WG21 PROPOSAL

IoAwaitables: A Coroutines-Only Framework

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Reply-to: Vinnie Falco vinnie.falco@gmail.com
Steve Gerbino steve@gerbino.co
Amlal El Mahrouss amlalelmahrouss@icloud.com
Mungo Gill mungo.gill@me.com

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Abstract

This paper asks: ***what would an execution model look like if designed from the ground up for coroutine-only asynchronous I/O?***

We built one and found out. A group of practitioners implemented a complete networking library using only coroutines - no callbacks, no sender/receiver chains, no completion tokens. The fundamental abstraction which emerged is the ***IoAwaitable*** protocol: a system for associating a coroutine with an executor, stop token, and allocator, and propagating this context forward through a coroutine chain to the operating system API boundary where asynchronous operations are performed.

This paper presents our findings. The protocol is small: two concepts, a type-erased executor, and a thread-local write-through cache that keeps allocator policy out of coroutine signatures. It delivers correctness through compile-time protocol checking, ergonomics through clean interfaces free of cross-cutting concerns, and performance through zero-allocation steady-state operation with recycling allocators. We compare our design against `std::execution` (P2300) and its evolution (P3826) to illuminate where the designs diverge and why.

Revision History

R0: March 2026 (pre-Croydon mailing)

- Initial version.

1. Introduction

This paper is a research report. We set out to answer a practical question: if you design a networking library from the ground up for C++ coroutines, what execution model emerges? Not as a thought experiment, but as working code - a complete library with sockets, timers, TLS, DNS resolution, HTTP, and WebSocket support, all built on a coroutine-only foundation.

The answer surprised us in its simplicity. The protocol that emerged is small: two concepts, a type-erased executor, and a thread-local write-through cache that keeps allocator policy out of coroutine signatures - yet it is the foundation from which a complete coroutine-only networking stack can be built. We could not find anything to remove from it without losing function. Like the narrow abstractions that have succeeded in C++: iterators for traversal, RAII for resource lifetime, allocators for memory strategy, it captures one essential property and leaves everything else to the user.

Readers unfamiliar with event loops, completion handlers, and executor models may find the background in Appendix A helpful before proceeding.

Design Priorities

We adopted three priorities, in strict order:

1. **Correctness.** Protocol invariants are enforced at compile time: coroutines without protocol compliance refuse to compile.
2. **Ergonomics.** The user story comes first: we studied every alternative to give developers the best experience.
3. **Performance.** We benchmarked at every step to measure the cost of our abstractions and ensure the best performance.

What Matters

Studying I/O-intensive applications reveals clear patterns. A network server completes read operations on I/O threads, resumes handlers on application threads, and serializes access to connection state. A file system service batches completions through io_uring, dispatches callbacks to worker pools, and manages buffer lifetimes across suspension points. These patterns repeat across every I/O application. The requirements they impose are specific:

- **The application decides executor policy.** Single-threaded or multi-threaded. One reactor per thread or a shared reactor with strand serialization. Completions running freely or serialized per connection. These are deployment decisions that a read operation should not need to know about.

- **The application sends stop signals.** A timeout, user abort, or graceful shutdown originates at the launch site and propagates to pending operations. Algorithms need control over stopping behavior: a simple pipeline passes the stop token through, while `when_all` or `when_any` hook the caller's token to an internal stop source with fanout. A good API builds on `std::stop_token` since that is what the standard provides.

- **The application decides allocation policy.** Memory strategies: recycling pools, bounded allocation, per-tenant budgets, these are a property of the coroutine chain. A good API makes stateful allocators a first-class user-facing customization point when it matters, and gets out of the way when sensible defaults suffice.

- **The execution context owns its I/O objects.** A socket registered with epoll on thread A cannot have completions delivered to thread B's epoll. The physical coupling is inherent. The call site cannot and should not know which event loop the socket uses, only the socket knows.

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2. Networking's Essentials

Networking has specific requirements that differ from heterogeneous computing. A socket read has **one implementation per platform** - there is no algorithm selection, no hardware heterogeneity to manage. What matters is the contract between the coroutine and the platform: the coroutine suspends, a platform-specific reactor (epoll, IOCP, io_uring) performs the asynchronous operation, and the coroutine resumes in a predictable way. "Predictable" means the application controls which thread resumes it, whether completions are serialized, and whether resumption is inline or deferred.

The ***IoAwaitable*** protocol handles this end to end. The executor solves the resumption part: given a suspended coroutine, resume it according to the application's policy. The stop token and the allocator handle the rest. Every executor is bound to an execution context - the object that owns the platform reactor and the I/O objects registered with it. A socket registered with epoll on one context cannot have completions delivered through another; P2762 acknowledges this physical coupling in §3.1:

> *"It was pointed out networking objects like sockets are specific to a context: that is necessary when using I/O Completion Ports or a TLS library and yields advantages when using, e.g., io_uring(2)."*

2.1 The Executor

An executor is to functions what an allocator is to memory: while an allocator controls ***where*** objects live, an executor controls ***how*** coroutines resume. A minimal executor needs only two operations: `dispatch` for continuations that can safely run inline, and `post` for work that must be deferred. The distinction is a correctness requirement, not an optimization - inline execution while holding a lock can deadlock, so the caller must be able to choose. A good coroutines-only design leverages symmetric transfer in `dispatch` whenever safe to do so, avoiding stack buildup entirely. Section 4 defines the concept and its semantics in full.

2.2 The `stop_token`

The stop token propagates forward through the coroutine chain from the launch site to the I/O object at the end:

```
http_client → http_request → write → write_some → socket
```

At the end of the chain, the I/O object acts on the token by invoking the appropriate OS primitive - `CancelIoEx` on Windows, `IORING_OP_ASYNC_CANCEL` on Linux, or `close()` on POSIX. The pending operation completes with an error, and the coroutine chain unwinds normally. Cancellation is cooperative and predictable: no operation is forcibly terminated mid-flight.

2.3 The Allocator

Coroutine frames are allocated continuously - every `co_await` may spawn new frames. Without allocation control, heap overhead dominates. Recycling allocators eliminate this by caching recently freed frames for immediate reuse:

Platform	Allocator	Time (ms)	vs std::allocator
MSVC	Recycling	1265.2	+210.4%
MSVC	mimalloc	1622.2	+142.1%
MSVC	`std::allocator`	3926.9	-
Apple clang	Recycling	2297.08	+55.2%
Apple clang	`std::allocator`	3565.49	-

The mimalloc result is the critical comparison: a state-of-the-art general-purpose allocator with per-thread caches, yet the recycling allocator is 28% faster. Different deployments need different strategies - bounded pools, per-tenant budgets, allocation tracking - so the execution model must make allocation a first-class customization point. The allocator must also be present at invocation time: `operator new` executes before the coroutine body, so any mechanism that delivers the allocator later arrives too late. Section 5 examines the timing constraint and our solution in detail.

2.4 Ergonomics

The executor, stop token, and allocator are infrastructure. They should be invisible to every coroutine in the chain except the launch site where the chain begins. A developer writing a route handler, a parser, or a protocol state machine should see none of this machinery - just their business logic expressed as coroutines. But when the developer needs to care - choosing a different executor, wiring up cancellation, selecting an allocation strategy - the API for doing so should be natural, easy to discover, and structured to prevent mistakes.

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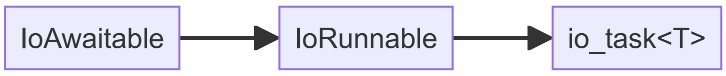
3. Our Solution: The *IoAwaitable* Protocol

The ***IoAwaitable*** protocol is a pair of concepts layered on top of each other, working together to deliver what coroutines and networking need for correctness and performance:



> *To help readers understand how these requirements fit together, this paper provides the `io_awaitable_promise_base` CRTP mixin (§8.1) as a non-normative reference implementation. It is not proposed for standardization - implementors may write their own machinery - but examining it clarifies how the protocol works in practice. The mixin also provides the `this_coro::environment` accessor, which allows coroutines to retrieve their bound context without suspending.*

Capy is our implementation of the ***IoAwaitable*** protocol. Corosio, built on Capy, provides sockets, timers, TLS, and DNS resolution on multiple platforms. Both libraries are in active use. The code examples in this paper are drawn from them.

3.1 *IoAwaitable*

The ***IoAwaitable*** concept propagates execution context forward from caller to callee at every suspension point. The context is three things a coroutine needs for I/O: the executor, the stop token, and the allocator. The entire protocol is captured in one struct and one concept:

```
struct io_env
{
    executor_ref executor;
    std::stop_token stop_token;
    std::pmr::memory_resource* allocator = nullptr;
};

template< typename A >
concept IoAwaitable =
    requires(
        A a, std::coroutine_handle<> h, io_env const* env )
    {
        a.await_suspend( h, env );
    };
```

What makes this work is the two-argument `await_suspend`. The caller's `await_transform` injects the environment as just an extra pointer parameter - no templates, no type leakage. `task<T>` remains `task<T>`, not `task<T, Environment>`. The environment is passed as a pointer, not by value, for two reasons: the launch function - the function that starts the coroutine chain - owns the `io_env` and every coroutine in the chain borrows it, so pointer semantics make the ownership model explicit; and copying an `io_env` is never the right choice, so the API makes it difficult to do accidentally. The allocator is part of the environment and propagates to coroutine frame allocation via a thread-local write-through cache, ensuring it is available before the frame is created (Section 5 covers the mechanism).

