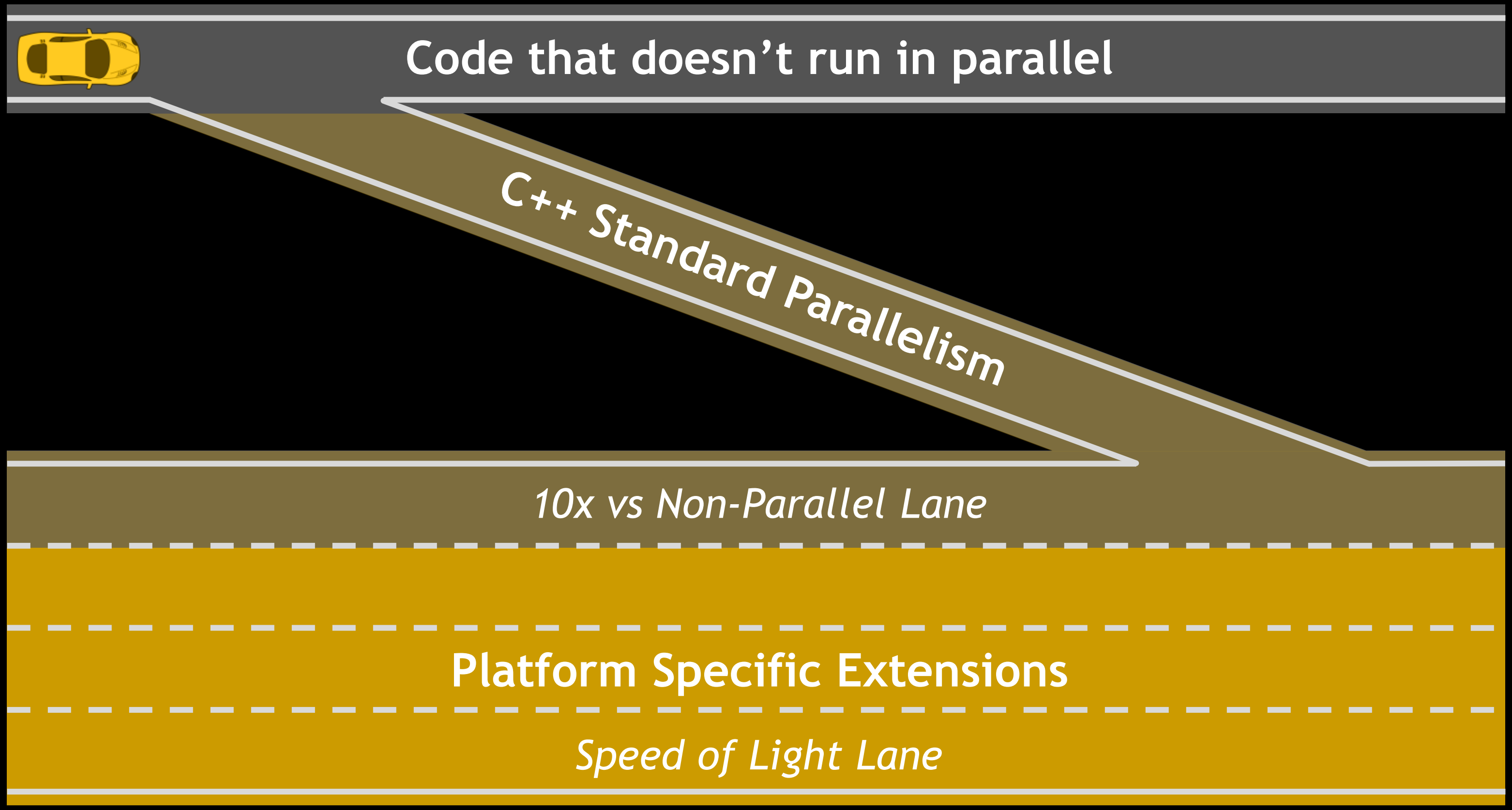
STANDARD PARALLELISM

Bryce Adelstein Lelbach
Principal Architect
Standard C++ Library Evolution Chair, US Programming Languages Chair

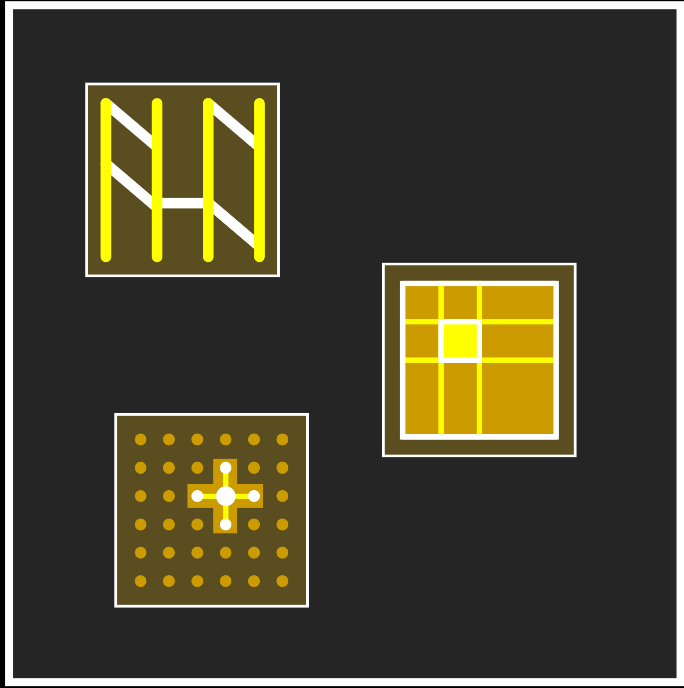
@blelbach

We Need On-Ramps



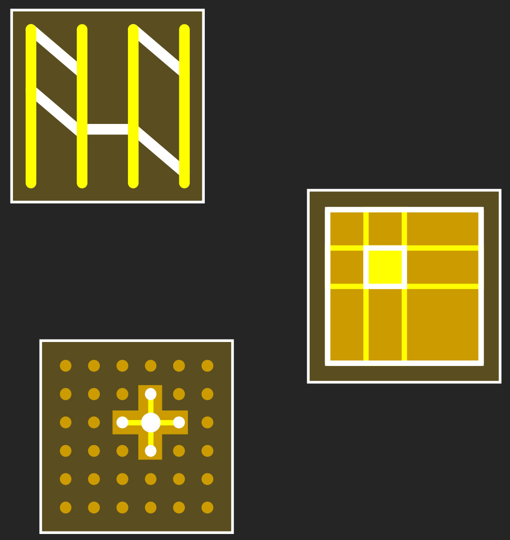
Pillars of C++ Standard Parallelism

Common Algorithms that Dispatch to Vendor-Optimized Parallel Libraries



Pillars of C++ Standard Parallelism

Common Algorithms that Dispatch to Vendor-Optimized Parallel Libraries

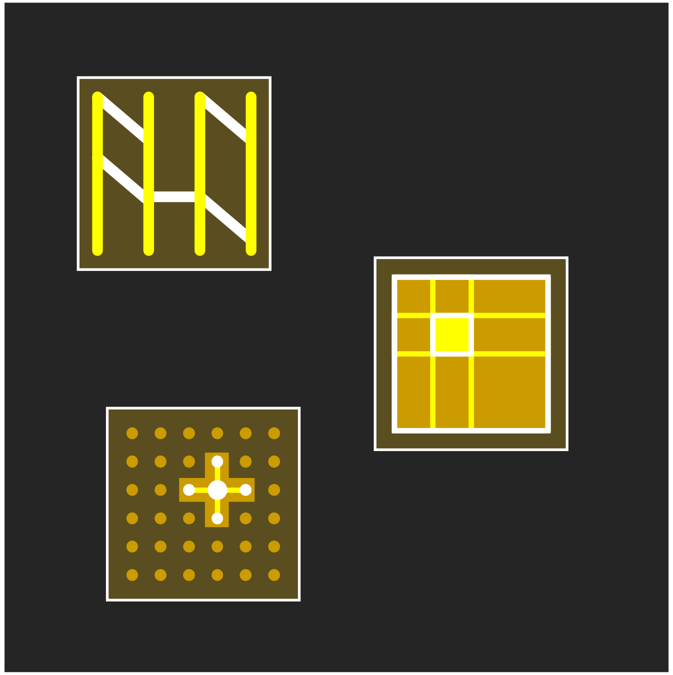


Tools to Write Your Own Parallel Algorithms that Run Anywhere

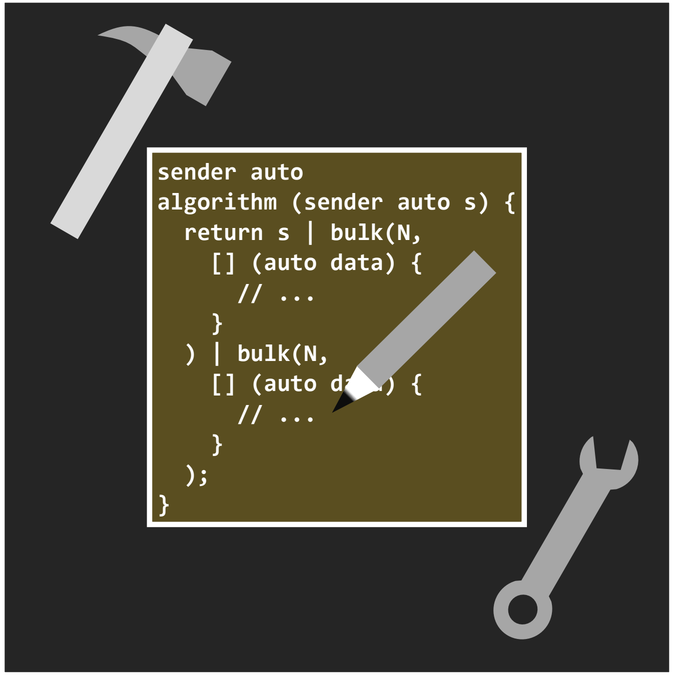
```
sender auto
algorithm (sender auto s) {
  return s | bulk(N,
    [] (auto data) {
      // ...
    }
  ) | bulk(N,
    [] (auto data) {
      // ...
    }
  );
}
```

Pillars of C++ Standard Parallelism

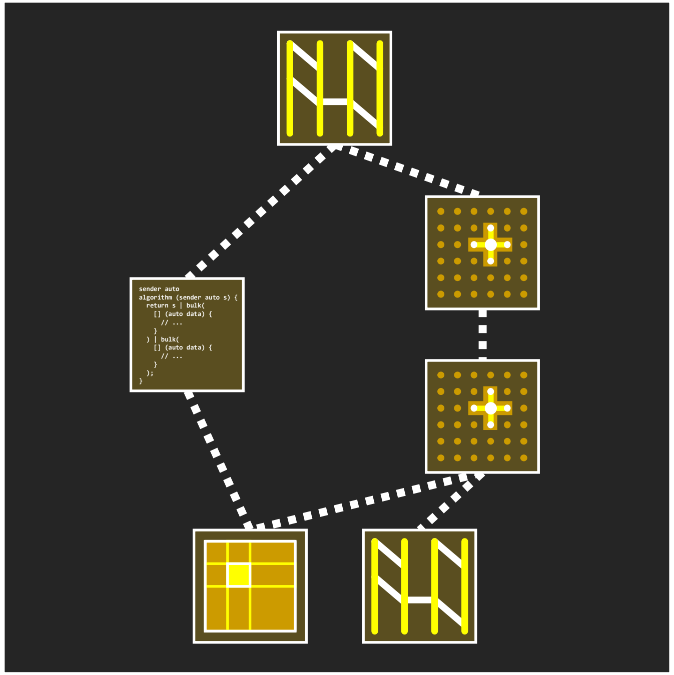
Common Algorithms that Dispatch to Vendor-Optimized Parallel Libraries



Tools to Write Your Own Parallel Algorithms that Run Anywhere



Mechanisms for Composing Parallel Invocations into Task Graphs



Standard Algorithms

Serial (C++98)

```
std::vector<T> x{…};

std::for_each(
 begin(x), end(x),
 f);

std::for_each(
 begin(x), end(x),
 g);

std::for_each(
 begin(x), end(x),
 h);
```

```
std::vector<double> x{…}, y{…};
double dot_product = std::transform_reduce(begin(x), end(x),
                                           begin(y));


std::span<std::string_view> s{…};
std::sort(begin(s), end(s));

std::unordered_map<std::string_view, int> db{…};
std::vector<std::pair<std::string_view, int>> m{…};
std::copy_if(begin(db), end(db), begin(m),
             [] (auto e) { return e.second > 0; });
```

Standard Algorithms

adjacent_difference	is_sorted[_until]	rotate[_copy]
adjacent_find	lexicographical_compare	search[_n]
all_of	max_element	set_difference
any_of	merge	set_intersection
copy[_if|_n]	min_element	set_symmetric_difference
count[_if]	minmax_element	set_union
equal	mismatch	sort
fill[_n]	move	stable_partition
find[_end|_first_of|_if|_if_not]	none_of	stable_sort
for_each	nth_element	swap_ranges
generate[_n]	partial_sort[_copy]	transform
includes	partition[_copy]	uninitialized_copy[_n]
inplace_merge	remove[_copy|_copy_if|_if]	uninitialized_fill[_n]
is_heap[_until]	replace[_copy|_copy_if|_if]	unique
is_partitioned	reverse[_copy]	unique_copy

Standard Algorithms

Serial (C++98)

```
std::vector<T> x{…};

std::for_each(
 begin(x), end(x),
 f);

std::for_each(
 begin(x), end(x),
 g);

std::for_each(
 begin(x), end(x),
 h);
```

Parallel (C++17)

```
std::vector<T> x{…};

std::for_each(
 ex::par_unseq,
 begin(x), end(x),
 f);
std::for_each(
 ex::par_unseq,
 begin(x), end(x),
 g);
std::for_each(
 ex::par_unseq,
 begin(x), end(x),
 h);
```

```cpp
std::vector<double> x{…}, y{…};
double dot_product = std::transform_reduce(ex::par_unseq,
                                           begin(x), end(x),
                                           begin(y));

std::span<std::string_view> s{…};
std::sort(ex::par_unseq, begin(s), end(s));

std::unordered_map<std::string_view, int> db{…};
std::vector<std::pair<std::string_view, int>> m{…};
std::copy_if(ex::par_unseq, begin(db), end(db), begin(m),
             [] (auto e) { return e.second > 0; });
```

Execution Policy	Operations occur …	Operations are …

Execution Policy	Operations occur …	Operations are …
`std::execution::seq`	In the calling thread	Indeterminately sequenced

Execution Policy	Operations occur …	Operations are …
`std::execution::seq`	In the calling thread	Indeterminately sequenced
`std::execution::unseq`	In the calling thread	Unsequenced

Execution Policy	Operations occur …	Operations are …
`std::execution::seq`	In the calling thread	Indeterminately sequenced
`std::execution::unseq`	In the calling thread	Unsequenced
`std::execution::par`	Potentially in multiple threads	Indeterminately sequenced within each thread

Execution Policy	Operations occur …	Operations are …
`std::execution::seq`	In the calling thread	Indeterminately sequenced
`std::execution::unseq`	In the calling thread	Unsequenced
`std::execution::par`	Potentially in multiple threads	Indeterminately sequenced within each thread
`std::execution::par_unseq`	Potentially in multiple threads	Unsequenced

```
std::size_t word_count(std::string_view s) {
  …
}
```

```
std::string_view frost = "Whose woods these are I think I know.\n"
                         "His house is in the village though;  \n"
                         "He will not see me stopping here     \n"
                         "To watch his woods fill up with snow.\n";

std::size_t result = word_count(frost);
```

```
std::size_t word_count(std::string_view s) {
  if (s.empty()) return 0;
  return std::transform_reduce(ex::par_unseq, …);
}
```

```
std::string_view frost = "Whose woods these are I think I know.\n"
                         "His house is in the village though;  \n"
                         "He will not see me stopping here     \n"
                         "To watch his woods fill up with snow.\n";

std::size_t result = word_count(frost);
```

```
std::size_t word_count(std::string_view s) {
  if (s.empty()) return 0;
  return std::transform_reduce(ex::par_unseq,
    begin(s), end(s) - 1, begin(s) + 1,
    …
  );
}



std::string_view frost = "Whose woods these are I think I know.\n"
                         "His house is in the village though;  \n"
                         "He will not see me stopping here     \n"
                         "To watch his woods fill up with snow.\n";

std::size_t result = word_count(frost);
```

```
std::size_t word_count(std::string_view s) {
  if (s.empty()) return 0;
  return std::transform_reduce(ex::par_unseq,
    begin(s), end(s) - 1, begin(s) + 1,
    …
  );
}



std::string_view frost = "Whose woods these are I think I know.\n"
                         "His house is in the village though;  \n"
                         "He will not see me stopping here     \n"
                         "To watch his woods fill up with snow.\n";

std::size_t result = word_count(frost);
```

```
std::size_t word_count(std::string_view s) {
  if (s.empty()) return 0;
  return std::transform_reduce(ex::par_unseq,
    begin(s), end(s) - 1, begin(s) + 1,
    …

    [] (char l, char r) { return std::isspace(l) && !std::isspace(r); }
  );
}

std::string_view frost = "Whose woods these are I think I know.\n"
                         "His house is in the village though;  \n"
                         "He will not see me stopping here     \n"
                         "To watch his woods fill up with snow.\n";

std::size_t result = word_count(frost);
```

```
std::size_t word_count(std::string_view s) {
  if (s.empty()) return 0;
  return std::transform_reduce(ex::par_unseq,
    begin(s), end(s) - 1, begin(s) + 1,
    …

    [] (char l, char r) { return std::isspace(l) && !std::isspace(r); }
  );
}

std::size_t result      =  0000010000010000010001010000010100000
                          10001000001001001000100000001000000000
                          10010000100010001001000000001000000000
                          10010000010001000001000010010000100000;
```

```
std::size_t word_count(std::string_view s) {
  if (s.empty()) return 0;
  return std::transform_reduce(ex::par_unseq,
    begin(s), end(s) - 1, begin(s) + 1,
    std::size_t(!std::isspace(s.front()) ? 1 : 0),
    …
    [] (char l, char r) { return std::isspace(l) && !std::isspace(r); }
  );
}

std::size_t result     = 10000010000010000010001010000010100000
                         10001000001001001000100000001000000000
                         10010000100010001001000000001000000000
                         10010000010001000001000010010000100000;
```

Copyright (C) 2022 NVIDIA

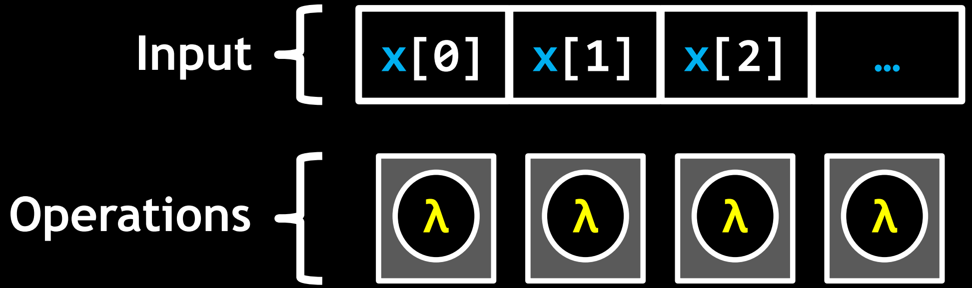
```
std::size_t word_count(std::string_view s) {
  if (s.empty()) return 0;
  return std::transform_reduce(ex::par_unseq,
    begin(s), end(s) - 1, begin(s) + 1,
    std::size_t(!std::isspace(s.front()) ? 1 : 0),
    std::plus(),
    [] (char l, char r) { return std::isspace(l) && !std::isspace(r); }
  );
}

std::size_t result     = 1  +  1  +  1  +  1 + 1+1  +  1+1 +
                         1 + 1  +  1 +1 +1 + 1   +   1     +
                         1 +1  + 1 + 1 + 1 +1   +    1     +
                         1 +1  +  1 + 1  +  1  + 1 +1  + 1 ;
```

```
std::size_t word_count(std::string_view s) {
  if (s.empty()) return 0;
  return std::transform_reduce(ex::par_unseq,
    begin(s), end(s) - 1, begin(s) + 1,
    std::size_t(!std::isspace(s.front()) ? 1 : 0),
    std::plus(),
    [] (char l, char r) { return std::isspace(l) && !std::isspace(r); }
  );
}

std::string_view frost = "Whose woods these are I think I know.\n"
                         "His house is in the village though;  \n"
                         "He will not see me stopping here     \n"
                         "To watch his woods fill up with snow.\n";

std::size_t result = word_count(frost);
```

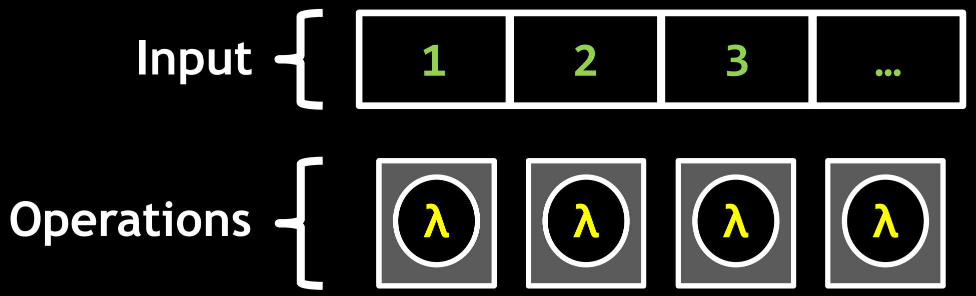
In C++20, the Standard Library introduced ranges.

