Futures without type erasure

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- Building chains of asynchronous computations
  - Think of `std::future<T>` composition
- Without using:
  - Type erasure
  - Dynamic allocation
- Many templates

```cpp
auto graph = leaf{[]{ return "hello"; }}
    .then([](std::string x){ return x + " world"; })
```

- Returns `"hello world"`
- Type of `graph`:

```cpp
node::seq<
    node::leaf<
        void,
        (lambda #0)
    >,
    node::leaf<
        std::string,
        (lambda #1)
    >
>
```

```cpp
auto graph = all{
   []{ return http_get_request("animals.com/cat/0.png"); },
   []{ return http_get_request("animals.com/dog/0.png"); }
}.then([](std::tuple<data, data> t){ /* ... */ });
```

- Type of `graph`:

```
node::seq<
    node::all<
        node::leaf<void, (lambda #0)>,
        node::leaf<void, (lambda #1)>
    >
    node::leaf<std::tuple<data, data>, (lambda #2)>
>
```

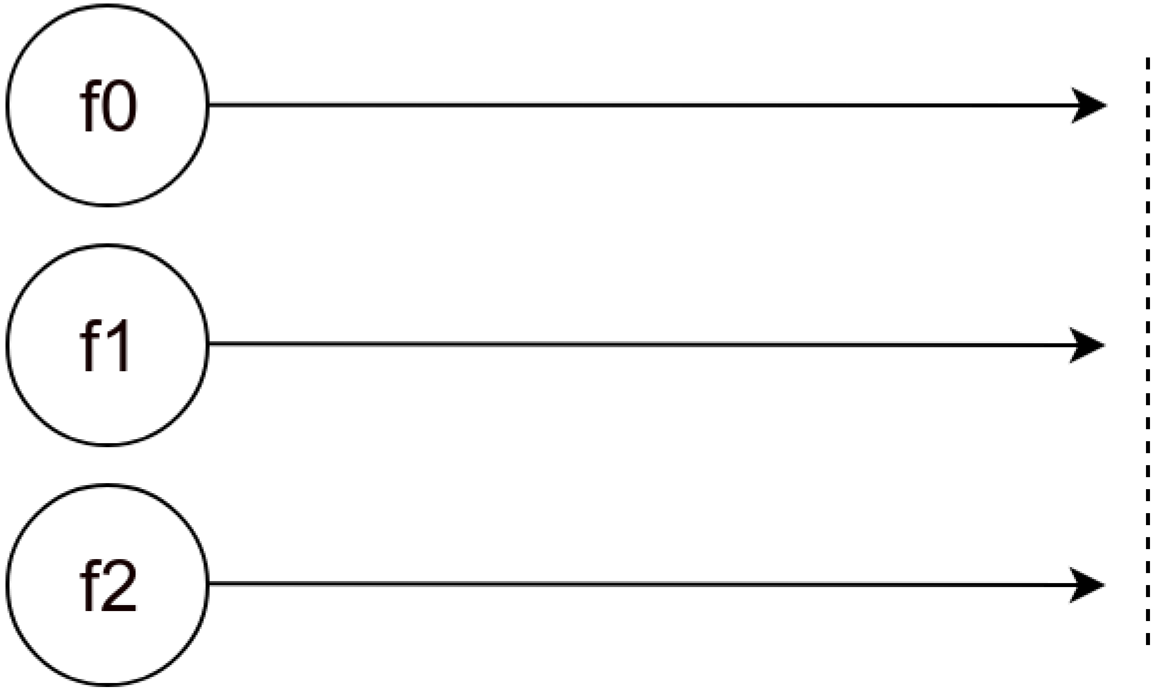
- `std::async` provides a way of running a function *asynchronously*
- It returns an `std::future` instance that will eventually contain its result

```
auto f = std::async(std::launch::async, []
{
    std::this_thread::sleep_for(100ms);
    std::cout << "world\n";
});

std::cout << "hello ";
```

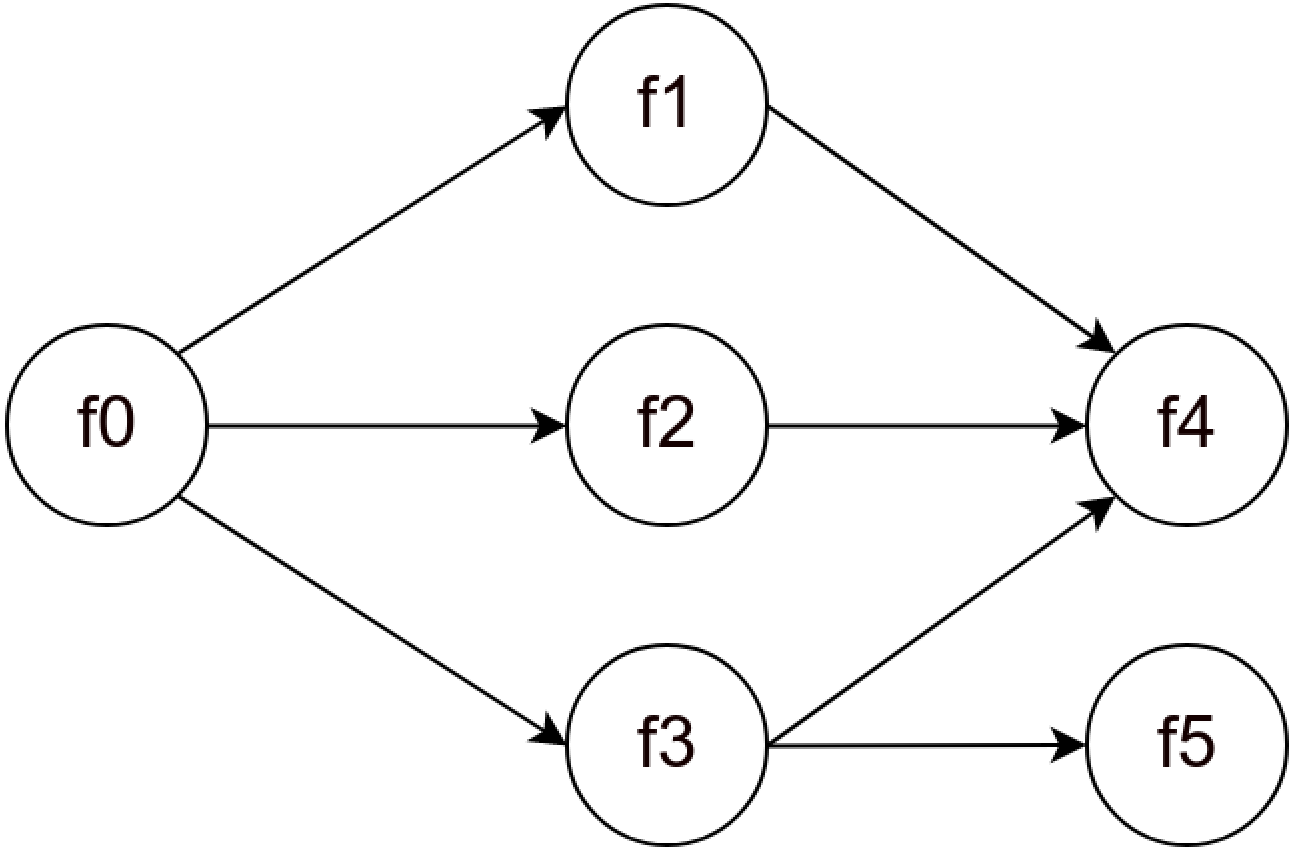
(on *wandbox.org*)

- `std::future` and `std::async` can easily model multiple tasks running in parallel

```
auto f0 = std::async(std::launch::async, []{ /* ... */ });
auto f1 = std::async(std::launch::async, []{ /* ... */ });
auto f2 = std::async(std::launch::async, []{ /* ... */ });
```



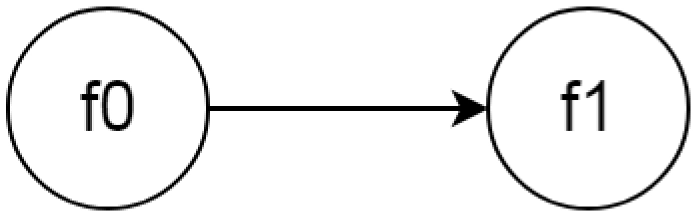
- They fall short when trying to model complicated dependency graphs



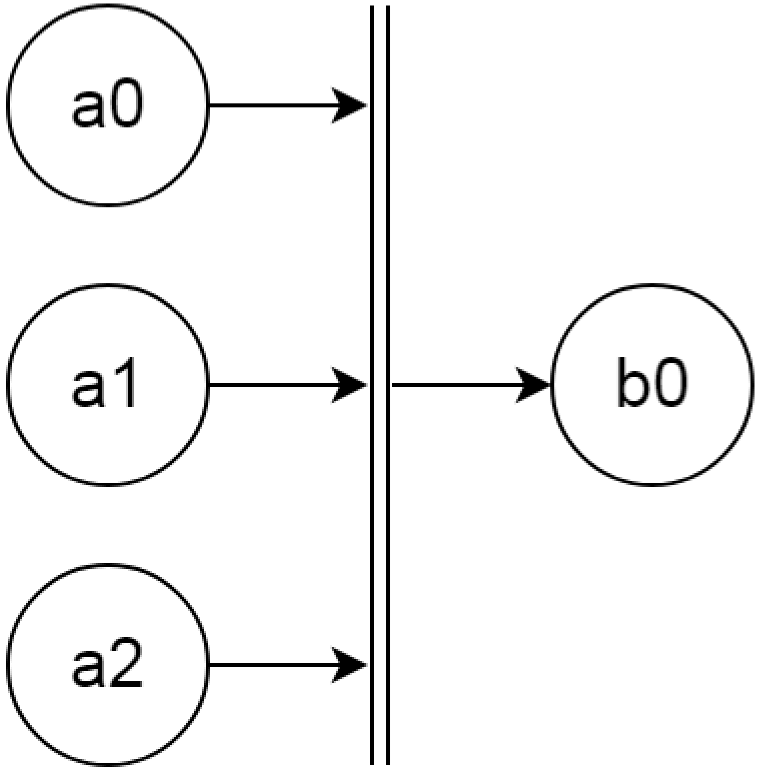
- *Sequential composition* implies nested `std::async` calls
- "*execute* `f0`, ***then*** *execute* `f1`"

```
auto f0 = std::async(std::launch::async, []
{
    std::cout << "hello ";
    auto f1 = std::async(std::launch::async, []
    {
        std::cout << "world\n";
    });
});
```

(on *wandbox.org*)



- Collecting multiple futures into a single one is not easy either
- "***when all*** `aX` *futures complete,* ***then*** *execute* `b0` "



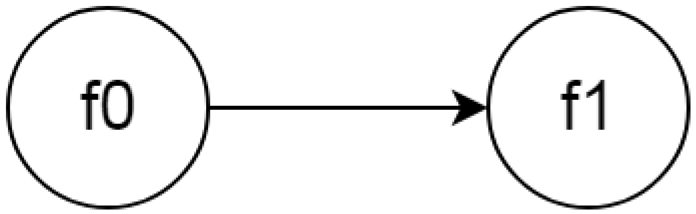
```cpp
std::future<void> f = std::async(std::launch::async, []
{
    auto a0 = std::async(std::launch::async, []{ std::cout << "a0\n"; });
    auto a1 = std::async(std::launch::async, []{ std::cout << "a1\n"; });
    auto a2 = std::async(std::launch::async, []{ std::cout << "a2\n"; });

    a0.get();
    a1.get();
    a2.get();

    auto b0 = std::async(std::launch::async, []{ std::cout << "b0\n"; });
});
```

(on *wandbox.org*)

- We want *intuitive* abstractions to express `future` composition
- Available in `boost::future`
- `std::experimental::future` attempts to standardize them
    - Part of the "Extensions For Concurrency" TS
    - Anthony Williams @ ACCU 2017
      "Concurrency, Parallelism and Coroutines"

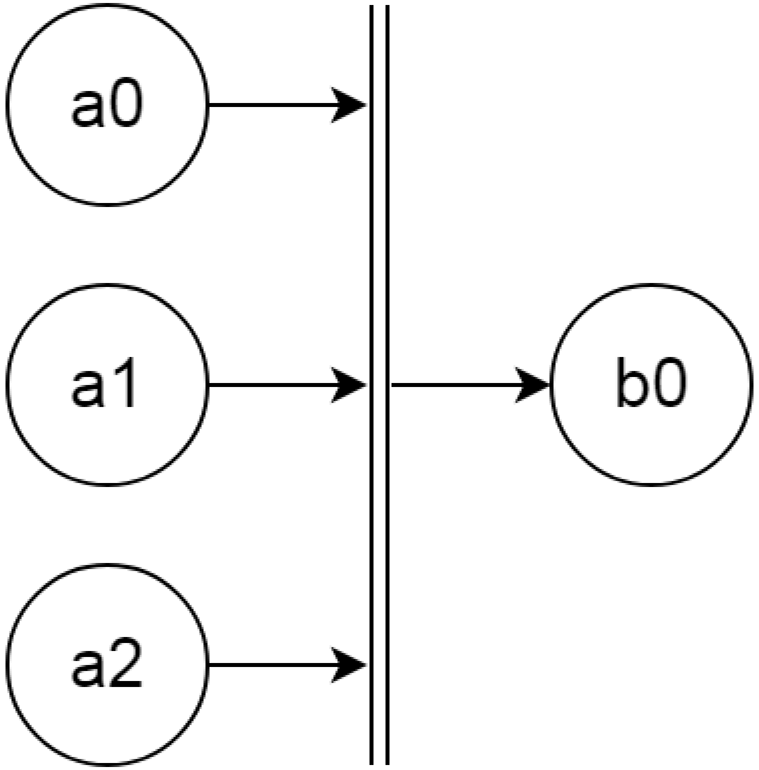
```
boost::async(boost::launch::async, []
{
    std::cout << "hello ";
})
.then([](auto)
{
    std::cout << "world\n";
});
```

(on *wandbox.org*)



```
boost::when_all(
    boost::async(boost::launch::async, []{ std::cout << "a0\n"; }),
    boost::async(boost::launch::async, []{ std::cout << "a1\n"; }),
    boost::async(boost::launch::async, []{ std::cout << "a2\n"; })
).then([](auto){ std::cout << "b0\n"; });
```

(on *wandbox.org*)



- Abstractions like `.then`, `when_all`, and `when_any` allow us to express future composition intuitively
- They always return a `future` that can be composed further

```
template <class F>
auto future<T>::then(F func) -> future<result_of_t<F(future<T>)>>;
```

```
template <class... Futures>
auto when_all(Futures... futures) -> future<std::tuple<Futures...>>;
```

```
boost::future<int> a = /* ... */;
boost::future<int> b = a.then([](auto){ /* ... */ });
```

- The result type of future composition is always `future<T>`
- This implies *type erasure*
- Additionally, `future` uses *dynamic allocation* to keep track of the "shared state"
- Can we avoid the overhead of *type erasure* and *dynamic allocation*?
    - Is it worth it?

