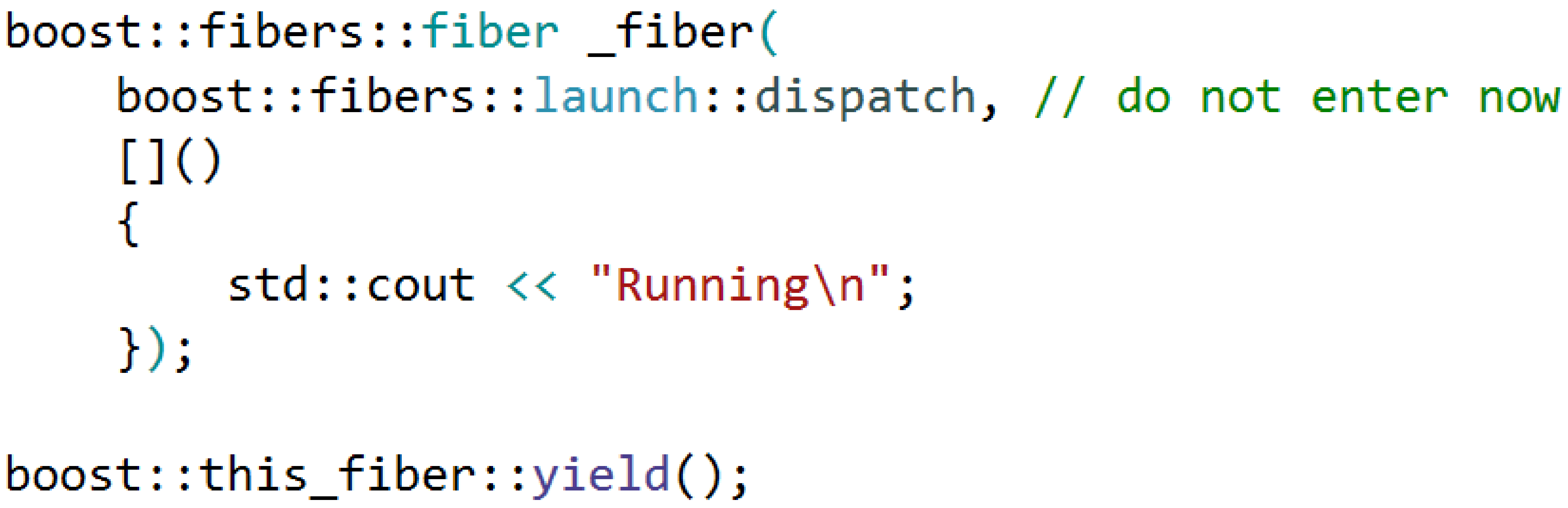
pthread	`std::thread`	`std::async`
54 µs - 73 µs	52 µs - 73 µs	106 µs - 122 µs

Table 1.4. time per fiber (average over 1.000.000)

fiber (16C/32T, work stealing, tcmalloc)	fiber (1C/1T, round robin, tcmalloc)
0.05 µs - 0.09 µs	1.69 µs - 1.79 µs