Unlike iterators, ranges are composable and can be lazy.

```
std::vector x{…};

std::for_each(
  ex::par_unseq,
  begin(x), end(x),
  […] (auto& obj) { … });
```

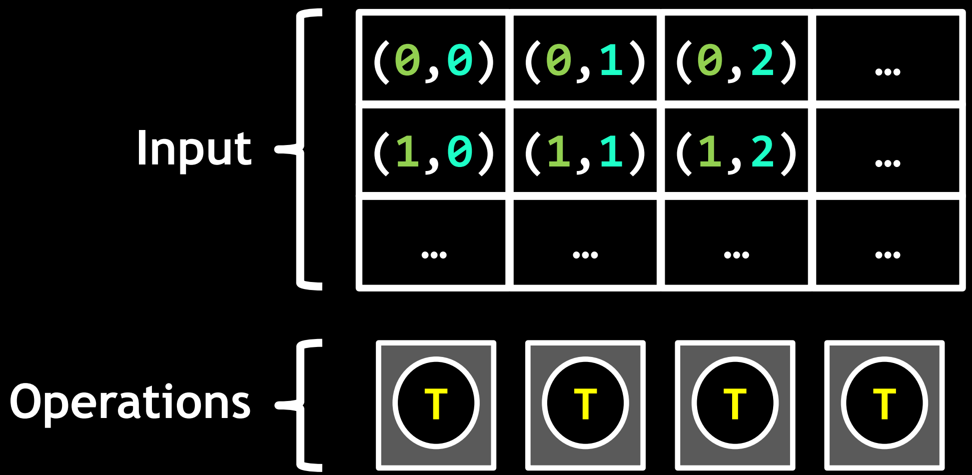


```
auto v = stdv::iota(1, N);

std::for_each(
  ex::par_unseq,
  begin(v), end(v),
  […] (auto idx) { … });
```

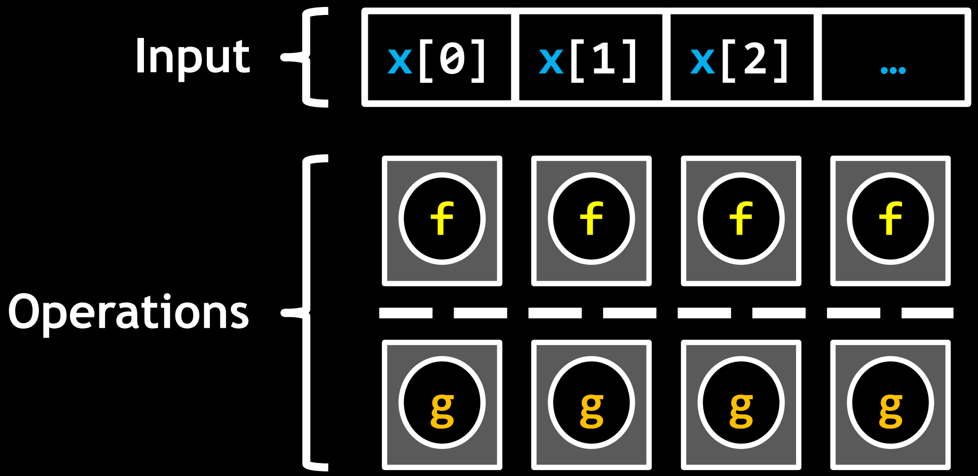


```
std::span A{input,  N * M};
std::span B{output, M * N};

auto v = stdv::cartesian_product(
  stdv::iota(0, N),
  stdv::iota(0, M));

std::for_each(ex::par_unseq,
  begin(v), end(v),
  [=] (auto idx) {
    auto [i, j] = idx;
    B[i + j * N] = A[i * M + j];
  });
```

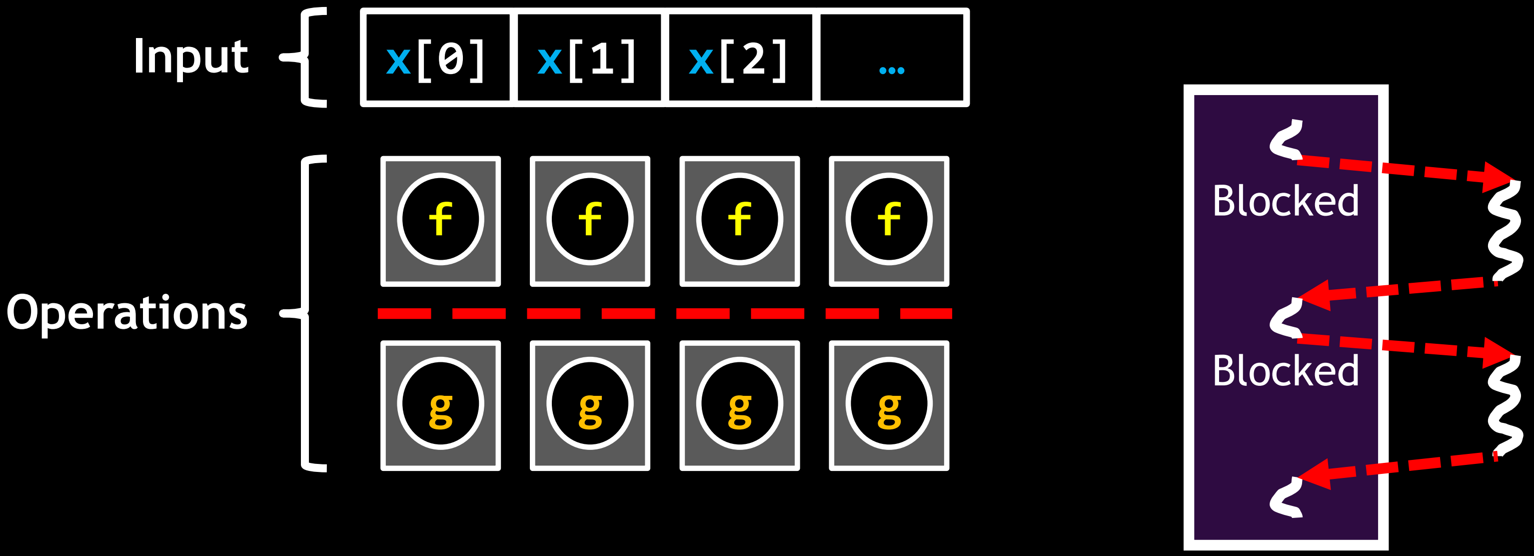
```
std::span A{input,  N * M};
std::span B{output, M * N};

auto v = stdv::cartesian_product(
  stdv::iota(0, N),
  stdv::iota(0, M));
```



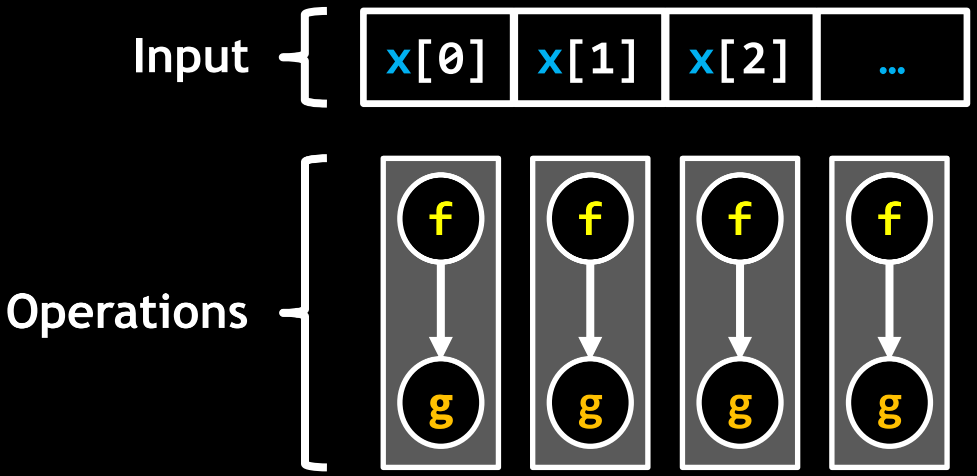
```
std::vector x{…};

std::for_each(ex::par_unseq,
              begin(x), end(x), f);
std::for_each(ex::par_unseq,
              begin(x), end(x), g);
```



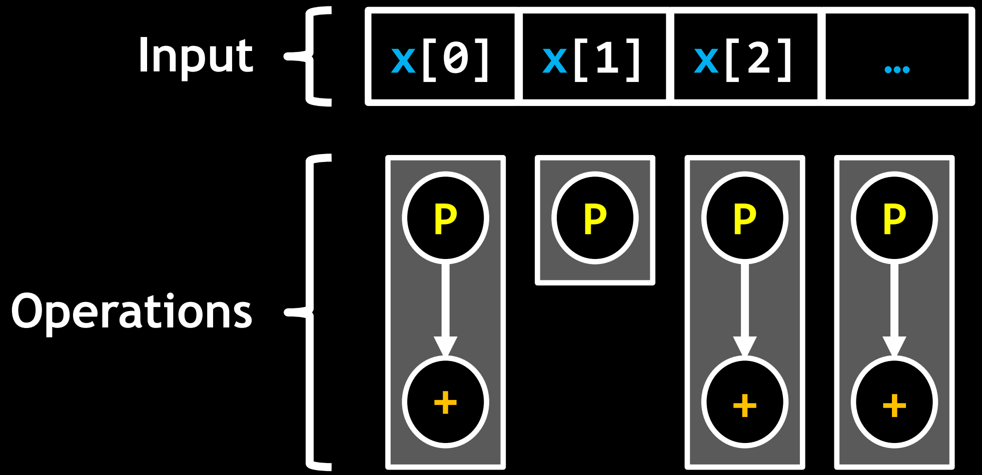
```
std::vector x{…};

std::for_each(ex::par_unseq,
              begin(x), end(x), f);
std::for_each(ex::par_unseq,
              begin(x), end(x), g);
```



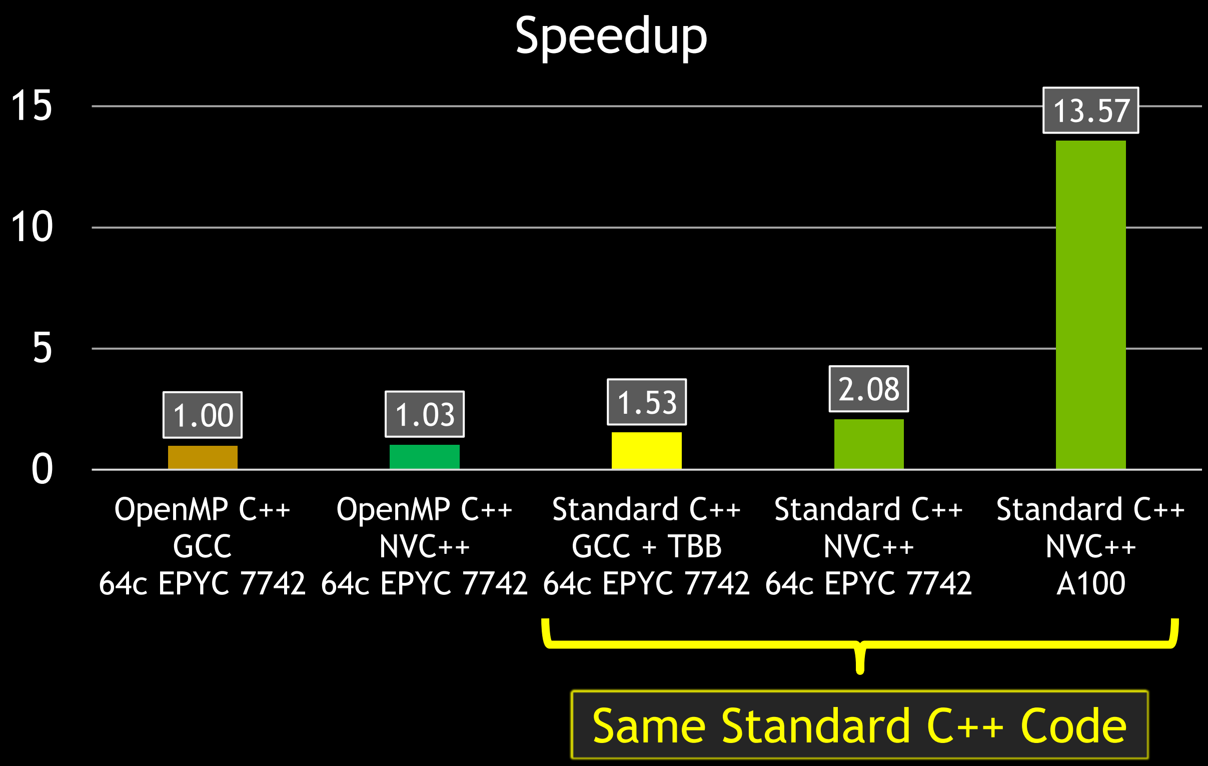
```
std::vector x{…};

auto v = stdv::transform(x, f);

std::for_each(ex::par_unseq,
              begin(v), end(v), g);
```

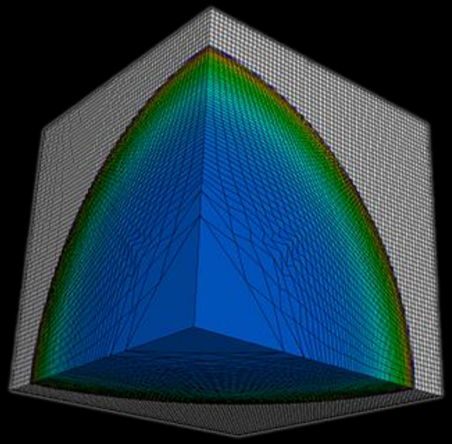


```
std::vector x{…};

auto v = stdv::filter(x,
  [] (auto e) { return e > 0; });

std::reduce(ex::par_unseq,
            begin(v), end(v));
```



LULESH

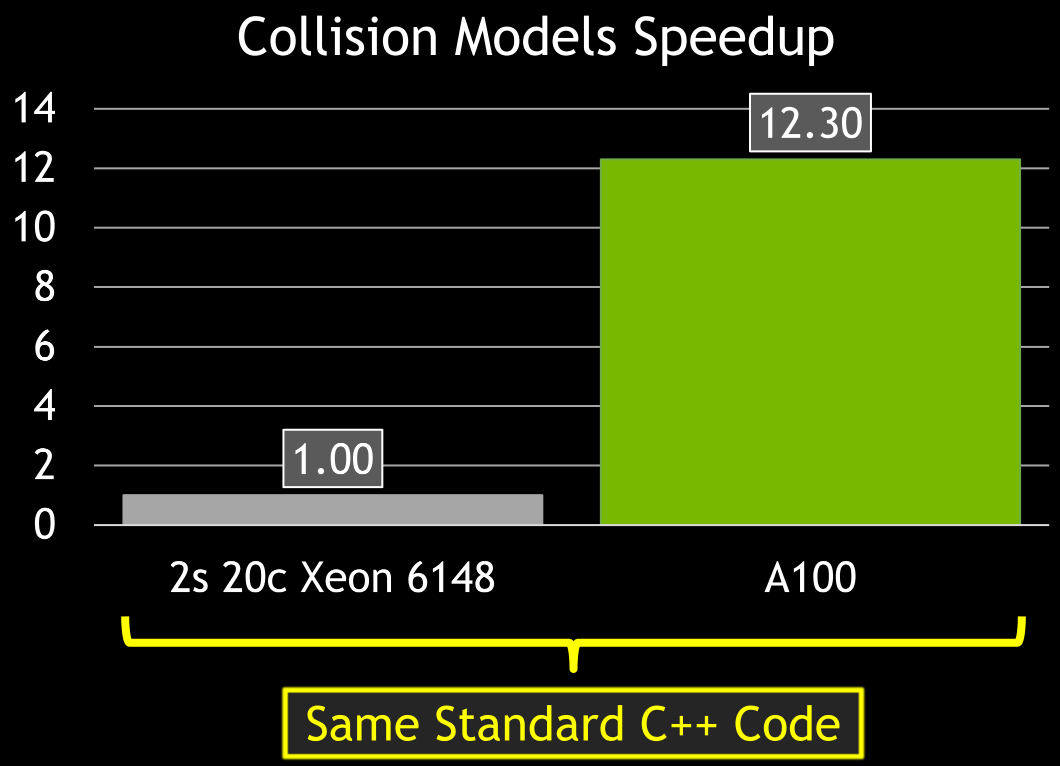




- Mini app for Lagrangian explicit shock hydrodynamics on an unstructured grid.
- Designed to stress vectorization, parallel overheads, & on-node parallelism.
- ~9000 lines of C++.
- Parallel versions in MPI, OpenMP, OpenACC, CUDA, RAJA, Kokkos, Standard C++, …

https://github.com/LLNL/LULESH

STLBM



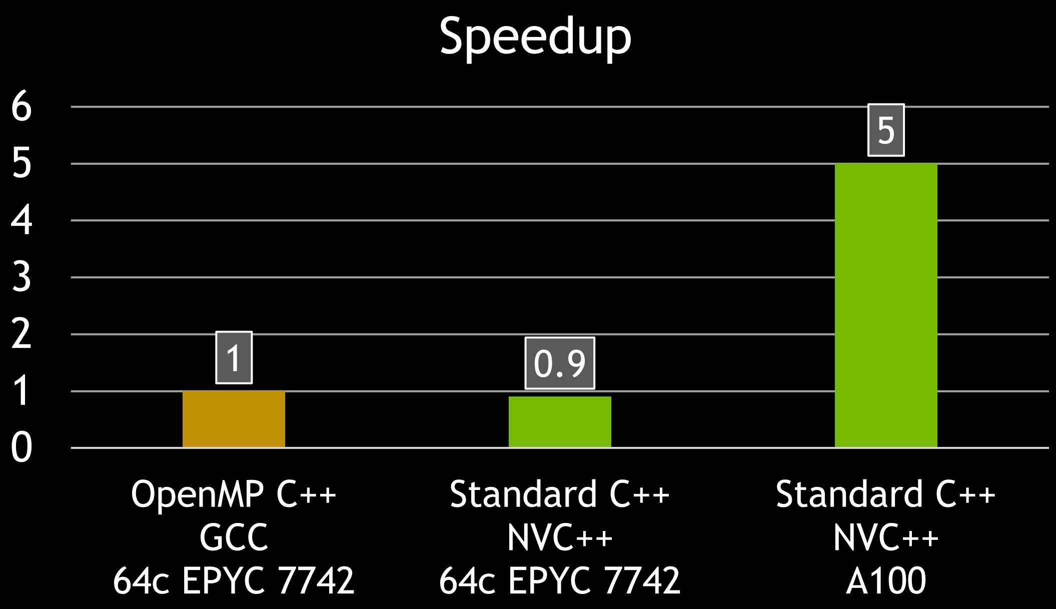
- Framework for parallel Lattice-Boltzmann simulations on multiple targets, including multicore CPUs & GPUs.
- Implemented with C++ Standard Parallelism.
- No language extensions, external libraries, vendor-specific code annotations, or pre-compilation steps.

"We have with delight discovered the NVIDIA "stdpar" implementation of C++ Standard Parallel Algorithms. … We believe that the result produces state-of-the-art performance, is highly didactical, and introduces a paradigm shift in cross-platform CPU/GPU programming in the community."

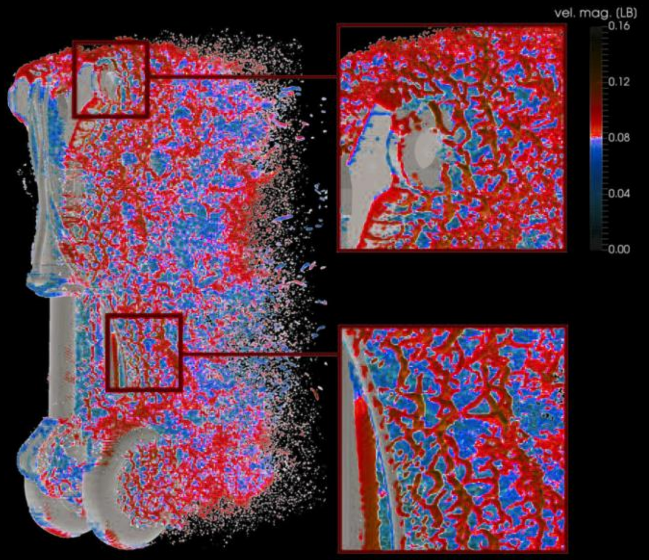
— Professor Jonas Latt, University of Geneva

https://gitlab.com/unigehpfs/stlbm

M-AIA



Same Standard C++ Code



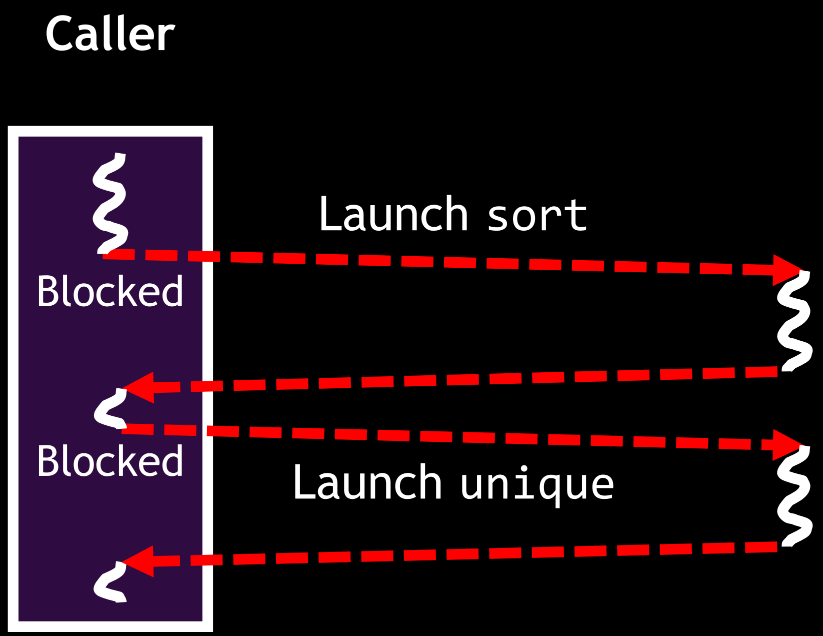
- Package for aerospace flow and noise simulations.
- Solvers include Finite Volume, Navier-Stokes, and Lattice-Boltzmann.
- Switching from OpenMP to C++ Standard Parallelism.

The C++ parallel algorithms introduced in C++17 are great,

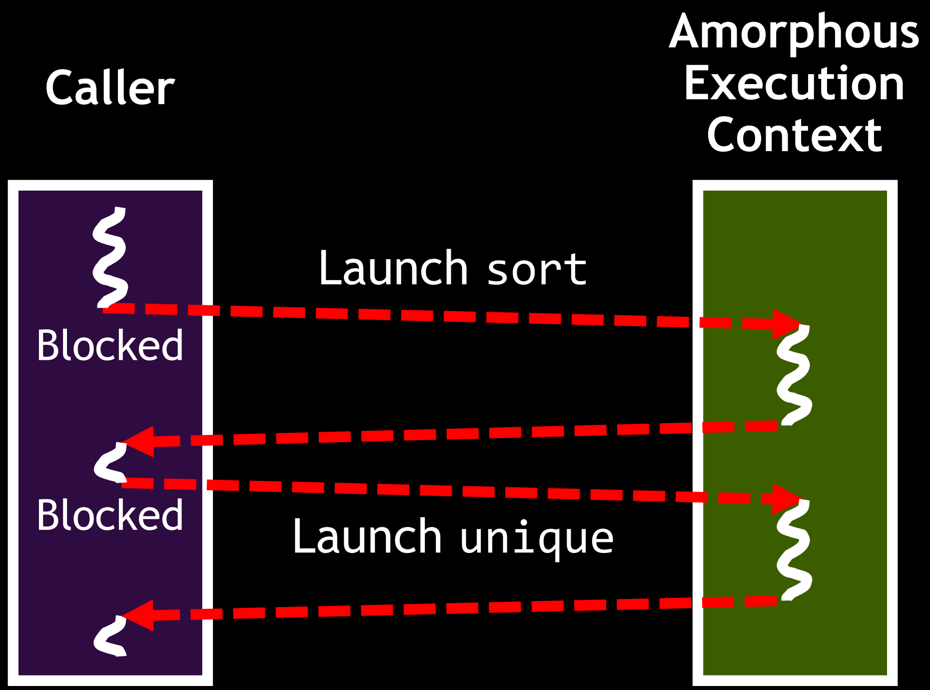
but they're just the start of the story.

```
std::vector<std::string_view> s{…};

std::sort(ex::par_unseq, begin(s), end(s));
std::unique(ex::par_unseq, begin(s), end(s));
```

```
std::vector<std::string_view> s{…};

std::sort(ex::par_unseq, begin(s), end(s));
std::unique(ex::par_unseq, begin(s), end(s));
```



```
std::vector<std::string_view> s{…};

std::sort(ex::par_unseq, begin(s), end(s));
std::unique(ex::par_unseq, begin(s), end(s));
```



Today, C++ has:

- No standard model for asynchrony.
- No standard way to express where things should execute.

Today, C++ has:

- No standard model for asynchrony.
- No standard way to express where things should execute.

