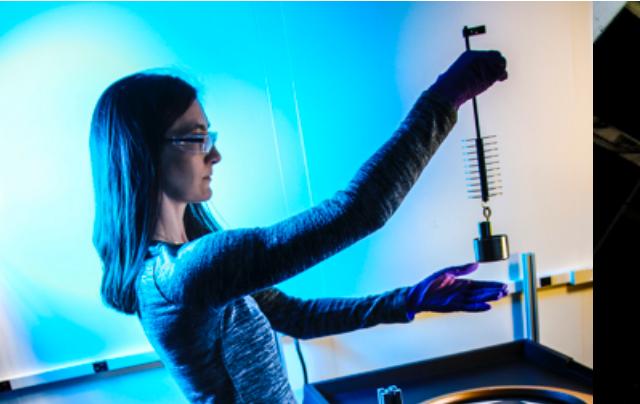


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A Universal Abstraction for Async

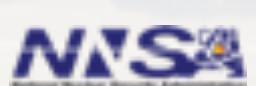


PRESENTED BY

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Goals for Async Interfaces

C++ needs an async abstraction:

- That is composable
- That has low abstraction overhead
- That works with coroutines, fibers, and threads, etc.
- That is extensible to multiple execution environments
(both concurrent and parallel)

Disclaimer

This talk doesn't represent the official views of WG21. It is merely sketching the ideas behind some recent proposals.

Disclaimer 2

This talk makes use of C-style casts.

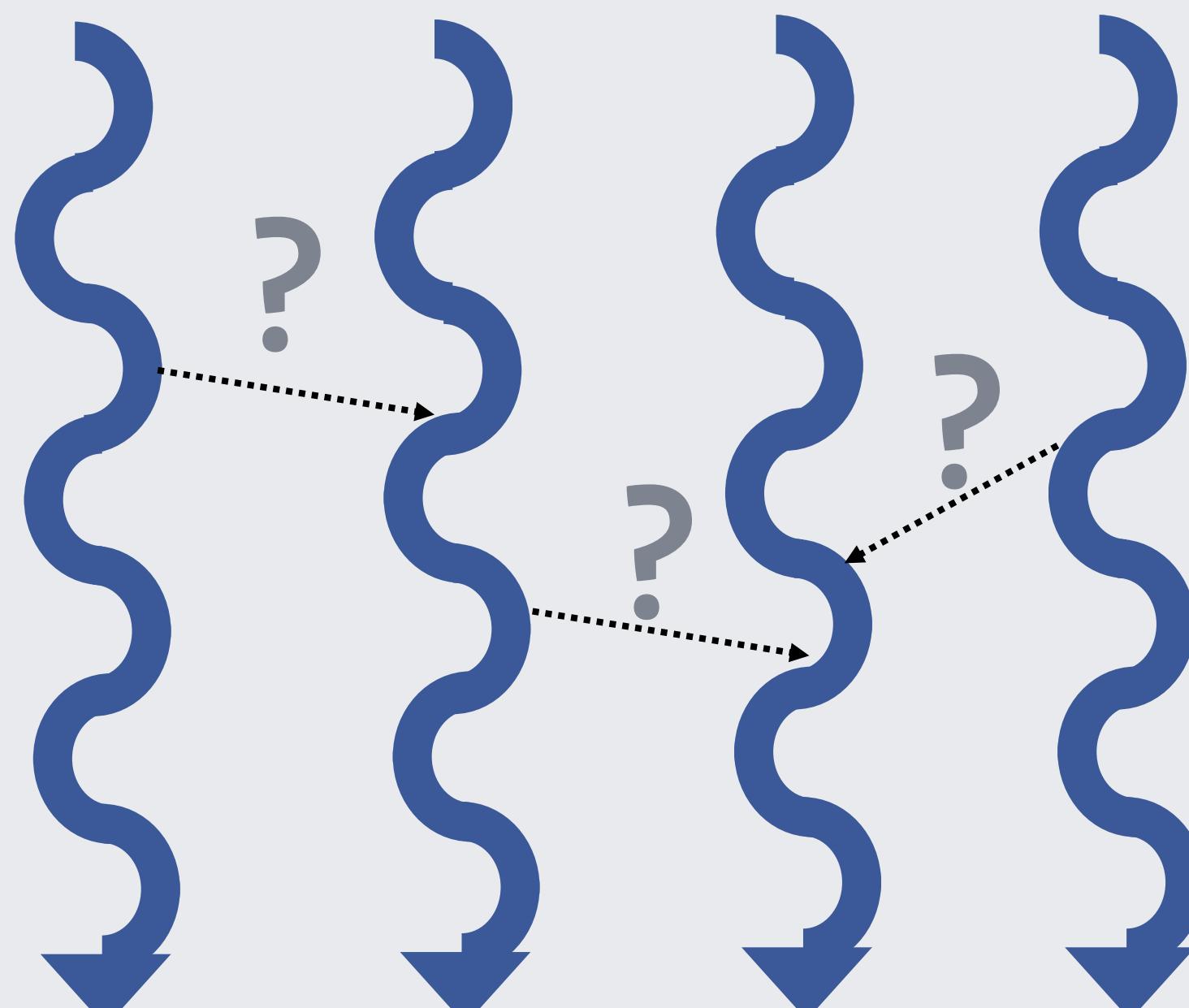
Viewer discretion is advised.