Satisfying *IoAwaitable*

Any type that can be `co_await`ed within the protocol must:

1. Implement `await_suspend(std::coroutine_handle<> cont, io_env const* env)`
2. Store the environment by pointer (never by copy); the pointed-to `io_env` is guaranteed to outlive the awaitable
3. Return `std::coroutine_handle<>` for symmetric transfer (or `void` / `bool` per standard rules)
4. Implement `await_ready()` and `await_resume()` per standard awaitable requirements

Example implementation:

```
template< typename T >
struct my_awaitable
{
    io_env const* env_ = nullptr;
    std::coroutine_handle<> cont_ = {};
    T result_;

    bool await_ready() const noexcept { return false; }

    // This signature satisfies IoAwaitable
    std::coroutine_handle<> await_suspend( std::coroutine_handle<> cont, io_env const* env )
    {
        cont_ = cont;
        env_ = env;
        start_async_operation( &result_ );
        return std::noop_coroutine();
    }

    T await_resume() { return result_; }
};
```

Compile-Time Protocol Checking

The two-argument `await_suspend` signature is not just an implementation detail - it is a deliberate design choice for correctness. When a compliant coroutine's `await_transform` calls the two-argument `await_suspend`, a non-compliant awaitable (lacking this signature) produces a compile error. Similarly, a compliant awaitable awaited from a non-compliant coroutine fails to compile. Both sides of every suspension point are statically verified:

```
template<typename A>
auto await_transform(A&& a) {
    static_assert(IoAwaitable<A>,
        "Awaitable does not satisfy IoAwaitable; "
        "await_suspend(std::coroutine_handle<>, io_env const*) is required");
    // Return wrapper that forwards to: a.await_suspend(h, environment())
    ...
}
```

This is also an interoperability feature. In a world with multiple coexisting async models, a coroutine that accidentally `co_await`s across model boundaries should fail at compile time, not silently misbehave at runtime. The two-argument signature makes each boundary explicit and verifiable.

An alternative design would place the environment in the promise type and let `await_suspend` discover it by templating on the promise:

```
// Promise-based approach (std::execution)
template<typename Promise>
auto await_suspend(std::coroutine_handle<Promise> h) {
    auto& env = h.promise().get_env();  // environment discovered here
    // ...
}
```

This has a timing problem. The caller's `await_transform` sees the awaitable's type but not the promise that will eventually resolve `await_suspend`. A non-compliant awaitable with a standard one-argument signature compiles and runs - it simply never receives the environment. Protocol mismatches become silent runtime errors. Our two-argument signature makes participation verifiable at the point where the caller can still reject the awaitable.

The Lifetime Invariant

The launch function owns the `io_env`. The pointer to it is stable for the lifetime of the entire coroutine chain - every coroutine, from parent to grandchild, borrows the same instance. No coroutine copies, moves, or reallocates the environment. When a launch function like `run` creates a new chain with a different executor, it creates a new `io_env`, cleanly breaking the old chain and establishing a new one.

3.2 IoRunnable

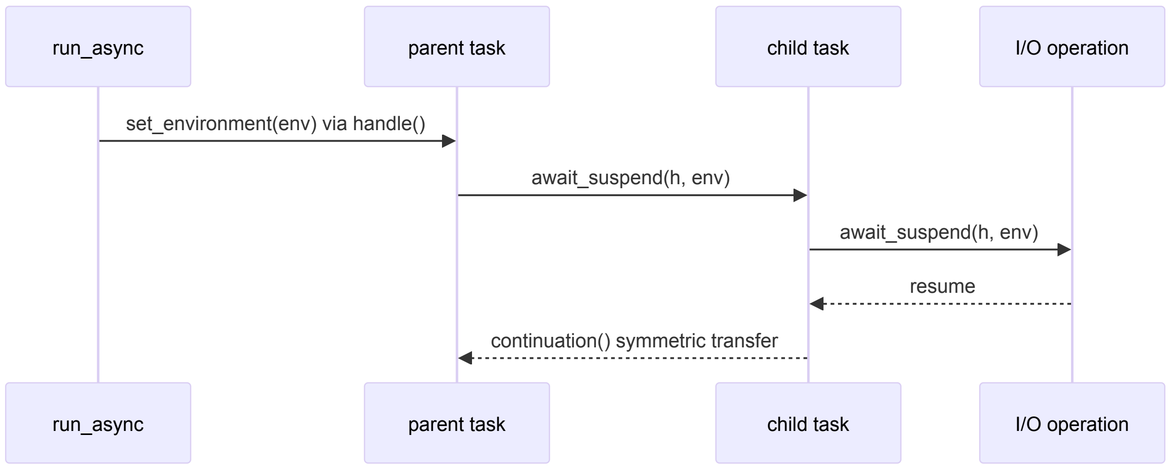
The ***IoRunnable*** concept refines ***IoAwaitable*** with the interface needed by launch functions. `run_async` starts a coroutine chain from non-coroutine code - `main()`, a callback, an event handler. `run` is used within a coroutine to bind a child task to a different executor or customize context. Both need to manage the task's lifetime, resume it, and extract results or exceptions after completion - operations that `co_await` handles natively but that launch functions must perform manually.

```
template<typename T>
concept IoRunnable =
    IoAwaitable<T> &&
    requires { typename T::promise_type; } &&
    requires( T& t, T const& ct,
              typename T::promise_type const& cp,
              typename T::promise_type& p )
    {
        { ct.handle() } noexcept
            -> std::same_as< std::coroutine_handle< typename T::promise_type> >;
        { cp.exception() } noexcept -> std::same_as< std::exception_ptr >;
        { t.release() } noexcept;
        { p.set_continuation( std::coroutine_handle<>{} ) } noexcept;
        { p.set_environment( static_cast<io_env const*>(nullptr) ) } noexcept;
    } &&
    ( std::is_void_v< decltype(std::declval<T&>().await_resume()) > ||
      requires( typename T::promise_type& p ) {
          p.result();
      });
```

Why *IoRunnable* exists. Within a coroutine chain, ***IoAwaitable*** alone is sufficient—a parent `co_await`s a child, and the compiler handles lifetime, result extraction, and exception propagation natively. But launch functions like `run_async` cannot `co_await` the task. The `run_async` trampoline must be allocated ***before*** the task (C++17 evaluation order guarantees this for LIFO allocation ordering with the recycling allocator), so the trampoline exists before the task type is known. It cannot be templated on the task type. Instead, the trampoline type-erases the task, reaching into the promise after the fact to extract results. That requires a common API on every conforming task:

- **`handle()`** — Returns the typed coroutine handle. The launch function needs it to start the coroutine and access the promise for type-erased result extraction.
- **`release()`** — Transfers frame ownership. The task object normally destroys the coroutine frame in its destructor. The launch function takes over lifetime management; `release()` tells the task not to destroy the frame.
- **`exception()`** — Returns any stored `std::exception_ptr` after the task completes. The trampoline calls this through a type-erased function pointer.
- **`result()`** — Returns the stored value (non-void tasks only). Same type-erased access pattern.

Launch functions inject context into the promise via `set_continuation` and `set_environment`, both required by the ***IoRunnable*** concept. The promise's `await_transform` then propagates context to child awaitables automatically.



- `run_async` is the root of a coroutine chain, launching from non-coroutine code
- `run` performs executor hopping from within coroutine code, binding a child task to a different executor

Because launch functions are constrained on the concept rather than a concrete type, they work with any conforming task:

```
// Two-phase invocation: f(context)(task)
// Phase 1 returns a wrapper; Phase 2 accepts any IoRunnable

template< Executor Ex, class... Args >
unspecified run_async( Ex ex, Args&&... args );
// run_async(ex)(my_task())  — wrapper::operator()(IoRunnable auto task)

template< Executor Ex, class... Args >
unspecified run( Ex ex, Args&&... args );
// co_await run(ex)(my_task())  — wrapper::operator()(IoRunnable auto task)
```

This decoupling enables library authors to write launch utilities that work with any conforming task type, and users to define custom task types that integrate seamlessly with existing launchers.