- *Type erasure* is necessary when the way futures are composed changes depending on **run-time control flow**
- If the **"shape"** of the future graph is **known at compile-time**, it can be encoded as part of the type system

```
auto f0 = leaf{[]{ std::cout << 'a'; }};
auto f1 = f0.then([]{ std::cout << 'b'; });
```

```
template <typename F>
leaf<F>::leaf(F&& f);
```

```
template <typename F>
template <typename FThen>
sequential<leaf<F>, leaf<FThen>> leaf<F>::then(FThen f_then);
```

- The type of `f0` is `leaf<lambda#0>`
- The type of `f1` is `sequential< leaf<lambda#0>, leaf<lambda#1> >`

```cpp
auto f0 = when_all([]{ std::cout << "a0"; },
                   []{ std::cout << "a1"; },
                   []{ std::cout << "a2"; });

auto f1 = f0.then([]{ std::cout << "b0"; });
```

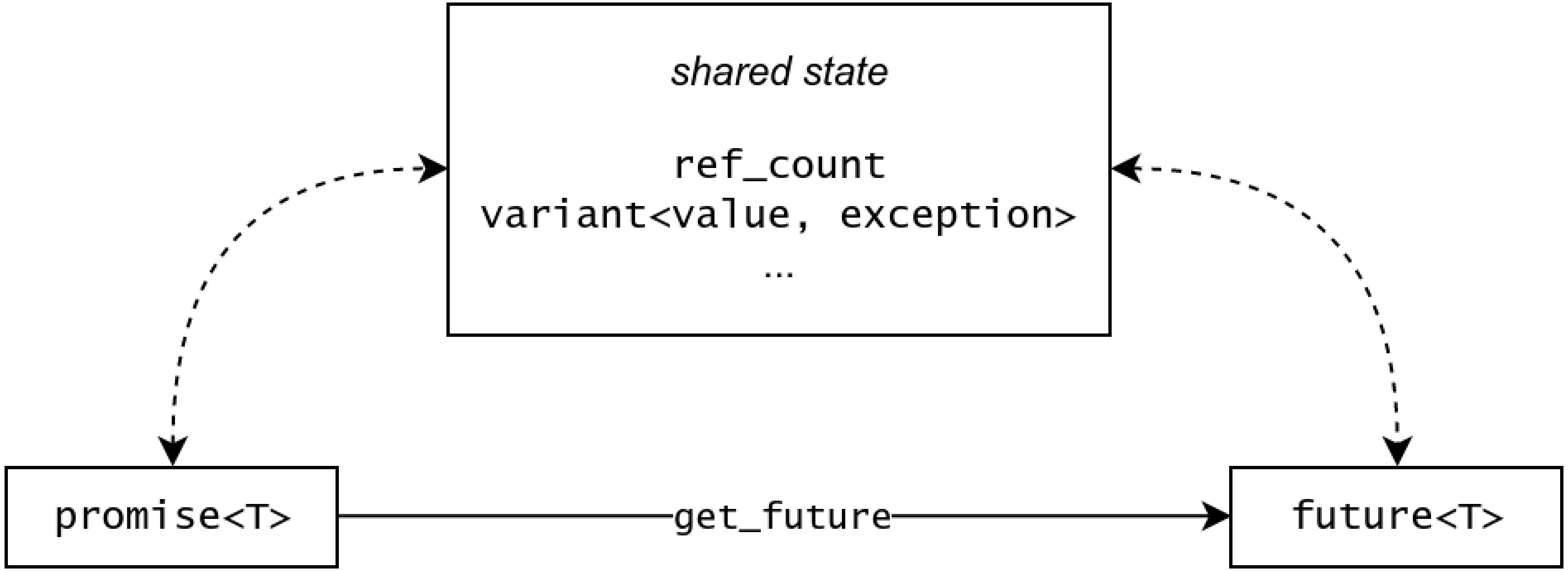
```cpp
template <typename... Fs>
parallel<leaf<Fs>...> when_all(Fs... fs);
```

- The type of `f1` is:

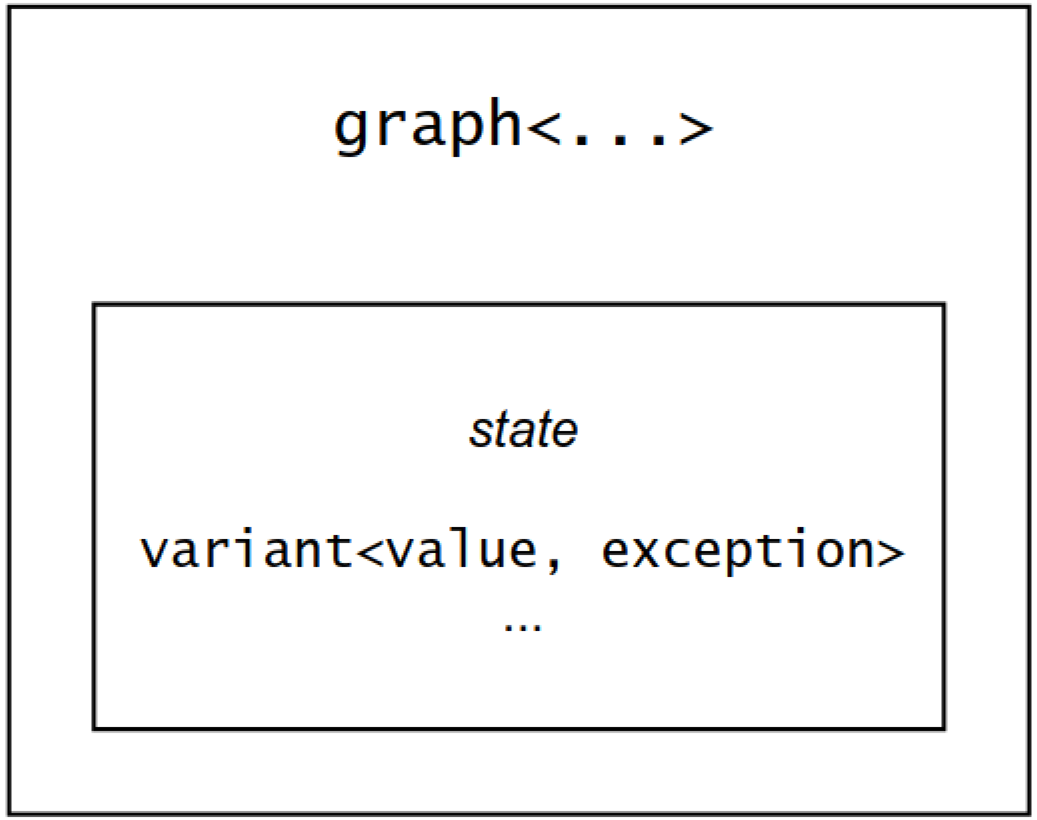
```cpp
sequential<   parallel< leaf<lambda#0-2>...  >, leaf<lambda#3>   >
```

- *Type erasure* can be avoided by encoding the structure of the graph in a **type**
- What about *dynamic allocation*?
- `future<T>` uses *dynamic allocation* in order to provide a **shared state** for the eventual result/exception
    - Additional synchronization primitives for abstraction such as `when_all` and `when_any` might also require *dynamic allocation*

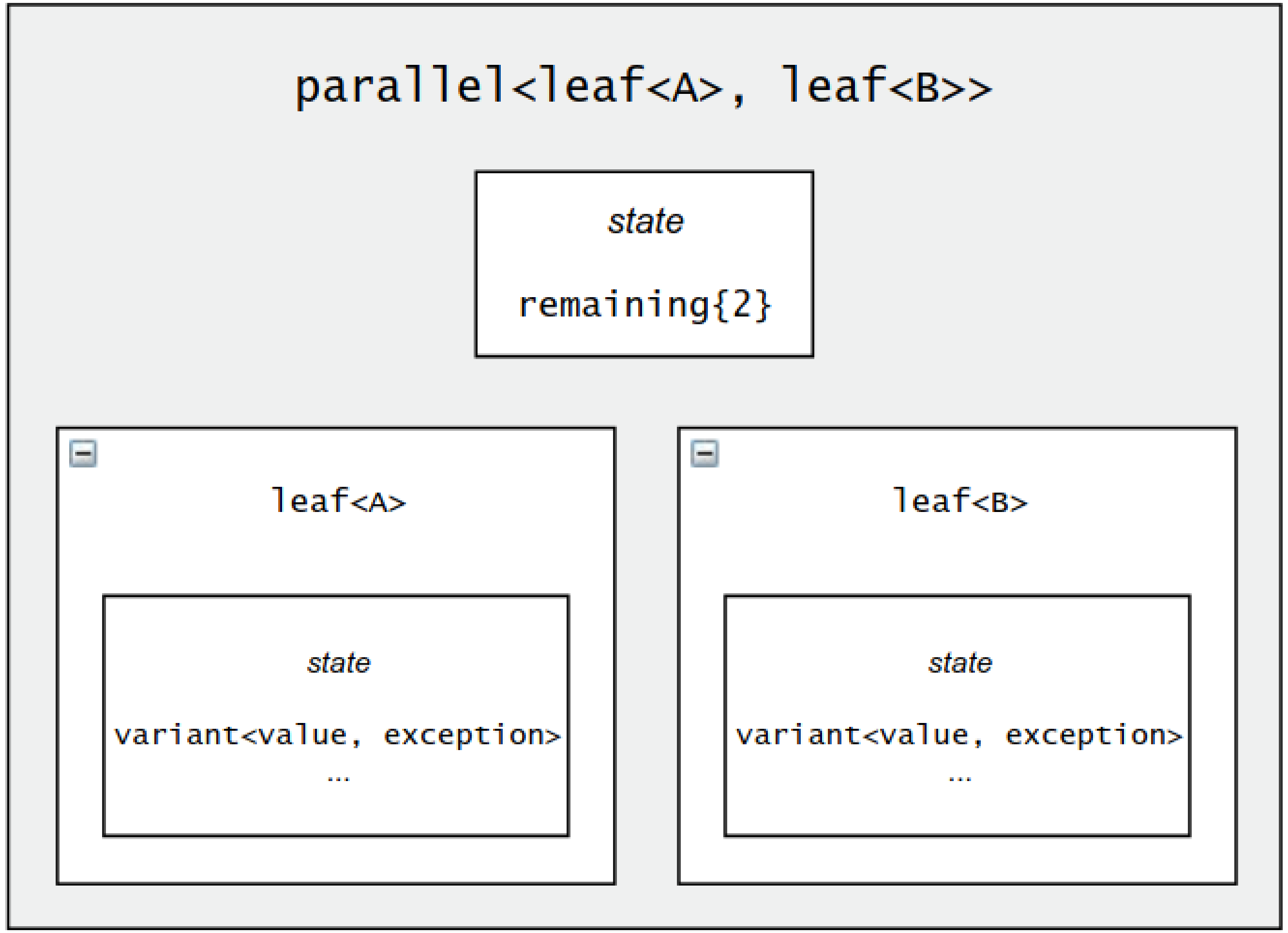
- `std::future<T>`, `std::promise<T>`, and the *shared state*



- What if we store the state *in-place* inside the final graph?
- This requires the graph object to be kept alive until execution is completed