I. Background and Introduction

Understanding Parallelism vs. Concurrency

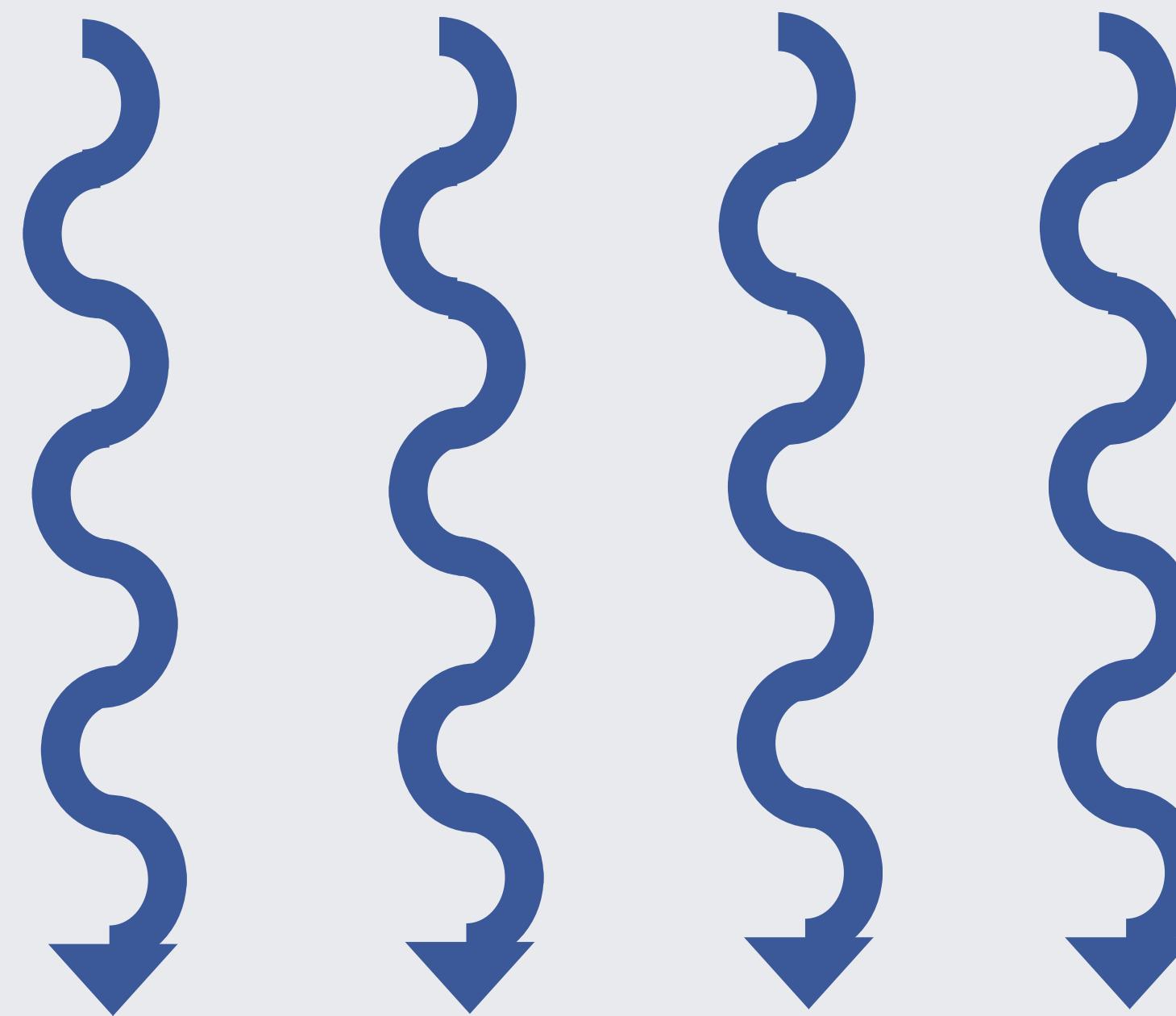
Spoiler alert: They're not the same thing.