Satisfying IoRunnable

Additional requirements (beyond *IoAwaitable*):

1. Define a nested `promise_type`
2. The task must provide `handle()` returning `std::coroutine_handle<promise_type>` (must be `noexcept`)
3. The task must provide `release()` to transfer ownership without destroying the frame (must be `noexcept`)
4. The promise must provide `exception()` returning any stored `std::exception_ptr` (must be `noexcept`)
5. For non-void tasks, the promise must provide `result()` returning the stored value

6. The promise's `await_transform` must intercept child awaitables and inject context
7. Support `operator new` overloads for allocator propagation (read TLS)

Example implementation:

```cpp
template<typename T>
struct task
{
    struct promise_type : io_awaitable_promise_base<promise_type>
    {
        std::exception_ptr ep_;
        std::optional<T> result_;

        std::exception_ptr exception() const noexcept { return ep_; }
        T&& result() noexcept { return std::move(*result_); }
    };

    std::coroutine_handle<promise_type> h_;

    bool await_ready() const noexcept { return false; }
    T await_resume() { return h_.promise().result(); }

    // Satisfies IoAwaitable
    std::coroutine_handle<> await_suspend( std::coroutine_handle<> cont, io_env const* env )
    {
        h_.promise().set_continuation( cont );
        h_.promise().set_environment( env );
        return h_;
    }

    // Satisfies IoRunnable
    std::coroutine_handle<promise_type> handle() const noexcept { return h_; }
    void release() noexcept { h_ = nullptr; }
};
```

The `handle()` method provides access to the typed coroutine handle, allowing launch functions to resume the coroutine and access the promise. The `release()` method transfers ownership—after calling it, the task wrapper no longer destroys the frame, leaving lifetime management to the launch function.

For `task<void>`, the `result()` method is not required since there is no value to retrieve. The concept uses a disjunction to handle this:

```
( std::is_void_v< decltype(std::declval<T&>().await_resume()) > ||
  requires( typename T::promise_type& p ) { p.result(); } );
```

> ***Non-normative note.*** *The `io_awaitable_promise_base` CRTP mixin (§8.1) provides the promise-internal machinery (context storage, continuation management, awaitable transformation) as a convenience. It is not proposed for standardization—implementors may write their own. The `handle()` and `release()` methods are task-specific and not part of the mixin.*

3.3 executor_ref

The `executor_ref` type is the mechanism that makes `io_env` concrete rather than templated. It is a type-erasing wrapper that stores any executor satisfying the ***Executor*** concept as two pointers: a `void const*` pointing to the actual executor object, and a pointer to a vtable of function pointers:

```
class executor_ref
{
    void const* ex_ = nullptr;
    detail::executor_vtable const* vt_ = nullptr;

public:
    template<Executor E>
    executor_ref(E const& e) noexcept
        : ex_(&e), vt_(&detail::vtable_for<E>) {}

    std::coroutine_handle<> dispatch(std::coroutine_handle<> h) const;
    void post(std::coroutine_handle<> h) const;
    execution_context& context() const noexcept;
    // ...
};
```

The vtable contains function pointers for each executor operation - `dispatch` , `post` , `context` , work tracking, and comparison. When `executor_ref` is constructed from a typed executor, the compiler generates a vtable for that executor type. Calls through `executor_ref` incur one pointer indirection - roughly 1-2 nanoseconds [13] - which is negligible for I/O operations that take 10,000+ nanoseconds.

The `dispatch` member returns a `coroutine_handle<>` for symmetric transfer: if the caller is already in the executor's context, it returns the handle directly for immediate resumption. Otherwise it posts the handle to the executor's queue and returns `noop_coroutine()` . This enables zero-overhead resumption in the common case where the coroutine is already on the right thread.

At just two pointers, `executor_ref` copies cheaply and stores naturally inside `io_env`. Launch functions preserve a copy of the user's typed ***Executor*** in their own coroutine frame. The `executor_ref` holds a pointer to that stored value. As the wrapper propagates through the call chain, the original executor remains valid - it cannot go out of scope until all coroutines in the chain are destroyed.

Coroutines can access their context directly using `this_coro::environment`. This never suspends—it returns immediately with the stored environment:

```
task<void> cancellable_work()
{
    auto env = co_await this_coro::environment;  // never suspends

    for (int i = 0; i < 1000; ++i)
    {
        if (env->stop_token.stop_requested())
            co_return;  // Exit gracefully on cancellation
        co_await process_chunk(env->executor, i);
    }
}
```

3.4 How Does a Coroutine Start?

Two basic functions are needed to launch coroutine chains, and authors can define their own custom launch functions to suit their needs.

`run_async` — launch from callbacks, main(), event handlers, top level of a coroutine chain.

This uses a two-call syntax where the first call captures context and returns a wrapper. The executor parameter is required. The remaining parameters are optional:

- `std::stop_token` to propagate cancelation signals
- `alloc` used to allocate all frames in the coroutine chain
- `h1`, invoked with the task's value at final suspend
- `h2`, invoked with `std::exception_ptr` on exception

```
// Basic: executor only
run_async( ex )( my_task() );

// Full: executor, stop_token, allocator, success handler, error handler
run_async( ex, st, alloc, h1, h2 )( my_task() );

// Example with handlers
run_async( ioc.get_executor(), source.get_token(),
    [](int result) { std::cout << "Got: " << result << "\n"; },
    [](std::exception_ptr ep) { /* handle error */ }
)( compute_value() );
```

While the syntax is unfortunate, it is ***the only way*** given the timing constraints of frame allocation. And hey, its better than callback hell. What makes this possible is a small but consequential change in C++17: guaranteed evaluation order for postfix expressions. The standard now specifies:

> *"The postfix-expression is sequenced before each expression in the expression-list and any default argument." — [expr.call]*

In `run_async(ex)(my_task())`, the outer postfix-expression `run_async(ex)` is fully evaluated—returning a wrapper that allocates the trampoline coroutine—before `my_task()` is invoked. This guarantees LIFO destruction order: the trampoline is allocated BEFORE the task and serves as the task's continuation.

`run` — switching executors or customizing context within coroutines.

This binds a child task to a different executor while returning to the caller's executor on completion. Like `run_async`, it uses the two-call syntax to ensure proper allocation ordering:

```
task<void> parent()
{
    // Child runs on worker_ex, but completion returns here
    int result = co_await run( worker_ex )( compute_on_worker() );
}
```

The executor is stored by value in the awaitable's frame, keeping it alive for the operation's duration. Additionally, `run` provides overloads without an executor parameter that inherit the caller's executor while customizing stop_token or allocator:

```
task<void> cancellable()
{
    std::stop_source source;
    // Child inherits caller's executor, but uses a different stop_token
    co_await run( source.get_token() )( subtask() );
}
```

3.5 Implementing a Launcher

A launch function (e.g., `run_async`, `run`) bridges non-coroutine code into the coroutine world or performs executor hopping within a coroutine chain. Launch functions are constrained on ***IoRunnable*** to work with any conforming task type:

```
template<Executor Ex, class... Args>
unspecified run_async( Ex ex, Args&&... args );  // returns wrapper, caller invokes with task

template<Executor Ex, class... Args>
unspecified run( Ex ex, Args&&... args );        // returns wrapper for co_await
```

Requirements:

1. Accept or provide an executor
2. Accept or default a stop token
3. Set thread-local allocator before invoking the child coroutine
4. Bootstrap context via `set_environment` on the promise
5. Manage the task lifetime via `handle()` and `release()`
6. Handle completion via `exception()` and `result()` on the promise

Example implementation sketch:

```
template<Executor Ex, IoRunnable Task>
void run_async( Ex ex, std::stop_token token, Task task )
{   // caller responsible for extending lifetime
    auto& promise = task.handle().promise();

    // Bootstrap context directly into the promise
    promise.set_environment( io_env{ex, token} );
    promise.set_continuation( /* trampoline handle */ );

    // Transfer ownership and start execution
    task.release();
    ex.post( task.handle() );
}
```

> ***Non-normative note.*** *This simplified example has the allocator ordering problem described in §5.1: the task's frame is allocated before `run_async` is called, so any thread-local allocator setup would arrive too late. A correct implementation uses the two-call syntax shown in §3.4— `run_async(ex)(my_task())` — where the first call returns a wrapper that sets up the allocator before the task expression is evaluated. A complete implementation is beyond the scope of this example.*

Because launch functions are constrained on the concept rather than a concrete type, they work with any conforming task implementation. This decoupling enables library authors to write launch utilities that interoperate with user-defined task types.