The solution is coming soon:

Senders & Receivers

```
ex::scheduler auto sch = thread_pool.scheduler();

ex::sender auto begin = ex::schedule(sch);
ex::sender auto hi    = ex::then(begin, [] { return 13; });
ex::sender auto add   = ex::then(hi, [] (int a) { return a + 42; });

auto [i] = this_thread::sync_wait(add).value();
```

```
ex::scheduler auto sch = thread_pool.scheduler();

ex::sender auto begin = ex::schedule(sch);
ex::sender auto hi    = ex::then(begin, [] { return 13; });
ex::sender auto add   = ex::then(hi, [] (int a) { return a + 42; });

auto [i] = this_thread::sync_wait(add).value();
```

```cpp
ex::scheduler auto sch = thread_pool.scheduler();

ex::sender auto begin = ex::schedule(sch);
ex::sender auto hi    = ex::then(begin, [] { return 13; });
ex::sender auto add   = ex::then(hi, [] (int a) { return a + 42; });

auto [i] = this_thread::sync_wait(add).value();
```

```
ex::scheduler auto sch = thread_pool.scheduler();

ex::sender auto begin = ex::schedule(sch);
ex::sender auto hi    = ex::then(begin, [] { return 13; });
ex::sender auto add   = ex::then(hi, [] (int a) { return a + 42; });

auto [i] = this_thread::sync_wait(add).value();
```

```
ex::scheduler auto sch = thread_pool.scheduler();

ex::sender auto begin = ex::schedule(sch);
ex::sender auto hi    = ex::then(begin, [] { return 13; });
ex::sender auto add   = ex::then(hi, [] (int a) { return a + 42; });

auto [i] = this_thread::sync_wait(add).value();
```

```cpp
ex::scheduler auto sch = thread_pool.scheduler();

ex::sender auto begin = ex::schedule(sch);
ex::sender auto hi    = ex::then(begin, [] { return 13; });
ex::sender auto add   = ex::then(hi, [] (int a) { return a + 42; });

auto [i] = this_thread::sync_wait(add).value();
```

Schedulers are handles to execution contexts.

Schedulers are handles to execution contexts.

Senders represent asynchronous work.

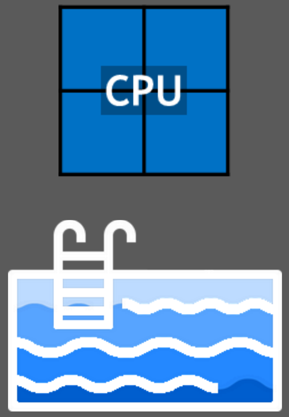
Schedulers are handles to execution contexts.

Senders represent asynchronous work.

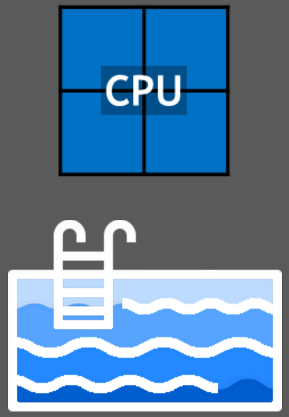
Receivers process asynchronous signals.

Schedulers are handles to execution contexts.

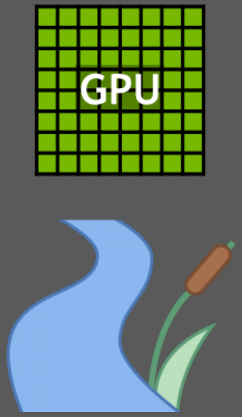
Execution Context:
CPU Thread Pool



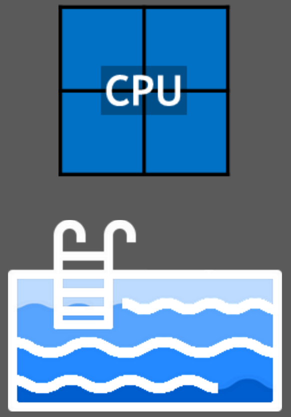
Execution Context:
CPU Thread Pool



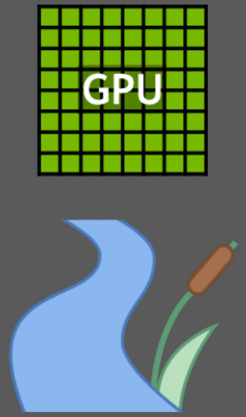
Execution Context:
GPU Stream



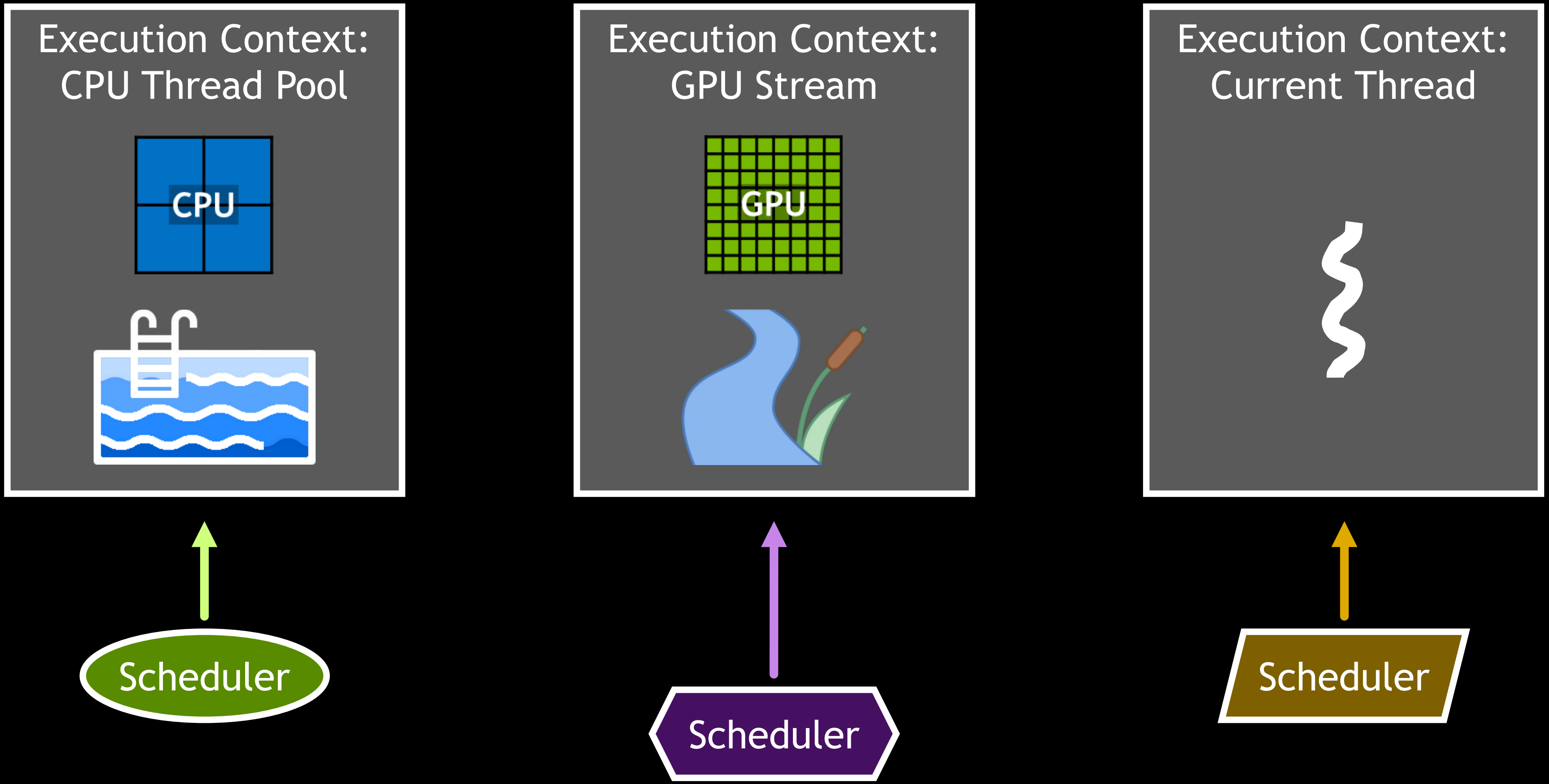
Execution Context:
CPU Thread Pool

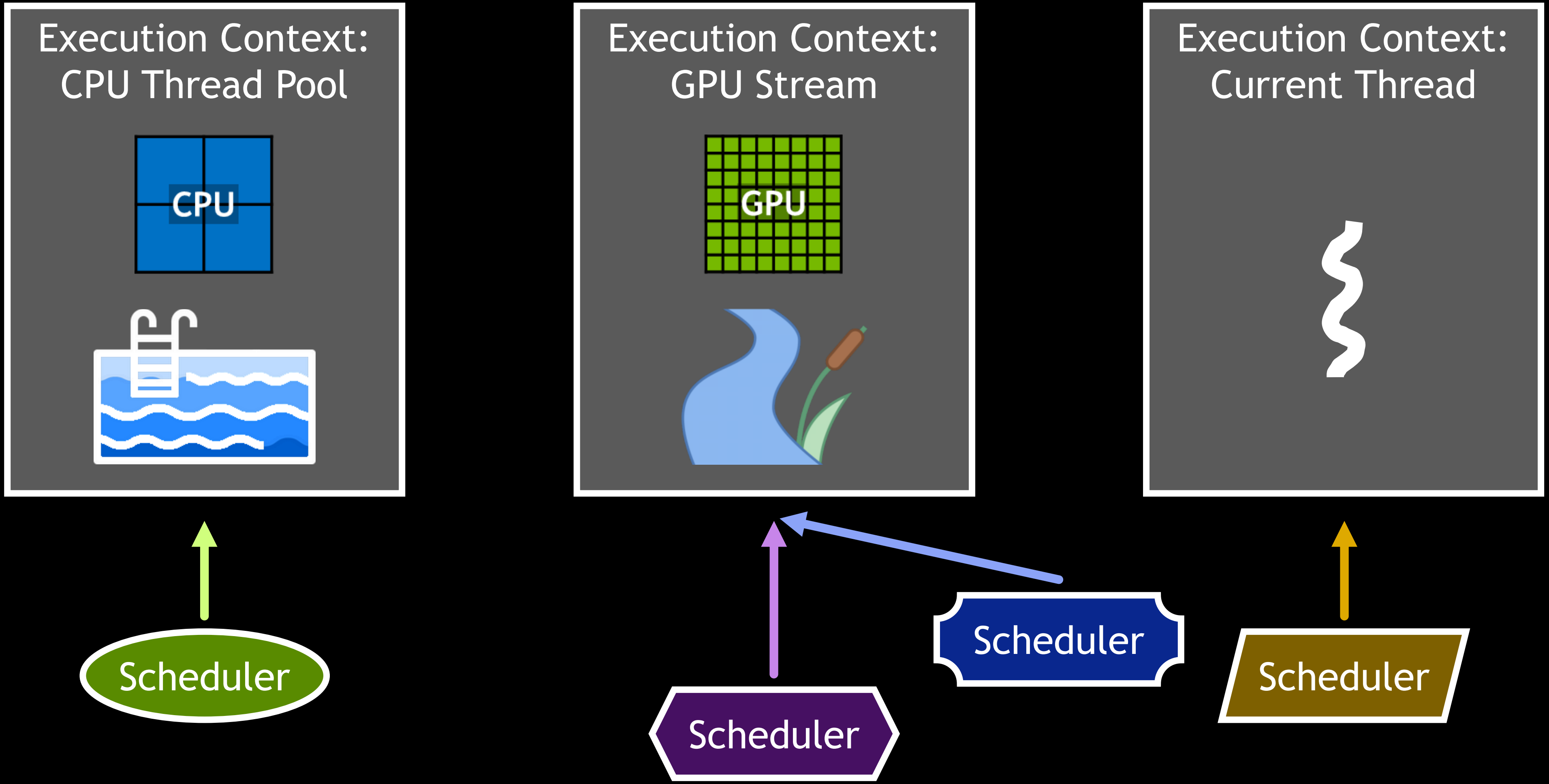


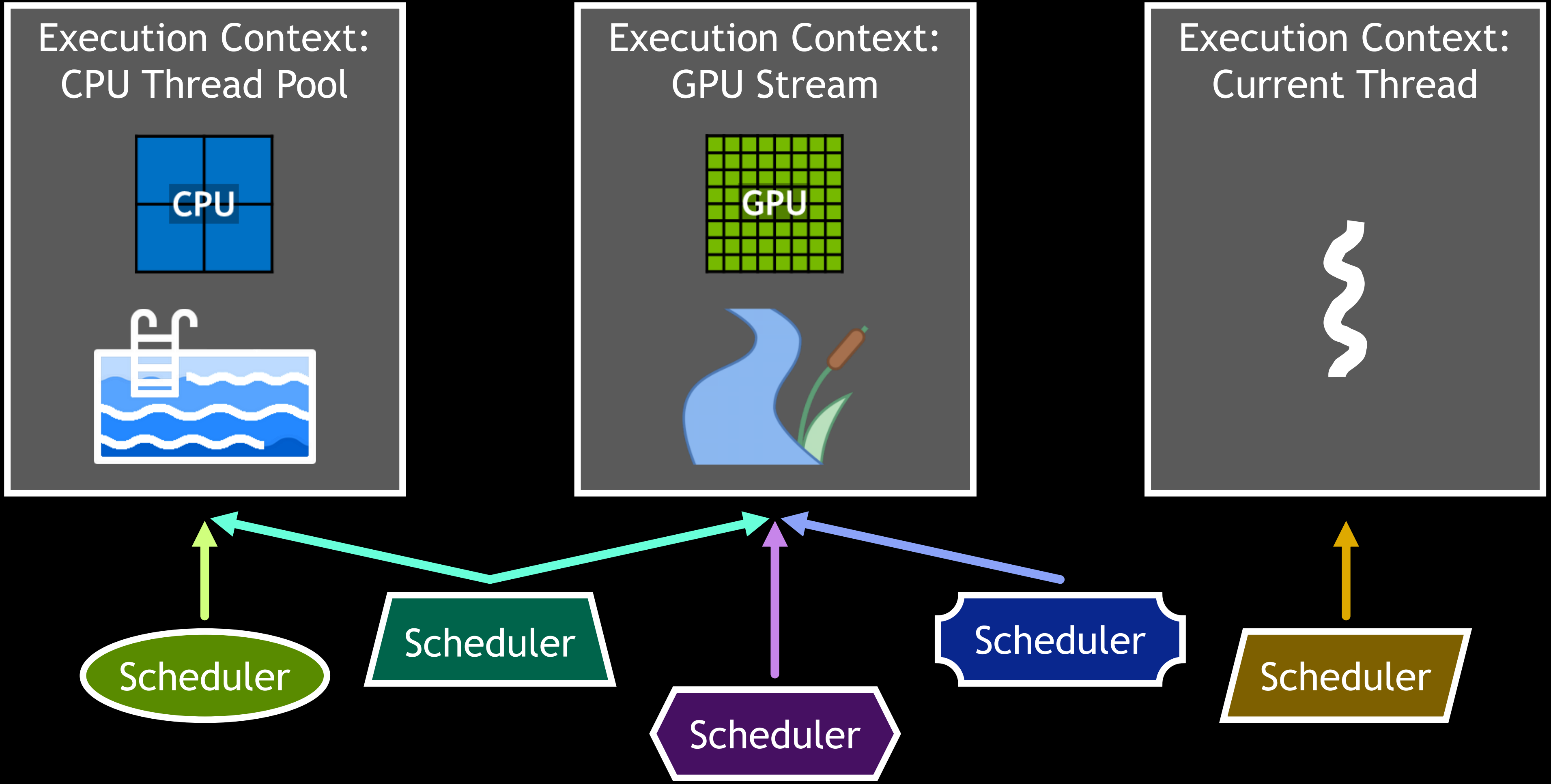
Execution Context:
GPU Stream



Execution Context:
Current Thread


Execution Context:
CPU Thread Pool
CPU
Execution Context:
GPU Stream
GPU
Execution Context:
Current Thread
Scheduler
Scheduler
Scheduler


Execution Context:
CPU Thread Pool
CPU
Execution Context:
GPU Stream
GPU
Execution Context:
Current Thread
Scheduler
Scheduler
Scheduler
Scheduler

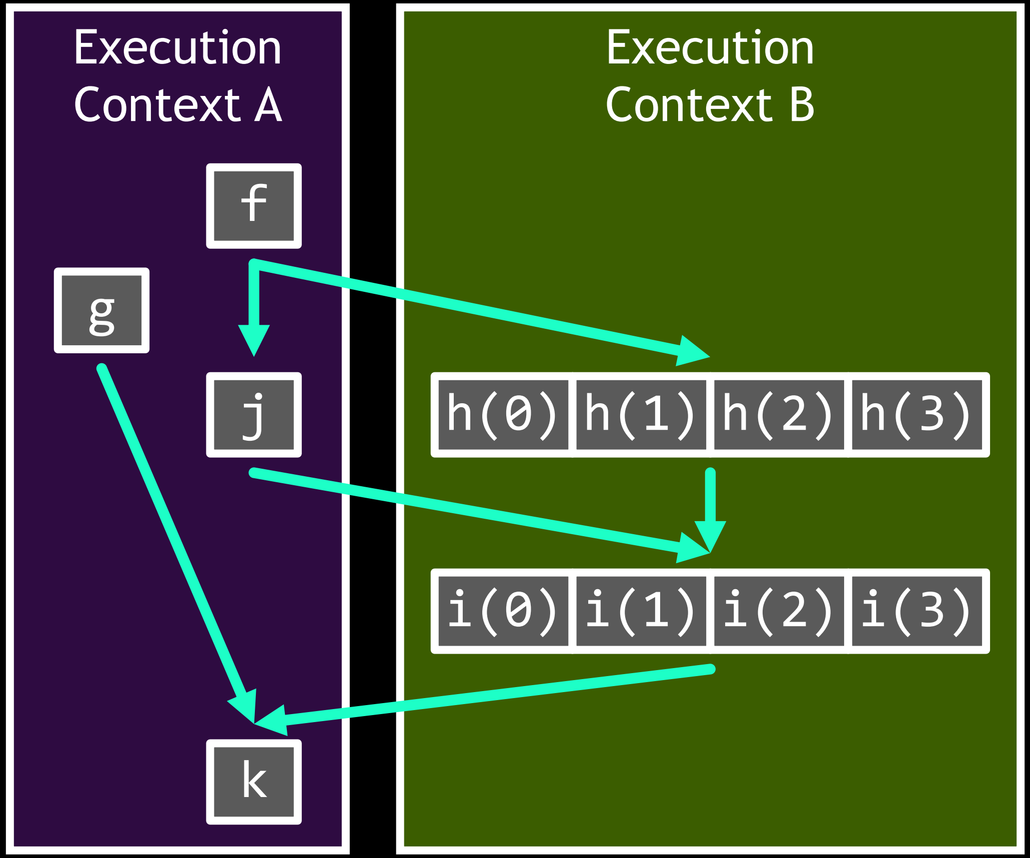


Execution Context: CPU Thread Pool
CPU
Execution Context: GPU Stream
GPU
Execution Context: Current Thread
Scheduler
Scheduler
Scheduler
Scheduler
Scheduler

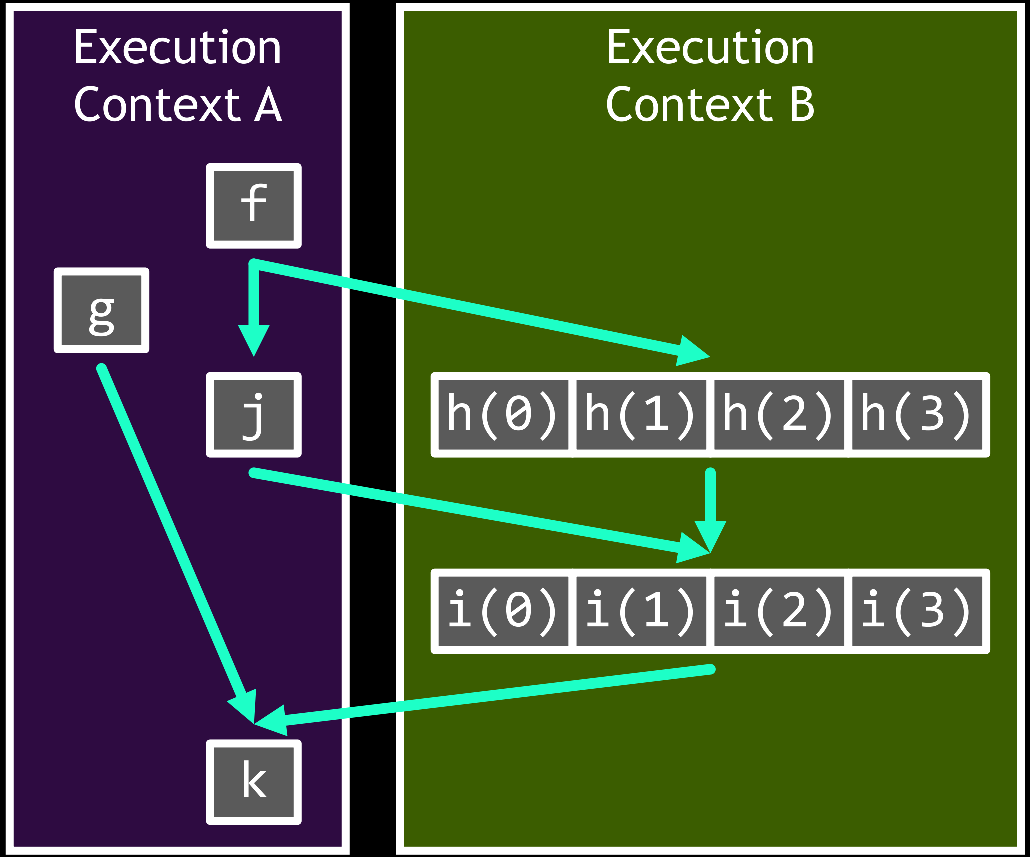
Schedulers produce senders.

- Senders represent asynchronous work.

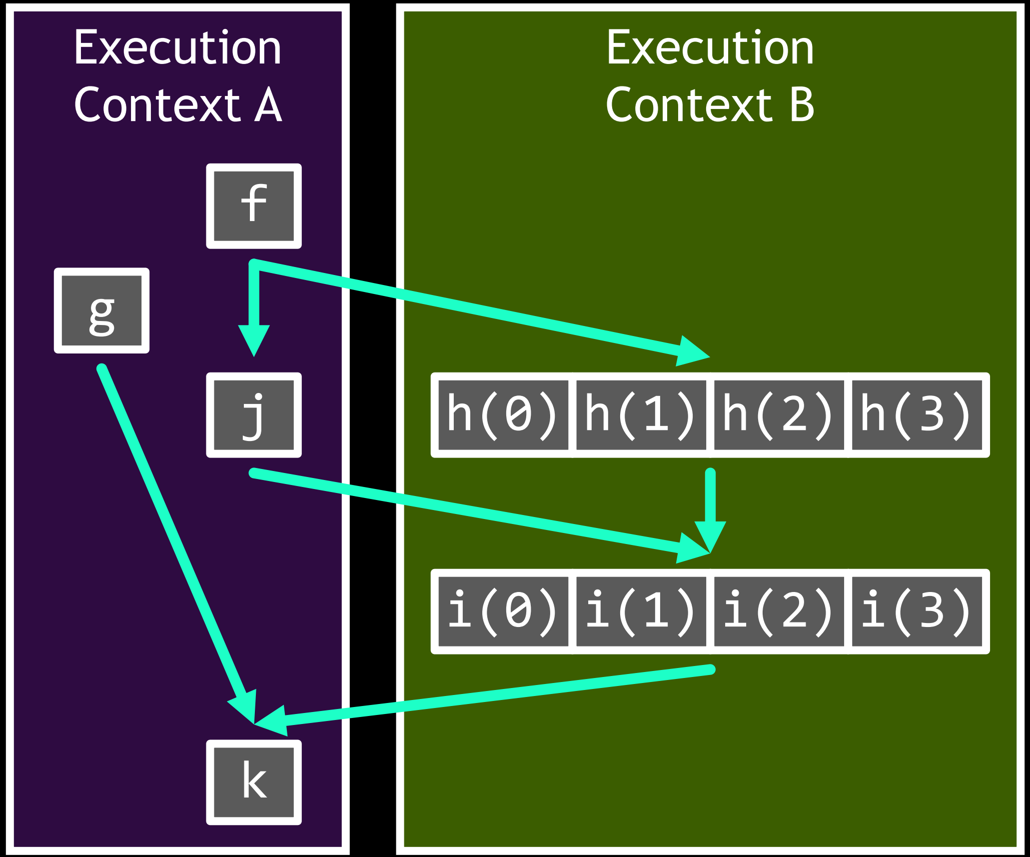
- Senders represent asynchronous work.
- Senders form the nodes of a task graph.