Concurrency vs. Parallelism



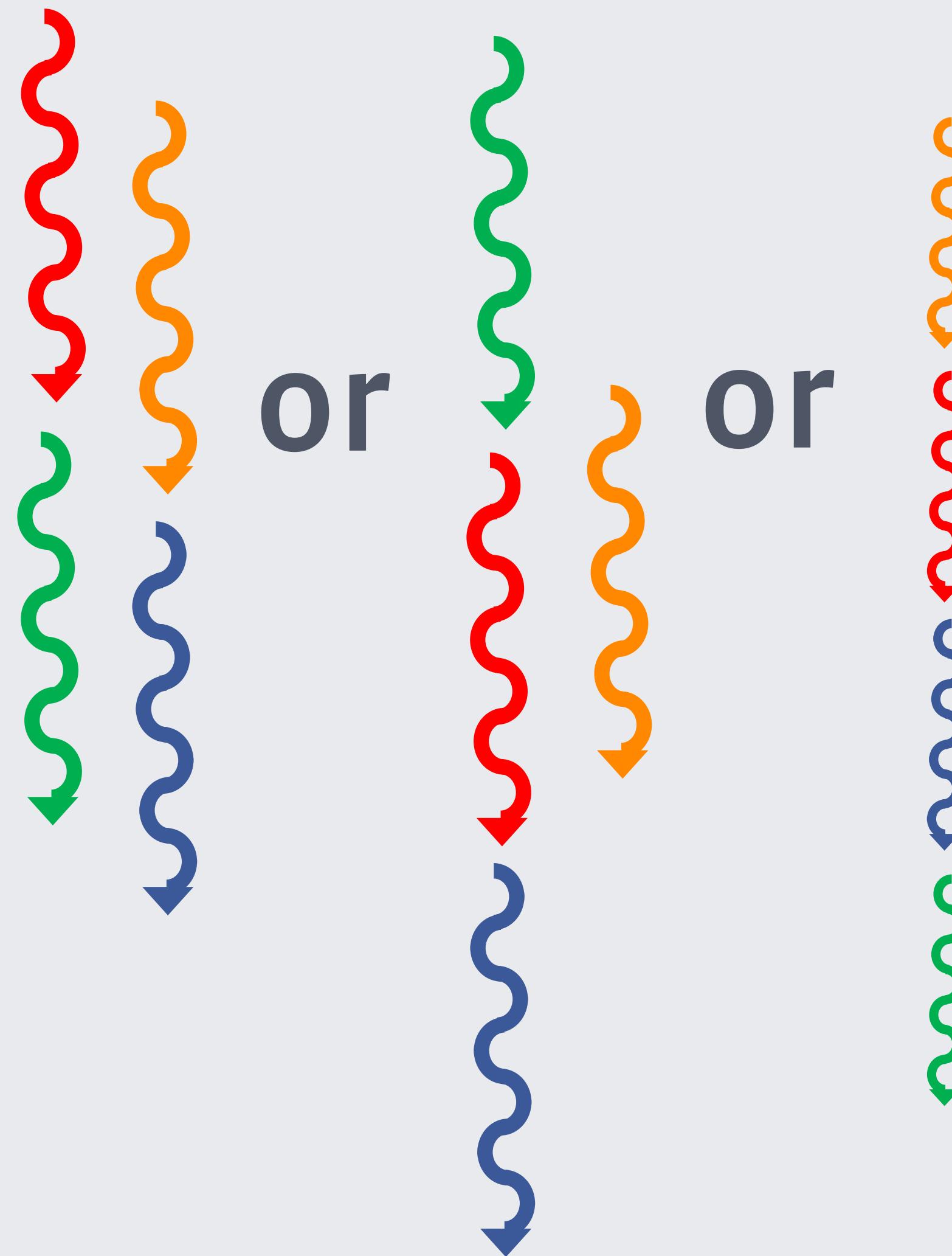
Concurrency:
Multiple logical threads
of execution with
unknown inter-task
dependencies.