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4. Executor concept

Terminology note. We use the term ***Executor*** rather than ***scheduler*** intentionally. In `std::execution`, schedulers are designed for heterogeneous computing—selecting GPU vs CPU algorithms, managing completion domains, and dispatching to hardware accelerators. Networking has different needs: strand serialization, I/O completion contexts, and thread affinity. By using ***executor***, we signal a distinct concept tailored to networking's requirements. This terminology also honors Christopher Kohlhoff's executor model in Boost.Asio, which established the foundation for modern C++ asynchronous I/O.

```cpp
template<class E>
concept Executor =
    std::is_nothrow_copy_constructible_v<E> &&
    std::is_nothrow_move_constructible_v<E> &&
    requires( E& e, E const& ce, E const& ce2, std::coroutine_handle<> h ) {
        { ce == ce2 } noexcept -> std::convertible_to<bool>;
        { ce.context() } noexcept;
        requires std::is_lvalue_reference_v<decltype(ce.context())> &&
            std::derived_from<
                std::remove_reference_t<decltype(ce.context())>,
                execution_context>;
        { ce.on_work_started() } noexcept;
        { ce.on_work_finished() } noexcept;

        // Work submission
        { ce.dispatch( h ) } -> std::convertible_to< std::coroutine_handle<> >;
        { ce.post(h) };
    };
```

Executors are lightweight, copyable handles to execution contexts. Users often provide custom executor types tailored to application needs—priority scheduling, per-connection strand serialization, or specialized logging and instrumentation. An execution model must respect these customizations. It must also support executor composition: wrapping one executor with another. The `strand` we provide, for example, wraps an I/O context's executor to add serialization guarantees without changing the underlying dispatch mechanism.

C++20 coroutines provide type erasure ***by construction***—but not through the handle type. `std::coroutine_handle<void>` and `std::coroutine_handle<promise_type>` are both just pointers with identical overhead. The erasure that matters is ***structural***:

1. **The frame is opaque**: Callers see only a handle, not the promise's layout
2. **The return type is uniform**: All coroutines returning `task` have the same type, regardless of body
3. **Suspension points are hidden**: The caller doesn't know where the coroutine may suspend

This structural erasure is often lamented as overhead, but we recognize it as opportunity. In our model, executor type-erasure happens late; only after the API has locked in the executor choice. Executor types are fully preserved at call sites even though they are type-erased internally. This enables zero-overhead composition at the API boundary while maintaining uniform internal representation.

4.1 Dispatch

Every coroutine resumption must go through either symmetric transfer or the scheduler queue – never through an inline `resume()` or `dispatch()` that creates a frame below the resumed coroutine.

`dispatch` returns a `std::coroutine_handle<>` for symmetric transfer. If the caller is already in the executor's context, `dispatch` returns the handle directly. Otherwise, the handle is posted to the scheduler queue and `std::noop_coroutine()` is returned. The caller never calls `resume()` on the handle inside `dispatch`—the returned handle is used by the caller for symmetric transfer from `await_suspend`, or called with `.resume()` at the event loop pump level.

Unlike general-purpose executors that accept templated callables, `dispatch` takes only `std::coroutine_handle<>`—this is a coroutine-only model. A coroutine handle is a simple pointer: no allocation, no type erasure overhead, no virtual dispatch.

Ordinary users writing coroutine tasks do not interact with `dispatch` and `post` directly. These operations are used by authors of coroutine machinery—`promise_type` implementations, awaitables, `await_transform`—to implement asynchronous algorithms such as `when_all`, `when_any`, `async_mutex`, channels, and similar primitives.

Some contexts prohibit inline execution. A strand currently executing work cannot dispatch inline without breaking serialization—`dispatch` then behaves like `post`, queuing unconditionally and returning `std::noop_coroutine()`.

4.2 Post

`post` queues work for later execution. Unlike `dispatch`, it never executes inline—the work item is always enqueued, and `post` returns immediately.

Use `post` for: - New work that is not a continuation of the current operation - Breaking call chains to bound stack depth - Safety under locks—posting while holding a mutex avoids deadlock risk from inline execution

4.3 The `execution_context`

An executor's `context()` function returns a reference to the `execution_context`, the proposed base class for any object that runs work (often containing the platform reactor or event loop). I/O objects coordinate global state here. Implementations install services—singletons with well-defined shutdown and destruction ordering for safe resource release. This design borrows heavily from Boost.Asio.

```
class execution_context
{
public:
    class service
    {
    public:
        virtual ~service() = default;
    protected:
        service() = default;
        virtual void shutdown() = 0;
    };

    execution_context( execution_context const& ) = delete;
    execution_context& operator=( execution_context const& ) = delete;
    ~execution_context();
    execution_context();

    template<class T> bool has_service() const noexcept;
    template<class T> T* find_service() const noexcept;
    template<class T> T& use_service();
    template<class T, class... Args> T& make_service( Args&&... args );

    std::pmr::memory_resource* get_frame_allocator() const noexcept;

    void set_frame_allocator( std::pmr::memory_resource* mr ) noexcept;

    template<class Allocator>
        requires (!std::is_pointer_v<Allocator>)
    void set_frame_allocator( Allocator const& a );

protected:
    void shutdown() noexcept;
    void destroy() noexcept;
};
```

Derived classes can provide: - **Platform reactor**: epoll, IOCP, io_uring, or kqueue integration - **Supporting singletons**: Timer queues, resolver services, signal handlers - **Orderly shutdown**: `stop()` and `join()` for graceful termination - **Work tracking**: `on_work_started()` / `on_work_finished()` for run-until-idle semantics - **Threads**: for example `thread_pool`.

I/O objects hold a reference to their execution context, and do not have an associated executor. A socket needs the context to register with the reactor; the executor alone cannot provide this.

Frame Allocator

The `execution_context` provides `set_frame_allocator` and `get_frame_allocator` as customization points for launchers when no allocator is specified at the launch site. Since every launcher requires an ***Executor***, the execution context naturally coordinates frame allocation policy. The default allocator can optimize for speed using recycling with thread-local pools, or for economy on constrained platforms. Using `std::pmr::memory_resource*` allows implementations to change the default without breaking ABI. Applications can set a policy once via `set_frame_allocator`, and all coroutines launched with the default will use it—including those in foreign libraries, without propagating allocator template parameters or recompiling.

4.4 ExecutionContext concept

While `execution_context` serves as a base class for contexts that manage I/O objects and services, concrete execution contexts that can launch coroutines must also provide an associated executor. The `ExecutionContext` concept captures this requirement: a type must derive from `execution_context`, expose an `executor_type` that satisfies `Executor`, and provide `get_executor()` to obtain an executor bound to the context.

```
template<class X>
concept ExecutionContext =
    std::derived_from<X, execution_context> &&
    requires(X& x) {
        typename X::executor_type;
        requires Executor<typename X::executor_type>;
        { x.get_executor() } noexcept -> std::same_as<typename X::executor_type>;
    };
```

The concept formalizes the relationship between execution contexts and their executors. Types like `io_context` and `thread_pool` satisfy `ExecutionContext`—they derive from `execution_context` for service management, and they provide executors for dispatching coroutines:

```
io_context ioc;
auto ex = ioc.get_executor();  // io_context::executor_type
run_async(ex)(my_task());      // Launch coroutine on this context
```

The destructor semantics are also significant: when an `ExecutionContext` is destroyed, all unexecuted function objects that were submitted via an associated executor are also destroyed. This ensures orderly cleanup—work queued but not yet executed does not leak or outlive its context.

5. The Allocator

Achieving high performance levels with coroutines demands allocator customization, yet allocator propagation presents a unique challenge. Unlike executors and stop tokens, which can be injected at suspension points via `await_transform`, the allocator must be available ***before*** the coroutine frame exists. This section examines why standard approaches fail and presents our solution.

5.1 The Timing Constraint

Coroutine frame allocation has a fundamental timing constraint: `operator new` executes before the coroutine body. When a coroutine is called, the compiler allocates the frame first, then begins execution. Any mechanism that injects context later—receiver connection, `await_transform`, explicit method calls—arrives too late.

```
auto t = my_coro(sock);  // operator new called HERE
co_await t;              // await_transform kicks in HERE (too late)

spawn( my_coro(sock) );  // my_coro(sock) evaluated BEFORE calling spawn (too late)
```

5.2 The Awkward Approach

C++ provides exactly one hook at the right time: **`promise_type::operator new`**. The compiler passes coroutine arguments directly to this overload, allowing the promise to inspect parameters and select an allocator. The standard pattern uses `std::allocator_arg_t` as a tag to mark the allocator parameter:

```
// Free function: allocator intrudes on the parameter list
task<int> fetch_data( std::allocator_arg_t, MyAllocator alloc,
                      socket& sock, buffer& buf ) { ... }

// Member function: same intrusion
task<void> Connection::process( std::allocator_arg_t, MyAllocator alloc,
                                request const& req) { ... }
```

The promise type must provide multiple `operator new` overloads to handle both cases:

```
struct promise_type {
    // For free functions
    template< typename Alloc, typename... Args >
    static void* operator new( std::size_t sz,
        std::allocator_arg_t, Alloc& a, Args&&...) {
        return a.allocate(sz);
    }

    // For member functions (this is first arg)
    template< typename T, typename Alloc, typename... Args >
    static void* operator new( std::size_t sz,
        T&, std::allocator_arg_t, Alloc& a, Args&&...) {
        return a.allocate(sz);
    }
};
```

This approach works, but it violates encapsulation. The coroutine's parameter list - which should describe the algorithm's interface - is polluted with allocation machinery unrelated to its purpose. A function that fetches data from a socket should not need to know or care about memory policy. Worse, every coroutine in a call chain must thread the allocator through its signature, even if it never uses it directly. The allocator becomes viral, infecting interfaces throughout the codebase.