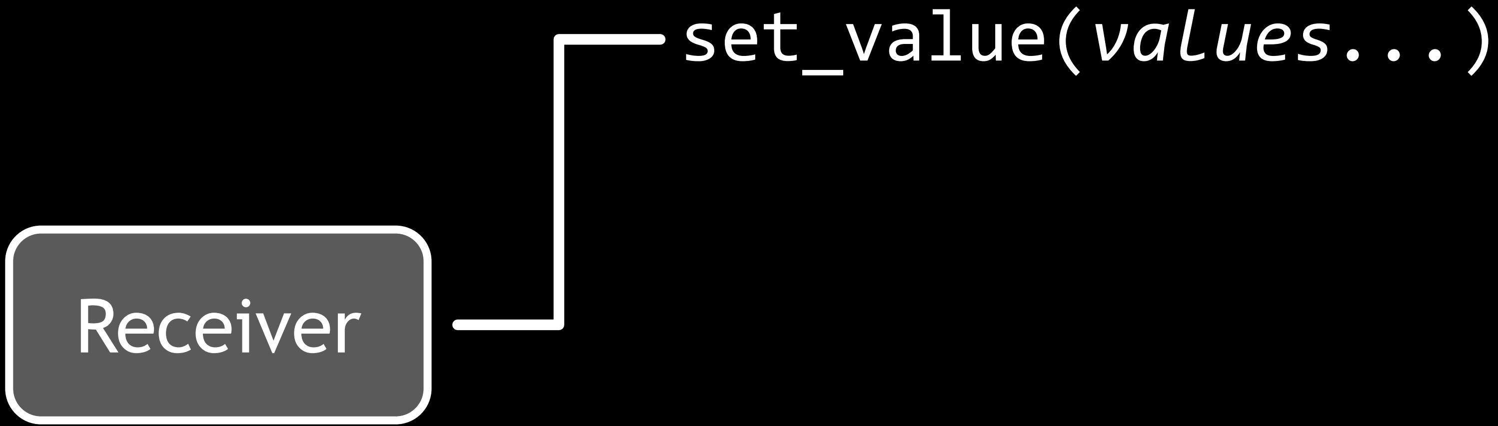
- Senders represent asynchronous work.
- Senders form the nodes of a task graph.
- Senders are lazy.

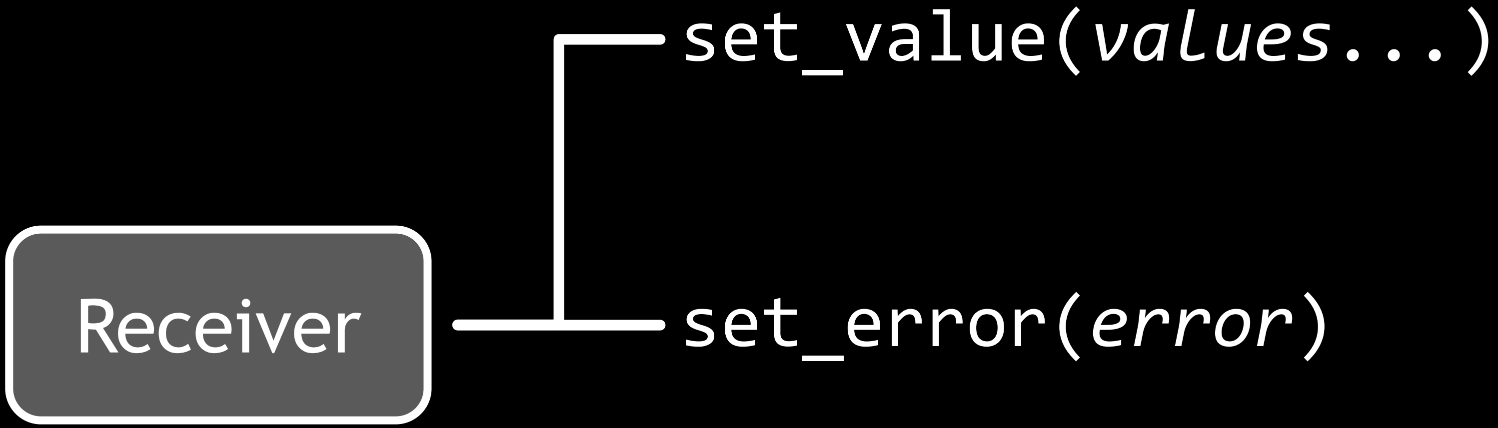


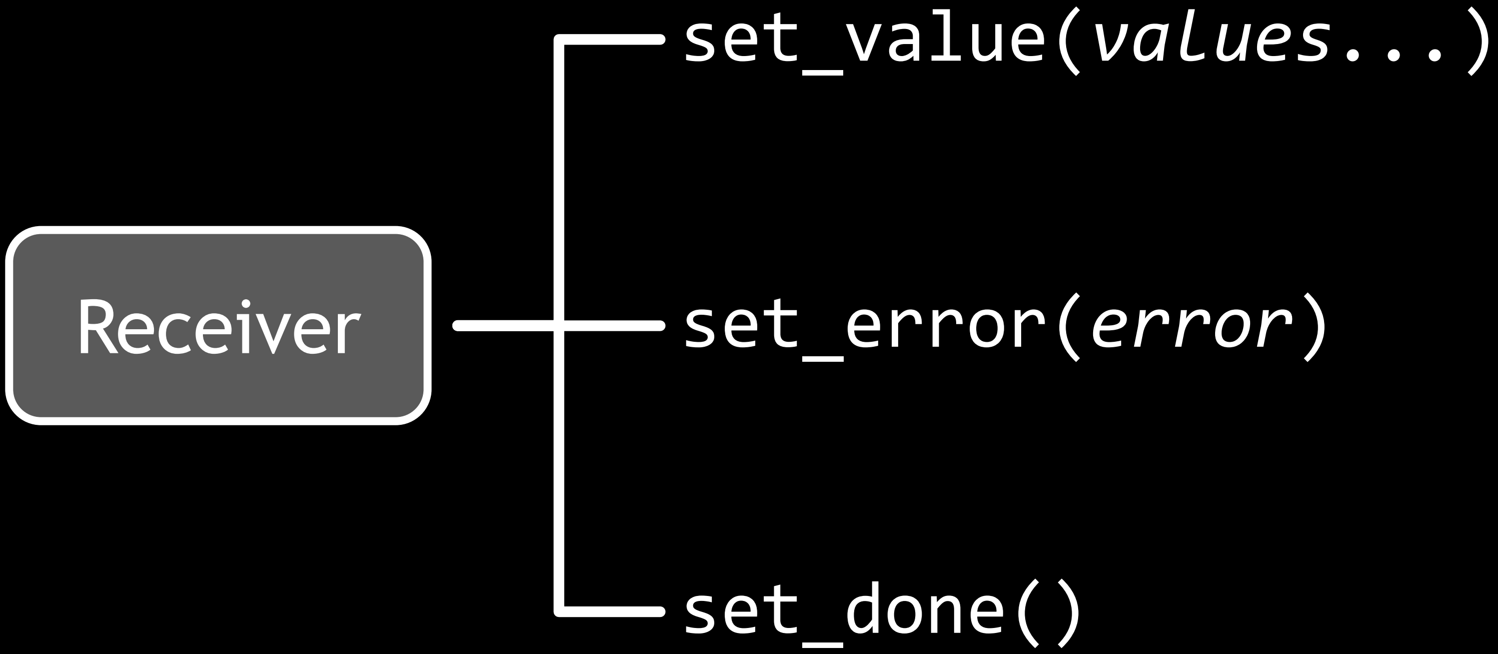
- Senders represent asynchronous work.
- Senders form the nodes of a task graph.
- Senders are lazy.
- When a sender's work completes, it sends a signal to the receivers attached to it.

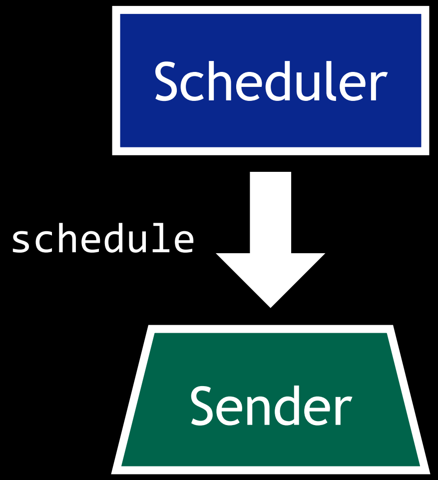


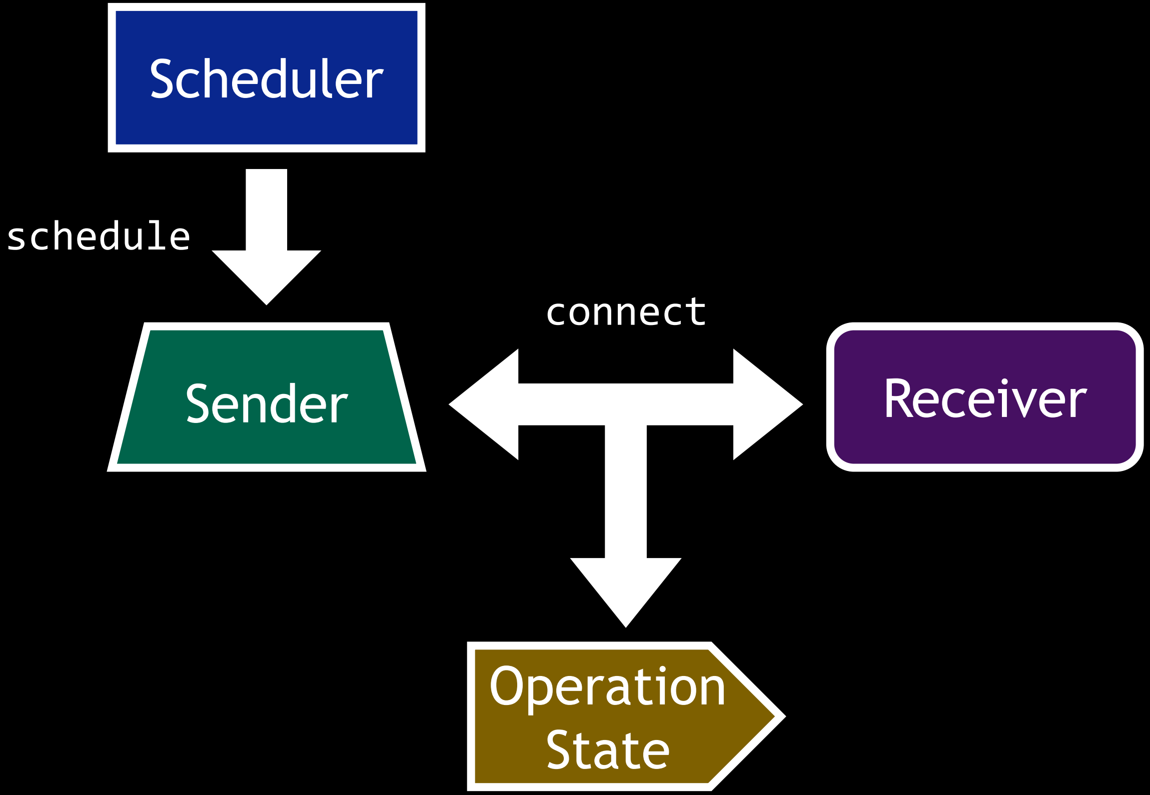
Receiver

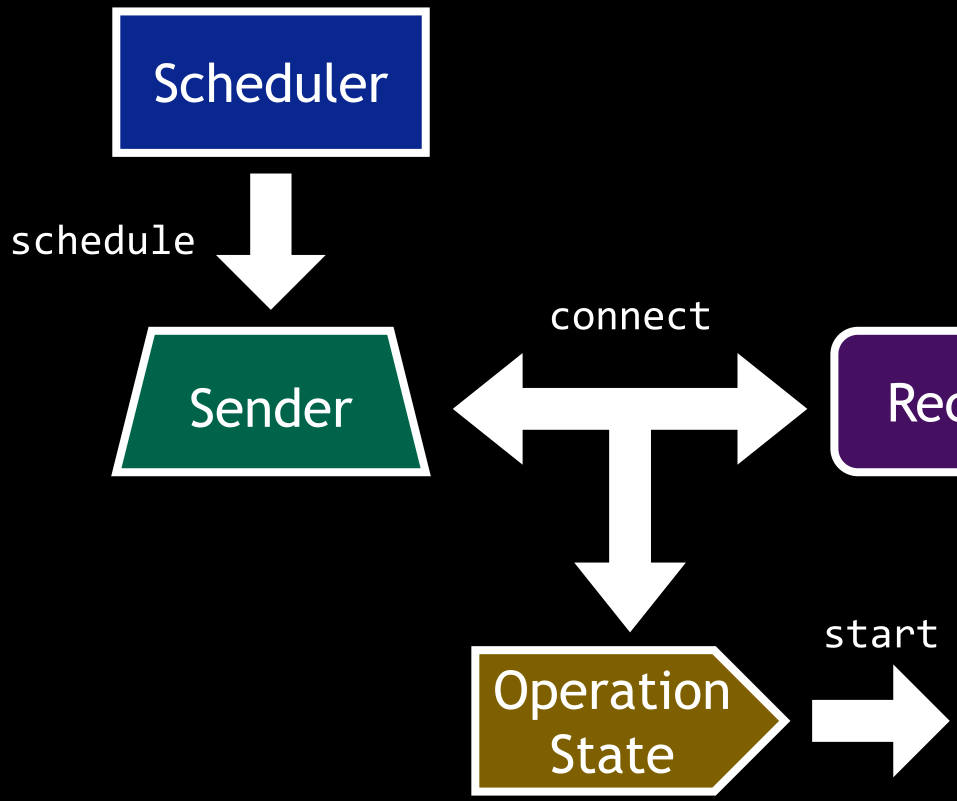

set_value(*values...*)
Receiver

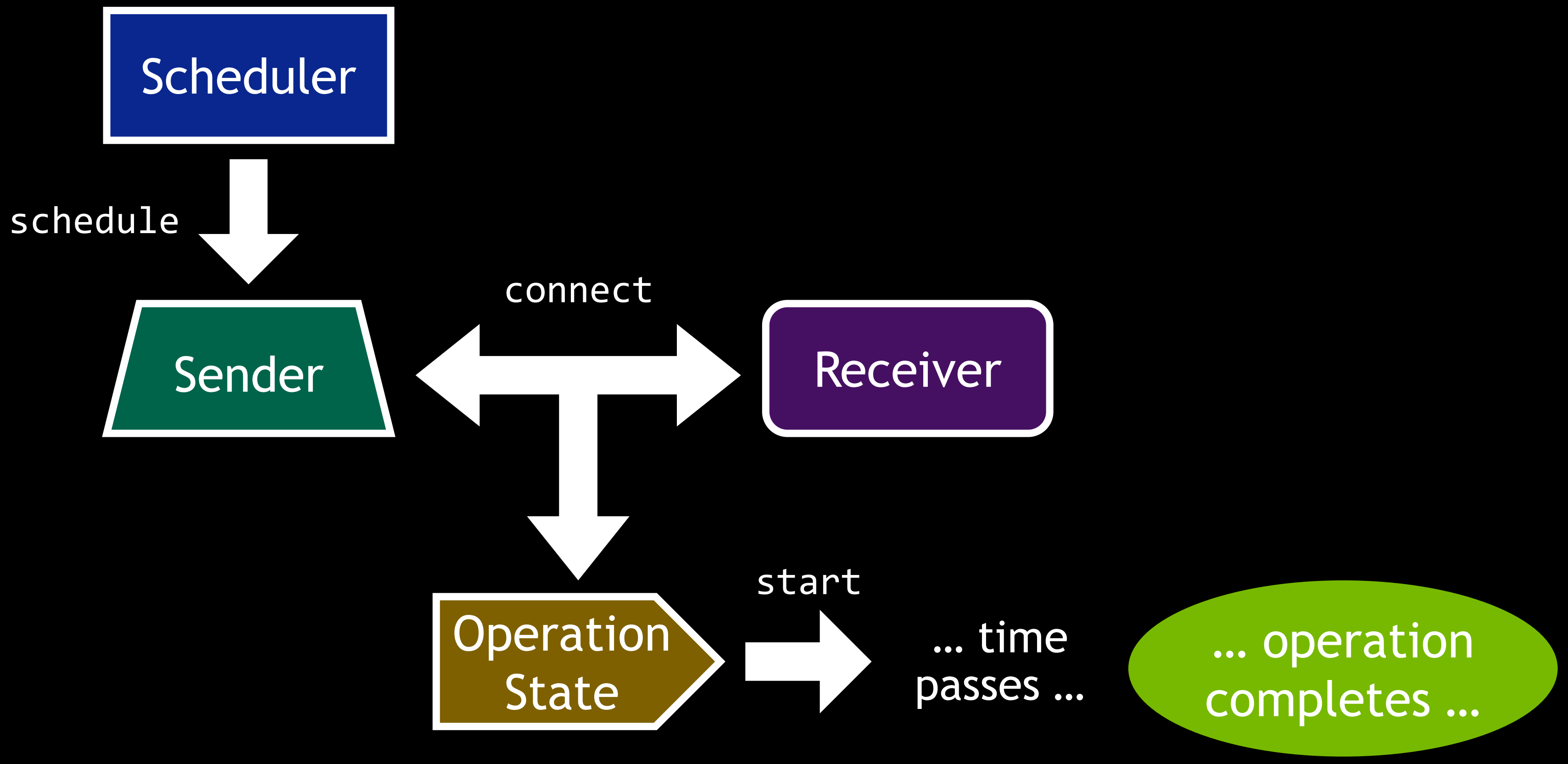

set_value(values...)
Receiver
set_error(error)

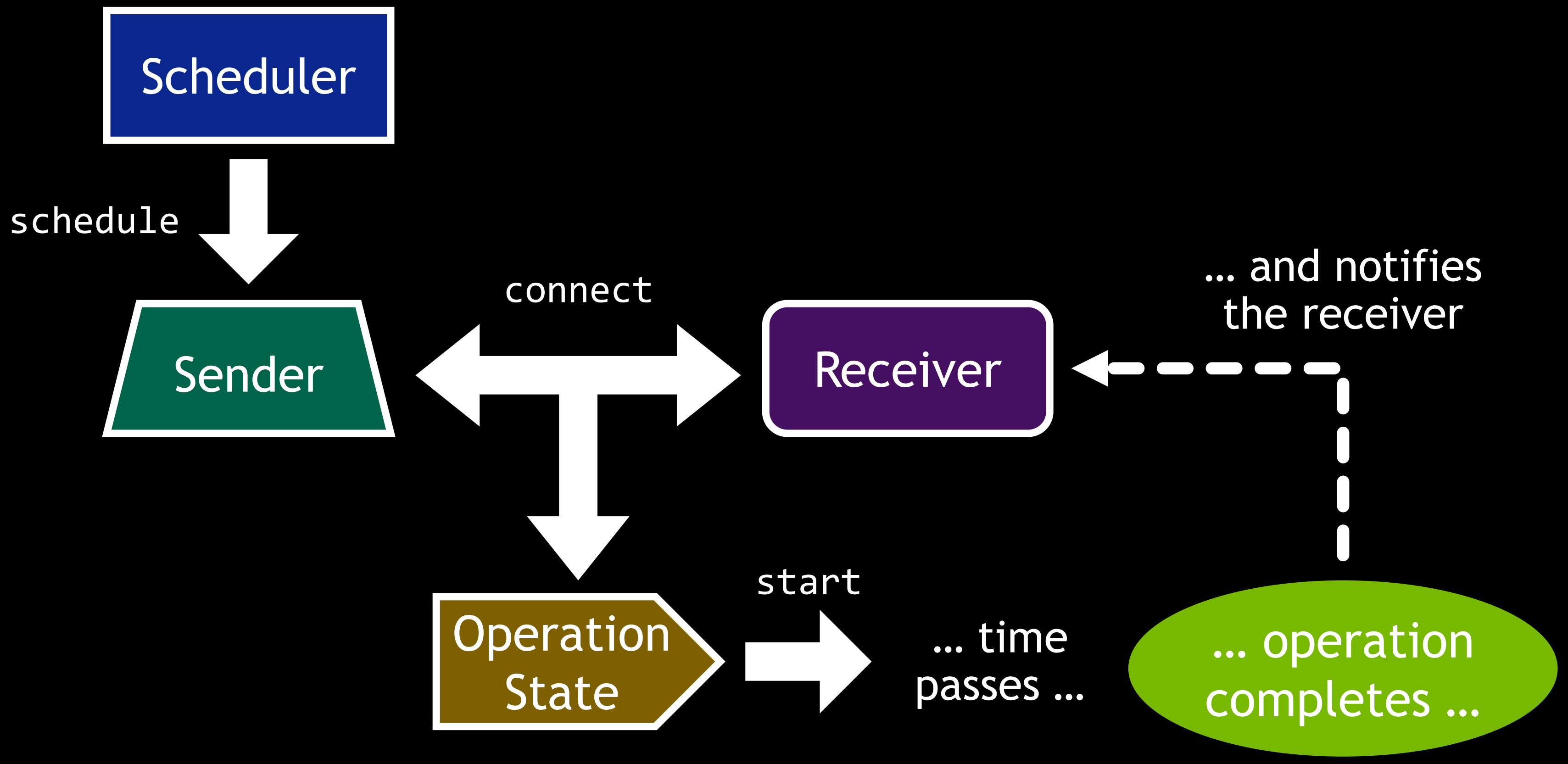

Receiver
set_value(values...)
set_error(error)
set_done()


Scheduler
schedule
Sender


Scheduler
schedule
Sender
connect
Receiver
Operation State


Scheduler
schedule
Sender
connect
Receiver
Operation State
start


Scheduler
schedule
Sender
connect
Receiver
Operation State
start
... time passes ...
... operation completes ...


Scheduler
schedule
Sender
connect
Receiver
... and notifies
the receiver
Operation
State
start
... time
passes ...
... operation
completes ...

```
sender auto f(sender auto p, ...);
```

```
sender auto f(sender auto p, ...);
```

- Takes one or more senders.

```
sender auto f(sender auto p, ...);
```

- Takes one or more senders.
- Return a sender.

```
sender auto f(sender auto p, ...);
```

- Takes one or more senders.
- Return a sender.
- Pipeable (think *nix shells):

```
snd | f | g
```

is equivalent to

```
g(f(snd))
```

```
std::vector<std::string_view> v{…};

ex::sender auto s = for_each_async(
                      ex::transfer(
                        unique_async(
                          sort_async(
                            ex::transfer_just(gpu_stream_scheduler{}, v)
                          )
                        ),
                        thread_pool.scheduler()
                      ),
                      [] (std::string_view e)
                      { std::print(file, "{}\n", e); }
                    );

this_thread::sync_wait(s);
```

```
std::vector<std::string_view> v{…};

ex::sender auto s0 = ex::transfer_just(gpu_stream_scheduler{}, v);
ex::sender auto s1 = sort_async(s0);
ex::sender auto s2 = unique_async(s1);
ex::sender auto s3 = ex::transfer(s2, thread_pool.scheduler());
ex::sender auto s4 = for_each_async(s3, [] (std::string_view e)
                                         { std::print(file, "{}\n", e); });

this_thread::sync_wait(s);
```

```
std::vector<std::string_view> v{…};

ex::sender auto s = ex::transfer_just(gpu_stream_scheduler{}, v)
                  | sort_async
                  | unique_async
                  | ex::transfer(thread_pool.scheduler())
                  | for_each_async([] (std::string_view e)
                                 { std::print(file, "{}\n", e); });

this_thread::sync_wait(s);
```

Sender Adaptor	Semantics Of Returned Sender

Sender Adaptor	Semantics Of Returned Sender
`then``(sender auto last, invocable auto f)`	Call `f` with the value sent by `last`.