Concurrency vs. Parallelism



Parallelism:
Multiple logical threads
of execution with no
inter-task dependencies.

Concurrency vs. Parallelism



Parallelism:
Scheduler has the
freedom to use the
fastest execution
order.

Concurrency, by Example

```
// variable accessible to both workers:  
std::atomic<int> x = { 0 };
```

```
// Worker A:  
while(x.load() == 0) { /* yield */ }  
cout << "Hello" << endl;
```

```
// Worker B:  
x.store(1);
```

- This program is not *guaranteed* to ever print Hello unless Worker A and Worker B are executed on agents with a **concurrent** forward progress guarantee.
- Generally speaking, concurrency imposes extra requirements on the scheduler.

Parallelism, by Example

```
// variable accessible to both workers:  
int x = 0;
```

```
// Worker A:  
// (not an atomic operation)  
x += 1;
```

```
// Worker B:  
// (not an atomic operation)  
x += 1;
```

- This program can result in $x == 1$ or $x == 2$ if Worker A and Worker B are executed in **parallel**.
- Parallelism is a **contract** that grants extra freedom to the scheduler (and imposes extra requirements on the *user*).

Parallelism and Concurrency are Opposites



Concurrency is a Stronger Scheduling Guarantee than Serial

```
std::atomic<int> x = { 0 };
```

```
// Worker A:  
while(x.load() == 0) { /* yield */ }  
cout << "Hello" << endl;
```

```
// Worker B:  
x.store(1);
```

```
// Serial program:  
std::atomic<int> x = { 0 };  
while(x.load() == 0) { /* yield */ }  
cout << "Hello" << endl;  
x.store(1);
```



When you use *serial* execution for the program with *concurrent* requirements, it (obviously) never prints Hello.

Parallelism is a Weaker Scheduling Requirement than Serial

```
int x = 0;
```

```
// Worker A:  
// (not an atomic operation)  
x += 1;
```

```
// Worker B:  
// (not an atomic operation)  
x += 1;
```

```
// Serial program:  
int x = 0;  
x += 1;  
x += 1;
```

When you use *serial* execution for the program with *parallel* requirements, it (obviously) results in $x == 2$.

Parallelism is “More Universal”

- When you use *concurrent* features to express *parallelism*, you end up with unreasonable overheads.
- The programming model is not *restrictive* enough for the compiler or runtime system to avoid these overheads.

Why are the parallel algorithms fast?

- Because they let the user communicate to the scheduler critical information about (the lack of) cross-task dependencies.
- In other words, it communicates the full structure of the algorithm's *task graph* to the scheduler.

II. Senders and Receivers

Why are standard futures slow?

Why are Futures slow?