To make this concrete, consider a real HTTP route handler as written with ***IoAwaitable***:

```
// IoAwaitable: clean interface describes only the algorithm
route_task https_redirect(route_params& rp)
{
    std::string url = "https://";
    url += rp.req.at(field::host);
    url += rp.url.encoded_path();
    rp.status(status::found);
    rp.res.set(field::location, url);
    auto [ec] = co_await rp.send("redirect");
    if (ec)
        co_return route_error(ec);
    co_return route_done;
}
```

Now consider the same handler under the `allocator_arg_t` approach. The allocator must appear in the parameter list, and every coroutine the handler calls must also accept it:

```
// allocator_arg_t: allocation machinery intrudes on every signature
route_task https_redirect(std::allocator_arg_t, Alloc alloc,
                          route_params& rp)
{
    std::string url = "https://";
    url += rp.req.at(field::host);
    url += rp.url.encoded_path();
    rp.status(status::found);
    rp.res.set(field::location, url);
    auto [ec] = co_await rp.send(std::allocator_arg, alloc, "redirect");
    if (ec)
        co_return route_error(ec);
    co_return route_done;
}
```

The handler's ***purpose*** is identical. The allocator adds nothing to its logic - it is a cross-cutting concern being threaded through the interface. The pollution compounds through a call chain. Consider a handler that calls two sub-coroutines:

```
// IoAwaitable: the chain is clean
route_task handle_upload(route_params& rp)
{
    auto meta = co_await parse_metadata(rp);
    co_await store_file(meta, rp);
    auto [ec] = co_await rp.send("OK");
    if (ec) co_return route_error(ec);
    co_return route_done;
}
```

```
// allocator_arg_t: every level in the chain carries the allocator
route_task handle_upload(std::allocator_arg_t, Alloc alloc,
                         route_params& rp)
{
    auto meta = co_await parse_metadata(std::allocator_arg, alloc, rp);
    co_await store_file(std::allocator_arg, alloc, meta, rp);
    auto [ec] = co_await rp.send(std::allocator_arg, alloc, "OK");
    if (ec) co_return route_error(ec);
    co_return route_done;
}
```

Every `co_await` in the chain must forward the allocator. Every function in the chain must accept it. `parse_metadata` and `store_file` must thread it through to their own sub-coroutines, and so on down. In a real server with dozens of route handlers, each calling several sub-coroutines, every author of every handler must remember to pass the allocator at every call site. This is the opposite of ergonomic.

Containers in the standard library accept allocators because they are written once by experts and used many times. Coroutine handlers are the reverse: they are written by application developers, often in large numbers, for specific business logic. Burdening every handler with allocation plumbing is a significant ergonomic cost.

5.3 Our Solution: Thread-Local Propagation

Thread-local propagation is the only approach that maintains clean interfaces while respecting the timing constraint. The premise is simple: **allocator customization happens at launch sites**, not within coroutine algorithms. Functions like `run_async` and `run` accept allocator parameters because they represent application policy decisions. Coroutine algorithms don't need to "allocator-hop"—they simply inherit whatever allocator the application has established.

Our approach:

1. **Receive the allocator at launch time.** The launch site (`run_async` , `run`) accepts a fully-typed ***Allocator*** parameter, or a `std::pmr::memory_resource*` at the caller's discretion.

2. **Type-erase it.** Typed allocators are stored as `std::pmr::memory_resource*` , providing a uniform interface for all downstream coroutines.

3. **Maintain lifetime via frame extension.** The allocator lives in the launch coroutine's frame. Because coroutine parameter lifetimes extend until final suspension, the allocator remains valid for the entire operation chain.

4. **Propagate through thread-locals.** Before any child coroutine is invoked, the current allocator is set in TLS. The child's `promise_type::operator new` reads it. TLS serves as a delivery mechanism, not the source of truth. The canonical allocator resides in `io_env` , a heap-stable structure owned by the launch coroutine's frame. Every resume point restores TLS from `io_env` , making TLS a write-through cache that is always repopulated before it is read. This is an example implementation (non-normative):

```
// Global accessors for the current frame allocator.
// An implementation using thread_local might look like this:
//
//   namespace detail {
//   inline std::pmr::memory_resource*&
//   current_frame_allocator_ref() noexcept {
//       static thread_local std::pmr::memory_resource* mr = nullptr;
//       return mr;
//   }
//   } // namespace detail
//
//   std::pmr::memory_resource*
//   get_current_frame_allocator() noexcept {
//       return detail::current_frame_allocator_ref();
//   }
//
//   void
//   set_current_frame_allocator(
//       std::pmr::memory_resource* mr) noexcept {
//       detail::current_frame_allocator_ref() = mr;
//   }
//
// Implementations without thread_local may use whatever
// mechanism is available.

std::pmr::memory_resource*
get_current_frame_allocator() noexcept;

void
set_current_frame_allocator(
    std::pmr::memory_resource* mr) noexcept;

// These accessors are a thin wrapper over a thread-local pointer.
// get always returns exactly what set stored, including nullptr.
// No dynamic initializer on the thread-local; a dynamic TLS
// initializer moves you into a costlier implementation bucket
// on some platforms - avoid it.
//
// Only IoAwaitable machinery and launch functions should call
// these accessors. The thread-local value is valid only during
// the execution window (Section 5.4): between a coroutine's
// resumption and its next suspension point.
//
// A null return from get means "not specified" - no allocator
// has been established for this chain. The caller is free to
// use whatever allocation strategy makes best sense for its
// situation. Null handling is the caller's responsibility;
// the accessor must not substitute a default, because there
// are multiple valid choices (new_delete_resource, the default
// pmr resource, or something else entirely).
//
// Use of the frame allocator is optional. An awaitable that
// ignores this value and allocates its frame by other means
// is never wrong. However, a conforming awaitable must still
// propagate the allocator faithfully (via set before invoking
// child coroutines) so that downstream frames can use it.

// In promise_type
static std::size_t aligned_offset(std::size_t n) noexcept {
    constexpr auto a = alignof(std::pmr::memory_resource*);
    return (n + a - 1) & ~(a - 1);
}

static void* operator new( std::size_t size ) {
    auto* mr = get_current_frame_allocator();
    if(!mr)
        mr = std::pmr::new_delete_resource();

    // Store allocator pointer at end of frame for correct deallocation
    std::size_t off = aligned_offset(size);
    std::size_t total = off + sizeof(std::pmr::memory_resource*);
    void* raw = mr->allocate(total, alignof(std::max_align_t));
    *reinterpret_cast<std::pmr::memory_resource**>(
        static_cast<char*>(raw) + off) = mr;
    return raw;
}

static void operator delete( void* ptr, std::size_t size ) {
    // Read the allocator pointer from the end of the frame
    std::size_t off = aligned_offset(size);
    auto* mr = *reinterpret_cast<std::pmr::memory_resource**>(
        static_cast<char*>(ptr) + off);
    std::size_t total = off + sizeof(std::pmr::memory_resource*);
    mr->deallocate(ptr, total, alignof(std::max_align_t));
}
```

`get_current_frame_allocator` can return null when a coroutine frame is created without going through a launch function:

```
auto co = my_coro();         // frame allocated here - no launcher set TLS
run_async( ex )( co );       // too late, frame already exists
```

The fallback to `pmr::new_delete_resource()` gives the same behavior the user would get if the coroutine had no custom `operator new` at all - plain `new` / `delete`. We choose `new_delete_resource` rather than `pmr::get_default_resource()` because the latter is a mutable global whose value can change at any time, which could produce surprising allocations depending on what some other part of the program stored there. One might ask why the thread-local is not simply initialized to `pmr::new_delete_resource()` so the null check is unnecessary. The reason is portability: thread-local storage works best when the variable is a plain pointer zero-initialized by the loader. A dynamic initializer - even a trivial function call - moves the variable into a costlier TLS implementation bucket on some platforms. Keeping the default as null and handling it at the call site avoids that cost entirely.

This design keeps allocator policy where it belongs - at the application layer - while coroutine algorithms remain blissfully unaware of memory strategy. The propagation happens during what we call "the window": a narrow interval of execution where the correct state is guaranteed in thread-locals.

Use of the frame allocator is optional. An awaitable whose `promise_type::operator new` ignores the thread-local value and allocates its frame by other means is never wrong - the program remains correct. The allocator controls ***where*** a frame's memory comes from, not what the coroutine does. However, a conforming awaitable must still propagate the allocator faithfully: before invoking any child coroutine, the currently running coroutine restores the thread-local from its `io_env` so that the child's `operator new` sees the intended value. An awaitable that consumes the allocator for its own frame without restoring it would silently break allocation policy for every downstream coroutine in the chain. Correct propagation is a protocol obligation even when the awaitable itself does not use the allocator.