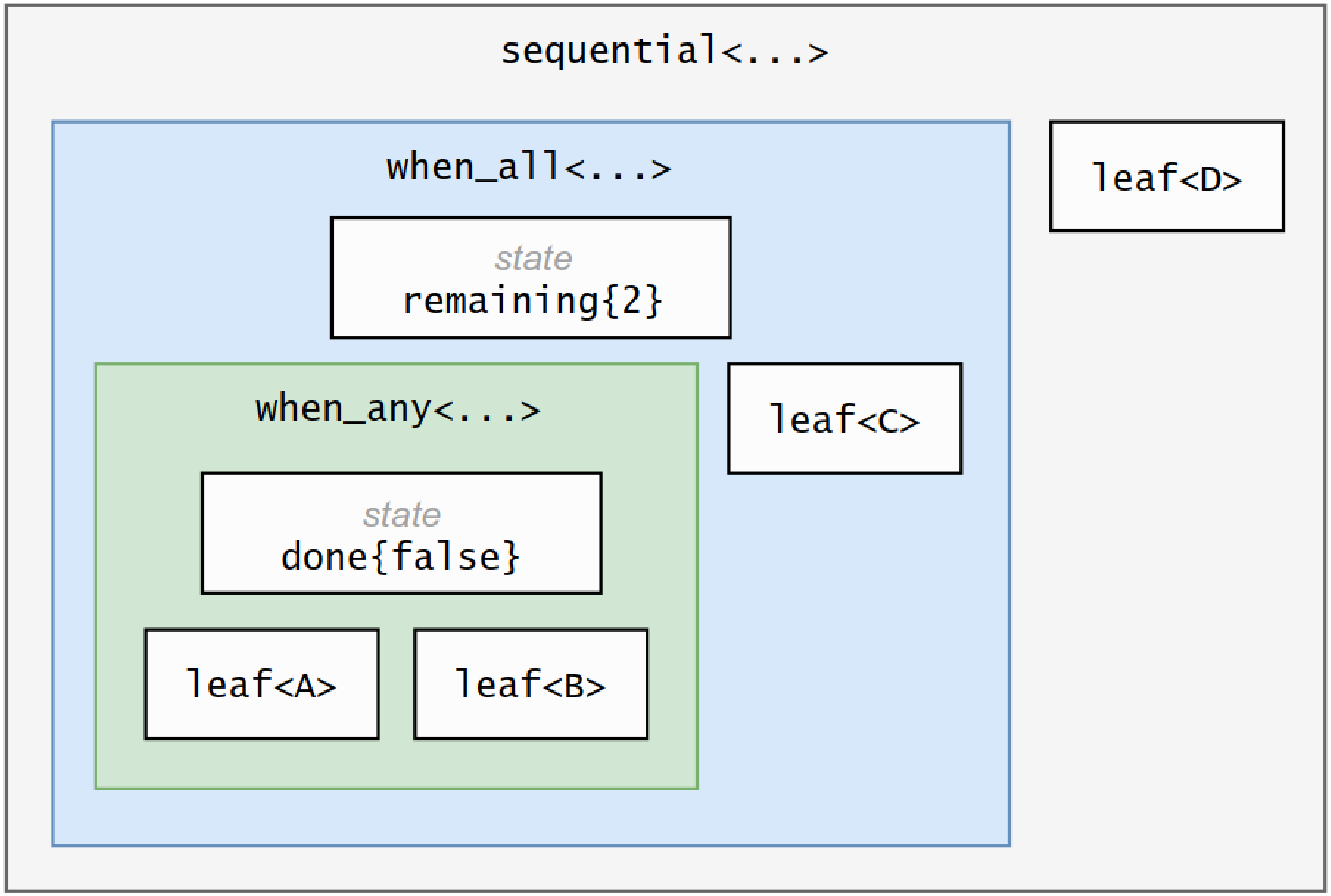


- E.g. the implementation of `when_all` could store an *atomic counter* of the remaining nodes *in-place* in the `parallel< ... >` node



an alternative design
avoiding dynamic allocation

```
when_all(  when_any(a, b), c  ).then(  d  )
```



```
auto f = when_all(when_any(a, b), c).then(d);
scheduler.execute(f);

// `f` must be kept alive until execution is completed
```

- If `f` is executed through an asynchronous non-blocking scheduler, the user must make sure that `f` lives long enough
    - Remember that the "shared" state exists *in-place* inside `f`

- *Type erasure* will be avoided by encoding the entire computation graph as part of the type system
  - The "shape" of the graph must be known at compile-time
- *Dynamic allocation* will be avoided by storing the "shared state" in-place inside the graph object
  - The final graph object must outlive the execution of its nodes

We will implement:

1. `leaf` node
2. `seq` node *(sequential composition)*
3. `all` node *("when all" composition)*
4. Return value propagation
5. Blocking execution
6. Continuation-style syntax (`.then`)
7. `any` node *("when any" composition)*

- All node types will expose the following member function:

```
template <typename Scheduler, typename Then>
void /* node */::execute(Scheduler& scheduler, Then&& then) &
{
    // * Execute stored computation through `scheduler`
    // * Asynchronously continue execution via `then`
}
```

- It will later be improved to support propagation of return values
- `scheduler(f)` can simply be `std::thread{f}.detach()`
- `execute` is `&` ref-qualified as it requires the node to be kept alive

- A `leaf` node simply wraps a single computation `F`
- It will expose `execute`, but won't make use of `scheduler`
    - The computation can be executed on the "current" thread
- Example usage:

```
leaf l{[]{ std::cout << "hello "; }};
l.execute(scheduler, []{ std::cout << "world\n"; });
```

  - `leaf`'s template parameters are being deduced thanks to C++17's *class template argument deduction*
  - The continuation is provided as a callback to avoid unnecessary blocking

```
template <typename F>
struct leaf : F
{
    leaf(F&& f) : F{std::move(f)}
    {
    }

    template <typename Scheduler, typename Then>
    void execute(Scheduler&, Then&& then) &
    {
        (*this)();
        std::forward<Then>(then)();
    }
};
```

(on *wandbox.org*)

- `F` is inherited to allow EBO *(empty base optimization)*

```
template <typename F>
leaf<F>::leaf(F&& f) : F{std::move(f)}
{
}
```

- `F` is deduced from the `leaf(F&&)` constructor:

  ```
  leaf l{some_lambda};
  ```

  ↓

  ```
  leaf<decltype(some_lambda)> l{some_lambda};
  ```

- The `leaf` node on its own is not really useful
- It is the smallest *composable* piece of the graph
- Let's implement `seq` next

- The `seq` node takes two nodes `A` and `B` as input
- It executes `A`, **then** `B`

```
leaf l0{[]{ std::cout << "hello "; }};
leaf l1{[]{ std::cout << "world"; }};

seq s0{std::move(l0), std::move(l1)};
s0.execute(scheduler, []{ std::cout << "!\n"; });
```

(on *wandbox.org*)

```
template <typename A, typename B>
struct seq : A, B
{
    seq(A&& a, B&& b) : A{std::move(a)}, B{std::move(b)}
    {
    }

    template <typename Scheduler, typename Then>
    void execute(Scheduler& scheduler, Then&& then) &
    {
        A::execute(scheduler, [this, &scheduler, then]
        {
            B::execute(scheduler, then);
        });
    }
};
```

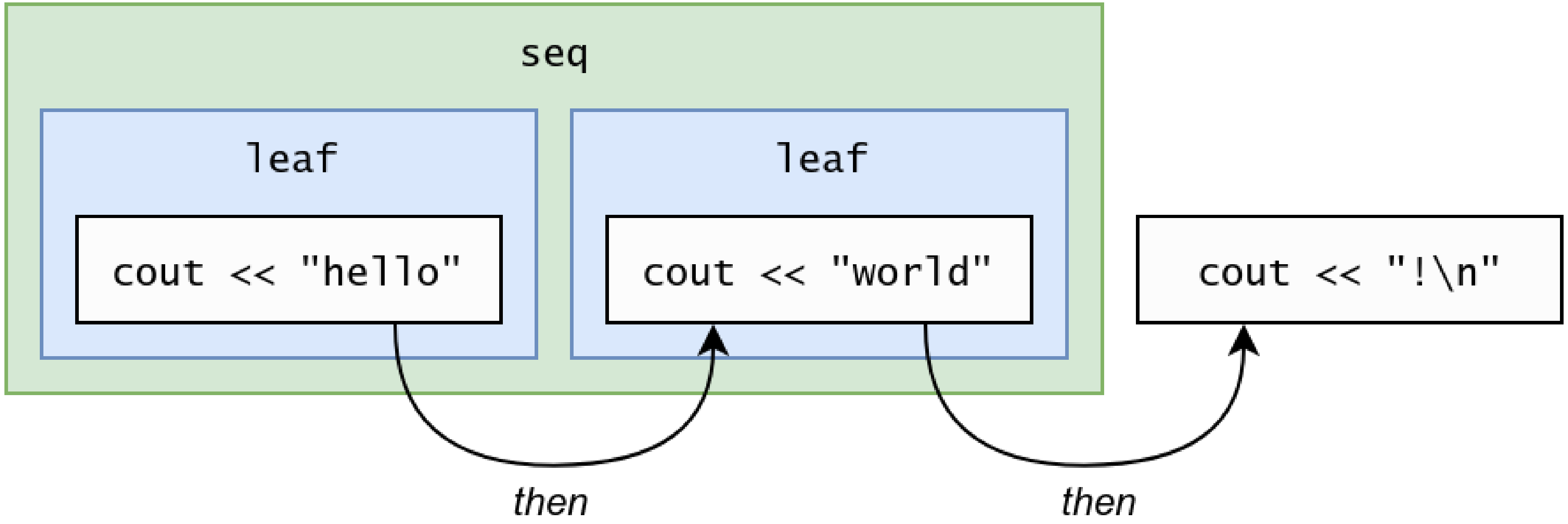
```
template <typename A, typename B>
template <typename Scheduler, typename Then>
void seq<A, B>::execute(Scheduler& scheduler, Then&& then) &
{
    A::execute(scheduler, [this, &scheduler, then]
    {
        B::execute(scheduler, then);
    });
}
```

- `A` is immediately executed
- The execution of `B` is passed as the `then` argument to `A::execute`
- This allows non-blocking asynchronous composition

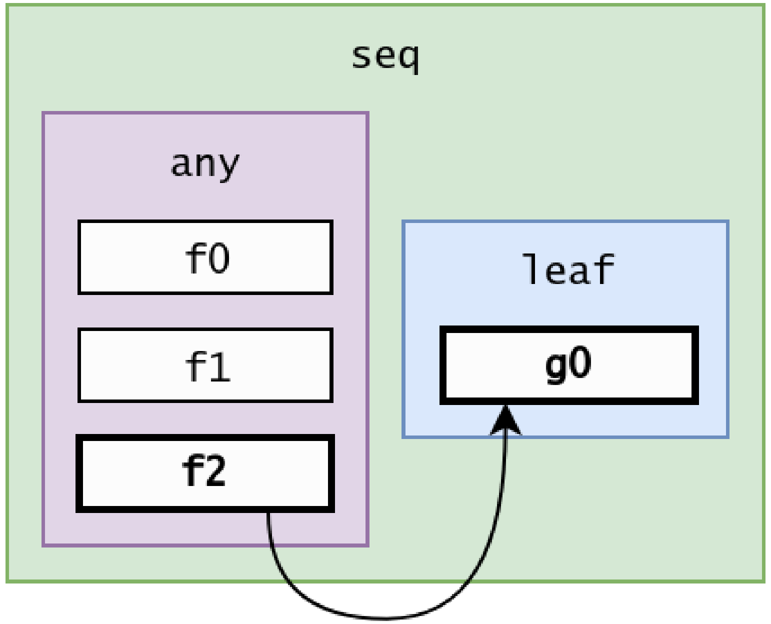
implementation

part 2 - `seq` node

```
leaf l0{[]{ std::cout << "hello "; }};
leaf l1{[]{ std::cout << "world"; }};

seq s0{std::move(l0), std::move(l1)};
s0.execute(scheduler, []{ std::cout << "!\n"; });
```



- The `seq` node allows *sequential composition* of nodes
- It executes two nodes, one after another, asynchronously
  - For `leaf` nodes, this is indistinguishable from blocking
  - For nodes like `any`, this is crucial