Sender Adaptor	Semantics Of Returned Sender
then`(sender auto last, invocable auto f)`	Call `f` with the value sent by `last`.
bulk`(sender auto last, shape auto n, invocable auto body)`	Call body for every index in n with the value sent by `last`.

Sender Adaptor	Semantics Of Returned Sender
`then(sender auto last, invocable auto f)`	Call `f` with the value sent by `last`.
`bulk(sender auto last, shape auto n, invocable auto body)`	Call `body` for every index in `n` with the value sent by `last`.
`transfer(sender auto last, scheduler auto sch)`	Transition to `sch` for the next sender.

Sender Adaptor	Semantics Of Returned Sender
`then(sender auto last, invocable auto f)`	Call `f` with the value sent by `last`.
`bulk(sender auto last, shape auto n, invocable auto body)`	Call body for every index in n with the value sent by `last`.
`transfer(sender auto last, scheduler auto sch)`	Transition to `sch` for the next sender.
`split(sender auto last)`	Can be connected to multiple receivers.

Sender Adaptor	Semantics Of Returned Sender
<u>**`then`**</u>`(sender auto last, invocable auto f)`	Call `f` with the value sent by `last`.
<u>**`bulk`**</u>`(sender auto last, shape auto n, invocable auto body)`	Call body for every index in n with the value sent by `last`.
<u>**`transfer`**</u>`(sender auto last, scheduler auto sch)`	Transition to `sch` for the next sender.
<u>**`split`**</u>`(sender auto last)`	Can be connected multiple times.
<u>**`when_all`**</u>`(sender auto... inputs)`	Combines multiple senders into an aggregate.

Sender Adaptor	Semantics Of Returned Sender
then`(sender auto last, invocable auto f)`	Call `f` with the value sent by `last`.
bulk`(sender auto last, shape auto n, invocable auto body)`	Call body for every index in n with the value sent by `last`.
transfer`(sender auto last, scheduler auto sch)`	Transition to `sch` for the next sender.
split`(sender auto last)`	Can be connected multiple times.
when_all`(sender auto... inputs)`	Combines multiple senders into an aggregate.
ensure_started`(sender auto last)`	Connects and starts `last`.

Sender Adaptor	Semantics Of Returned Sender
then(sender auto last, invocable auto f)	Call f with the value sent by last.
bulk(sender auto last, shape auto n, invocable auto body)	Call body for every index in n with the value sent by last.
transfer(sender auto last, scheduler auto sch)	Transition to sch for the next sender.
split(sender auto last)	Can be connected multiple times.
when_all(sender auto... inputs)	Combines multiple senders into an aggregate.
ensure_started(sender auto last)	Connects and starts last.

Sender Factories	Semantics Of Returned Sender

Sender Adaptor	Semantics Of Returned Sender
`then``(sender auto last, invocable auto f)`	Call `f` with the value sent by `last`.
`bulk``(sender auto last, shape auto n, invocable auto body)`	Call body for every index in n with the value sent by `last`.
`transfer``(sender auto last, scheduler auto sch)`	Transition to `sch` for the next sender.
`split``(sender auto last)`	Can be connected multiple times.
`when_all``(sender auto... inputs)`	Combines multiple senders into an aggregate.
`ensure_started``(sender auto last)`	Connects and starts `last`.

Sender Factories	Semantics Of Returned Sender
`schedule``(scheduler auto sch)`	Completes on `sch`.

Sender Adaptor	Semantics Of Returned Sender
then(sender auto last, invocable auto f)	Call f with the value sent by last.
bulk(sender auto last, shape auto n, invocable auto body)	Call body for every index in n with the value sent by last.
transfer(sender auto last, scheduler auto sch)	Transition to sch for the next sender.
split(sender auto last)	Can be connected multiple times.
when_all(sender auto... inputs)	Combines multiple senders into an aggregate.
ensure_started(sender auto last)	Connects and starts last.

Sender Factories	Semantics Of Returned Sender
schedule(scheduler auto sch)	Completes on sch.
just(T&&... ts)	Send the values ts.

Sender Adaptor	Semantics Of Returned Sender
`then(sender auto last, invocable auto f)`	Call `f` with the value sent by `last`.
`bulk(sender auto last, shape auto n, invocable auto body)`	Call body for every index in n with the value sent by `last`.
`transfer(sender auto last, scheduler auto sch)`	Transition to `sch` for the next sender.
`split(sender auto last)`	Can be connected multiple times.
`when_all(sender auto... inputs)`	Combines multiple senders into an aggregate.
`ensure_started(sender auto last)`	Connects and starts `last`.

Sender Factories	Semantics Of Returned Sender
`schedule(scheduler auto sch)`	Completes on `sch`.
`just(T&&... ts)`	Send the values `ts`.

Sender Consumers	Semantics

Sender Adaptor	Semantics Of Returned Sender
then(sender auto last, invocable auto f)	Call f with the value sent by last.
bulk(sender auto last, shape auto n, invocable auto body)	Call body for every index in n with the value sent by last.
transfer(sender auto last, scheduler auto sch)	Transition to sch for the next sender.
split(sender auto last)	Can be connected multiple times.
when_all(sender auto... inputs)	Combines multiple senders into an aggregate.
ensure_started(sender auto last)	Connects and starts last.

Sender Factories	Semantics Of Returned Sender
schedule(scheduler auto sch)	Completes on sch.
just(T&&... ts)	Send the values ts.

Sender Consumers	Semantics
sync_wait(sender auto snd) -> *values-sent-by-sender*	Block until snd completes and return or throw whatever it sent.

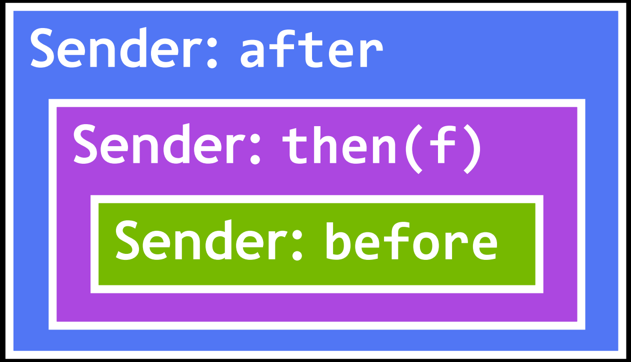
```
before | then(f) | after;
```

```
before | then(f) | after;
```

```
sender auto before_snd = …;
sender auto then_f_snd = then_sender(before_snd, f);
sender auto after_snd  = after_sender(then_f_snd);
```

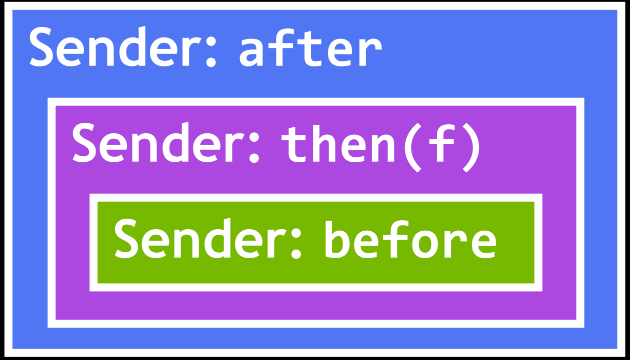
before | then(f) | after;

```
sender auto before_snd = …;
sender auto then_f_snd = then_sender(before_snd, f);
sender auto after_snd  = after_sender(then_f_snd);
```



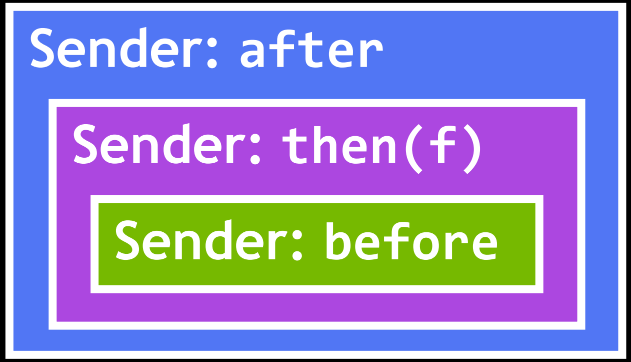
before | then(f) | after;

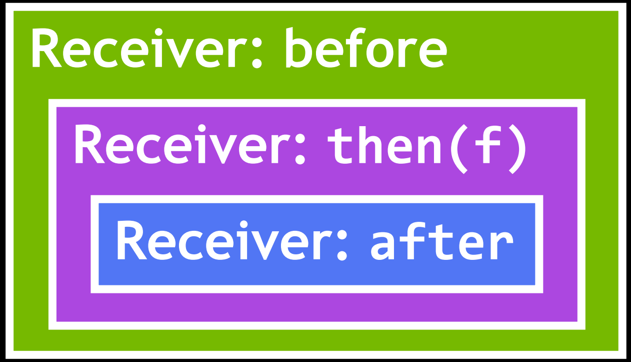
```
sender auto before_snd = …;
sender auto then_f_snd = then_sender(before_snd, f);
sender auto after_snd  = after_sender(then_f_snd);

…
    return connect(after_snd, …);
        return connect(then_f_snd, after_rcv);
            return connect(before_snd, then_f_rcv);
                …
```



before | then(f) | after;

```
sender auto before_snd = …;
sender auto then_f_snd = then_sender(before_snd, f);
sender auto after_snd  = after_sender(then_f_snd);

 …
     return connect(after_snd, …);
         return connect(then_f_snd, after_rcv);
             return connect(before_snd, then_f_rcv);
                 …
```





before | then(f) | after;

```
sender auto before_snd = …;
sender auto then_f_snd = then_sender(before_snd, f);
sender auto after_snd  = after_sender(then_f_snd);

 …
     return connect(after_snd, …);
         return connect(then_f_snd, after_rcv);
             return connect(before_snd, then_f_rcv);
                 …
```

Sender: after

Sender: then(f)

Sender: before

Receiver: before

Receiver: then(f)

Receiver: after

```
 …
     set_value(before_rcv, …);
         set_value(then_f_rcv, before_val);
             set_value(after_rcv, f(before_val));
                 …
```

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (…) -> ex::sender auto {
  …
}
```

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  …
}
```

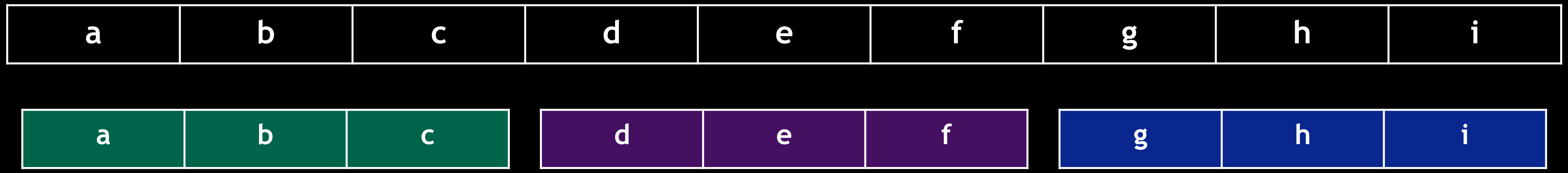
```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                   …
                 })
  …
}
```

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                    std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                    partials[0] = init;
                    return send_values(input, std::move(partials));
                  })
  …
}
```

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                   std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                   partials[0] = init;
                   return send_values(input, std::move(partials));
                 })
  …
}
```

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                      std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                      partials[0] = init;
                      return send_values(input, std::move(partials));
                    })
       | ex::bulk(tile_count,
                    [=] (std::size_t i, auto input, auto partials) {
                       …
                    })
  …
}
```

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                    std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                    partials[0] = init;
                    return send_values(input, std::move(partials));
                  })
       | ex::bulk(tile_count,
                  [=] (std::size_t i, auto input, auto partials) {
                    auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                    auto start      = i * tile_size;
                    auto end        = std::min(input.size(), (i + 1) * tile_size);
                    …
                  })
  …
}
```


a b c d e f g h i
a b c
d e f
g h i

a	b	c	d	e	f	g	h	i

a	ab	abc

`std::inclusive_scan`

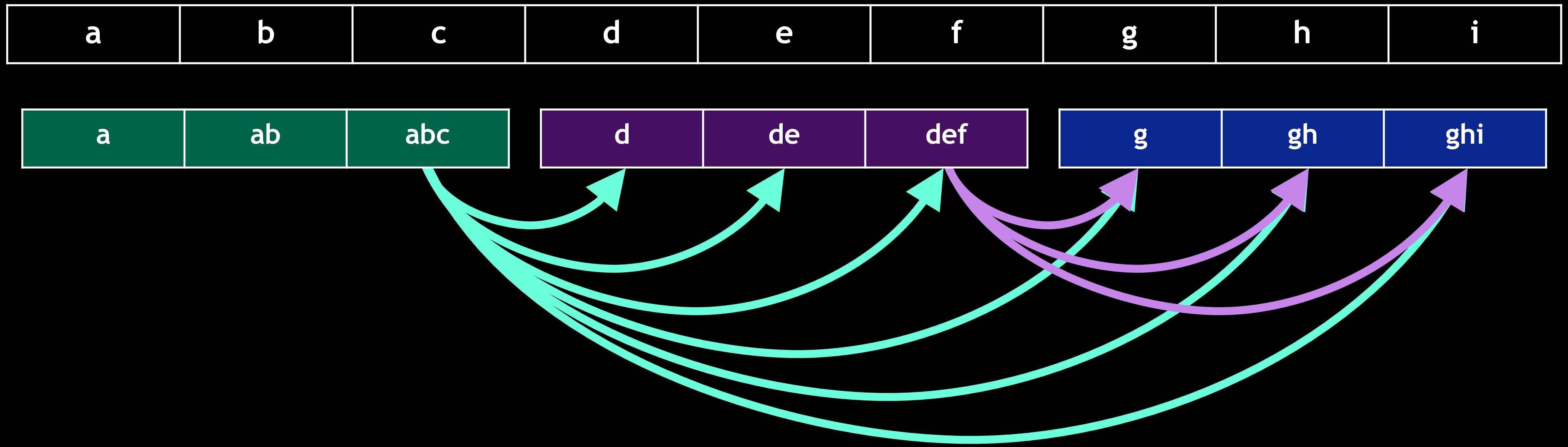
d	de	def

`std::inclusive_scan`

g	gh	ghi

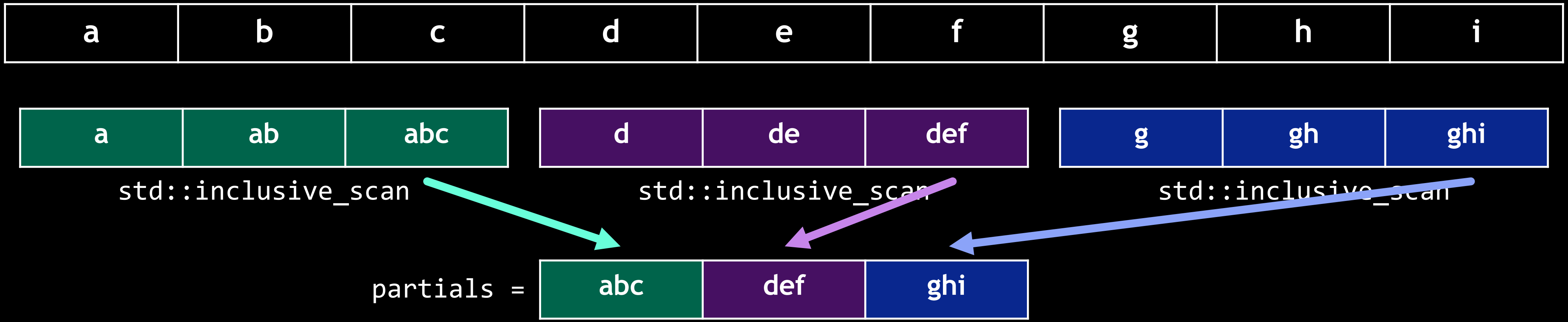
`std::inclusive_scan`

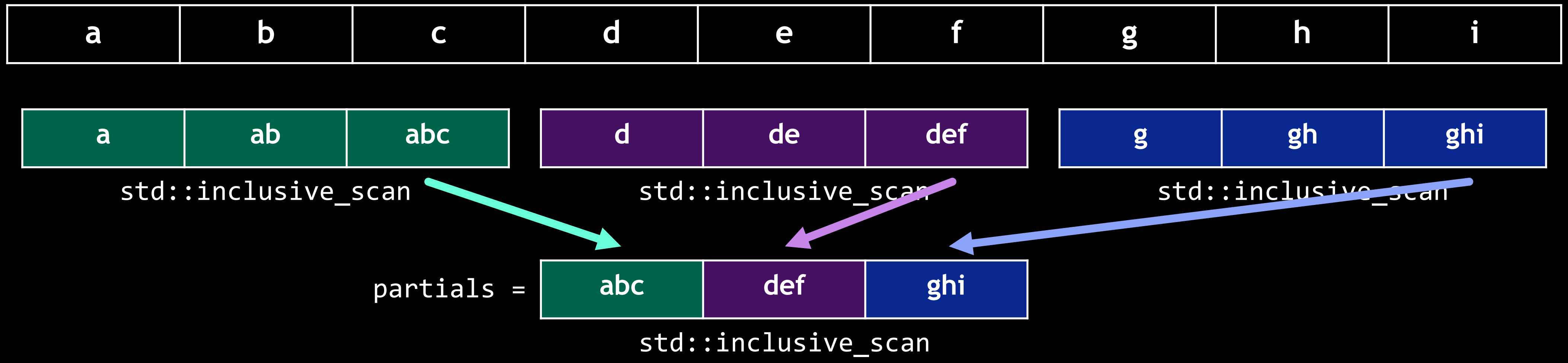
```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                  std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                  partials[0] = init;
                  return send_values(input, std::move(partials));
                })
       | ex::bulk(tile_count,
                [=] (std::size_t i, auto input, auto partials) {
                  auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                  auto start      = i * tile_size;
                  auto end        = std::min(input.size(), (i + 1) * tile_size);
                  …                    std::inclusive_scan(begin(input) + start,
                                                          begin(input) + end,
                                                          begin(input) + start);

                })
  …
}
```


a
b
c
d
e
f
g
h
i
a
ab
abc
d
de
def
g
gh
ghi

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                     std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                     partials[0] = init;
                     return send_values(input, std::move(partials));
                   })
       | ex::bulk(tile_count,
                   [=] (std::size_t i, auto input, auto partials) {
                     auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                     auto start      = i * tile_size;
                     auto end        = std::min(input.size(), (i + 1) * tile_size);
                     …               = *--std::inclusive_scan(begin(input) + start,
                                                              begin(input) + end,
                                                              begin(input) + start);
                   })
  …
}
```

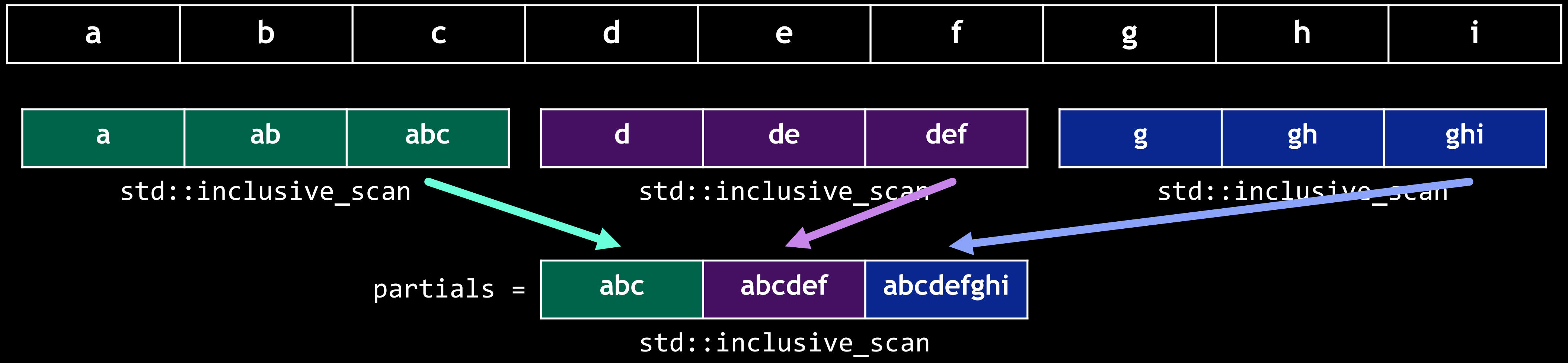
```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                  std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                  partials[0] = init;
                  return send_values(input, std::move(partials));
                })
       | ex::bulk(tile_count,
                [=] (std::size_t i, auto input, auto partials) {
                  auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                  auto start      = i * tile_size;
                  auto end        = std::min(input.size(), (i + 1) * tile_size);
                  partials[i + 1] = *--std::inclusive_scan(begin(input) + start,
                                                           begin(input) + end,
                                                           begin(input) + start);
                })
  …
}
```


a
b
c
d
e
f
g
h
i
a
ab
abc
d
de
def
g
gh
ghi
std::inclusive_scan
std::inclusive_scan
std::inclusive_scan
partials =
abc
def
ghi


a
b
c
d
e
f
g
h
i
a
ab
abc
d
de
def
g
gh
ghi
std::inclusive_scan
std::inclusive_scan
std::inclusive_scan
partials =
abc
def
ghi
std::inclusive_scan

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                      std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                      partials[0] = init;
                      return send_values(input, std::move(partials));
                    })
       | ex::bulk(tile_count,
                    [=] (std::size_t i, auto input, auto partials) {
                      auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                      auto start      = i * tile_size;
                      auto end        = std::min(input.size(), (i + 1) * tile_size);
                      partials[i + 1] = *--std::inclusive_scan(begin(input) + start,
                                                               begin(input) + end,
                                                               begin(input) + start);
                    })
       | ex::then([] (auto input, auto partials) {
                      std::inclusive_scan(begin(partials), end(partials), begin(partials));
                      …
                    })
  …
}
```