An important distinction: other coroutine libraries that use thread-local storage for allocation set it once globally, so all coroutine chains share the same allocator for the lifetime of the program. Our approach is per-chain. Each launch site can choose a different allocator, and that allocator is scoped to the specific chain it launches. When a chain suspends for I/O, another chain with a different allocator can run without interference. When the first chain resumes, the window mechanism restores its allocator before any child coroutines are created. This is how allocators should work in practice - stateful and scoped to the work they serve, not a global policy that every coroutine chain must share.

5.4 The Window

Thread-local propagation relies on a narrow, deterministic execution window. Consider:

```
task<void> parent() {        // parent is RUNNING here
    co_await child();        // child() called while parent is running
}
```

When `child()` is called: 1. `parent` coroutine is actively executing (not suspended) 2. `child()`'s `operator new` is called 3. `child()`'s frame is created 4. `child()` returns task 5. THEN `parent` suspends

The window is the period while the parent coroutine body executes. If `parent` sets TLS when it resumes and `child()` is called during that execution, `child`'s `operator new` sees the correct TLS value.

TLS remains valid between `await_suspend` and `await_resume`:

```
auto initial_suspend() noexcept {
    struct awaiter {
        promise_type* p_;
        bool await_ready() const noexcept { return false; }
        void await_suspend(std::coroutine_handle<>) const noexcept {
            // Capture TLS allocator while it's still valid
            p_->set_frame_allocator( get_current_frame_allocator() );
        }
        void await_resume() const noexcept {
            // Restore TLS when body starts executing
            if( p_->frame_allocator() )
                set_current_frame_allocator( p_->frame_allocator() );
        }
    };
    return awaiter{this};
}
```

Every time the coroutine resumes (after any `co_await`), it sets TLS to its allocator. When `child()` is called, TLS is already pointing to `parent`'s allocator. The flow:

```
parent resumes → TLS = parent.alloc
    ↓
parent calls child()
    ↓
child operator new → reads TLS → uses parent.alloc
    ↓
child created, returns task
    ↓
parent's await_suspend → parent suspends
    ↓
child resumes → TLS = child.alloc (inherited value)
    ↓
child calls grandchild() → grandchild uses TLS
```

This is safe because: - TLS is only read in `operator new` - no other code path inspects the thread-local allocator - TLS is written by the currently-running coroutine before any child is created, and restored from the heap-stable `io_env` on every resume via `await_resume` - Thread migration is handled: when a coroutine suspends on thread A and resumes on thread B, the `await_resume` path writes the correct allocator into thread B's TLS before the coroutine body continues. TLS is never ***read*** on a thread unless the coroutine that wrote it is actively executing on that thread - No dangling: the coroutine that set TLS is still on the call stack when `operator new` reads it - Deallocation is thread-independent: `operator delete` reads the allocator from a pointer embedded in the frame footer, not from TLS. A frame can be destroyed on any thread

5.5 Addressing TLS Concerns

Thread-local storage has a well-deserved reputation for creating hidden coupling and brittle behavior. The concerns are familiar and worth addressing directly.

Concern: Hidden Behavior

TLS has earned its bad name: a global variable by another name. Functions behave differently depending on who called them last. The objection is sound in the general case.

This is not the general case. The thread-local here is a **write-through cache** with exactly one purpose: deliver a `memory_resource*` to `operator new`. It is written before every coroutine invocation and read in exactly one place. The canonical value lives in `io_env`, heap-stable and owned by the launch function, repopulated on every resume. No algorithm inspects it. No behavior changes based on its contents. It controls where memory comes from, not what the program does.

The reason TLS is involved at all is `operator new`'s fixed signature. The allocator cannot arrive as a parameter without polluting every coroutine signature with `allocator_arg_t` (Section 5.2). The standard library already accepted this tradeoff: `std::pmr::get_default_resource()` is a process-wide thread-local allocator channel, adopted in C++17. Ours is the same principle, scoped per-chain instead of per-process.

Concern: Thread Migration

Thread migration is the obvious objection: suspend on thread A, resume on thread B, read stale TLS. The invariant that prevents this is simple: **TLS is never read on a thread unless the coroutine that wrote it is actively executing on that same thread.**

Every resume path - `initial_suspend`, every subsequent `co_await` via `await_transform` - unconditionally writes the allocator from `io_env` into TLS ***before*** the coroutine body continues:

```
void await_resume() const noexcept
{
    // Restore TLS from heap-stable io_env
    set_current_frame_allocator(p_->io_env_->allocator);
}
```

The write always precedes the read on the new thread. No suspended coroutine depends on TLS retaining a value across a suspension point.

Deallocation is thread-independent. Each frame stores its `memory_resource*` in a footer. `operator delete` reads from the footer, not from TLS. A frame allocated on thread A can be destroyed on thread C.

Concern: Implicit Propagation and Lifetime

Coroutine chains differ structurally from containers. A container can outlive its creator. A coroutine chain cannot outlive its launch site. The allocator outlives every frame that uses it - not by convention, but by the structural nesting of coroutine lifetimes.

`std::execution`'s `get_allocator(get_env(receiver))` is also an implicit lookup. The mechanism is structurally similar: an ambient environment provides the allocator. The difference is timing. In `std::execution`, the lookup happens after `connect()`, which is too late for coroutine frame allocation.

In the ***IoAwaitable*** model, the lookup happens before the frame is created - the one point in time where it can actually work.

6. The Ergonomics of Type Erasure

C++20 coroutines allocate a frame for every coroutine invocation. The frame stores local variables, awaitables, intermediate state - everything the coroutine needs across suspension points. This allocation is the cost that critics point to. It cannot be eliminated for I/O coroutines (HALO cannot apply when lifetime depends on an external event). Every coroutine pays it.

The allocation we cannot avoid can pay for the type erasure we need.

6.1 Coroutine Frames as Type Erasure

A socket, an SSL context, an HTTP parser, a database connection - all of these can live inside a coroutine frame, and the caller's type system never knows. The caller sees `task<Response>`, not the types hidden inside. You can put the body of a coroutine in a `.cpp` file and expose only the signature in a header. The awaitable types, the I/O objects, the implementation details - all hidden behind a pointer. This is the foundation of ABI stability for coroutine-based libraries.

6.2 Type-Erased Streams

Our research produced `any_read_stream`, a type-erased wrapper for any type satisfying the `ReadStream` concept (full listing in Appendix B). It is not part of the ***IoAwaitable*** protocol itself, but it demonstrates what the protocol enables: zero-steady-state-allocation type erasure for I/O, with cached awaitable storage and a vtable that dispatches through the two-argument `await_suspend`.

We are developing Boost.Http (not yet accepted into Boost), an HTTP library built on Capy rather than Corosio. It works entirely in terms of type-erased streams - reading requests, parsing headers, dispatching to route handlers, and sending responses without knowing whether the underlying transport is a TCP socket, a TLS connection, or a test harness. This demonstrates the viability of implementing protocol logic away from platform sockets: the HTTP library depends only on Capy's type-erased abstractions, not on any specific I/O backend. If the ***IoAwaitable*** protocol were standardized, an HTTP layer like this could ship as a compiled library with stable ABI. Users could relink against different I/O backends without recompiling their application code.

6.3 One Template Parameter

The ***IoAwaitable*** protocol type-erases the environment through `executor_ref` and `std::pmr::memory_resource*`. The task type has one template parameter:

```
template<class T> class task;
```

This enables separate compilation and ABI stability. A coroutine returning `task<int>` can be defined in a `.cpp` file and called from any translation unit without exposing the executor type, the allocator, or the stop token in the public interface. Libraries built on ***IoAwaitable*** can ship as compiled binaries. P4007R1 Section 7.4 examines why alternative designs require a second template parameter and what the ecosystem's response has been.

6.4 Ergonomic Impact

The ergonomic consequences compound in real applications. An HTTP server has dozens of route handlers, each a coroutine. A database access layer has query functions. A WebSocket handler has message processors. All of these are written by application developers, not framework experts.

With ***IoAwaitable***, the executor, allocator, and stop token are invisible. They propagate automatically through the coroutine chain. The developer focuses on business logic:

```
route_task serve_api( route_params& rp )
{
    auto result = co_await db.query("SELECT ...");
    auto json = serialize(result);
    auto [ec] = co_await rp.send(json);
    if (ec) co_return route_error(ec);
    co_return route_done;
}
```

Compare with the same handler under `allocator_arg_t`:

```
route_task serve_api( std::allocator_arg_t, std::pmr::polymorphic_allocator<>,
    route_params& rp ) // <-- the business logic param is LAST
{
    auto result = co_await db.query(
        std::allocator_arg, alloc, "SELECT ...");
    auto json = serialize(result);
    auto [ec] = co_await rp.send(
        std::allocator_arg, alloc, json);
    if (ec) co_return route_error(ec);
    co_return route_done;
}
```

Nothing here is ***wrong***. `allocator_arg_t` follows the standard convention. The forwarding is correct. The types check out. And yet no one would choose to write the second version if they had a choice. That gap between correctness and usability is the design problem this paper addresses.