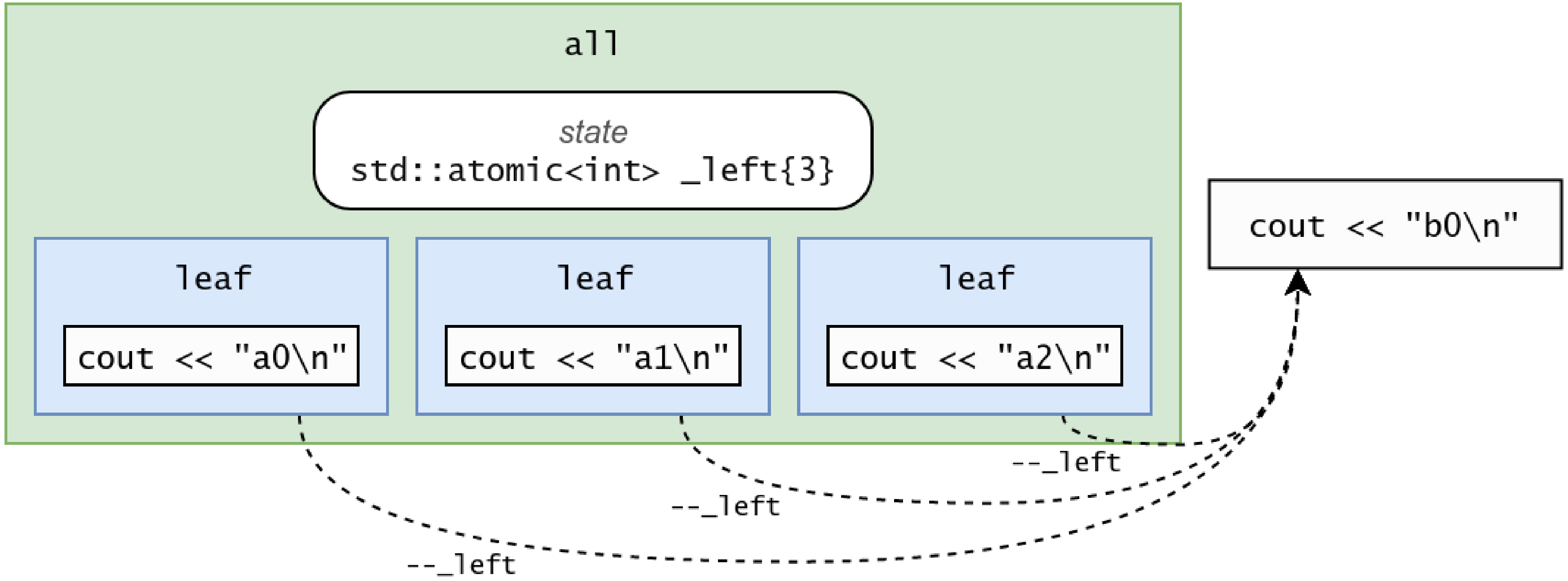
- The `all` node will be the first one to make use of `scheduler`
- It takes an arbitrary number of nodes `Fs ...` as input
- It executes `Fs ...` in parallel
- The execution of `all<Fs ...>` is completed when all `Fs ...` are completed

```
all graph{leaf{[]{ std::cout << "a0\n"; }},
          leaf{[]{ std::cout << "a1\n"; }},
          leaf{[]{ std::cout << "a2\n"; }}};

graph.execute(scheduler, []{ std::cout << "b0\n"; });
std::this_thread::sleep_for(100ms);
```

(on *wandbox.org*)

```
all graph{leaf{[]{ std::cout << "a0\n"; }},
          leaf{[]{ std::cout << "a1\n"; }},
          leaf{[]{ std::cout << "a2\n"; }}};

graph.execute(scheduler, []{ std::cout << "b0\n"; });
```

(on *wandbox.org*)



- `all<Fs...>` contains an `atomic` counter initialized to `sizeof...(Fs)`
    - It keeps track of how many nodes need to complete their execution
    - When it reaches `0`, the `then` continuation of the `all` node is executed
    - Every node in `Fs...` decrements the counter upon completion
- Since the nodes can be executed on separated threads, the `all<Fs...>` object must be kept alive until all nodes have finished
    - This is why we added a `this_thread::sleep_for`
    - We'll see a more robust solution later

```
template <typename ... Fs>
struct all : Fs ...
{
    std::atomic<int> _left;

    all(Fs&& ... fs) : Fs{std::move(fs)} ...
    {
    }

    template <typename Scheduler, typename Then>
    void execute(Scheduler& scheduler, Then&& then) &;
};
```

- Inheritance is used not only for EBO, but also because it makes it easier to work with `Fs ...` as a pack

```cpp
template <typename... Fs>
template <typename Scheduler, typename Then>
void all<Fs...>::execute(Scheduler& scheduler, Then&& then) &
{
    _left.store(sizeof...(Fs));

    (scheduler([this, &scheduler, &f = static_cast<Fs&>(*this), then]
    {
        f.execute(scheduler, [this, then]
        {
            if(_left.fetch_sub(1) == 1) { then(); }
        });
    }), ...);
}
```

```
(scheduler([this, &scheduler, &f = static_cast<Fs&>(*this), then]
{
    f.execute(scheduler, [this, then]
    {
        if(_left.fetch_sub(1) == 1) { then(); }
    });
}), ...);
```

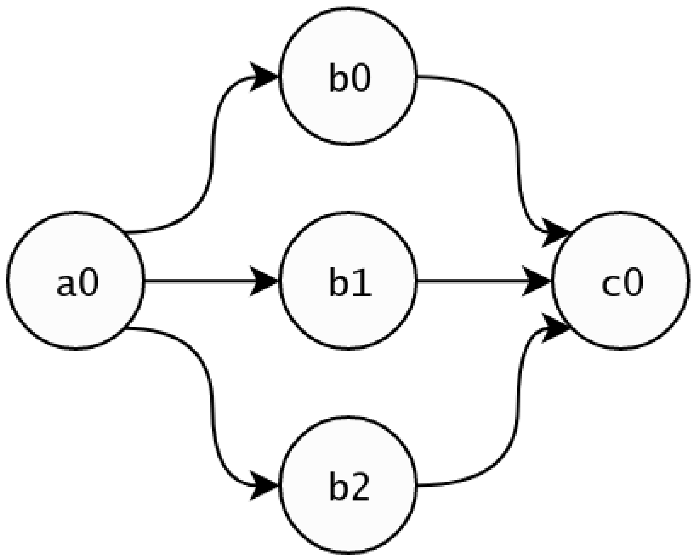
- This entire snippet is a *fold expression* over the *comma operator*
- In short, it schedules the execution of every `f` in `Fs...`
    - The atomic counter is decremented as part of the `then` continuation of `f`
    - The last `f` will execute the `then` continuation of `all<Fs...>`

Example expansion for two hypotetical `a` and `b` nodes:

```
_left.store(2);
scheduler([this, &scheduler, &a, then]
{
    a.execute(scheduler, [this, then]
    {
        if(_left.fetch_sub(1) == 1) { then(); }
    });
}),
scheduler([this, &scheduler, &b, then]
{
    b.execute(scheduler, [this, then]
    {
        if(_left.fetch_sub(1) == 1) { then(); }
    });
});
```

- `leaf<F>` : wraps a computation into a node, allows composition
- `seq<A, B>` : executes `A` , then `B`
- `all<Fs ... >` : executes all `Fs ...` in parallel

- We can model arbitrary fork/join computation graphs



```cpp
auto graph = seq{seq{leaf{[]{ std::cout << "a0\n"; }},
                     all{leaf{[]{ std::cout << "b0\n"; }},
                         leaf{[]{ std::cout << "b1\n"; }},
                         leaf{[]{ std::cout << "b2\n"; }}}},
                 leaf{[]{ std::cout << "c0\n"; }}};
```

(on *wandbox.org*)

- We still can't return values from a node and pass them onwards
  - Let's deal with that next

- The execution of any graph always begins from a `leaf`
- `leaf` nodes must be able to *produce* and *accept* values
- Composition nodes such as `seq` and `all` must be aware of what values their children are producing
- This information can be encoded as part of the node type

- Let's begin by computing the `in_type` and `out_type` of `leaf`

```
template <typename In, typename F>
struct leaf : F
{
    using in_type = In;
    using out_type = std::result_of_t<F&(In)>;

    // ...
};
```

- A new `In` template parameter was added
- How can we make it play nicely with *class template argument deduction*?

```cpp
template <typename F>
leaf(F&&) -> leaf<first_arg_t<decltype(&std::decay_t<F>::operator())>,
                  std::decay_t<F>>;
```

```cpp
template <typename F>
using first_arg_t = std::tuple_element_t<
    1,
    boost::callable_traits::args_t<F>
>;
```

- `boost::callable_traits::args_t<F>` returns a `std::tuple` containing all the argument types of `F`
    - If `F` is a `Callable`, the first type is the type of the object itself

- We can now instantiate `leaf` objects as follows:

```
leaf{[](int){ }};
// Deduced as `leaf<int, /* lambda */>`

leaf{[](std::string){ }};
// Deduced as `leaf<std::string, /* lambda */>`
```

(on *wandbox.org*)

- However, `leaf<In, F>::execute` still looks like this:

```
template <typename Scheduler, typename Then>
void leaf<In, F>::execute(Scheduler&, Then&& then) &
{
    (*this)(/* ? */);
    std::forward<Then>(then)();
}
```

- The solution is simple: accept an input argument in `execute`

```cpp
template <typename Scheduler, typename Input, typename Then>
void leaf<In, F>::execute(Scheduler&, Input&& input, Then&& then) &
{
    std::forward<Then>(then)(
        (*this)(std::forward<Input>(input));
    );
}
```

- We invoke `*this` with the input, and pass the result to `then`
- Usage example:

```cpp
auto graph = leaf{[](int x){ return x * 2; }};
graph.execute(scheduler, 21, [](int x){ std::cout << x << '\n'; });
```

(on *wandbox.org*)

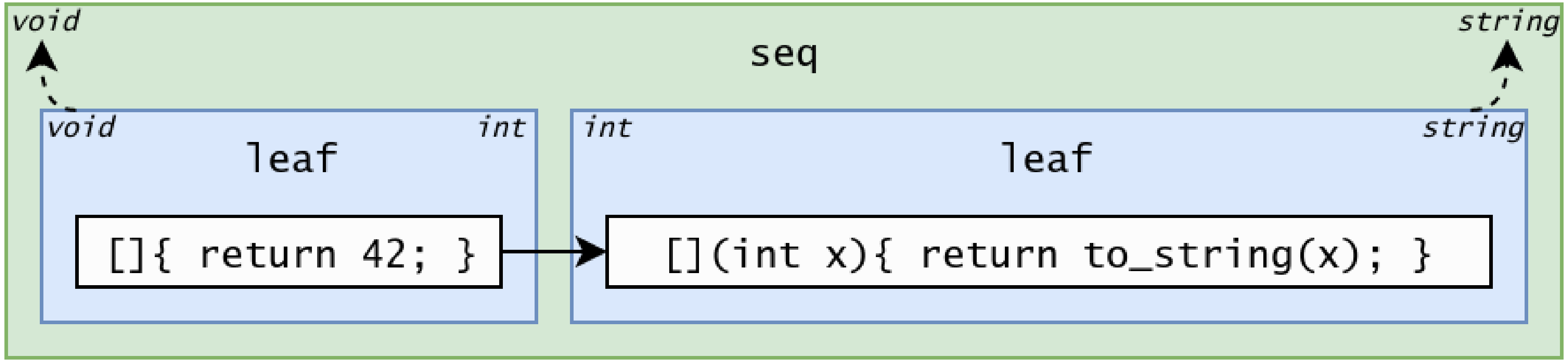
implementation

part 4 - return value propagation


```cpp
template <typename In, typename F>
struct leaf : F
{
    using in_type = In;
    using out_type = std::result_of_t<F&(In)>;

    leaf(F&& f) : F{std::move(f)}
    {
    }

    template <typename Scheduler, typename Input, typename Then>
    void execute(Scheduler&, Input&& input, Then&& then) &
    {
        std::forward<Then>(then)((*this)(std::forward<Input>(input)));
    }
};

template <typename F>
leaf(F&&) -> leaf<first_arg_t<decltype(&std::decay_t<F>::operator())>,
                  std::decay_t<F>>;
```

- All the other node types will require the same modifications:
  - Expose `in_type` and `out_type`
  - Accept an `input` argument in `execute`
  - Execute the child nodes by passing `input`
  - Invoke the `then` continuation by passing the result of the above operation
- Let's apply these changes to `seq`

```
template <typename A, typename B>
struct seq : A, B
{
    using in_type = typename A::in_type;
    using out_type = typename B::out_type;

    // ...
};
```



```
template <typename Scheduler, typename Then>
void seq<A, B>::execute(Scheduler& scheduler, Then&& then) &
{
    A::execute(scheduler, [this, &scheduler, then]
    {
        B::execute(scheduler, then);
    });
}
```

...becomes...

```
template <typename Scheduler, typename Input, typename Then>
void seq<A, B>::execute(Scheduler& scheduler, Input&& input, Then&& then) &
{
    A::execute(scheduler, FWD(input), [this, &scheduler, then](auto&& r)
    {
        B::execute(scheduler, FWD(r), then);
    });
}
```

- Usage example:

```
auto graph = seq{leaf{[](int x){ return x * 2; }},
                 leaf{[](int x){ return std::to_string(x); }}};

graph.execute(scheduler, 21, [](std::string x)
{
    std::cout << x << '\n';
});
```

(on *wandbox.org*)

```
template <typename A, typename B>
struct seq : A, B
{
    using in_type = typename A::in_type;
    using out_type = typename B::out_type;

    seq(A&& a, B&& b) : A{std::move(a)}, B{std::move(b)}
    {
    }

    template <typename Scheduler, typename Input, typename Then>
    void execute(Scheduler& scheduler, Input&& input, Then&& then) &
    {
        A::execute(scheduler, FWD(input), [this, &scheduler, then](auto&& out)
        {
            B::execute(scheduler, FWD(out), then);
        });
    }
};
```