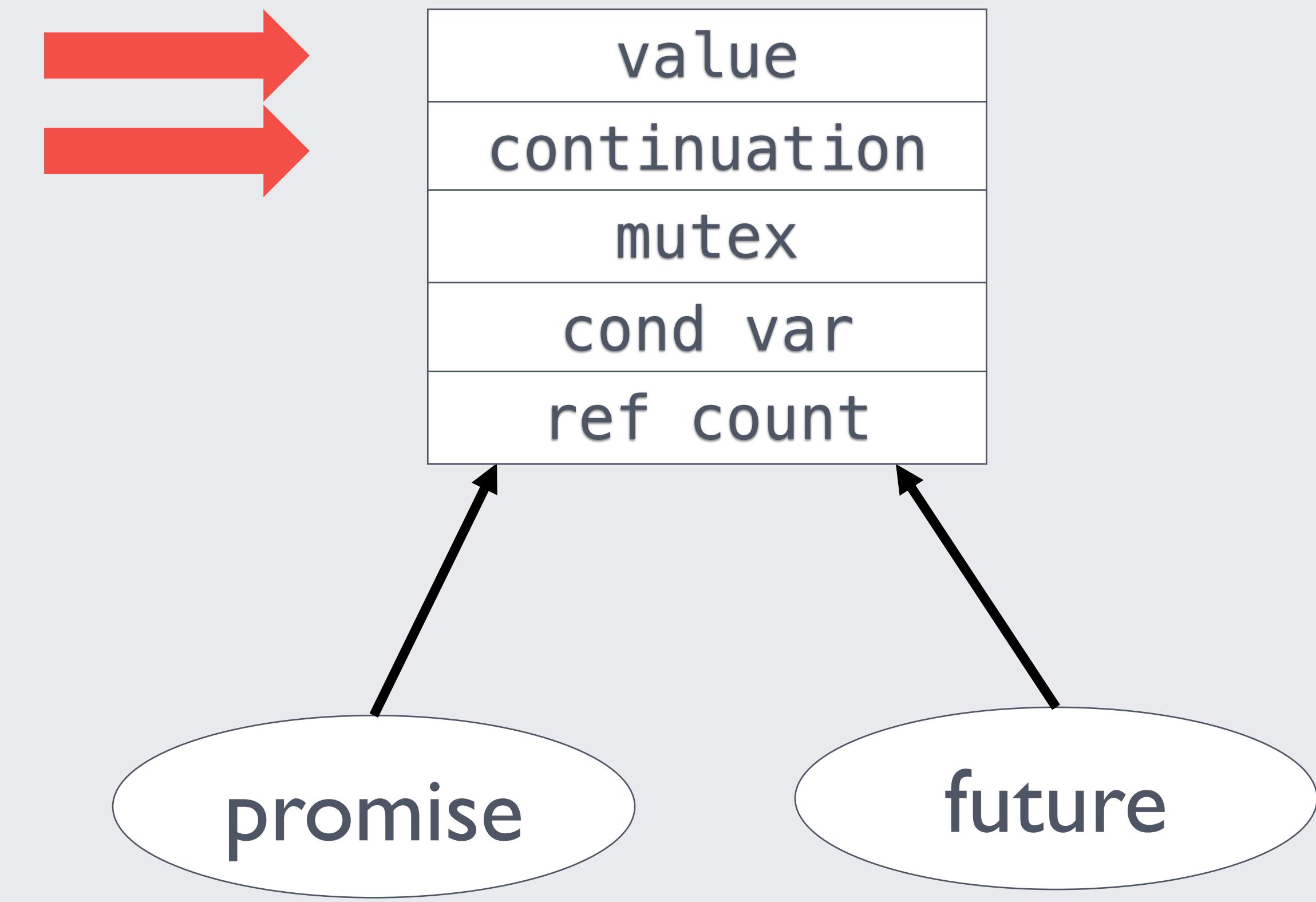
```
future<int> async_algo() {
    promise<int> p;
    auto f = p.get_future();
    thread t { [p = move(p)]() mutable {
        int answer = // compute!
        p.set_value(answer);
    }};
    t.detach();
    return f;
}
```

```
int main() {
    auto f = async_algo();
    auto f2 = f.then([](int i) {
        return i + rand();
    });
    printf("%d\n", f2.get());
}
```

Why are Futures slow?

```
future<int> async_algo() {
    promise<int> p;
    auto f = p.get_future();
    thread t { [p = move(p)]() mutable {
        int answer = // compute!
        p.set_value(answer);
    }};
    t.detach();
    return f;
}
```

```
int main() {
    auto f = async_algo();
    auto f2 = f.then([](int i) {
        return i + rand();
    });
    printf("%d\n", f2.get());
}
```



How successful
would the STL be if
iterators all did
allocation,
synchronization,
and
type-erasure?