* Boost Fiber Documentation

Launch a fiber

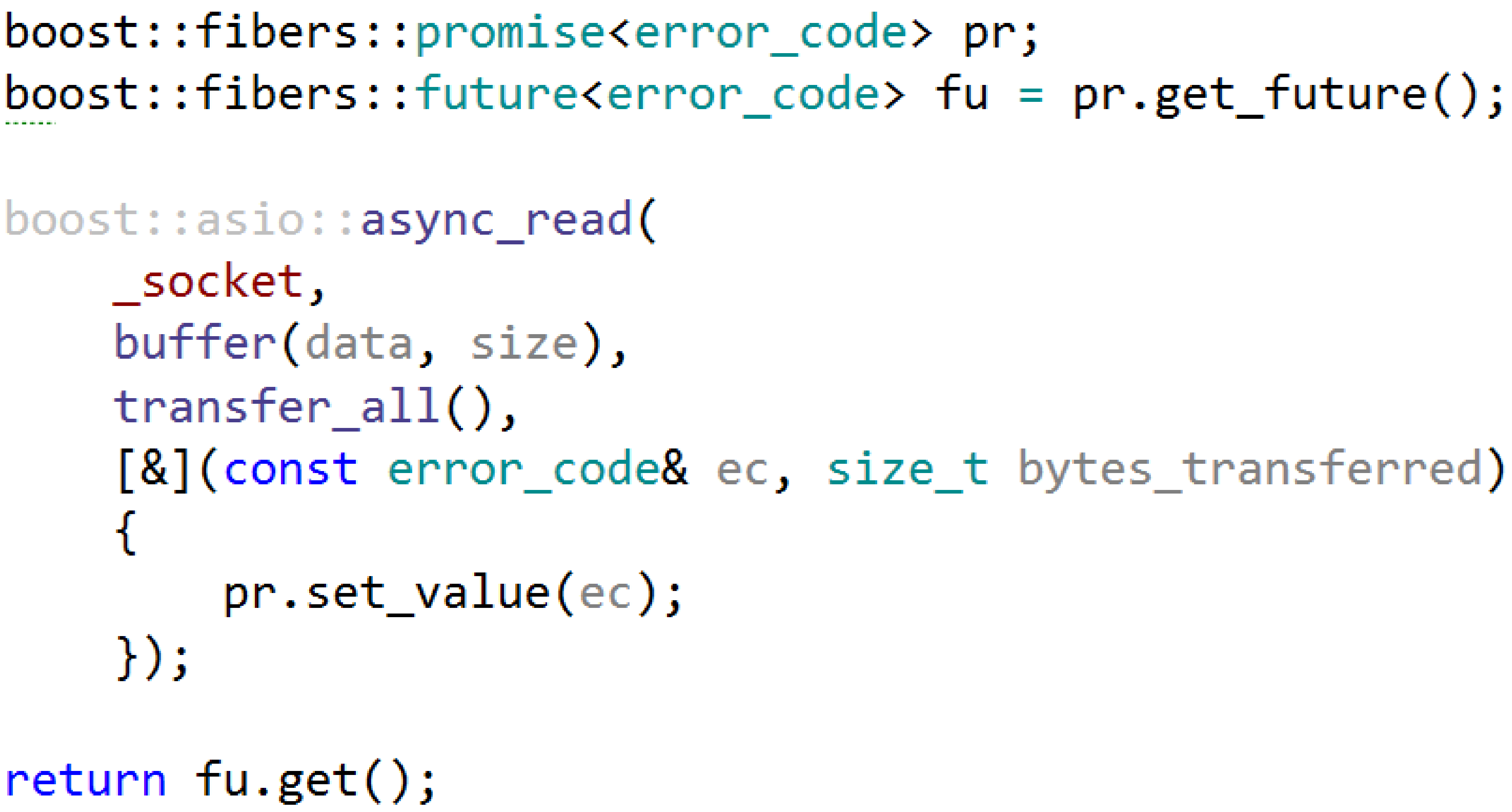


```
boost::fibers::fiber _fiber(
    boost::fibers::launch::dispatch, // do not enter now
    []()
    {
        std::cout << "Running\n";
    });

boost::this_fiber::yield();
```

Using an unbuffered_channel

```
char WaitForChar()
{
    boost::fibers::unbuffered_channel<char> channel;

    std::thread canceller([&] {
        char c = getchar();
        channel.push(c);
    });

    canceller.detach();

    char c;
    channel.pop(c);
    return c;
}
```