7. Comparison with `std::execution`

The design choices in this paper diverge from `std::execution` (P2300) in ways that reflect fundamentally different use cases. This section examines the divergence technically, without claiming that either approach is universally superior. Each is optimized for its primary workload.

7.1 The Late Binding Problem

Coroutine frame allocation happens ***before*** the coroutine body executes. The allocator must be known at invocation, not discovered later through receiver queries. P2300 acknowledges this timing in its "Dependently-typed senders" section:

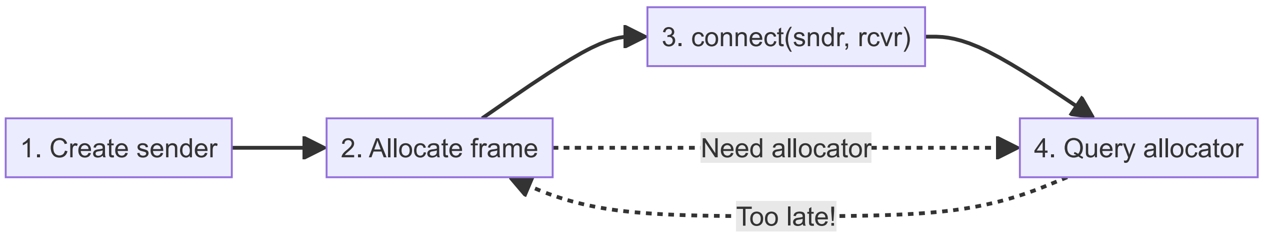
> *"The implication of the above is that the sender alone does not have all the information about the async computation it will ultimately initiate; some of that information is provided late via the receiver."*

This "late" information includes the allocator. Consider what happens with a coroutine-based sender:

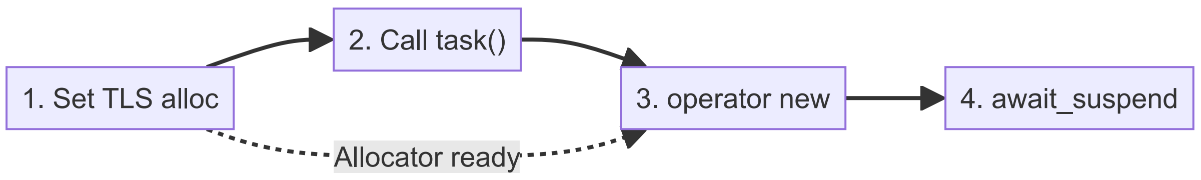
```
// P2300 query model: allocator discovered AFTER connect
template<receiver Rcvr>
struct my_operation_state {
    Rcvr rcvr_;
    void start() & noexcept {
        auto alloc = get_allocator(get_env(rcvr_));
        // But coroutine frame was allocated BEFORE connect() returned
    }
};

task<int> async_work();              // Frame allocated NOW
auto sndr = async_work();
auto op = connect(sndr, receiver);   // Allocator available NOW — too late
start(op);
```

The timing mismatch is fundamental:



Our forward flow model resolves this by making the allocator available before the frame is allocated:



The same timing constraint applies to stop tokens. In `std::execution`, the token is discovered via `get_stop_token(get_env(receiver))` - available only after `connect()`. In our model, the token propagates forward alongside the executor via `await_suspend`, available from the moment the coroutine begins.

7.2 Type Visibility and Erasure

In `std::execution`, sender types encode the entire operation chain:

```
auto sndr = schedule(sched) | then(f) | then(g);
// Type: then_sender<then_sender<schedule_sender<Sched>, F>, G>
```

These deeply nested types must be visible at every composition boundary. Storing them in data structures or passing them through non-templated interfaces requires type erasure - but C++26 `std::execution` provides none. Facebook's libunifex offered `any_sender_of`, but it heap-allocates every erased sender, is hard-coded to `std::exception_ptr`, and is effectively abandoned. Eric Niebler acknowledged in 2021 that `any_sender_of` cannot handle error types beyond `exception_ptr`. The fix remains unimplemented.

The `connect_result_t` pattern requires full type visibility of nested operations:

```
template<class S, class R>
struct _retry_op {
    using _child_op_t = stdexec::connect_result_t<S&, _retry_receiver<S, R>>;
    optional<_child_op_t> o_;  // Nested operation state, fully typed
};
```

For GPU workloads, this compile-time visibility enables real optimization: inlining kernel launches, eliminating intermediate buffers, selecting memory transfer strategies. This is not an accident - the sender/receiver model was designed around compile-time work graphs, where the entire operation chain is visible to the optimizer before execution begins. That design choice serves GPU workloads well, but it structurally prevents the kind of type erasure that coroutine frames provide for free. The two designs made different bets about what matters most, and those bets lead to different tradeoffs.

For networking, where I/O latency dwarfs dispatch overhead by orders of magnitude, compile-time operation chain visibility provides no benefit while imposing compile-time and ABI costs.

Our design achieves zero type leakage. Composed algorithms expose only concrete task return types:

Aspect	*IoAwaitable*	`std::execution`
Task types	Simple `task<T>`	Encode operation chain
Standard solution	Native `coroutine_handle<>`	None in C++26
Coroutine cost	Frame only	Frame + erasure wrapper
Error types	Any (`error_code` , etc.)	Only `exception_ptr`
Conversion overhead	None	Required

7.3 The Integration Tax

Networking code that participates in the sender/receiver ecosystem must implement `get_env` , `get_domain` , `get_completion_scheduler` , and satisfy sender/receiver concepts - even when only returning defaults. P2300/P3826 don't break networking code - defaults work. The question is whether networking should pay for abstractions it does not use.

Abstraction	Networking Need	GPU/Parallel Need
Domain-based dispatch	None	Critical
Completion scheduler queries	Unused	Required
Sender transforms	Pass-through only	Algorithm selection
Typed operation state	ABI liability	Optimization benefit
Executor/Scheduler	`dispatch` , `post`	`schedule` , `transfer`
Context discovery	Forward	Backward (query)

A simpler, networking-focused design achieves the same I/O goals without this overhead.

---

8. Reference Implementation

This section is non-normative. It provides implementation guidance for library authors who want to adopt the ***IoAwaitable*** protocol.

8.1 The `io_awaitable_promise_base` Mixin

This utility simplifies promise type implementation by providing the internal machinery that every ***IoRunnable***-conforming promise type needs:

```
template<typename Derived>
class io_awaitable_promise_base
{
    io_env const* env_ = nullptr;
    mutable std::coroutine_handle<> cont_{
        std::noop_coroutine()};

public:
    // Frame allocation using thread-local allocator.
    // Stores the memory_resource* at the end of each
    // frame so deallocation is correct even when TLS
    // has changed.

    static void* operator new(std::size_t size)
    {
        auto* mr = get_current_frame_allocator();
        if (!mr)
            mr = std::pmr::new_delete_resource();
        auto total =
            size + sizeof(std::pmr::memory_resource*);
        void* raw = mr->allocate(
            total, alignof(std::max_align_t));
        std::memcpy(
            static_cast<char*>(raw) + size,
            &mr, sizeof(mr));
        return raw;
    }

    static void operator delete(
        void* ptr, std::size_t size) noexcept
    {
        std::pmr::memory_resource* mr;
        std::memcpy(
            &mr, static_cast<char*>(ptr) + size,
            sizeof(mr));
        auto total =
            size + sizeof(std::pmr::memory_resource*);
        mr->deallocate(
            ptr, total,
            alignof(std::max_align_t));
    }

    ~io_awaitable_promise_base()
    {
        // Abnormal teardown: destroy orphaned continuation
        if (cont_ != std::noop_coroutine())
```

```
            cont_.destroy();
    }

    // Continuation for symmetric transfer at final_suspend

    void set_continuation(
        std::coroutine_handle<> cont) noexcept
    {
        cont_ = cont;
    }

    std::coroutine_handle<>
    continuation() const noexcept
    {
        return std::exchange(
            cont_, std::noop_coroutine());
    }

    // Environment storage

    void set_environment(
        io_env const* env) noexcept
    {
        env_ = env;
    }

    io_env const* environment() const noexcept
    {
        return env_;
    }

    // Default pass-through; derived classes override
    // to add custom awaitable transformation.

    template<typename A>
    decltype(auto) transform_awaitable(A&& a)
    {
        return std::forward<A>(a);
    }

    // Intercepts this_coro tags, delegates the rest
    // to transform_awaitable.

    template<typename T>
    auto await_transform(T&& t)
    {
        using Tag = std::decay_t<T>;
        if constexpr (
            std::is_same_v<Tag, environment_tag>)
        {
            struct awaiter
            {
                io_env const* env_;
                bool await_ready() const noexcept
                    { return true; }
                void await_suspend(
                    std::coroutine_handle<>)
                    const noexcept {}
                io_env const* await_resume()
                    const noexcept { return env_; }
            };
            return awaiter{env_};
        }
        else
        {
            return static_cast<Derived*>(this)
                ->transform_awaitable(
                    std::forward<T>(t));
        }
    }
};
```

Promise types inherit from this mixin to gain:

- **Frame allocation:** `operator new` / `delete` using the thread-local frame allocator, with the allocator pointer stored via `memcpy` at the end of each frame for correct deallocation. Bypasses virtual dispatch for the recycling allocator
- **Continuation support:** `set_continuation` / `continuation` for unconditional symmetric transfer at `final_suspend`
- **Environment storage:** `set_environment` / `environment` for executor and stop token propagation
- **Awaitable transformation:** `await_transform` intercepts `environment_tag`, delegating all other awaitables to `transform_awaitable`

The `await_transform` method uses `if constexpr` to dispatch tag types to immediate awaiters (where `await_ready()` returns `true`), enabling `co_await this_coro::environment` without suspension. Other awaitables pass through to `transform_awaitable`, which derived classes can override to add custom transformation logic.