A simple observation...

```
template <class Cont>
future<int> async_algo(Cont c) {
    promise<int> p;
    auto f = p.get_future();
    thread t { [p = move(p), c]() mutable {
        int answer = // compute!
        p.set_value(c(answer));
    }};
    t.detach();
    return f;
}
```

This calling code knows
the continuation at the
point it calls the algorithm!

```
sync_algo(
    [](int i) {
        return i + rand();
    });
    printf("%d\n", f.get());
}
```

A less simple observation...

- Passing in a continuation avoids (some) synchronization overhead because it removes the race on reading and writing the continuation.
- We can achieve the same result by starting async work suspended and letting the caller add the continuation *before* launching the work.

A less simple observation...

```
auto async_algo() {
    return [](auto p) {
        thread t { [p = move(p)]() mutable {
            int answer = // compute!
            p.set_value(answer);
        }};
        t.detach();
    };
}
```

Defer the thread launch -- return a *function* that takes a promise instead.

The function returned from `async_algo` is like a *lazy future*..

```
int main() {
    auto f = async_algo();
    auto f2 = then(f, [](int i) {
        return i + rand();
    });
    // ...
}
```

then() is just an algorithm

```
auto then(auto task, auto fun) {  
    return [=](auto p) {  
        struct _promise {  
            decltype(p) p_;  
            decltype(fun) fun_;  
            void set_value(auto ...vs) { p_.set_value(fun_(vs...)); }  
            void set_exception(auto e) { p_.set_exception(e); }  
        };  
        task(_promise{p, fun});  
    };  
}
```

Lazy futures expect promise-like things.

then() returns a lazy future that applies a function to the value produced by another lazy future.

```
int main() {  
    auto f = async_algo();  
    auto f2 = then(f, [](int i) {  
        return i + rand();  
    });  
    // ...  
}
```

Use `then()` to compose lazy futures

```
auto async_algo() {
    return [](auto p) {
        thread t { [p = move(p)]() mutable {
            int answer = // compute!
            p.set_value(answer);
        }};
        t.detach();
    };
}

struct sink {
    void set_value(auto...) {}
    void set_exception(auto) {
        std::terminate();
    }
};
```

Oops, printf in wrong thread!

Oops, main no longer blocks!

```
int main() {
    auto f = async_algo();
    auto f2 = then(f, [](int i) {
        return i + rand();
    });
    auto f3 = then(f2, [](int j) { // ???
        printf("%d\n", j);
    });
    f3( sink{} ); // Launch
}
```

Blocking is just an algorithm, too

```
template< class T, class Task >
T sync_wait(Task task) {
    // Define some state:
    _state<T> state;

    // launch the operation:
    task(_promise<T>{&state});

    // wait for it to finish:
    {
        auto lk = unique_lock{state.mtx};
        state.cv.wait(lk, [&state]{
            return state.data.index() != 0; });
    }
    // throw or return the result:
    if (state.data.index() == 1)
        rethrow_exception( get<1>(state.data) );
    return move(get<2>(state.data));
}
```

```
template< class T >
struct _state {
    mutex mtx;
    condition_variable cv;
    variant<monostate, exception_ptr, T> data;
};
```

```
template< class T >
struct _promise {
    _state<T>* pst;

    template <int I> void _set(auto... xs) {
        auto lk = unique_lock{pst->mtx};
        pst->data.template emplace<I>(xs...);
        pst->cv.notify_one();
    }
    void set_value(auto... vs) { _set<2>(vs...); }
    void set_exception(auto e) { _set<1>(e); }
};
```

Use sync_wait() algo to block

```
auto async_algo() {
    return [](auto p) {
        thread t { [p = move(p)]() mutable {
            int answer = // compute!
            p.set_value(answer);
        }};
        t.detach();
    };
}
```

```
int main() {
    auto f = async_algo();
    auto f2 = then(f, [](int i) {
        return i + rand();
    });
    printf("%d\n", sync_wait<int>(f2));
}
);
f3( sink{} ); // Launch
}
```

Separation of concerns

```
auto new_thread() {
    return [](auto p) {
        thread t { [p = move(p)]() mutable {
            p.set_value();
        }};
        t.detach();
    };
}

auto async_algo(auto task) {
    return then(task, [] {
        int answer = // compute!
        return answer;
    });
}
```

Why is thread creation the responsibility of `async_algo()`?