Using a future and a promise

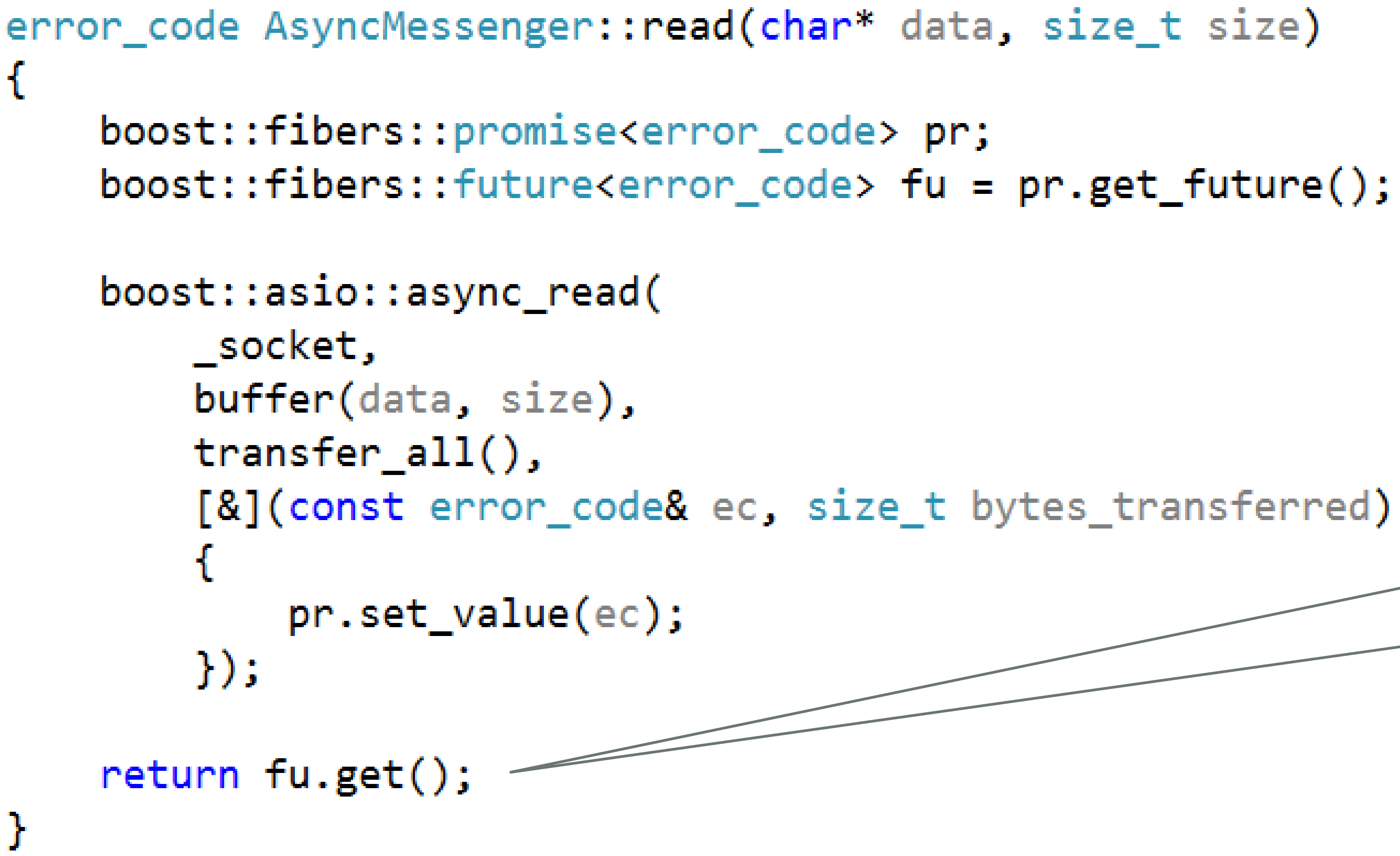


```
boost::fibers::promise<error_code> pr;
boost::fibers::future<error_code> fu = pr.get_future();

boost::asio::async_read(
    _socket,
    buffer(data, size),
    transfer_all(),
    [&](const error_code& ec, size_t bytes_transferred)
    {
        pr.set_value(ec);
    });

return fu.get();
```

D. AsioAsyncFibers

- AsioAsyncFibers
  Like A only fibers are used instead of threads and asynchronous IO is used in combination with boost::fibers::future

Asynchronously with Fiber



```
error_code AsyncMessenger::read(char* data, size_t size)
{
    boost::fibers::promise<error_code> pr;
    boost::fibers::future<error_code> fu = pr.get_future();

    boost::asio::async_read(
        _socket,
        buffer(data, size),
        transfer_all(),
        [&](const error_code& ec, size_t bytes_transferred)
        {
            pr.set_value(ec);
        });

    return fu.get();
}
```

Blocks the current fiber only

D. AsioAsyncFibers

- AsioAsyncFibers
  Like A only fibers are used instead of threads and asynchronous IO is used in combination with boost::fibers::future
- The Good
  - All of the advantages of A-B
- The Bad
  - Need to introduce grouping of connections on multiple threads.

Questions

Summary

- We have two implementations of coroutines
  - Stackless (in standardization process) and Stackful (Boost)
- Coroutines enable inversion of control
  - Generators
  - Asynchronous operations
- Threads should be used for parallel computation (or for a small number of background tasks)
- Fibers help organize the execution of asynchronous IO on a thread.