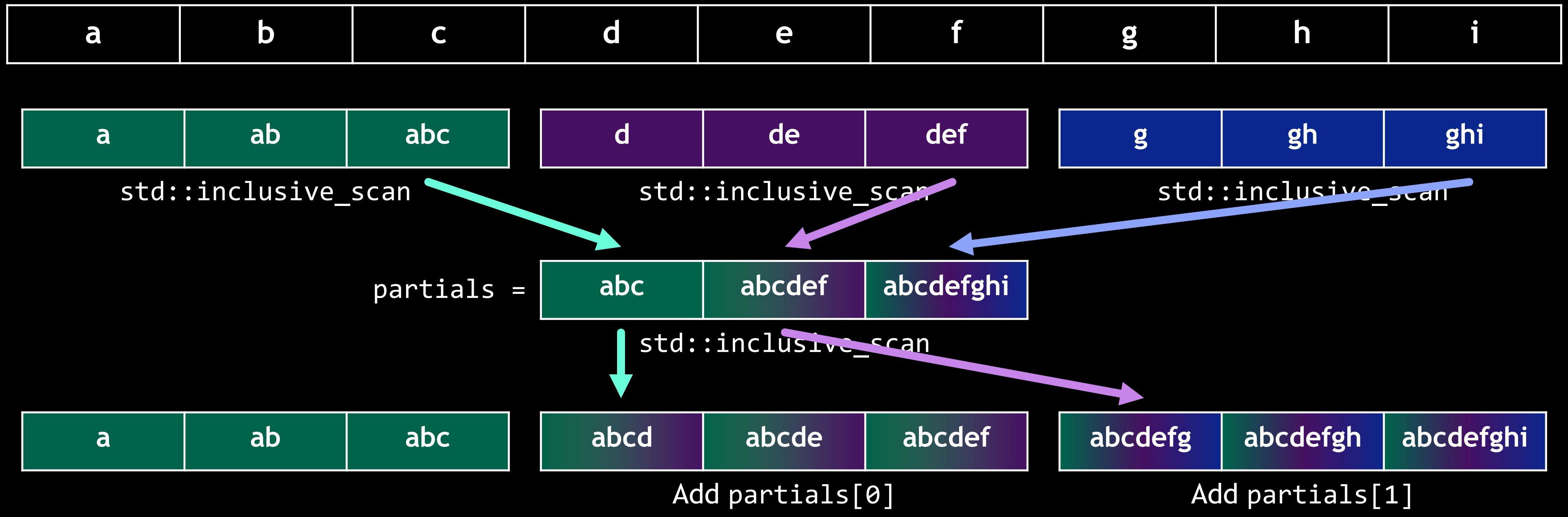
```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                    std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                    partials[0] = init;
                    return send_values(input, std::move(partials));
                  })
       | ex::bulk(tile_count,
                  [=] (std::size_t i, auto input, auto partials) {
                    auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                    auto start      = i * tile_size;
                    auto end        = std::min(input.size(), (i + 1) * tile_size);
                    partials[i + 1] = *--std::inclusive_scan(begin(input) + start,
                                                             begin(input) + end,
                                                             begin(input) + start);
                  })
       | ex::then([] (auto input, auto partials) {
                    std::inclusive_scan(begin(partials), end(partials), begin(partials));
                    return send_values(input, std::move(partials));
                  })
  …
}
```


a
b
c
d
e
f
g
h
i
a
ab
abc
d
de
def
g
gh
ghi
std::inclusive_scan
std::inclusive_scan
std::inclusive_scan
partials =
abc
abcdef
abcdefghi
std::inclusive_scan

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                  std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                  partials[0] = init;
                  return send_values(input, std::move(partials));
                })
       | ex::bulk(tile_count,
                [=] (std::size_t i, auto input, auto partials) {
                  auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                  auto start      = i * tile_size;
                  auto end        = std::min(input.size(), (i + 1) * tile_size);
                  partials[i + 1] = *--std::inclusive_scan(begin(input) + start,
                                                           begin(input) + end,
                                                           begin(input) + start);
                })
       | ex::then([] (auto input, auto partials) {
                  std::inclusive_scan(begin(partials), end(partials), begin(partials));
                  return send_values(input, std::move(partials));
                })
       | ex::bulk(tile_count,
                [=] (std::size_t i, auto input, auto partials) {
                  …
                })
  …
}
```

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                    std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                    partials[0] = init;
                    return send_values(input, std::move(partials));
                  })
       | ex::bulk(tile_count,
                  [=] (std::size_t i, auto input, auto partials) {
                    auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                    auto start      = i * tile_size;
                    auto end        = std::min(input.size(), (i + 1) * tile_size);
                    partials[i + 1] = *--std::inclusive_scan(begin(input) + start,
                                                             begin(input) + end,
                                                             begin(input) + start);
                  })
       | ex::then([] (auto input, auto partials) {
                    std::inclusive_scan(begin(partials), end(partials), begin(partials));
                    return send_values(input, std::move(partials));
                  })
       | ex::bulk(tile_count,
                  [=] (std::size_t i, auto input, auto partials) {
                    auto tile_size = (input.size() + tile_count - 1) / tile_count;
                    auto start     = i * tile_size;
                    auto end       = std::min(input.size(), (i + 1) * tile_size);
                    …
                  })
  …
}
```

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                  std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                  partials[0] = init;
                  return send_values(input, std::move(partials));
                })
       | ex::bulk(tile_count,
                [=] (std::size_t i, auto input, auto partials) {
                  auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                  auto start      = i * tile_size;
                  auto end        = std::min(input.size(), (i + 1) * tile_size);
                  partials[i + 1] = *--std::inclusive_scan(begin(input) + start,
                                                           begin(input) + end,
                                                           begin(input) + start);
                })
       | ex::then([] (auto input, auto partials) {
                  std::inclusive_scan(begin(partials), end(partials), begin(partials));
                  return send_values(input, std::move(partials));
                })
       | ex::bulk(tile_count,
                [=] (std::size_t i, auto input, auto partials) {
                  auto tile_size = (input.size() + tile_count - 1) / tile_count;
                  auto start     = i * tile_size;
                  auto end       = std::min(input.size(), (i + 1) * tile_size);
                  std::for_each(begin(input) + start, begin(input) + end,
                                [&] (auto& e) { e = partials[i] + e; });
                })
  …
}
```


a
b
c
d
e
f
g
h
i
a
ab
abc
d
de
def
g
gh
ghi
std::inclusive_scan
std::inclusive_scan
std::inclusive_scan
partials =
abc
abcdef
abcdefghi
std::inclusive_scan
a
ab
abc
abcd
abcde
abcdef
abcdefg
abcdefgh
abcdefghi
Add partials[0]
Add partials[1]

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                      std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                      partials[0] = init;
                      return send_values(input, std::move(partials));
                    })
       | ex::bulk(tile_count,
                    [=] (std::size_t i, auto input, auto partials) {
                      auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                      auto start      = i * tile_size;
                      auto end        = std::min(input.size(), (i + 1) * tile_size);
                      partials[i + 1] = *--std::inclusive_scan(begin(input) + start,
                                                               begin(input) + end,
                                                               begin(input) + start);
                    })
       | ex::then([] (auto input, auto partials) {
                      std::inclusive_scan(begin(partials), end(partials), begin(partials));
                      return send_values(input, std::move(partials));
                    })
       | ex::bulk(tile_count,
                    [=] (std::size_t i, auto input, auto partials) {
                      auto tile_size = (input.size() + tile_count - 1) / tile_count;
                      auto start     = i * tile_size;
                      auto end       = std::min(input.size(), (i + 1) * tile_size);
                      std::for_each(begin(input) + start, begin(input) + end,
                                    [&] (auto& e) { e = partials[i] + e; });
                    })
       | ex::then([=] (auto input, auto partials) { return input; });
}
```

```
inline constexpr sender_adaptor
inclusive_scan_async = [] (ex::sender auto last, auto init, std::size_t tile_count) -> ex::sender auto {
  return last
       | ex::then([=] (stdr::random_access_range auto input) {
                  std::vector<stdr::range_value_t<decltype(input)>> partials(tile_count + 1);
                  partials[0] = init;
                  return send_values(input, std::move(partials));
                })
       | ex::bulk(tile_count,
                [=] (std::size_t i, auto input, auto partials) {
                  auto tile_size  = (input.size() + tile_count - 1) / tile_count;
                  auto start      = i * tile_size;
                  auto end        = std::min(input.size(), (i + 1) * tile_size);
                  partials[i + 1] = *--std::inclusive_scan(begin(input) + start,
                                                          begin(input) + end,
                                                          begin(input) + start);
                })
       | ex::then([] (auto input, auto partials) {
                  std::inclusive_scan(begin(partials), end(partials), begin(partials));
                  return send_values(input, std::move(partials));
                })
       | ex::bulk(tile_count,
                [=] (std::size_t i, auto input, auto partials) {
                  auto tile_size = (input.size() + tile_count - 1) / tile_count;
                  auto start     = i * tile_size;
                  auto end       = std::min(input.size(), (i + 1) * tile_size);
                  std::for_each(begin(input) + start, begin(input) + end,
                                [&] (auto& e) { e = partials[i] + e; });
                })
       | ex::then([=] (auto input, auto partials) { return input; });
}
```

```
stdr::for_each(rng, f);
stdr::for_each(rng, g);
stdr::for_each(rng, h);
```

```
ex::sender_of<stdr::range> auto
transform_async(ex::sender_of<stdr::range> auto rng, std::callable auto c);
```

```
stdr::for_each(rng, f);
stdr::for_each(rng, g);
stdr::for_each(rng, h);
```

```
ex::sender snd =
    ex::transfer_just(sch, rng)
  | transform_async(f)
  | transform_async(g)
  | transform_async(h);
```

```
auto max = *stdr::max_element(rng);

stdr::for_each(rng,
  [=] (auto x) { return x / max; });
```

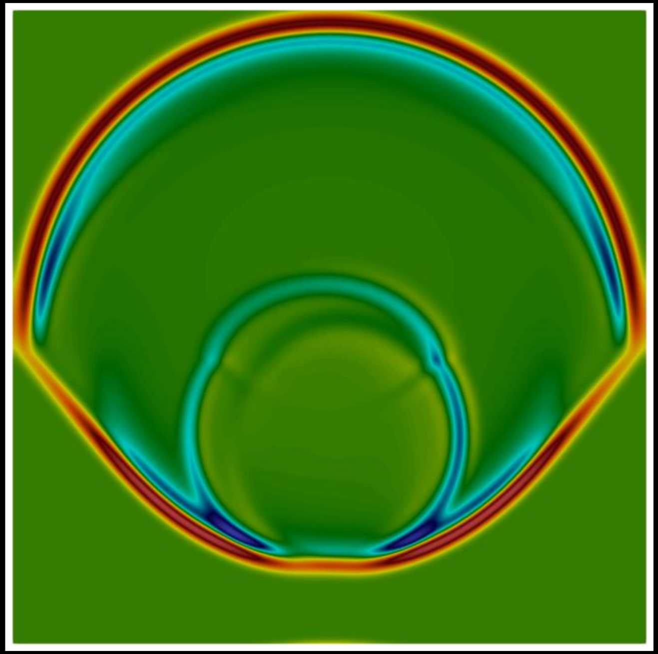
```
ex::sender_of<stdr::range, stdr::range, …> auto
transform_async(ex::sender_of<stdr::range, stdr::range, …> auto rngs,
                std::callable auto f);

ex::sender_of<stdr::range, std::forward_iterator> auto
max_element_async(ex::sender_of<stdr::range> auto rng);
```

```
auto max = *stdr::max_element(rng);

stdr::for_each(rng,
  [=] (auto x) { return x / max; });
```

```
ex::sender auto snd =
    ex::transfer_just(sch, rng)
  | max_element_async
  | ex::let_value(
      [] (auto r, auto max) {
        return ex::just(r, max);
      })
  | transform_async(std::divides);
```

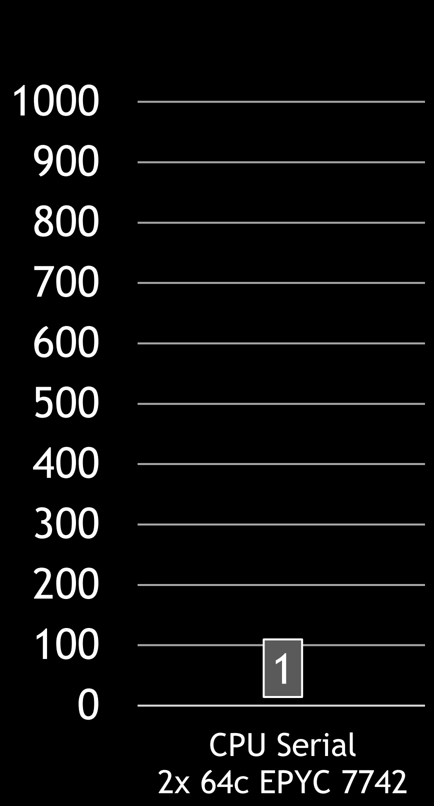
Maxwell’s Equations

```
sender auto maxwell_eqs(scheduler auto& compute,
                        grid_accessor A, …) {
  return repeat_n(n_outer_iterations,
           repeat_n(n_inner_iterations,
               schedule(compute)
             | bulk(G.cells, update_h(G))
             | halo_exchange(G, hx, hy)
             | bulk(G.cells, update_e(time, dt, G))
             | halo_exchange(G, hx, hy))
           | transfer(cpu_serial_scheduler)
           | then(output_results))
         );
}
```



Maxwell's Equations

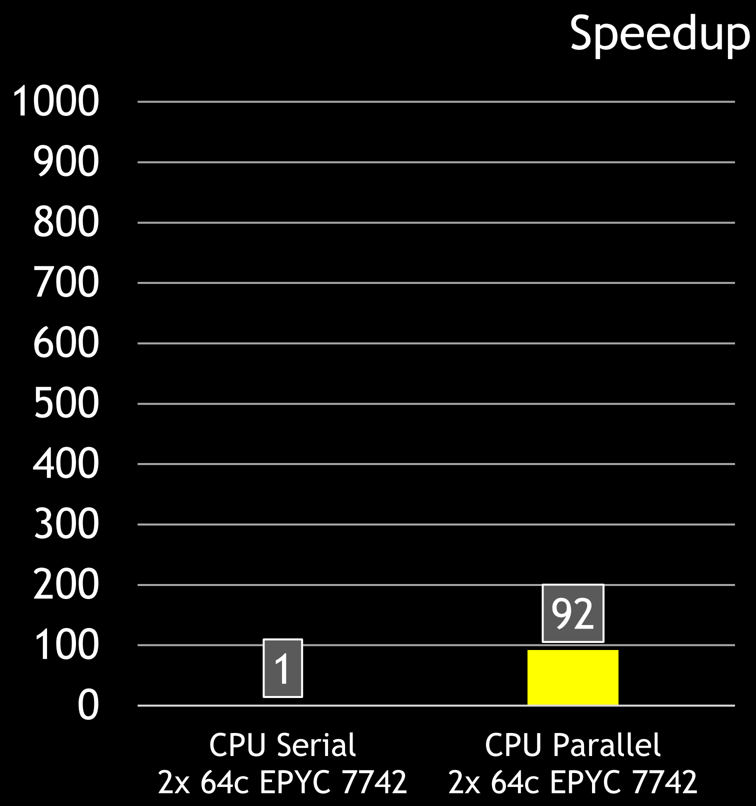
Change one line of code and scale from a single CPU thread…




```
sync_wait(maxwell_eqs(cpu_serial_scheduler), …);
```

Maxwell's Equations

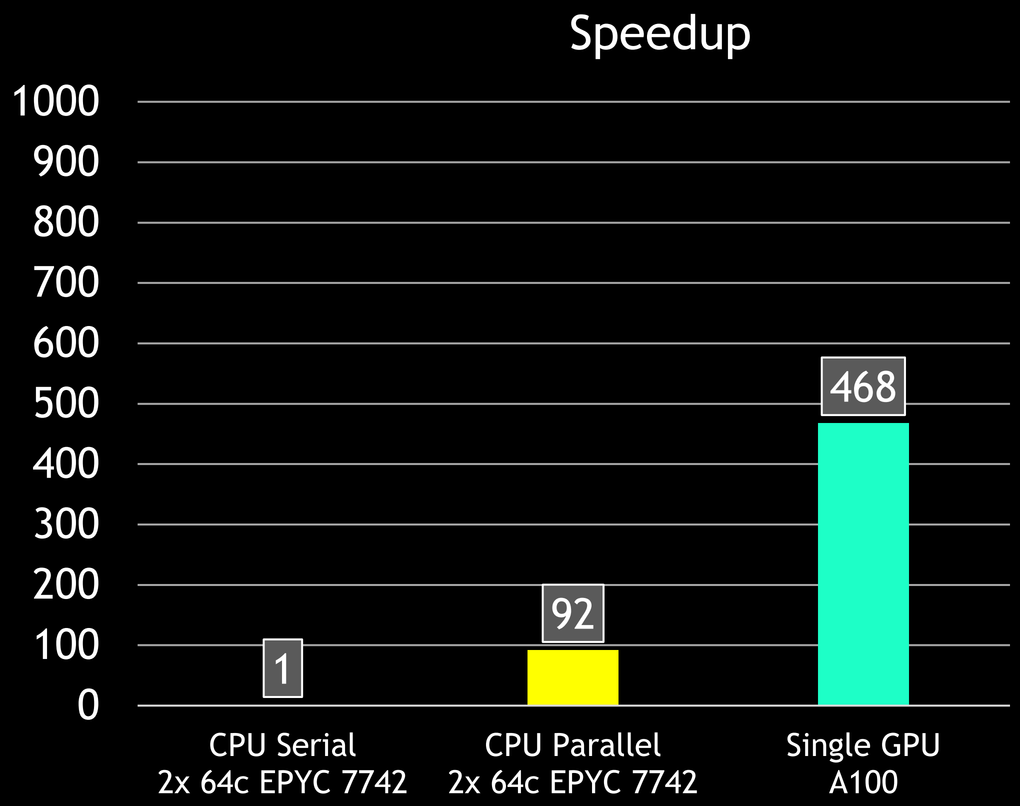
Change one line of code and scale from a single CPU thread up to multiple CPU threads…




```
sync_wait(maxwell_eqs(cpu_parallel_scheduler), …);
```

Maxwell's Equations

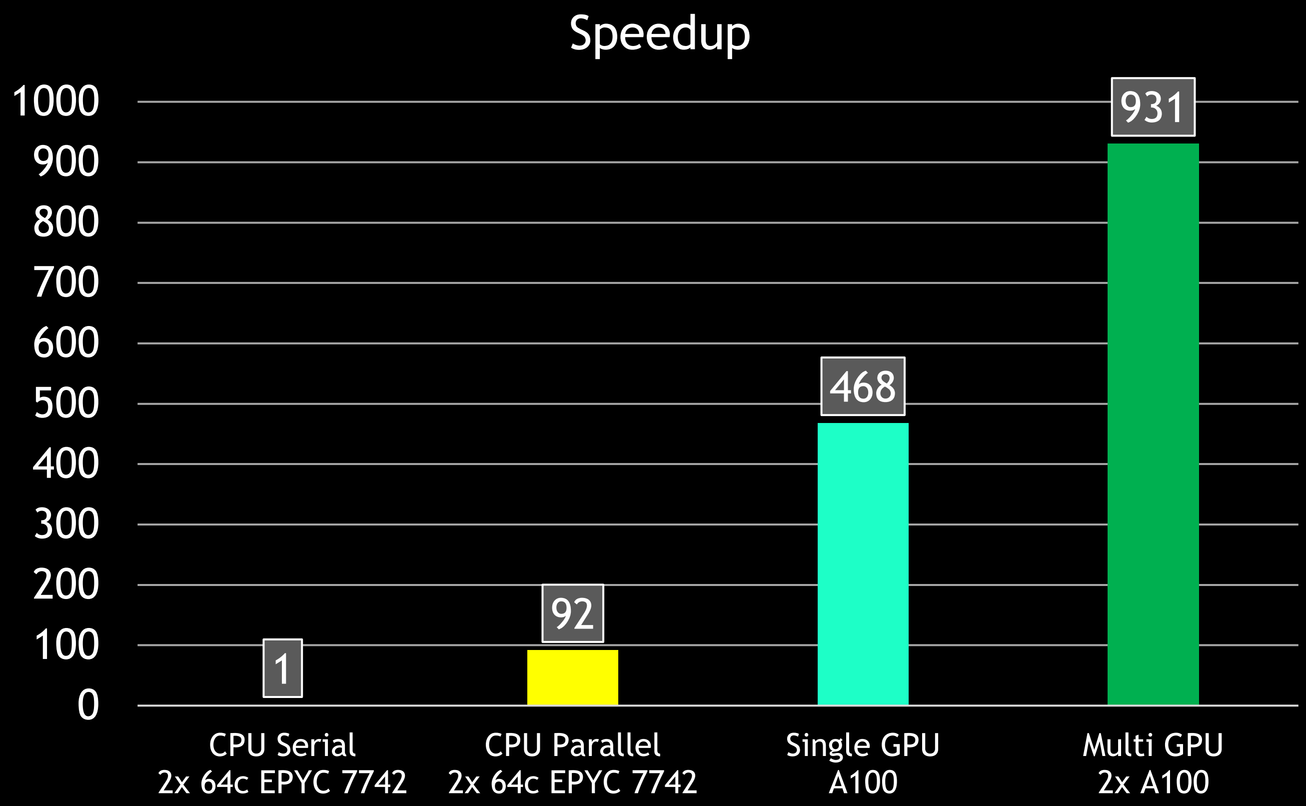
Change one line of code and scale from a single CPU thread up to a GPU…




```
sync_wait(maxwell_eqs(single_gpu_scheduler), …);
```

Maxwell's Equations

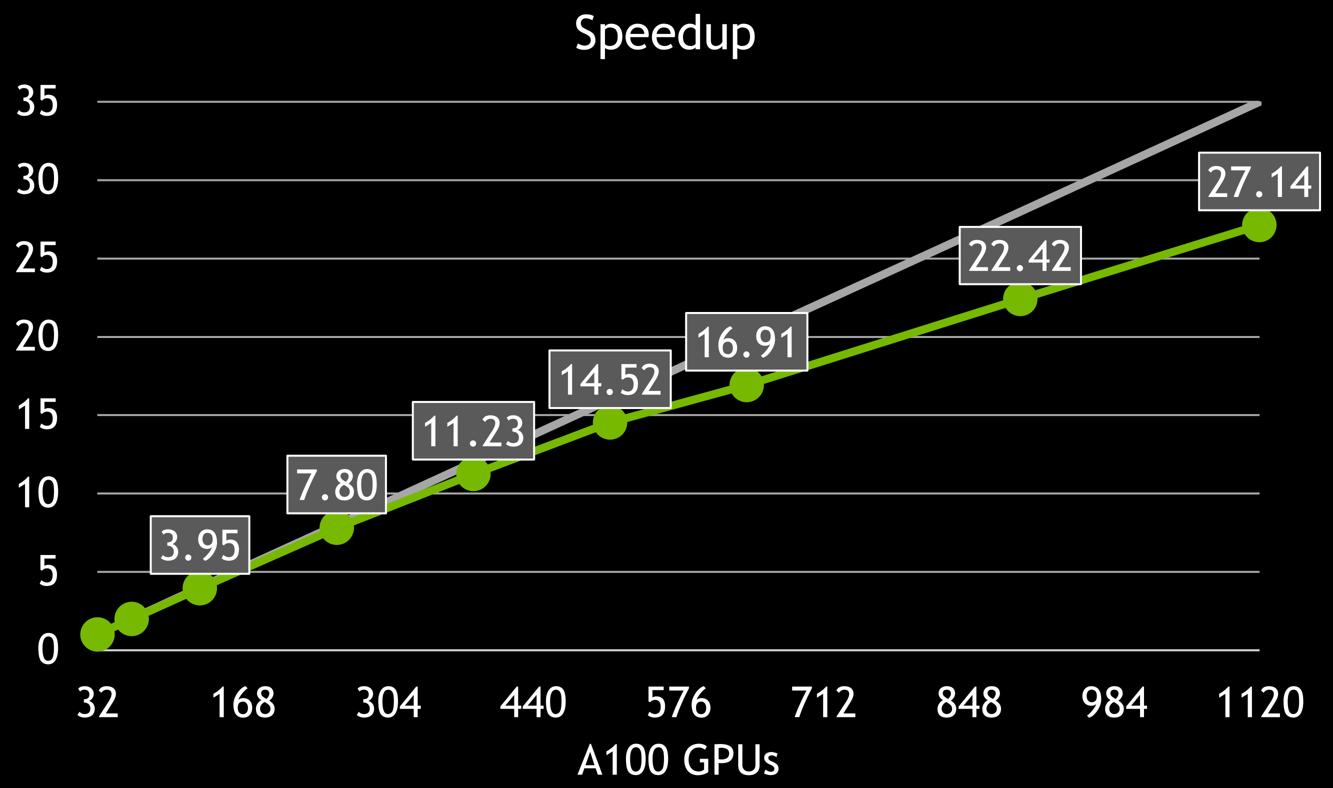
Change one line of code and scale from a single CPU thread up to multiple GPUs…




```
sync_wait(maxwell_eqs(multi_gpu_scheduler), …);
```