`new_thread()` is an “executor”

```
int main() {
    auto f = async_algo(new_thread());
    auto f2 = then(f, [](int i) {
        return i + rand();
    });
    printf("%d\n", sync_wait<int>(f2));
}
```

Lazy future advantages

- Async tasks can be composed...
 - ... without allocation
 - ... without synchronization
 - ... without type-erasure
- Composition is a generic algorithm
- Blocking is a generic algorithm

Generic is as Generic does

```
template <class P, class E = exception_ptr>
concept Receiver =
    requires (P& p, E&& e) {
        p.set_error( (E&&) e );
        p.set_done();
    };
template <class P, class... Vs>
concept Receiver0f =
    Receiver<P> &&
    Invocable<P, Vs...>;
```

Called by a lazy future in response to a request for cancellation.

Generic is as Generic does

```
template <class F>
concept Sender =
    is_sender_v<decay_t<F>>;  
  
template <class F, class R>
concept SenderTo =
    Sender<F> &&
    Receiver<R> &&
    requires (F&& f, R&& r) {
        submit( forward<F>(f), forward<R>(r) );
    };
```

III. Sender/Receiver and Coroutines

Coroutines and callbacks

```
task<int> async_helper();  
  
task<void> async_algorithm() {  
    // ...  
    int result = co_await async_helper();  
    // use result  
    printf("%d\n", result);  
}
```

Everything after a `co_await` or a `co_yield` expression is implicitly a callback.

If suspended coroutines are callbacks,
and if callbacks are Receivers, then...

Coroutines are Receivers
and Awaitables are Senders

(Some) Senders are Awaitable

```
// In a future version of C++, perhaps?  
namespace std { inline namespace awaitable_senders {  
    template <Sender S>  
    auto operator co_await(S&& s) {  
        return _awaiter_sndr{S&&s};  
    };  
}}
```

Must be find-able by ADL

(Some) Senders are Awaitable

```
struct DuMb_SeNdEr : std::sender_of<int> {
    void submit( ReceiverOf<int> auto r ) {
        r(42);
    }
};

coro_task<int> async_algo( Sender auto s ) {
    int the_answer = co_await s;
    assert( the_answer == 42 );
    co_return the_answer;
}

int main() {
    int res = sync_wait<int>( async_algo( DuMb_SeNdEr{} ) );
}
```

Senders can be
co_awaited in a
coroutine.

Awaitables (coro_task)
can be treated as
Senders!

(All) Awaitables are Senders

All awaitable types
satisfy the
requirements of
the Sender
concept

```
// A simple co-awaitable type:  
struct my_awaitable {  
    friend auto operator co_await(my_awaitable) {  
        return ...;  
    }  
};  
  
// A simple receiver:  
struct my_receiver {  
    void operator()(auto...);  
    void set_error(exception_ptr);  
    void set_done();  
};  
  
int main() {  
    // OK, can use awaitables as senders:  
    submit( my_awaitable{}, my_receiver{} );  
}
```

(All) Awaitables are Senders

```
// Make all awaitables senders:
template <Awaitable A, ReceiverOf<await_result_t<A>> R>
void submit(A awaitable, R to) noexcept {
    try {
        invoke([](A a, R&& r) -> oneway_task {
            R rCopy((R&&) r);
            try {
                rCopy(co_await (A&&) a);
            }
            catch (...) {
                rCopy.set_error(current_exception());
            }
        }, (A&&) awaitable, (R&&) to);
    }
    catch (...) {
        to.set_error(current_exception());
    }
}
```

```
struct [[maybe_unused]] oneway_task {
    struct promise_type {
        oneway_task get_return_object() noexcept { return {}; }
        suspend_never initial_suspend() noexcept { return {}; }
        suspend_never final_suspend() noexcept { return {}; }
        void return_void() noexcept {}
        void unhandled_exception() noexcept { std::terminate(); }
    };
};
```

IV. Building on Sender/Receiver

Building on Sender/Receiver

- Higher-level functionality can be built efficiently on top of Sender/Receiver:
 - Generic algorithms: sync_wait, wait_all, wait_any, etc.
 - Promises and Futures
 - Channels
 - Async Ranges and Reactive streams

Example: Futures

We can build eager futures on top of lazy Senders with no overhead beyond that which is inherent in eager execution;
i.e., allocation and synchronization.