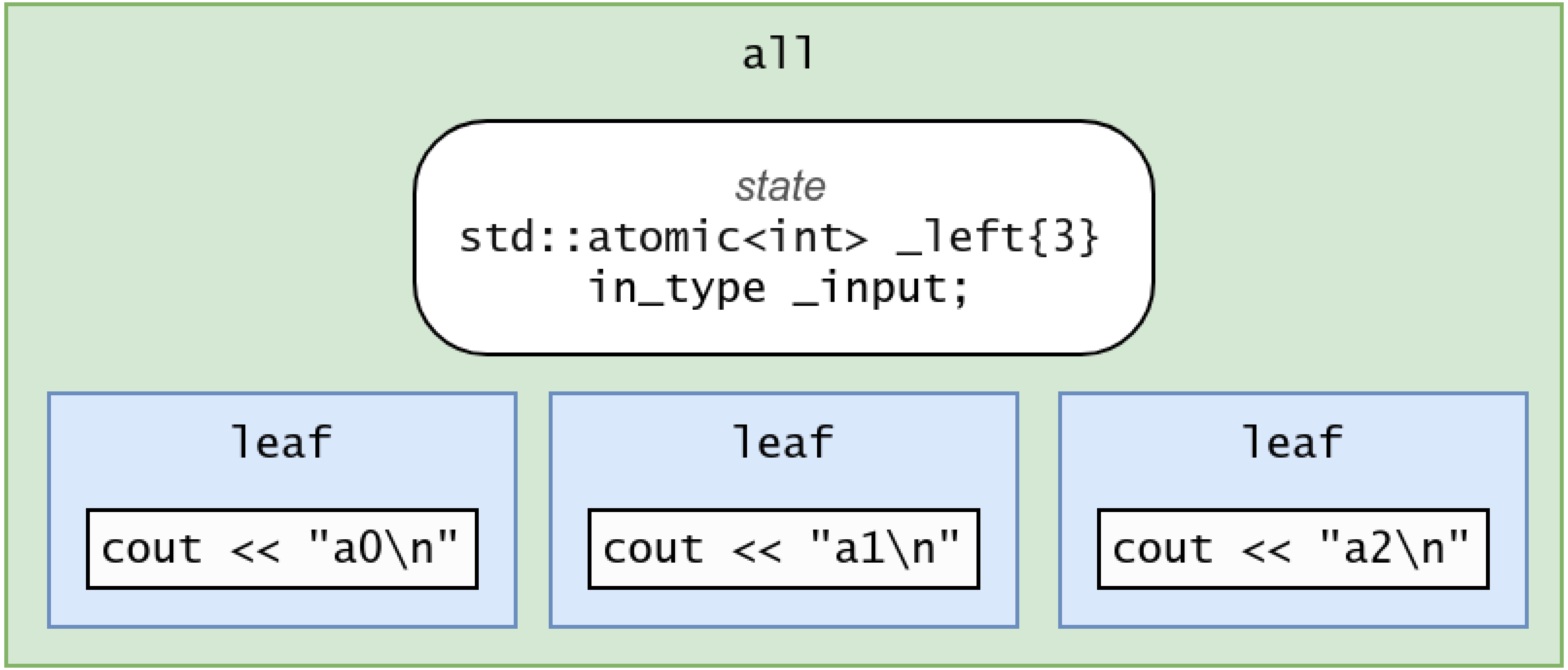
(on *wandbox.org*)

- `leaf` and `seq` now support asynchronous propagation of values
- `all` is slightly more complicated:
  - Multiple parallel computations need access to the `input` value
  - It cannot be passed directly from the stack, as it is not guaranteed to outlive the parallel computations
  - The value could be copied for each computation, but that might be expensive
  - We will store it inside `all` itself, so that it is guaranteed to live long enough

implementation

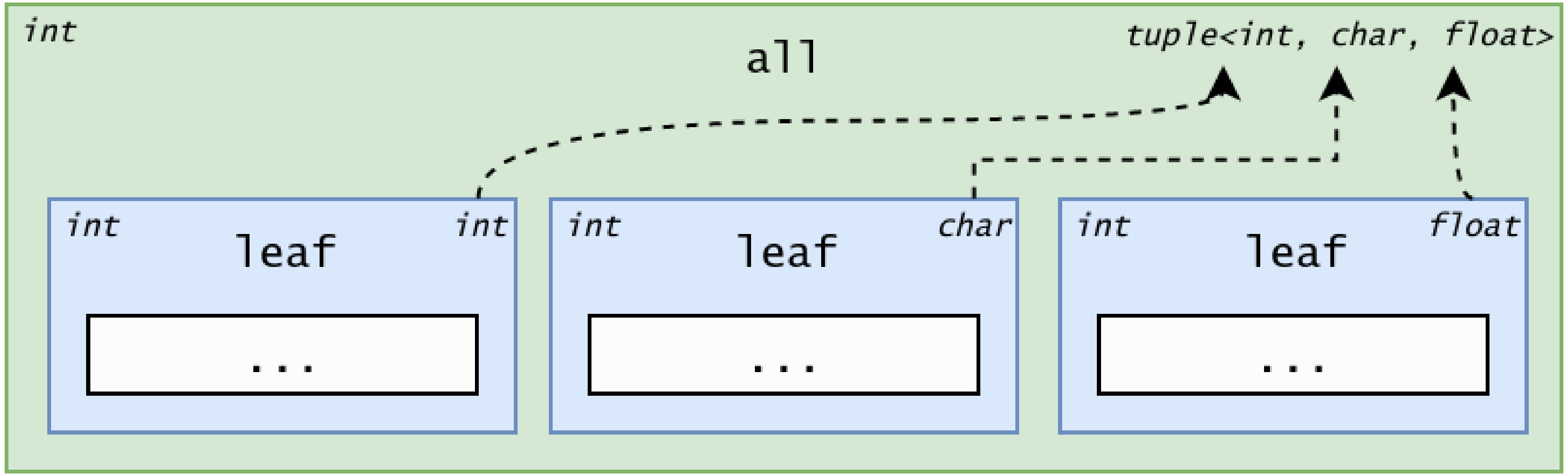
part 4 - return value propagation


```
template <typename Scheduler, typename Input, typename Then>
void all<Fs...>::execute(Scheduler& sched, Input&& input, Then&& then) &
{
    _left.store(sizeof...(Fs));

    (sched([this, &sched, &input,
//                        ^~~~~~
                &f = static_cast<Fs&>(*this), then]
    {
        f.execute(sched, input, [this, then]
        {//                      ^~~~~
         //        dangling reference (!)

            if(_left.fetch_sub(1) == 1) { then(); }
        });
    }), ...);
}
```



- Children nodes will simply *refer* to the `_input` stored in the `all` node

```
template <typename... Fs>
struct all : Fs...
{
    using in_type = std::common_type_t<typename Fs::in_type...>;
    using out_type = std::tuple<typename Fs::out_type...>;

    // ...
};
```



```
template <typename... Fs>
struct all : Fs...
{
    struct shared_state
    {
        in_type _input;
        std::atomic<int> _left;

        template <typename Input>
        shared_state(Input&& input) : _input{FWD(input)}
        {
            _left.store(sizeof...(Fs));
        }
    };

    // ...
};
```

```
template <typename... Fs>
struct all : Fs...
{
    using in_type = std::common_type_t<typename Fs::in_type...>;
    using out_type = std::tuple<typename Fs::out_type...>;

    struct shared_state { /* ... */ };

    aligned_storage_for<shared_state> _state;
    out_type _values;

    // ...
};
```

- `_state` is constructed when calling `execute`, destroyed on completion
- `_values` will be filled during `execute` and passed down to children nodes

```
template <typename Scheduler, typename Input, typename Then>
void all<Fs...>::execute(Scheduler& sched, Input&& input, Then&& then) &
{
    _state.construct(FWD(input));
    // * schedule children nodes...
    // * fill `_values` with each node's result...
    // * finally: invoke `then` and destroy `_state` on completion...
}
```

- We need to fill the `_values` tuple with the results of each node
    - Therefore we need an index to use `std::get`
- Our beautiful *fold expression* will have to be replaced with something a little bit more powerful

```
template <typename Scheduler, typename Input, typename Then>
void all<Fs...>::execute(Scheduler& sched, Input&& input, Then&& then) &
{
    _state.construct(FWD(input));

    enumerate_types<Fs...>([&](auto i, auto t)
    {
        // ...
    });
}
```

- `enumerate_types<Fs...>` will invoke the passed lambda with:
  - `i` : `std::integral_constant<int, I>{}` storing the current index
  - `t` : `type_wrapper<T>{}` storing the current type

```
template <typename Scheduler, typename Input, typename Then>
void all<Fs...>::execute(Scheduler& sched, Input&& input, Then&& then) &
{
    _state.construct(FWD(input));

    enumerate_types<Fs...>([&](auto i, auto t)
    {
        sched([this, &sched,
               &f = static_cast<unwrap<decltype(t)>&>(*this), then]
        {
            // ...
        });
    });
}
```

- `f` evaluates to `*this`, casted to the type in `Fs...` of the current iteration

```
template <typename Scheduler, typename Input, typename Then>
void all<Fs...>::execute(Scheduler& sched, Input&& input, Then&& then) &
{
    _state.construct(FWD(input));

    enumerate_types<Fs...>([&](auto i, auto t)
    {
        sched([this, &sched,
               &f = static_cast<unwrap<decltype(t)>&>(*this), then]
        {
            f.execute(sched, _state->_input, [this, then](auto&& r)
            {
                // ...
            });
        });
    });
}
```

- `f` is executed with `_state->_input`, which lives as long as needed

```cpp
template <typename Scheduler, typename Input, typename Then>
void all<Fs...>::execute(Scheduler& sched, Input&& input, Then&& then) &
{
    _state.construct(FWD(input));
    enumerate_types<Fs...>([&](auto i, auto t)
    {
        sched([this, &sched,
               &f = static_cast<unwrap<decltype(t)>&>(*this), then]
        {
            f.execute(sched, _state->_input, [this, then](auto&& r)
            {
                std::get<decltype(i){}>(_values) = FWD(r);
                if(_state->_left.fetch_sub(1) == 1)
                {
                    _state.destroy();
                    then(std::move(_values));
                }
            });
        });
    });
}
```

(on *wandbox.org*)

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- Usage example:

```
auto graph = seq{all{leaf{[](int x){ return x; }},
                     leaf{[](int x){ return x + 1; }},
                     leaf{[](int x){ return x + 2; }}},
                leaf{[](std::tuple<int, int, int> y)
                {
                    return get<0>(y) + get<1>(y) + get<2>(y);
                }}};

graph.execute(scheduler, 0, [](int x){ std::cout << x << '\n'; });
```

(on *wandbox.org*)

`all<Fs...>` return value propagation recap:

- The `input` and the *atomic counter* are stored **in-place** in `shared_state`
    - It is constructed when calling `execute`, destroyed on completion
- The output values are stored in a `std::tuple<typename Fs::out_type...>`
    - This lives **in-place** inside the node
    - It is filled by enumerating `Fs...` at compile-time
    - The last computation to finish invokes `then` with the tuple
- While enumerating `Fs...`, we can apply an optimization:
    - If `i == 0`, do not schedule the current computation

- I've carefully avoided using `void` in all the examples
- It is not a "*regular type*" - it requires extra care
- A preliminary step is defining an empty `nothing` type and using it place of `void`

```
struct nothing { };
```

- A real solution uses *metaprogramming* to automatically convert `void` to `nothing` transparently to the user
  - github.com/SuperV1234/orizzonte/nothing.hpp
  - This will not be covered in the talk

- So far we have used `this_thread::sleep_for` in order to prevent `graph` from being destroyed too early

```
all graph{leaf{[]{ std::cout << "a0\n"; }},
          leaf{[]{ std::cout << "a1\n"; }},
          leaf{[]{ std::cout << "a2\n"; }}};

graph.execute(scheduler, []{ std::cout << "b0\n"; });
std::this_thread::sleep_for(100ms);
```

- Can we do better?