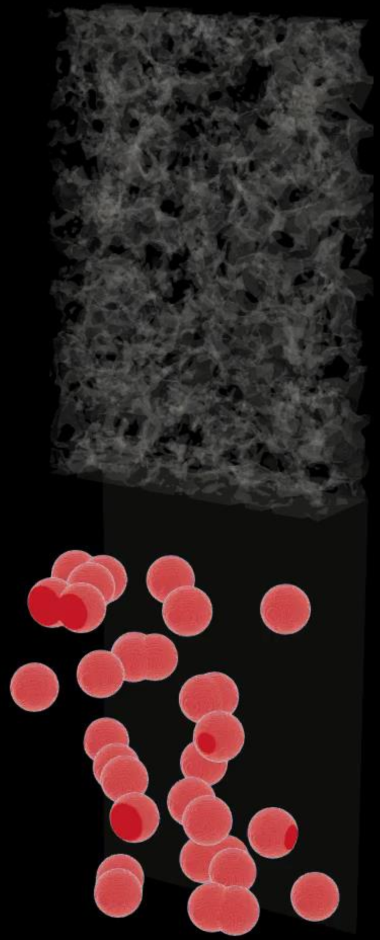
Maxwell’s Equations

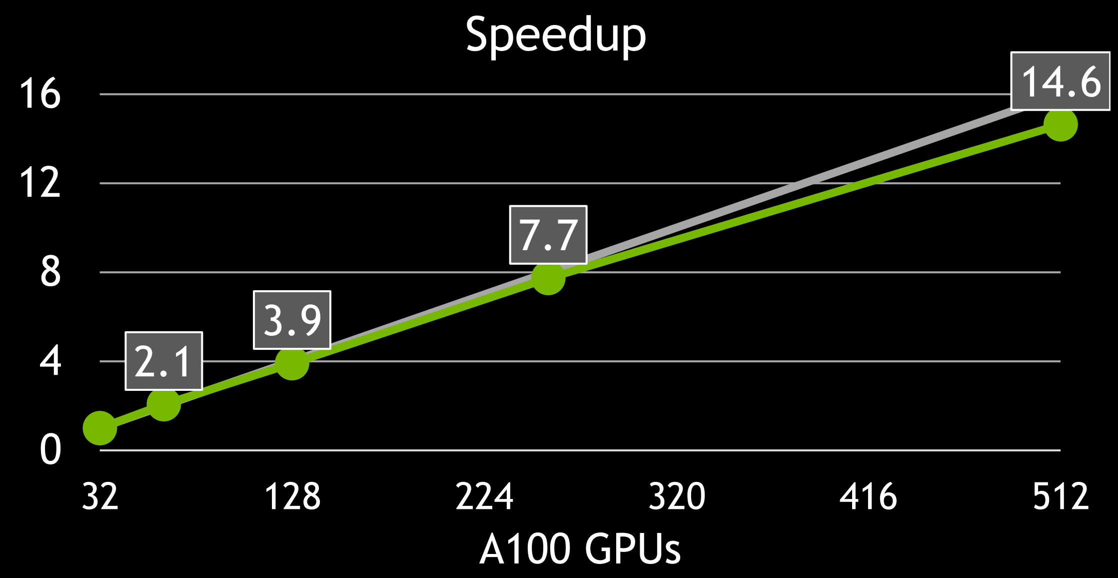
Change one line of code and scale from a single CPU thread up to a cluster of GPUs!




```
sync_wait(maxwell_eqs(multi_node_gpu_scheduler), …);
```

Palabos Carbon Sequestration



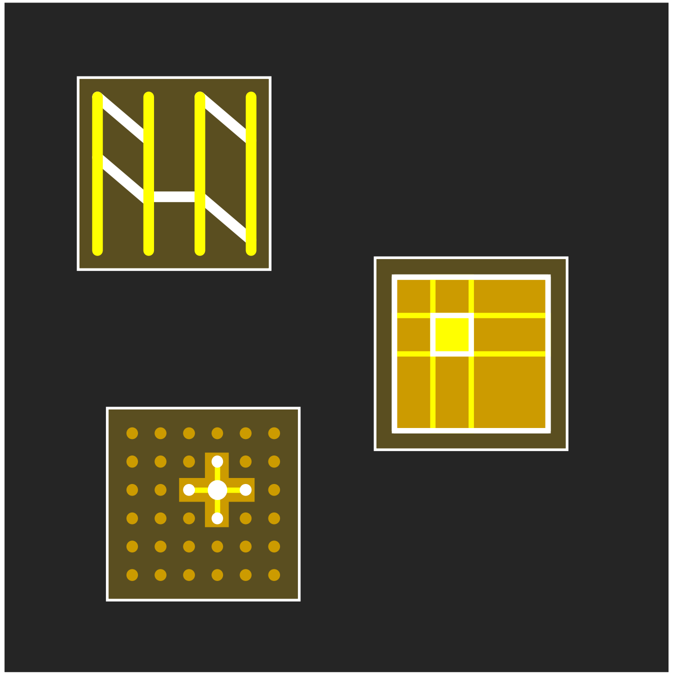


- Palabos is a framework for parallel computational fluid dynamics simulations using the Lattice-Boltzmann method.
- Code for multi-component flow through a porous media ported to C++ Senders and Receivers.
- Application: simulating carbon sequestration in sandstone.

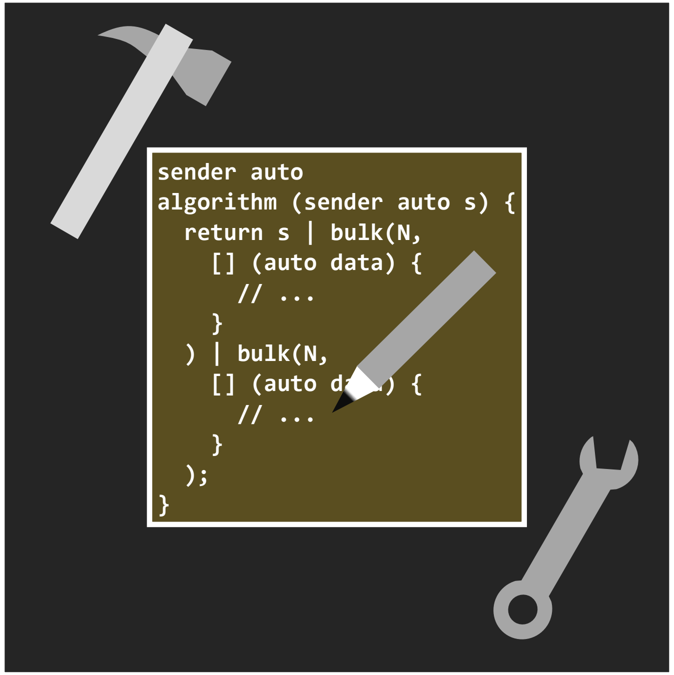
Jonas Latt (University of Geneva), Christian Huber (Brown University)
Georgy Evtushenko (NVIDIA), Gonzalo Brito (NVIDIA)

Pillars of C++ Standard Parallelism

Common Algorithms that Dispatch to Vendor-Optimized Parallel Libraries

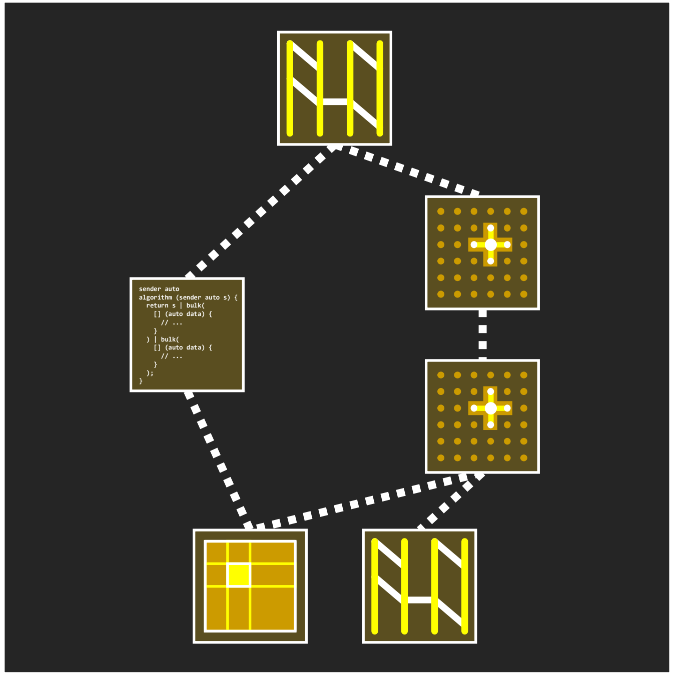


Tools to Write Your Own Parallel Algorithms that Run Anywhere



```
sender auto
algorithm (sender auto s) {
  return s | bulk(N,
    [] (auto data) {
      // ...
    }
  ) | bulk(N,
    [] (auto data) {
      // ...
    }
  );
}
```

Mechanisms for Composing Parallel Invocations into Task Graphs



Today

With Senders & Receivers

Standard Algorithms

Serial (C++98)

```
std::vector<T> x{…};

std::for_each(
 begin(x), end(x),
 f);

std::for_each(
 begin(x), end(x),
 g);

std::for_each(
 begin(x), end(x),
 h);
```

Parallel (C++17)

```
std::vector<T> x{…};

std::for_each(
 ex::par_unseq,
 begin(x), end(x),
 f);
std::for_each(
 ex::par_unseq,
 begin(x), end(x),
 g);
std::for_each(
 ex::par_unseq,
 begin(x), end(x),
 h);
```

Asynchronous

```
std::vector<T> x(…);

ex::sender auto s
 = ex::transfer_just(sch, x)
 | for_each_async(f)
 | for_each_async(g)
 | for_each_async(h);

this_thread::sync_wait(s);
```

Today, C++ has no reasonable abstraction for multi-dimensional data.

Today, C++ has no reasonable abstraction for multi-dimensional data.

The solution is coming in C++23:

`std::mdspan`

`std::mdspan`

- Non-owning; pointer + metadata.

`std::mdspan`

- Non-owning; pointer + metadata.
- Metadata can be dynamic or static.

`std::mdspan`

- Non-owning; pointer + metadata.
- Metadata can be dynamic or static.
- Parameterizes layout.

`std::mdspan`

- Non-owning; pointer + metadata.
- Metadata can be dynamic or static.
- Parameterizes layout and access.

```
template <typename Size, Size... Extents>
class std::extents;
```

```
template <typename Size, Size... Extents>
class std::extents;

std::extents e0{16, 32};
// Equivalent to:
std::extents<std::dynamic_extent, std::dynamic_extent> e1{16, 32};


e0.rank()     == 2
e0.extent(0) == 16
e0.extent(1) == 32
```

```cpp
template <typename Size, Size... Extents>
class std::extents;

std::extents e0{16, 32};
// Equivalent to:
std::extents<std::dynamic_extent, std::dynamic_extent> e1{16, 32};
std::dextents<2> e2{16, 32};

e0.rank()     == 2
e0.extent(0) == 16
e0.extent(1) == 32
```

```cpp
template <typename Size, Size... Extents>
class std::extents;

std::extents e0{16, 32};
// Equivalent to:
std::extents<std::dynamic_extent, std::dynamic_extent> e1{16, 32};
std::dextents<2> e2{16, 32};

e0.rank()     == 2
e0.extent(0) == 16
e0.extent(1) == 32

std::extents<16, 32> e3;
```

```
template <typename Size, Size... Extents>
class std::extents;

std::extents e0{16, 32};
// Equivalent to:
std::extents<std::dynamic_extent, std::dynamic_extent> e1{16, 32};
std::dextents<2> e2{16, 32};

e0.rank()     == 2
e0.extent(0) == 16
e0.extent(1) == 32

std::extents<16, 32> e3;

std::extents<16, std::dynamic_extent> e4{32};
```

```
template <typename Size, Size... Extents>
class std::extents;

std::extents e0{16, 32};
// Equivalent to:
std::extents<std::dynamic_extent, std::dynamic_extent> e1{16, 32};
std::dextents<2> e2{16, 32};

e0.rank()     == 2
e0.extent(0) == 16
e0.extent(1) == 32

std::extents<16, 32> e3;

std::extents<16, std::dynamic_extent> e4{32};

std::extents e5{16, 32, 48, 4};
```

```
template <

                                                          >
class std::mdspan;
```

```
template <class T,

                                                            >

class std::mdspan;
```

```
template <class T,
          class Extents,


                                                          >
class std::mdspan;
```

```
template <class T,
          class Extents,
          class LayoutPolicy = std::layout_right,

                                                  >
class std::mdspan;
```

```
template <class T,
          class Extents,
          class LayoutPolicy = std::layout_right,
          class AccessorPolicy = std::default_accessor<T>>
class std::mdspan;
```

```
template <class T,
          class Extents,
          class LayoutPolicy = std::layout_right,
          class AccessorPolicy = std::default_accessor<T>>
class std::mdspan;

std::mdspan m0{data, 16, 32};
// Equivalent to:
std::mdspan<double, std::dextents<2>> m1{data, 16, 32};
```

```
template <class T,
          class Extents,
          class LayoutPolicy = std::layout_right,
          class AccessorPolicy = std::default_accessor<T>>
class std::mdspan;

std::mdspan m0{data, 16, 32};
// Equivalent to:
std::mdspan<double, std::dextents<2>> m1{data, 16, 32};

m0[i, j] == data[i * M + j]
```

```
template <class T,
          class Extents,
          class LayoutPolicy = std::layout_right,
          class AccessorPolicy = std::default_accessor<T>>
class std::mdspan;

std::mdspan m0{data, 16, 32};
// Equivalent to:
std::mdspan<double, std::dextents<2>> m1{data, 16, 32};

m0[i, j] == data[i * M + j]

std::mdspan m2{data, std::extents<16, 32>{}};
// Equivalent to:
std::mdspan<double, std::extents<16, 32>> m3{data};

std::mdspan m4{data, std::extents<16, std::dynamic_extent>{32}};
```

Row-Major AKA Right

- C++, NumPy (default)
- Rightmost extent is contiguous

```
mdspan A{data, N, M};
mdspan A{data, layout_right::mapping{N, M}};

A[i, j]      == data[i * M + j]
A.stride(0) == M
A.stride(1) == 1
```

Row-Major AKA Right

- C++, NumPy (default)
- Rightmost extent is contiguous

```
mdspan A{data, N, M};
mdspan A{data, layout_right::mapping{N, M}};

A[i, j]      == data[i * M + j]
A.stride(0) == M
A.stride(1) == 1
```

Location	Element
0	a_{11}
1	a_{12}
2	a_{21}
3	a_{22}

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

Row-Major AKA Right

- C++, NumPy (default)
- Rightmost extent is contiguous

Column-Major AKA Left

- Fortran, MATLAB
- Leftmost extent is contiguous

```
mdspan A{data, N, M};
mdspan A{data, layout_right::mapping{N, M}};

A[i, j]     == data[i * M + j]
A.stride(0) == M
A.stride(1) == 1
```

```
mdspan B{data, layout_left::mapping{N, M}};

B[i, j]     == data[i + j * N]
B.stride(0) == 1
B.stride(1) == N
```

Location	Element
0	a_{11}
1	a_{12}
2	a_{21}
3	a_{22}

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

Row-Major AKA Right

- C++, NumPy (default)
- Rightmost extent is contiguous

```
mdspan A{data, N, M};
mdspan A{data, layout_right::mapping{N, M}};

A[i, j]      == data[i * M + j]
A.stride(0) == M
A.stride(1) == 1
```

Location	Element
0	a_{11}
1	a_{12}
2	a_{21}
3	a_{22}

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

Column-Major AKA Left

- Fortran, MATLAB
- Leftmost extent is contiguous

```
mdspan B{data, layout_left::mapping{N, M}};

B[i, j]      == data[i + j * N]
B.stride(0) == 1
B.stride(1) == N
```

Location	Element
0	a_{11}
1	a_{21}
2	a_{12}
3	a_{22}

Row-Major AKA Right

- C++, NumPy (default)
- Rightmost extent is contiguous

```
mdspan A{data, N, M};
mdspan A{data, layout_right::mapping{N, M}};

A[i, j]      == data[i * M + j]
A.stride(0) == M
A.stride(1) == 1
```

Column-Major AKA Left

- Fortran, MATLAB
- Leftmost extent is contiguous

```
mdspan B{data, layout_left::mapping{N, M}};

B[i, j]      == data[i + j * N]
B.stride(0) == 1
B.stride(1) == N
```

User-Defined Strides

```
mdspan C{data, layout_stride::mapping{extents{N, M}, {X, Y}}};

A[i, j]      == data[i * X + j * Y]
A.stride(0) == X
A.stride(1) == Y
```

Layouts map $(i, j, k, \ldots)$ to a data location.

Layouts map $(i, j, k, \ldots)$ to a data location.

Anyone can define a layout.

Layouts map $(i, j, k, \dots)$ to a data location.

Anyone can define a layout.

Layouts may:

- Be non-contiguous.

Layouts map $(i, j, k, \ldots)$ to a data location.

Anyone can define a layout.

Layouts may:

- Be non-contiguous.
- Map multiple indices to the same location.

Layouts map $(i, j, k, \ldots)$ to a data location.

Anyone can define a layout.

Layouts may:

- Be non-contiguous.
- Map multiple indices to the same location.
- Perform complicated computations.

Layouts map $(i, j, k, \ldots)$ to a data location.

Anyone can define a layout.

Layouts may:

- Be non-contiguous.
- Map multiple indices to the same location.
- Perform complicated computations.
- Have or refer to state.

Parametric layout enables generic multi-dimensional algorithms.

```
void your_function(Eigen::Matrix<double, Eigen::Dynamic, Eigen::Dynamic>& m);
```

```
void your_function(Eigen::Matrix<double, Eigen::Dynamic, Eigen::Dynamic>& m);

your_function(Eigen::Matrix<double, Eigen::Dynamic, Eigen::Dynamic>{…});
```

```
void your_function(Eigen::Matrix<double, Eigen::Dynamic, Eigen::Dynamic>& m);

your_function(Eigen::Matrix<double, Eigen::Dynamic, Eigen::Dynamic>{…});
your_function(boost::numeric::ublas::matrix<double>{…});
your_function(Mat{…}); // PETSc
your_function(blaze::DynamicMatrix<double, blaze::rowMajor>{…});
your_function(cutlass::HostTensor<float, cutlass::layout::ColumnMajor>{…});
// …
```

```
void your_function(std::mdspan<T, Extents, Layout, Accessor> m);

your_function(Eigen::Matrix<double, Eigen::Dynamic, Eigen::Dynamic>{…});
your_function(boost::numeric::ublas::matrix<double>{…});
your_function(Mat{…}); // PETSc
your_function(blaze::DynamicMatrix<double, blaze::rowMajor>{…});
your_function(cutlass::HostTensor<float, cutlass::layout::ColumnMajor>{…});
// …
```

```
struct my_matrix {
public:
  my_matrix(std::size_t N, std::size_t M)
    : num_rows_(N), num_cols_(M), storage_(num_rows_ * num_cols_) {}

  double& operator()(size_t i, size_t j)
  { return storage_[i * num_cols_ + j]; }
  const double& operator()(size_t i, size_t j) const
  { return storage_[i * num_cols_ + j]; }

  std::size_t num_rows() const { return num_rows_; }
  std::size_t num_cols() const { return num_cols_; }




private:
  std::size_t         num_rows_, num_cols_;
  std::vector<double> storage_;
};
```

```cpp
struct my_matrix {
public:
  my_matrix(std::size_t N, std::size_t M)
    : num_rows_(N), num_cols_(M), storage_(num_rows_ * num_cols_) {}

  double& operator()(size_t i, size_t j)
  { return storage_[i * num_cols_ + j]; }
  const double& operator()(size_t i, size_t j) const
  { return storage_[i * num_cols_ + j]; }

  std::size_t num_rows() const { return num_rows_; }
  std::size_t num_cols() const { return num_cols_; }

  operator std::mdspan<double, std::dextents<2>>() const
  { return {storage_, num_rows_, num_cols_}; }

private:
  std::size_t         num_rows_, num_cols_;
  std::vector<double> storage_;
};
```

```
std::mdspan A{input,  N, M, O};

std::mdspan B{output, N, M, O};



auto v = stdv::cartesian_product(
  stdv::iota(1, A.extent(0) - 1),
  stdv::iota(1, A.extent(1) - 1),
  stdv::iota(1, A.extent(2) - 1));

std::for_each(ex::par_unseq,
  begin(v), end(v),
  [=] (auto idx) {
    auto [i, j, k] = idx;
    B[i, j, k] =   ( A[i, j, k-1] +
                     A[i-1, j, k] +
      A[i, j-1, k] + A[i, j,   k] + A[i, j+1, k]
                   + A[i+1, j, k]
                   + A[i, j, k+1] ) / 7.0
  });
```

```
std::mdspan A{input,
              std::layout_left::mapping{N, M, O}};
std::mdspan B{output,
              std::layout_left::mapping{N, M, O}};


auto v = stdv::cartesian_product(
  stdv::iota(1, A.extent(0) - 1),
  stdv::iota(1, A.extent(1) - 1),
  stdv::iota(1, A.extent(2) - 1));

std::for_each(ex::par_unseq,
  begin(v), end(v),
  [=] (auto idx) {
    auto [i, j, k] = idx;
    B[i, j, k] =   ( A[i, j, k-1] +
                     A[i-1, j, k] +
      A[i, j-1, k] + A[i, j,   k] + A[i, j+1, k]
                   + A[i+1, j, k]
                   + A[i, j, k+1] ) / 7.0
  });
```

```
std::span A{input,  N * M};
std::span B{output, M * N};

auto v = stdv::cartesian_product(
  stdv::iota(0, N),
  stdv::iota(0, M));

std::for_each(ex::par_unseq,
  begin(v), end(v),
  [=] (auto idx) {
    auto [i, j] = idx;
    B[i + j * N] = A[i * M + j];
  });
```

```
std::mdspan A{input,  N, M};
std::mdspan B{output, M, N};

auto v = stdv::cartesian_product(
  stdv::iota(0, A.extent(0)),
  stdv::iota(0, A.extent(1)));

std::for_each(ex::par_unseq,
  begin(v), end(v),
  [=] (auto idx) {
    auto [i, j] = idx;
    B[j, i] = A[i, j];
  });
```

```
std::mdspan A{input,  N, M};
std::mdspan B{output, M, N};

stdr::for_each(
  ex::par_unseq,
  A.indices(),
  [=] (auto [i, j]) {
    B[j, i] = A[i, j];
  });
```

```
std::mdspan A{input,  N, M};
std::mdspan B{output, M, N};

ex::sender auto s =
    ex::transfer_just(sch, A.indices())
  | for_each_async(
      [=] (auto [i, j]) {
        B[j, i] = A[i, j];
      });
```

```
submdspan(mdspan<…> m, SliceSpecifiers... ss)
                         -> mdspan<…>
```

```
submdspan(mdspan<…> m, SliceSpecifiers... ss)
    -> mdspan<…>
```

Slice Specifier	Argument	Reduces Rank?
Single Index	`Integral`	☑

```
submdspan(mdspan<…> m, SliceSpecifiers... ss)
    -> mdspan<…>
```

Slice Specifier	Argument	Reduces Rank?
Single Index	`Integral`	☑
Range of Indices	`std::pair<Integral, Integral>` `std::tuple<Integral, Integral>`	☒

```
submdspan(mdspan<…> m, SliceSpecifiers... ss)
  -> mdspan<…>
```