Futures

```
template <class T>
struct MyFuture {
private:
    shared_ptr<_my_state<T>> _st =
        make_shared<_my_state<T>>();
public:
    template <SenderOf<T> S>
    explicit MyFuture(S&& src) {
        ((S&&)src).submit(
            _st->make_receiver());
    }
    T get() && {
        return move(*_st).get();
    }
};
```

Futures

```
temp template <class T>
stru struct MyFuture {
    va private:
    mu    shared_ptr<_my_state<T>> _st =
        co    make_shared<_my_state<T>>();
    au public:
        template <SenderOf<T> S>
        explicit MyFuture(S&& src) {
            T ((S&&)src).submit(
                _st->make_receiver());
        }
        T get() && {
            return move(*_st).get();
        }
    } };
};
```

```
_this<_my_state<T>> {
    > _v;
    )};
    lex() != 0; });
    ;
```

Futures

```
template <class T>
template <class T>
struct _my_recvr {
    shared_ptr<_my_state<T>> _st;

    template <int I, class U> void _set(U&& u) {
        lock_guard lk(_st->_m);
        _st->_v.template emplace<I>((U&&) u);
        _st->_cv.notify_one();
    }
    void operator()(T t) { _set<1>(move(t)); }
    void set_error(exception_ptr e) { _set<2>(e); }
    void set_done() {
        _set<2>(make_exception_ptr(cancelled{}));
    }
};
```

<T>> {

```
template <class T>
struct MyFuture {
private:
    shared_ptr<_my_state<T>> _st =
        make_shared<_my_state<T>>();
public:
    template <SenderOf<T> S>
    explicit MyFuture(S&& src) {
        ((S&&)src).submit(
            _st->make_receiver());
    }
    T get() && {
        return move(*_st).get();
    }
};
```

Futures: Summary

- Eager interfaces can be layered on top of lazy without additional overhead.
- *The converse is not true:* we cannot “lazy-ify” an eager async operation while also removing its inherent overhead.
- *Therefore, lazy operations are more fundamental.*
- The optimal way to “eager-ify” a lazy operation depends on many things; there should be many such algorithms.

But remember:

Concurrency is only half of the story

If we can't also express *parallel* use cases,

are we really being generic?

FLASHBACK:

Why are the parallel algorithms fast?

- Because they let the user communicate to the scheduler critical information about (the lack of) cross-task dependencies.
- In other words, it communicates the full structure of the algorithm's *task graph* to the scheduler.

Sender/Receiver and Parallelism

- A non-intrusive `parallel_fork` algorithm, like `then`, creates a node in a task graph of lazy Senders.
- By composing lazy Senders, we build a representation of the data flow graph *independent of its execution*.
- How that graph gets executed can then be left up to the scheduler.

Lazy + Parallel == 

VI. Summary

“ “

It is very important that we design a system that does not only satisfy Facebook's needs, or Nvidia's, or that satisfies special case argument combinations for individual use cases, but one that cleanly generalizes for interoperation between different libraries, from different vendors with different goals.

Lee Howes, Facebook on the need to formalize callbacks

Async Abstraction

- Sender/Receiver is a generalization of Future/Promise that:
 - Accommodates both eager and lazy async
 - Supports cancellation and error propagation
 - Composes with low overhead
 - Permits generic algorithms with efficient default implementations
 - Naturally accommodates “executors” as a special case of a Sender.
 - Generalizes over concurrency and parallelism

Be lazy.

Additional Resources

- The Ongoing Saga of Executors by David Hollman
https://www.youtube.com/watch?v=iYMfYdO0_OU
- A Compromise Executors Design Sketch by <lots> [P1660](#)
- Callbacks and Composition by Kirk Shoop [P1678](#)
- Cancellation is not an Error by Kirk Shoop [P1677](#)