- We can use a **latch** (e.g. `std::experimental::latch` or `boost::latch`)
- It basically is a **counter** + **condition variable** + **mutex**
    - The current thread is blocked until the counter reaches zero

```
std::experimental::latch l{3};

std::thread{[&l]{ l.count_down(); }}.detach();
std::thread{[&l]{ l.count_down(); }}.detach();
std::thread{[&l]{ l.count_down(); }}.detach();

l.wait(); // blocks until `counter == 0`
```

- Let's create a `sync_execute` abstraction that uses a latch

```cpp
template <typename Scheduler, typename Graph, typename Then>
void sync_execute(Scheduler& scheduler, Graph&& graph, Then&& then)
{
    std::experimental::latch l{1};

    graph.execute(scheduler, nothing{}, [&](auto&& res)
    {
        then(FWD(res));
        l.count_down();
    });

    l.wait();
}
```

- Given a `graph`, it is executed under a latch `l`
- The continuation attached at the end of the graph will unblock the latch

- Usage example:

```
auto graph = seq{all{leaf{[](int x){ return x; }},
                     leaf{[](int x){ return x + 1; }},
                     leaf{[](int x){ return x + 2; }}},
                leaf{[](std::tuple<int, int, int> y)
                {
                    return get<0>(y) + get<1>(y) + get<2>(y);
                }}};

sync_execute(scheduler, graph, [](int x){ std::cout << x << '\n'; });
```

(on *wandbox.org*)

- Removes the need for `sleep_for`, providing a deterministic lifetime for `graph`

- Which one is better?

```
auto graph = seq{seq{leaf{a}, leaf{b}}, leaf{c}};
```

```
auto graph = leaf{a}.then(b).then(c);
```

- Let's add a `.then` member function to every node type

```
template <typename In, typename F>
struct leaf : F
{
    template <typename X>
    auto then(X&& x);

    // ...
};
```

- It will take an arbitrary object `x`:
    - If `x` is a node, it will return a `seq{std::move(*this), x}`
    - If `x` is not a node, it will return `seq{std::move(*this), leaf{x}}`

```
template <typename X>
auto leaf<In, F>::then(X&& x)
{
    if constexpr(detail::is_executable<X>{})
    {
        return seq{std::move(*this), FWD(x)};
    }
    else
    {
        return seq{std::move(*this), leaf{FWD(x)}};
    }
}
```

- `is_executable` uses the *detection idiom* to detect whether or not `x` exposes `.execute`

- Usage example:

```
auto graph = leaf{[]{ return 10; }}
    .then([](int x){ return x * 2; })
    .then(all{leaf{[](int x){ return x + 5; }},
              leaf{[](int x){ return x - 5; }}})
    .then([](std::tuple<int, int> y)
    {
        return std::get<0>(y) + std::get<1>(y);
    });
```

(on *wandbox.org*)

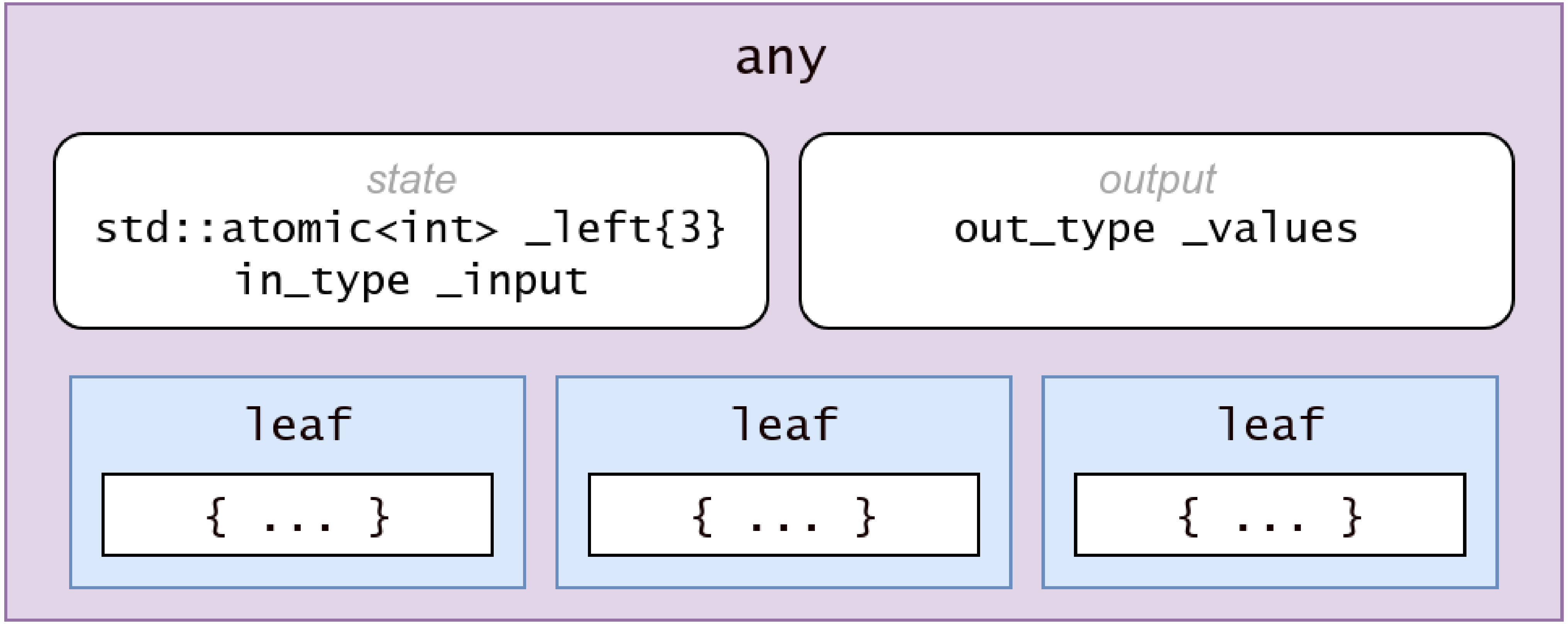
- The `any` node is the most complicated one
- It takes `Fs ...` as input, and as soon as any of them it's completed, the `then` continuation is invoked
- The remaining computations still run in the background

```
any graph{a.then(b), c.then(d)};
```

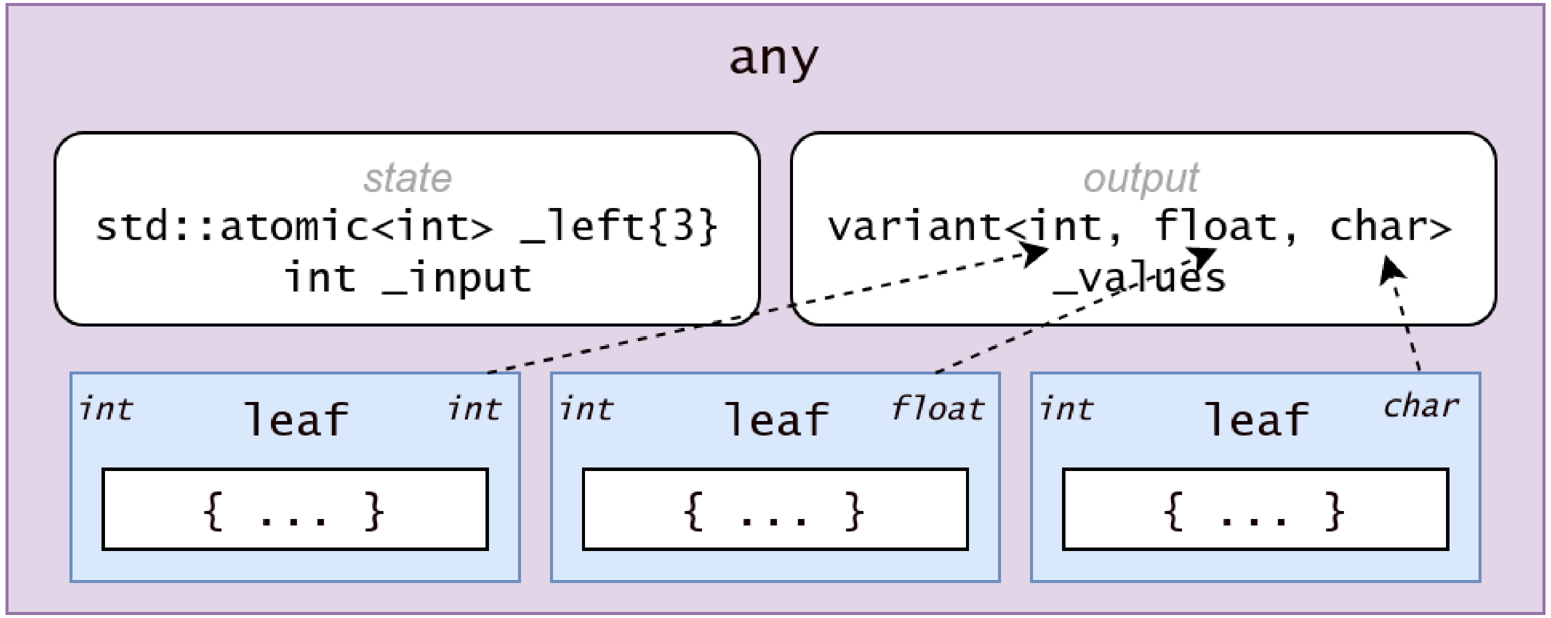
- How do we know when we can safely destroy `graph`?
  - `b` could finish before `c` or `d`
  - Our previous `latch` solution will not work

```cpp
any graph{leaf{[]{ std::cout << "a0\n"; }},
          leaf{[]{ std::cout << "a1\n"; }},
          leaf{[]{ std::cout << "a2\n"; }}};

graph.execute(scheduler, []{ std::cout << "b0\n"; });
```

(on *wandbox.org*)



```
template <typename... Fs>
struct any : Fs...
{
    using in_type = std::common_type_t<typename Fs::in_type...>;
    using out_type = std::variant<typename Fs::out_type...>;

    any(Fs&&... fs) : Fs{std::move(fs)}... { }
    // ...
```



```
template <typename ... Fs>
struct any : Fs ...
{
    struct shared_state
    {
        in_type _input;
        std::atomic<int> _left;

        template <typename Input>
        shared_state(Input&& input) : _input{FWD(input)}
        {
            _left.store(sizeof ... (Fs));
        }
    };

    aligned_storage_for<shared_state> _state;
    out_type _values;
    // ...
```

```
template <typename Scheduler, typename Input, typename Then, typename Cleanup>
void execute(Scheduler& sched, Input&& input, Then&& then, Cleanup&& cleanup) &
{
    _state.construct(FWD(input));
    (sched([this, &sched, &f = static_cast<Fs&>(*this), then, cleanup]
    {
        // ...
    }), ... );
}
```

- Every node gets a new argument in `execute`: `cleanup`
- Similarly to `then`, it is executed when a node is ready to be cleaned up
  - For `leaf`, `seq`, and `all`: cleanup is the same as completion
  - For `any`: cleanup and completion may happen at different times

```
(sched([this, &sched, &f = static_cast<Fs&>(*this), then, cleanup]
{
    f.execute(sched, _state->_input, [this, then, cleanup](auto&& r)
    {
        // ...
    }, cleanup);
}), ... );
```

- `cleanup` is copied alongside `then`
- `cleanup` is propagated to children nodes' `execute`

```cpp
f.execute(sched, _state->_input, [this, then, cleanup](auto&& r)
{
    const auto l = _state->_left.fetch_sub(1);
    if(l == sizeof...(Fs))
    {
        _values = FWD(r);
        then(std::move(_values));
    }

    if(l == 1) { _state.destroy(); cleanup(); }
}, cleanup);
```

- `l == sizeof...(Fs)` is the "completion condition"
- `l == 1` is the "cleanup condition"

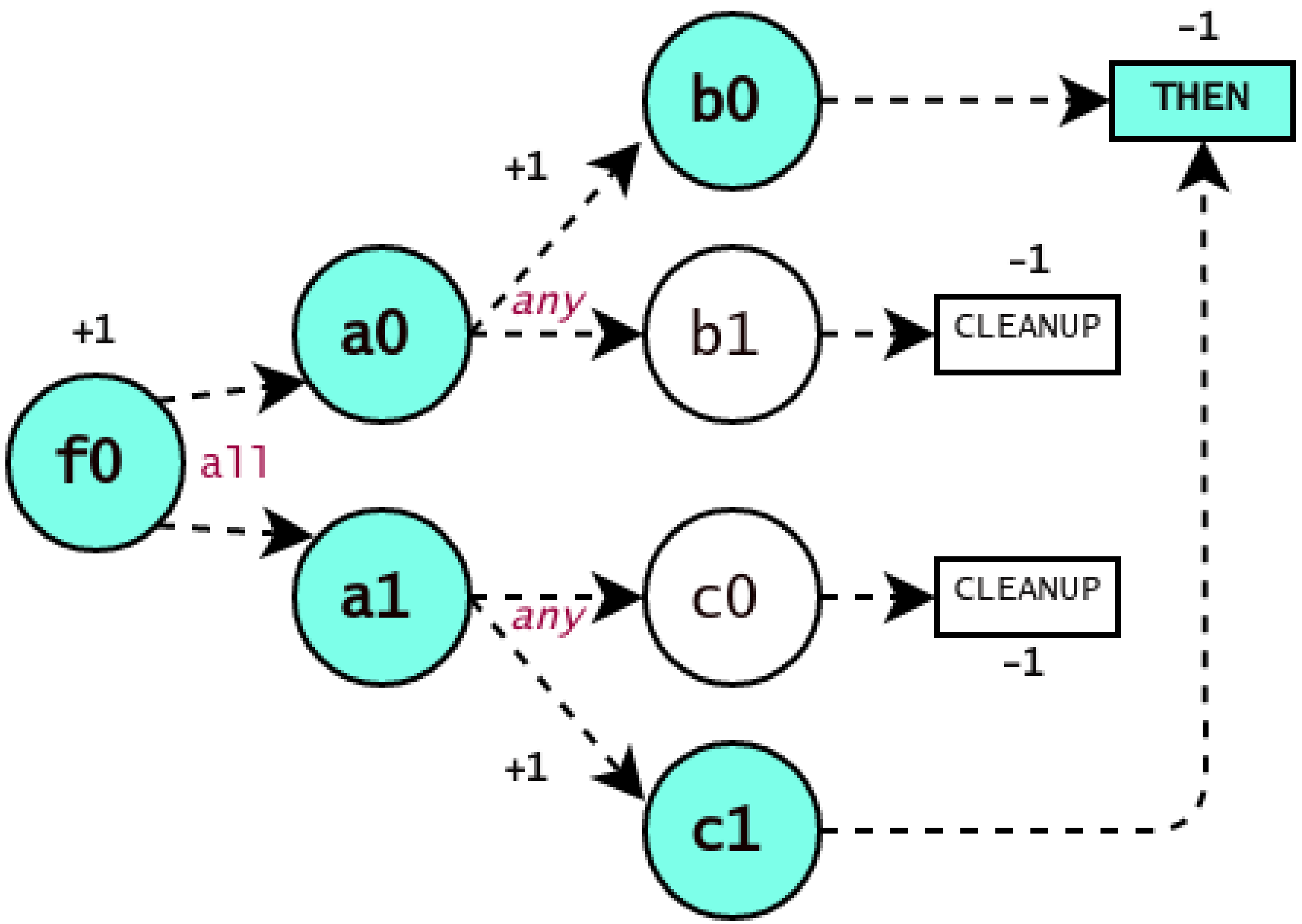
```
template <typename Scheduler, typename Input, typename Then, typename Cleanup>
void execute(Scheduler& sched, Input&& input, Then&& then, Cleanup&& cleanup) &
{
    _state.construct(FWD(input));
    (sched([this, &sched, &f = static_cast<Fs&>(*this), then, cleanup]
    {
        f.execute(sched, _state->_input, [this, then, cleanup](auto&& r)
        {
            const auto l = _state->_left.fetch_sub(1);
            if(l == sizeof...(Fs))
            {
                _values = FWD(r);
                then(std::move(_values));
            }

            if(l == 1) { _state.destroy(); cleanup(); }
        }, cleanup);
    }), ...);
}
```