Slice Specifier	Argument	Reduces Rank?
Single Index	`Integral`	☑
Range of Indices	`std::pair<Integral, Integral>` `std::tuple<Integral, Integral>`	☒
All Indices	`std::full_extent`	☒

```
std::mdspan m0{data, 64, 128, 32};

auto m1 = std::submdspan(m0, std::tuple{15, 23},
                             std::tuple{31, 39},
                             std::tuple{ 7, 15});
```

```
std::mdspan m0{data, 64, 128, 32};

auto m1 = std::submdspan(m0, std::tuple{15, 23},
                             std::tuple{31, 39},
                             std::tuple{ 7, 15});

m1.rank()    == 3
```

```
std::mdspan m0{data, 64, 128, 32};

auto m1 = std::submdspan(m0, std::tuple{15, 23},
                             std::tuple{31, 39},
                             std::tuple{ 7, 15});

m1.rank()     == 3
m1.extent(0) == 8
m1.extent(1) == 8
m1.extent(2) == 8
```

```
std::mdspan m0{data, 64, 128, 32};

auto m1 = std::submdspan(m0, std::tuple{15, 23},
                             std::tuple{31, 39},
                             std::tuple{ 7, 15});

m1.rank()     == 3
m1.extent(0) == 8
m1.extent(1) == 8
m1.extent(2) == 8
m1[i, j, k]  == m0[i + 15, j + 31, k + 7]
```

```
std::mdspan m0{data, 64, 128, 32};

auto m1 = std::submdspan(m0, std::tuple{15, 23},
                             std::tuple{31, 39},
                             std::tuple{ 7, 15});

m1.rank()     == 3
m1.extent(0) == 8
m1.extent(1) == 8
m1.extent(2) == 8
m1[i, j, k]  == m0[i + 15, j + 31, k + 7]

auto m2 = std::submdspan(m0, 15,
                             std::full_extent,
                             31);
```

```
std::mdspan m0{data, 64, 128, 32};

auto m1 = std::submdspan(m0, std::tuple{15, 23},
                             std::tuple{31, 39},
                             std::tuple{ 7, 15});
m1.rank()     == 3
m1.extent(0) == 8
m1.extent(1) == 8
m1.extent(2) == 8
m1[i, j, k]  == m0[i + 15, j + 31, k + 7]

auto m2 = std::submdspan(m0, 15,
                             std::full_extent,
                             31);
m2.rank()     == 1
```

```
std::mdspan m0{data, 64, 128, 32};

auto m1 = std::submdspan(m0, std::tuple{15, 23},
                             std::tuple{31, 39},
                             std::tuple{ 7, 15});

m1.rank()     == 3
m1.extent(0) == 8
m1.extent(1) == 8
m1.extent(2) == 8
m1[i, j, k]  == m0[i + 15, j + 31, k + 7]

auto m2 = std::submdspan(m0, 15,
                             std::full_extent,
                             31);

m2.rank()     == 1
m2.extent(0) == 128
```

```
std::mdspan m0{data, 64, 128, 32};

auto m1 = std::submdspan(m0, std::tuple{15, 23},
                             std::tuple{31, 39},
                             std::tuple{ 7, 15});
m1.rank()     == 3
m1.extent(0) == 8
m1.extent(1) == 8
m1.extent(2) == 8
m1[i, j, k]  == m0[i + 15, j + 31, k + 7]

auto m2 = std::submdspan(m0, 15,
                             std::full_extent,
                             31);
m2.rank()     == 1
m2.extent(0) == 128
m2[j]         == m0[15, j, 31]
```

```
std::mdspan A{input,  N, M};
std::mdspan B{output, M, N};
std::size_t T = ...;
```

```
std::mdspan A{input,  N, M};
std::mdspan B{output, M, N};
std::size_t T = ...;

auto outer = stdv::cartesian_product(stdv::iota(0, (N + T - 1) / T),
                                     stdv::iota(0, (M + T - 1) / T));
```

```
std::mdspan A{input,  N, M};
std::mdspan B{output, M, N};
std::size_t T = ...;

auto outer = stdv::cartesian_product(stdv::iota(0, (N + T - 1) / T),
                                     stdv::iota(0, (M + T - 1) / T));

std::for_each(ex::par_unseq, begin(outer), end(outer),
  [=] (auto tile) {
    auto [x, y] = tile;
    …
  });
```

```
std::mdspan A{input,  N, M};
std::mdspan B{output, M, N};
std::size_t T = ...;

auto outer = stdv::cartesian_product(stdv::iota(0, (N + T - 1) / T),
                                     stdv::iota(0, (M + T - 1) / T));

std::for_each(ex::par_unseq, begin(outer), end(outer),
  [=] (auto tile) {
    auto [x, y] = tile;
    std::tuple selectN{T * x, std::min(T * (x + 1), N)};
    std::tuple selectM{T * y, std::min(T * (y + 1), M)};

    …
  });
```

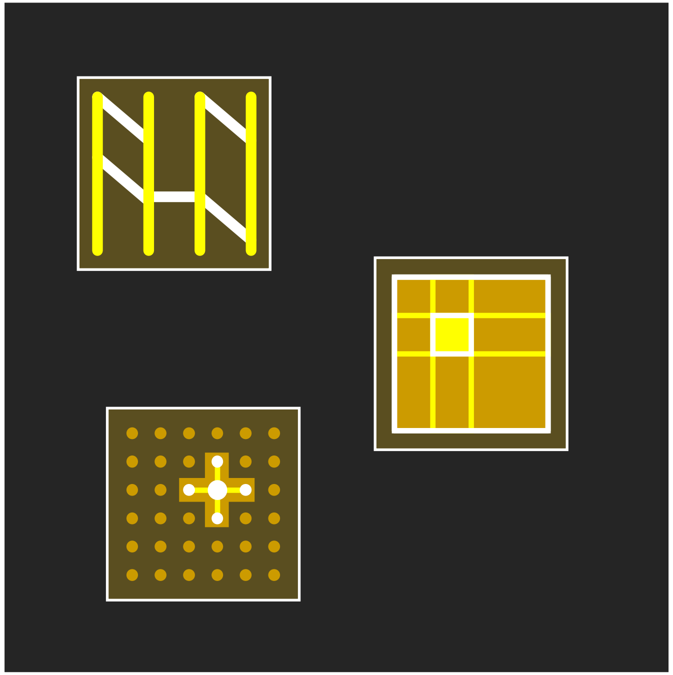
```
std::mdspan A{input,  N, M};
std::mdspan B{output, M, N};
std::size_t T = ...;

auto outer = stdv::cartesian_product(stdv::iota(0, (N + T - 1) / T),
                                     stdv::iota(0, (M + T - 1) / T));

std::for_each(ex::par_unseq, begin(outer), end(outer),
  [=] (auto tile) {
    auto [x, y] = tile;
    std::tuple selectN{T * x, std::min(T * (x + 1), N)};
    std::tuple selectM{T * y, std::min(T * (y + 1), M)};

    auto TA = std::submdspan(A, selectN, selectM);
    auto TB = std::submdspan(B, selectM, selectN);

    …
  });
```

```cpp
std::mdspan A{input,  N, M};
std::mdspan B{output, M, N};
std::size_t T = ...;

auto outer = stdv::cartesian_product(stdv::iota(0, (N + T - 1) / T),
                                     stdv::iota(0, (M + T - 1) / T));

std::for_each(ex::par_unseq, begin(outer), end(outer),
  [=] (auto tile) {
    auto [x, y] = tile;
    std::tuple selectN{T * x, std::min(T * (x + 1), N)};
    std::tuple selectM{T * y, std::min(T * (y + 1), M)};

    auto TA = std::submdspan(A, selectN, selectM);
    auto TB = std::submdspan(B, selectM, selectN);

    auto inner = stdv::cartesian_product(stdv::iota(0, TA.extent(0)),
                                         stdv::iota(0, TA.extent(1)));


    …
  });
```

```
std::mdspan A{input,  N, M};
std::mdspan B{output, M, N};
std::size_t T = ...;

auto outer = stdv::cartesian_product(stdv::iota(0, (N + T - 1) / T),
                                     stdv::iota(0, (M + T - 1) / T));

std::for_each(ex::par_unseq, begin(outer), end(outer),
  [=] (auto tile) {
    auto [x, y] = tile;
    std::tuple selectN{T * x, std::min(T * (x + 1), N)};
    std::tuple selectM{T * y, std::min(T * (y + 1), M)};

    auto TA = std::submdspan(A, selectN, selectM);
    auto TB = std::submdspan(B, selectM, selectN);

    auto inner = stdv::cartesian_product(stdv::iota(0, TA.extent(0)),
                                         stdv::iota(0, TA.extent(1)));

    for (auto [i, j] : inner)
      TB[j, i] = TA[i, j];
  });
```

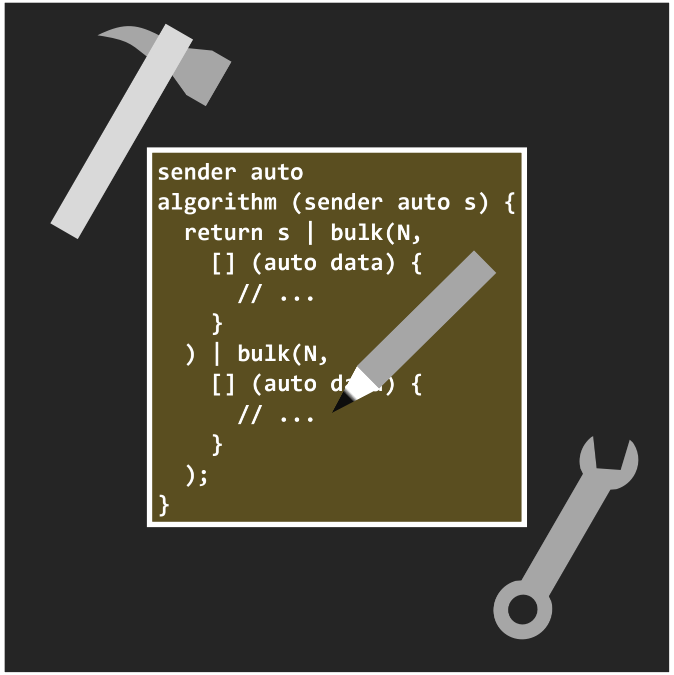
Pillars of C++ Standard Parallelism

Common Algorithms that Dispatch to Vendor-Optimized Parallel Libraries

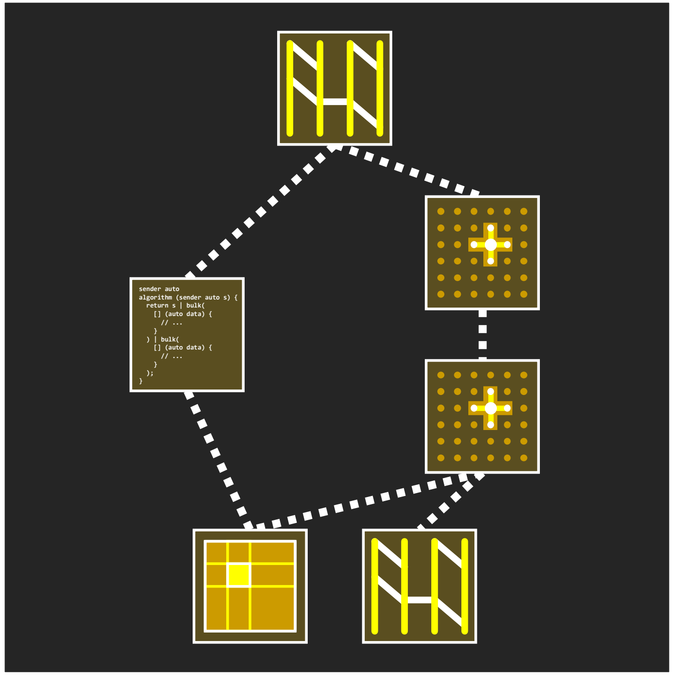


Expanding the Set

Tools to Write Your Own Parallel Algorithms that Run Anywhere



Mechanisms for Composing Parallel Invocations into Task Graphs



```
double *A = …, *x = …, *y = …;

double *dA, *dx, *dy;
cudaMalloc(&dA, N * M * sizeof(double));
cudaMalloc(&dx, M * sizeof(double));
cudaMalloc(&dy, N * sizeof(double));

cublasSetMatrix(N, M, sizeof(double), &A, N, dA, N);
cublasSetVector(M, sizeof(double), &x, 1, dx, 1);
cublasSetVector(N, sizeof(double), &y, 1, dy, 1);

cublasHandle_t handle;
cublasCreate(&handle);

double alpha = 3.0, beta = 2.0;
cublasSgemv(handle, CUBLAS_OP_N, N, M,
            &alpha, dA, N, dx, 1, &beta, dy, 1);

cublasGetVector(N, sizeof(double), &y, 1, dy, 1);
```

```
std::mdspan A{…, N, M};
std::mdspan x{…, M};
std::mdspan y{…, N};

// y = 3.0 A x + 2.0 y
std::matrix_vector_product(
  ex::par_unseq,
  std::scaled(3.0, A), x,
  std::scaled(2.0, y), y);
```

```
std::mdspan A{…, N, M};
std::mdspan x{…, M};
std::mdspan y{…, N};

// y = 3.0 A x + 2.0 y
std::matrix_vector_product(
  ex::par_unseq,
  std::scaled(3.0, A), x,
  std::scaled(2.0, y), y);
```

```
std::mdspan A{…, N, M};
std::mdspan x{…, M};
std::mdspan y{…, N};

// y = 3.0 A x + 2.0 y
std::matrix_vector_product(
  ex::par_unseq,
  std::scaled(3.0, A), x,
  std::scaled(2.0, y), y);
```

```cpp
std::mdspan A{…, N, M};
std::mdspan x{…, M};
std::mdspan b{…, N};

// Solve A x = b where A = U^T U

// Solve U^T c = b, using x to store c
std::triangular_matrix_vector_solve(ex::par_unseq,
                                    std::transposed(A),
                                    std::upper_triangle, std::explicit_diagonal,
                                    b, x);

// Solve U x = c, overwriting x with result
std::triangular_matrix_vector_solve(ex::par_unseq,
                                    A,
                                    std::upper_triangle, std::explicit_diagonal,
                                    x);
```

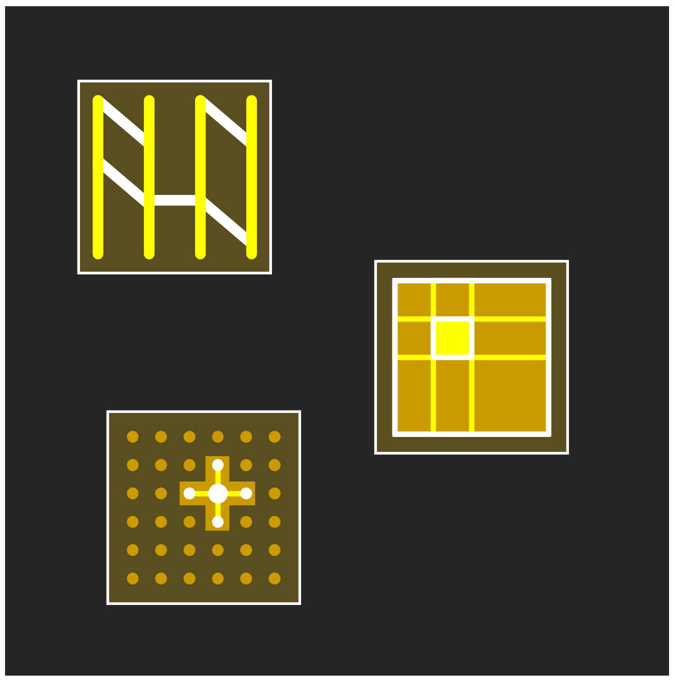
```
std::mdspan A{…, N, M};
std::mdspan x{…, M};
std::mdspan b{…, N};

// Solve A x = b where A = U^T U

// Solve U^T c = b, using x to store c
std::triangular_matrix_vector_solve(ex::par_unseq,
                                    std::transposed(A),
                                    std::upper_triangle, std::explicit_diagonal,
                                    b, x);

// Solve U x = c, overwriting x with result
std::triangular_matrix_vector_solve(ex::par_unseq,
                                    A,
                                    std::upper_triangle, std::explicit_diagonal,
                                    x);
```

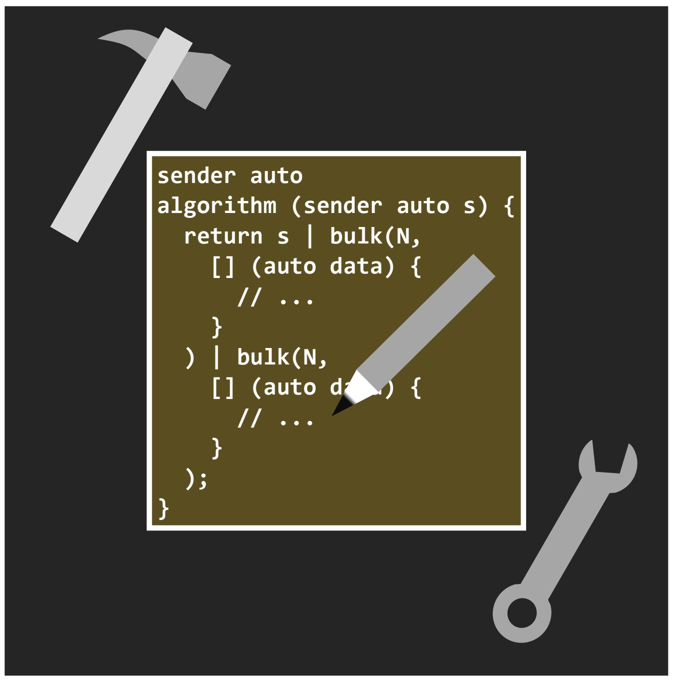
Pillars of C++ Standard Parallelism

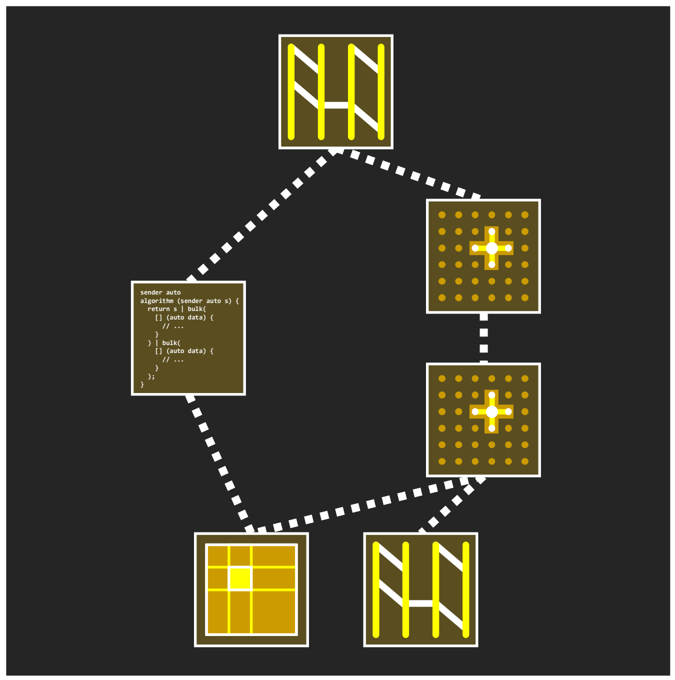
Common Algorithms that Dispatch to Vendor-Optimized Parallel Libraries

Tools to Write Your Own Parallel Algorithms that Run Anywhere

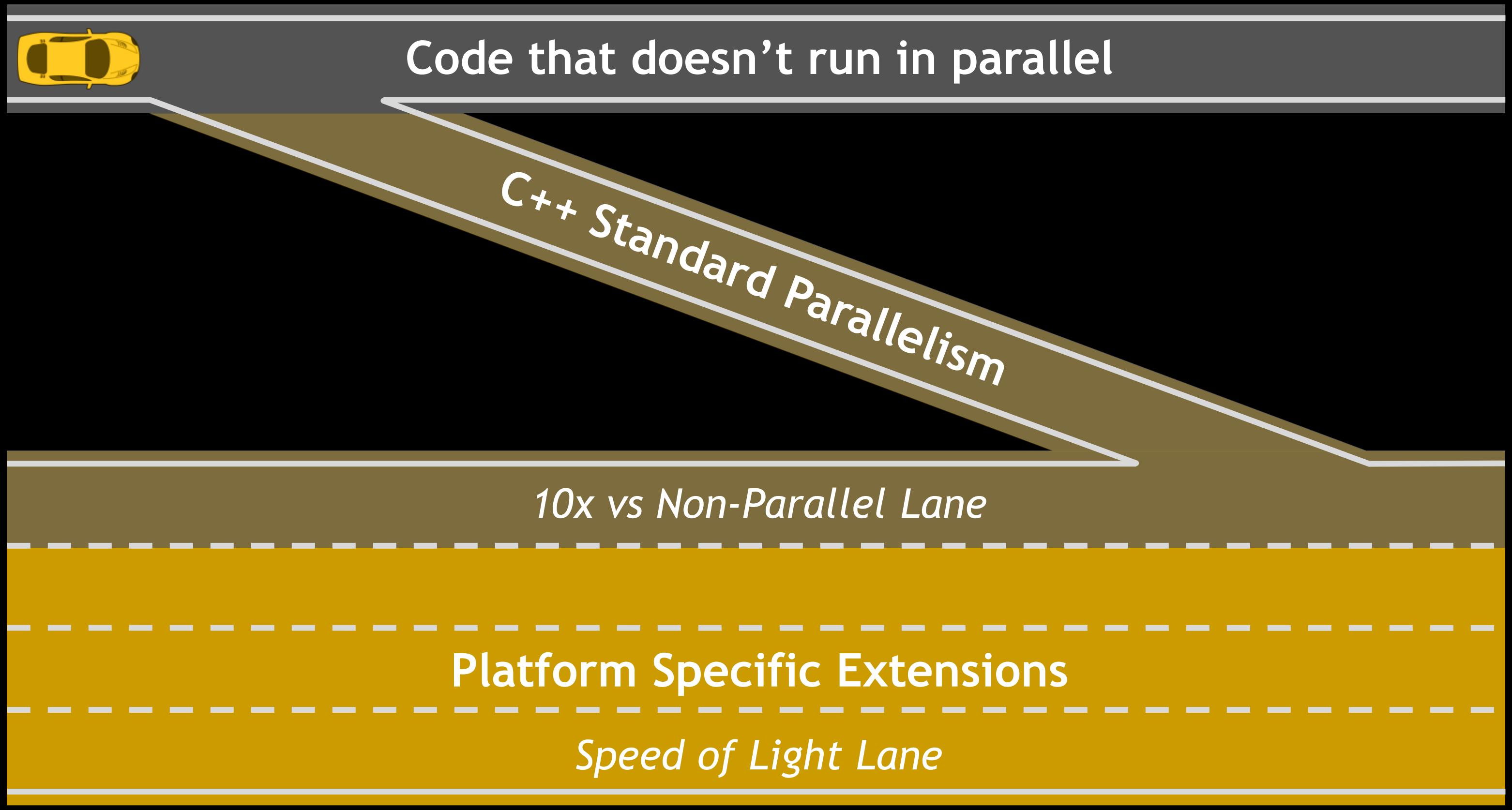
Mechanisms for Composing Parallel Invocations into Task Graphs







We Need On-Ramps



Conventions

Conventions

```
namespace stdv = std::views;

namespace stdr = std::ranges;

namespace ex = std::execution;

namespace this_thread = std::this_thread;
```

Conventions

```
namespace stdv = std::views;

namespace stdr = std::ranges;

namespace ex = std::execution;

namespace this_thread = std::this_thread;
```

Class Template Argument Deduction (CTAD)

```
std::tuple t{3.14, 42}; ⟶ std::tuple<double, int>

std::array a{0, 1, 1, 0}; ⟶ std::array<int, 4>
```