(on *wandbox.org*)

```cpp
template <typename Scheduler, typename Graph, typename Then>
void sync_execute(Scheduler& scheduler, Graph&& graph, Then&& then)
{
    latch l{std::decay_t<Graph>::cleanup_count() + 1};

    graph.execute(scheduler, nothing{},
        [&](auto&&... res) { then(FWD(res)...); l.count_down(); },
        [&] { l.count_down(); });
}
```

- `cleanup_count` returns the count of `any` nodes in the graph

```
auto f0 = all{any{b0, b1}, any{c0, c1}};
sync_execute(scheduler, f0, []{ /* then */ });
```

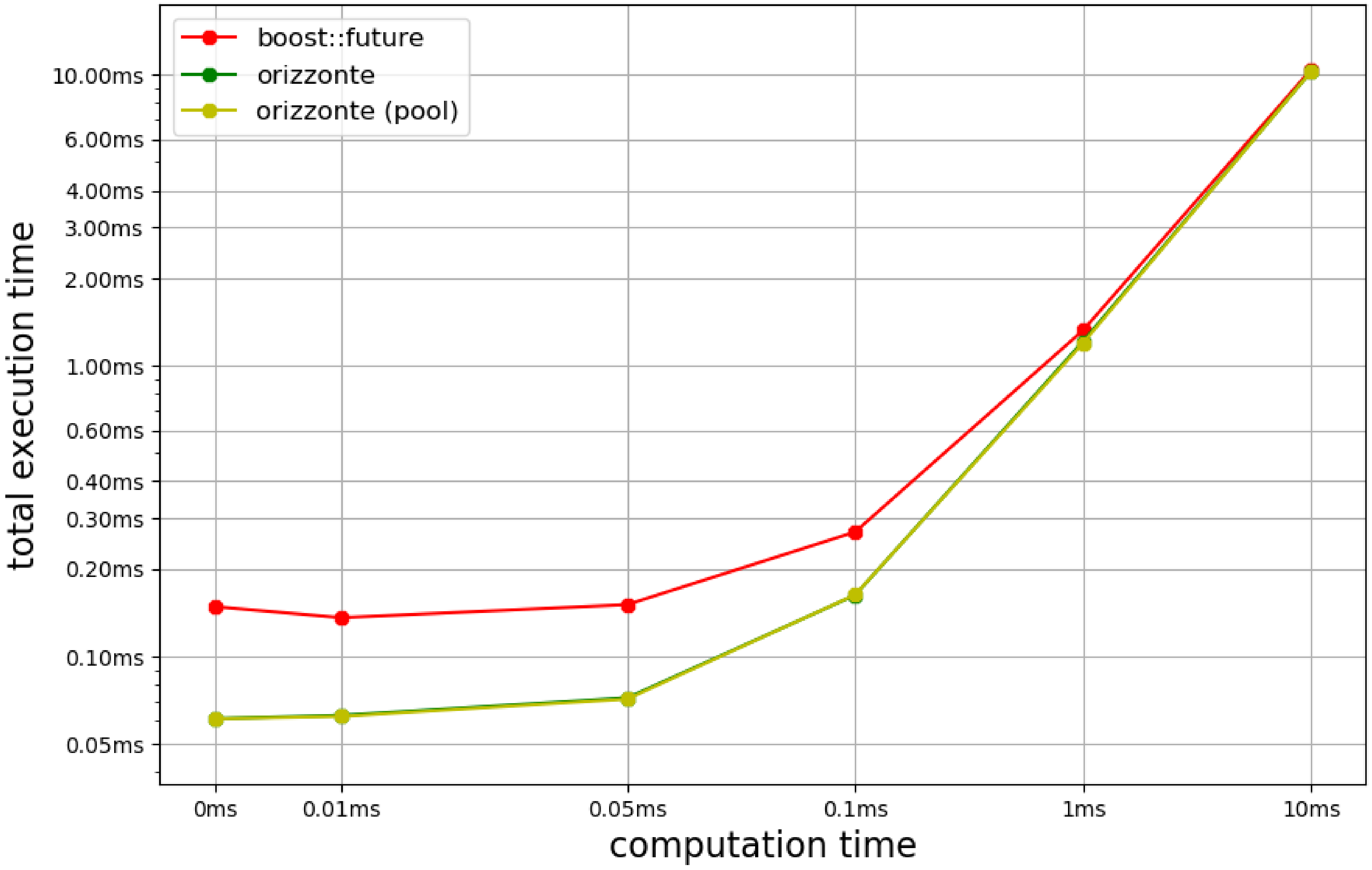


`all<Fs ... >` node recap:

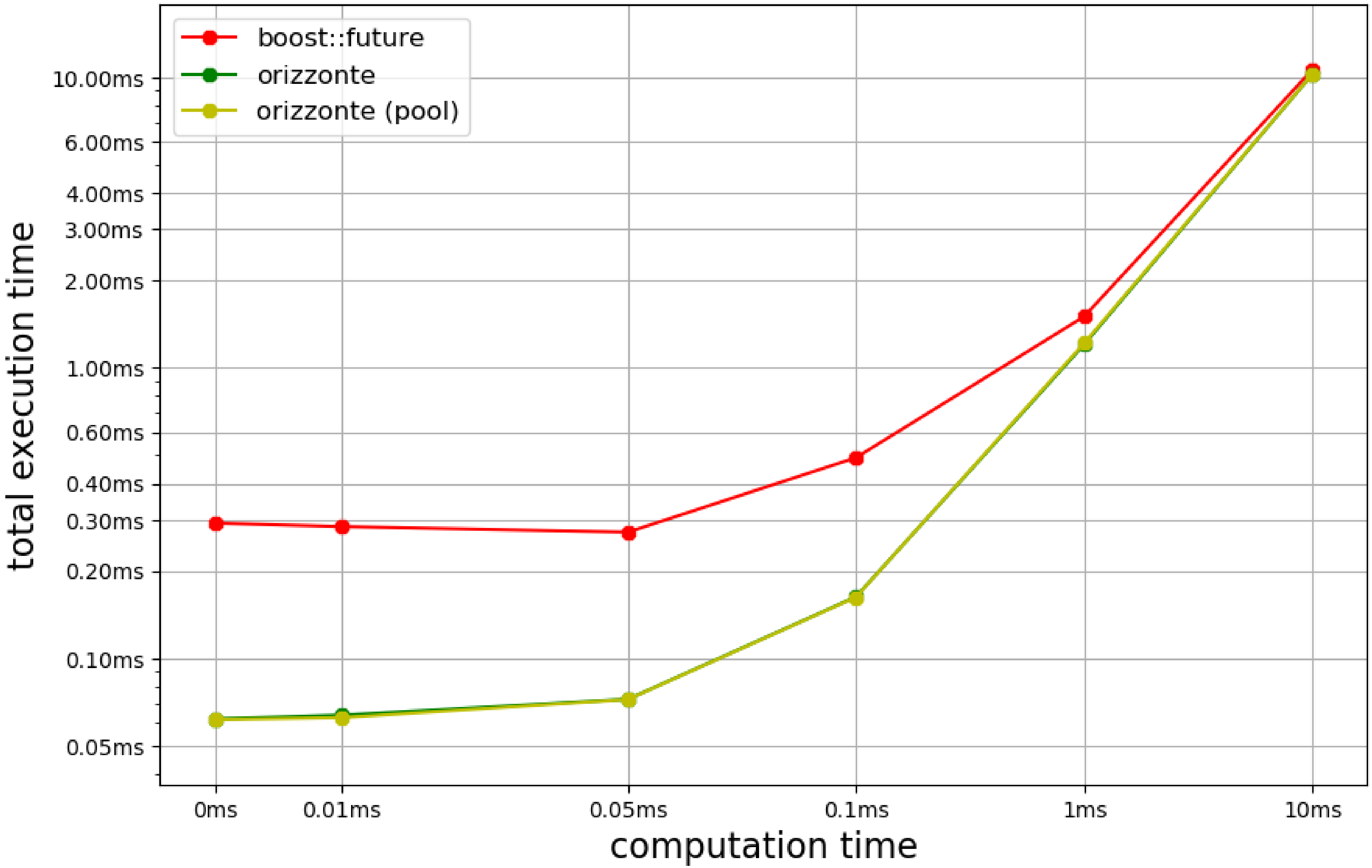
- Invokes the `then` continuation as soon as one of `Fs ...` is completed
  - The remaining computations are run in the background
  - The node must be kept alive until **all** computations are done
- Output values are stored in a `std::variant<typename Fs::out_type ... >`
- Introduces an additional `cleanup` step for each node type
  - Only `any` actively invokes it when all `Fs ...` are done
  - The latch is initializes to `1 + count_of_any_nodes`
  - This allows to block until the graph can be destroyed

Run-time benchmarks vs `boost::future`

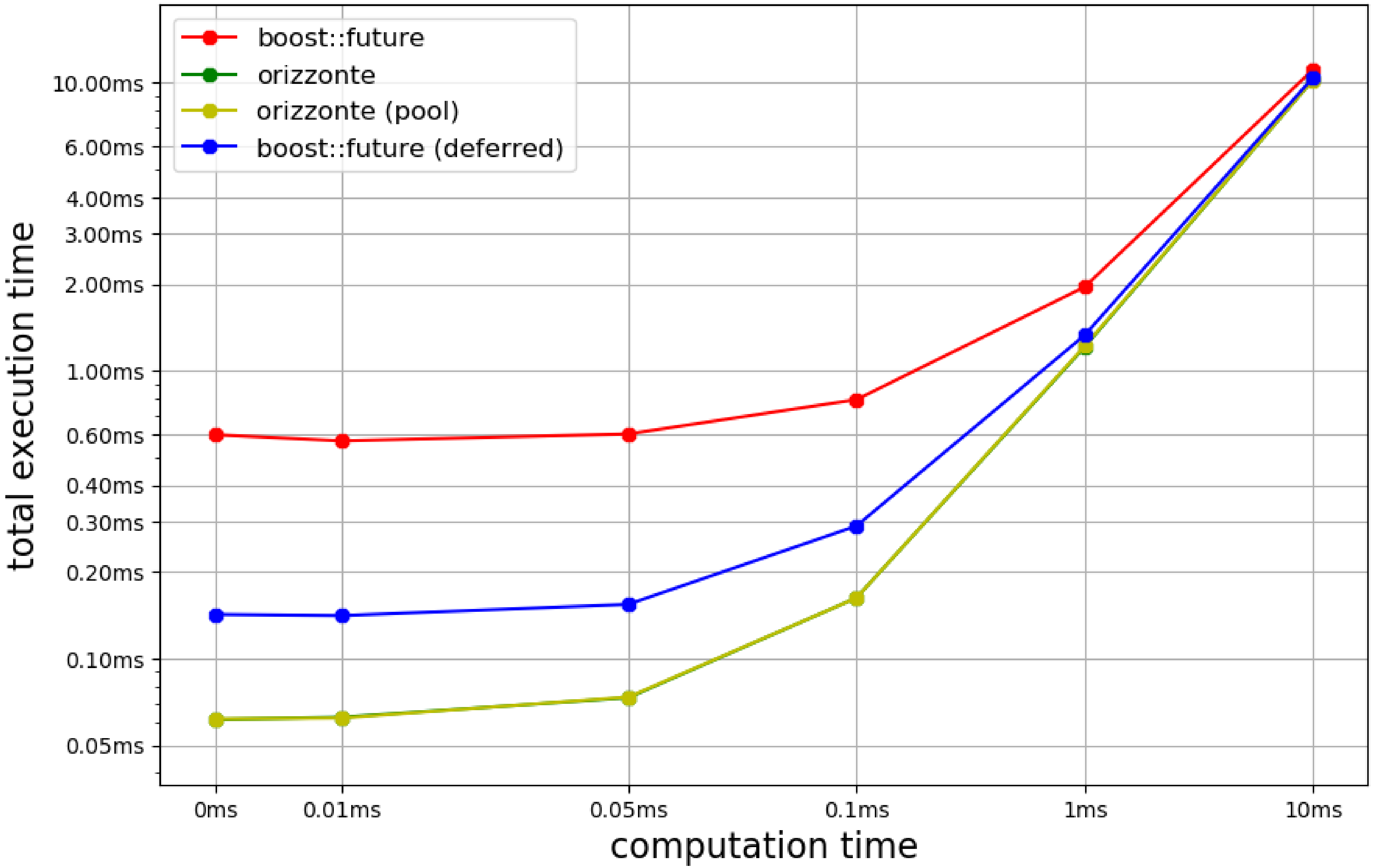
Single node


boost::future
orizzonte
orizzonte (pool)
10.00ms
6.00ms
4.00ms
3.00ms
2.00ms
1.00ms
0.60ms
0.40ms
0.30ms
0.20ms
0.10ms
0.05ms
total execution time
0ms
0.01ms
0.05ms
0.1ms
1ms
10ms
computation time

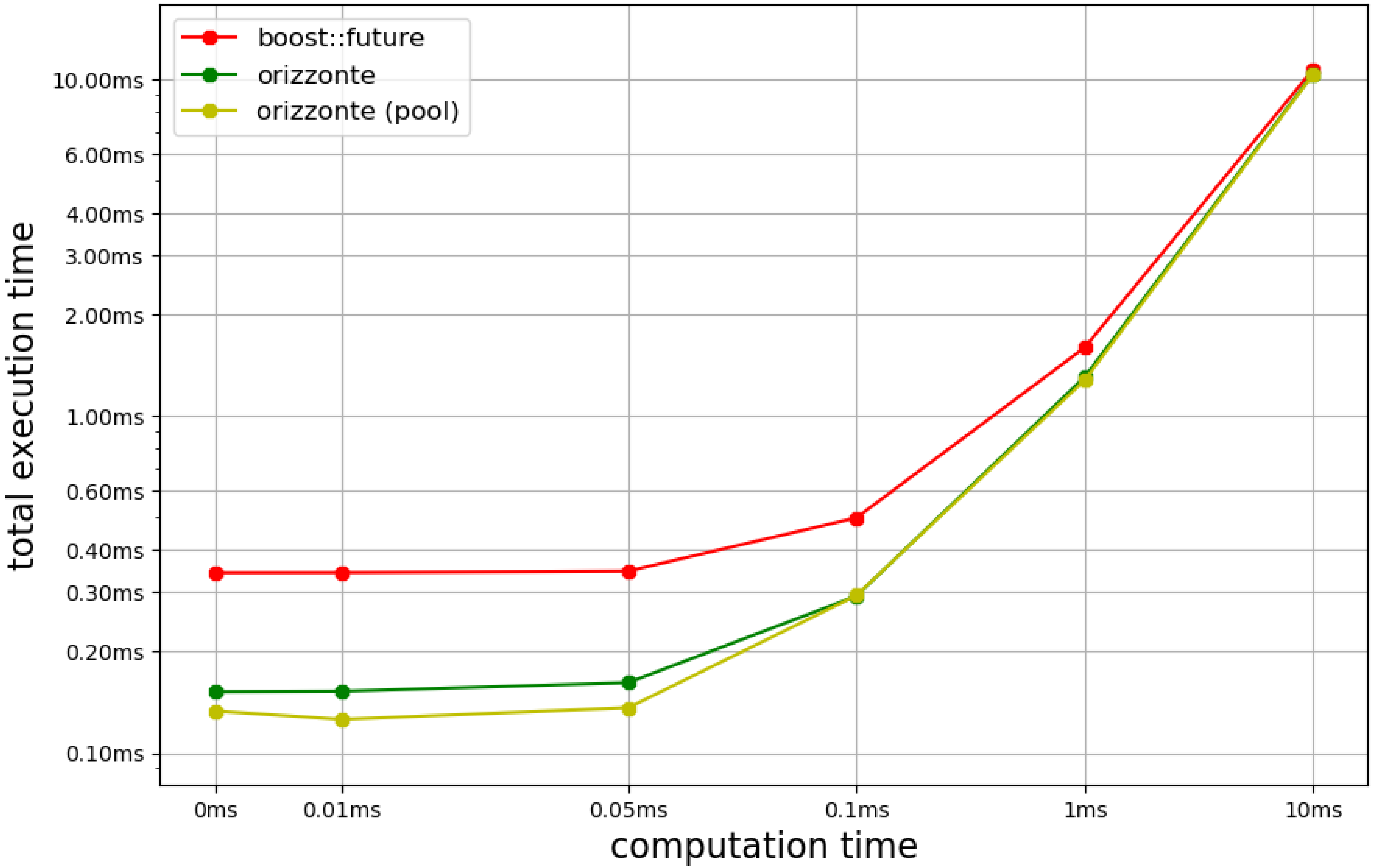
`a.then(b).then(c)`



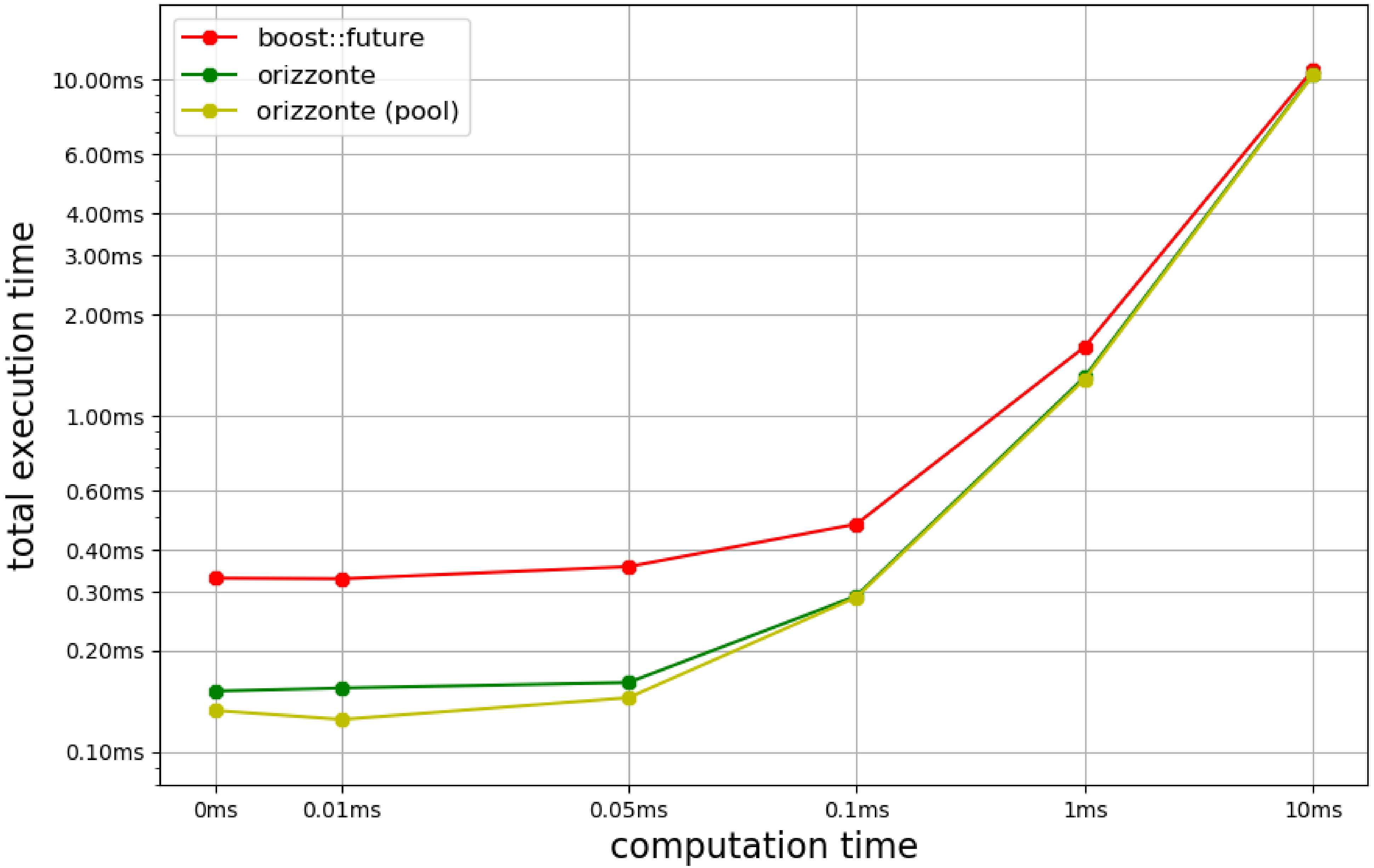
```
a.then(b).then(c).then(d).then(e).then(f).then(g).then(h)
```



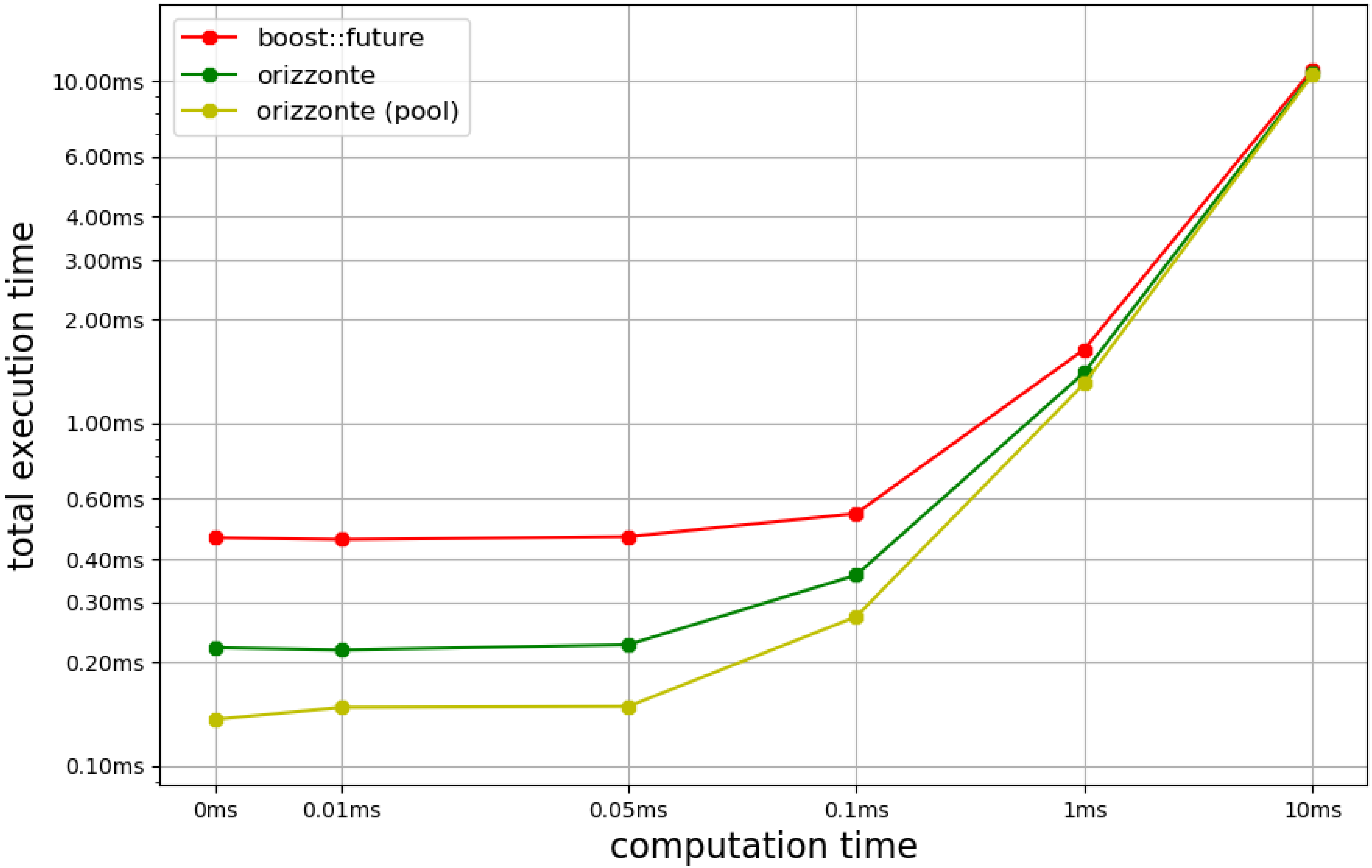
`all{a0, a1, a2}.then(b0)`



```
any{a0, a1, a2}.then(b0)
```



`any{a0.then(all{c0, c1, c2}), a1, a2}.then(b0)`



- WIP library available at: https://github.com/SuperV1234/orizzonte
- "*Expression templates*" can be applied to pretty much anything
- Sanitizers are invaluable (especially `ThreadSanitizer`)
- C++17 features **greatly** simplify the implementation
- Future directions/ideas:
  - Automatic cancellation in `any` nodes
  - Composable type-erasing wrapper
  - Exception handling (automatic failure path)

Thanks!

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https://github.com/SuperV1234/orizzonte