> ***Non-normative note.*** *Derived promise types that need additional `await_transform` overloads should override `transform_awaitable` rather than `await_transform` itself. Defining `await_transform` in the derived class shadows the base class version, silently breaking `this_coro::environment` support. If a separate `await_transform` overload is truly necessary, import the base class overloads with a using-declaration:*
>
> ```
> struct promise_type : io_awaitable_promise_base<promise_type>
> {
>     using io_awaitable_promise_base<promise_type>::await_transform;
>     auto await_transform(my_custom_type&& t); // additional overload
> };
> ```

This mixin encapsulates the boilerplate that every ***IoRunnable***-compatible promise type would otherwise duplicate.

---

9. Conclusion

We set out to answer a practical question: what execution model emerges when networking requirements drive the design? The answer is smaller than we expected.

What we found:

1. **A minimal executor abstraction.** Two operations - `dispatch` and `post` - suffice for I/O workloads.

2. **A clear responsibility model.** The application decides execution, allocation, and stop policy at the launch site. Coroutine algorithms remain free of cross-cutting concerns.

3. **Complete type hiding.** Executor types do not leak into public interfaces. Platform I/O types remain hidden in translation units. Composed algorithms expose only concrete task return types. This directly enables ABI stability and separate compilation.

4. **Forward context propagation.** Execution context flows with control flow. The allocator is available before the frame is allocated. The environment is available from the first suspension point.

5. **A conscious tradeoff.** One pointer indirection per I/O operation (~1-2 nanoseconds [13]) buys encapsulation, ABI stability, and fast compilation. For I/O-bound workloads where operations take 10,000+ nanoseconds, this cost is negligible.

On Universal Models

C++ has a strong track record with universal abstractions, but the ones that succeed share a distinctive property: they are narrow. Iterators, allocators, ranges, each captures a focused set of requirements and enables a broad category of use cases.

Attempting to impose a universal model of asynchrony does a disservice to C++ users. Networking asynchrony is fundamentally different from GPU computing, which is different from CPU-bound parallel algorithms. A socket read has one implementation per platform. A GPU kernel has multiple implementations selected at compile time based on hardware capabilities. These are different problems with different optimization opportunities and different correctness requirements.

The ***IoAwaitable*** protocol is designed for networking. We would not suggest using it for GPU workloads, and we would not suggest adapting a GPU-focused framework for networking. Each domain deserves a model that fits its requirements, and interoperability at the boundaries is achievable without forcing everything through a single abstraction.

Implementation and Next Steps

A reference implementation of this protocol exists as a complete library: Capy. It is the foundation for Corosio, which provides sockets, timers, signals, DNS resolution, and TLS on multiple platforms. An HTTP server, WebSocket support, and a URL parser are built on top. A self-contained demonstration of the protocol is available on Compiler Explorer.

These libraries arose from use-case-first development with a simple mandate: produce a networking library built only for coroutines. Every design decision emerged from solving real problems in production I/O code. Standards should follow implementations, not the reverse. The ***IoAwaitable*** protocol is offered in that spirit: not as a theoretical construct, but as a distillation of patterns proven in practice.

In October 2021, LEWG polled:

> ***"Networking should be based on the sender/receiver model" - Weak consensus in favor***

This direction was reasonable given the information available at the time. The evidence presented in this paper suggests the committee may wish to revisit this guidance. A "weak consensus" is not a mandate; it is an invitation to reconsider as new information emerges.

10. Thoughts on Wording

> ***Non-normative note.*** *The wording below is not primarily intended for standardization. Its purpose is to demonstrate how a networking-focused, use-case-first design produces a lean specification footprint. Compare this compact specification against the machinery required by P2300/P3826 - domains, completion schedulers, sender transforms, query protocols - and observe how much simpler an execution model becomes when designed specifically for I/O workloads.*

10.1 Header `<io_awaitable>` synopsis [ioawait.syn]

```
namespace std {
  // [ioawait.env], struct io_env
  struct io_env;

  // [ioawait.concepts], concepts
  template<class A> concept io_awaitable = see-below;
  template<class T> concept io_runnable = see-below;
  template<class E> concept executor = see-below;
  template<class X> concept execution_context = see-below;

  // [ioawait.execref], class executor_ref
  class executor_ref;

  // [ioawait.execctx], class execution_context
  class execution_context;

  // [ioawait.launch], launch functions
  template<executor Ex, class... Args>
    unspecified run_async(Ex ex, Args&&... args);

  template<executor Ex, class... Args>
    unspecified run(Ex ex, Args&&... args);

  template<class... Args>
    unspecified run(Args&&... args);  // inherits caller's executor

  // [ioawait.thiscoro], namespace this_coro
  namespace this_coro {
    struct environment_tag {};
    inline constexpr environment_tag environment{};
  }
}
```

10.2 Struct `io_env` [ioawait.env]

```
namespace std {
  struct io_env {
    executor_ref executor;
    stop_token stop_token;
    pmr::memory_resource* allocator = nullptr;
  };
}
```

1 The struct `io_env` holds the execution environment propagated through a coroutine chain. It is created by a launch function and passed by pointer through `await_suspend` at each suspension point.

2 All coroutines in a chain share the same `io_env` instance. The launch function owns the object; coroutines borrow it by pointer.

3 The `executor` member identifies the executor bound to the coroutine chain.

4 The `stop_token` member carries the cancellation token for the chain. I/O objects at the end of the chain observe this token to support cooperative cancellation.

5 The `allocator` member, when non-null, identifies the memory resource used for coroutine frame allocation in the chain. A null value indicates that no allocator was specified at the launch site; the implementation is free to use any allocation strategy.

10.3 Concepts [ioawait.concepts]

10.3.1 Concept `io_awaitable` [ioawait.concepts.awaitable]

```
template<class A>
concept io_awaitable =
  requires(A a, coroutine_handle<> h, io_env const* env) {
    a.await_suspend(h, env);
  };
```

1 A type `A` meets the `io_awaitable` requirements if it satisfies the syntactic requirements above and the semantic requirements below.

2 In Table 1, `a` denotes a value of type `A`, `h` denotes a value of type `coroutine_handle<>` representing the calling coroutine, and `env` denotes a value of type `io_env const*`.

Table 1 — io_awaitable requirements

expression	return type	assertion/note pre/post-conditions
`a.await_suspend(h, env)`	`void`, `bool`, or `coroutine_handle<>`	***Effects:*** Initiates the asynchronous operation represented by `a`. The environment `env` is propagated to the operation. If the return type is `coroutine_handle<>`, the returned handle is suitable for symmetric transfer. ***Preconditions:*** `h` is a suspended coroutine. `env->executor` refers to a valid executor. The pointed-to `io_env` object remains valid for the duration of the asynchronous operation; the caller is responsible for ensuring this lifetime guarantee. ***Synchronization:*** The call to `await_suspend` synchronizes with the resumption of `h` or any coroutine to which control is transferred.

3 [***Note:*** The two-argument `await_suspend` signature distinguishes `io_awaitable` types from standard awaitables. A compliant coroutine's `await_transform` calls this signature, enabling static detection of protocol mismatches at compile time. — ***end note***]

10.3.2 Concept `io_runnable` [ioawait.concepts.runnable]

```
template<class T>
concept io_runnable =
  io_awaitable<T> &&
  requires { typename T::promise_type; } &&
  requires(T& t, T const& ct, typename T::promise_type const& cp,
           typename T::promise_type& p) {
    { ct.handle() } noexcept -> same_as<coroutine_handle<typename T::promise_type>>;
    { cp.exception() } noexcept -> same_as<exception_ptr>;
    { t.release() } noexcept;
    { p.set_continuation(coroutine_handle<>{}) } noexcept;
    { p.set_environment(static_cast<io_env const*>(nullptr)) } noexcept;
  } &&
  (is_void_v<decltype(declval<T&>().await_resume())> ||
   requires(typename T::promise_type& p) { p.result(); });
```

1 A type `T` meets the `io_runnable` requirements if it satisfies `io_awaitable<T>`, has a nested type `promise_type`, and satisfies the semantic requirements below.

2 In Table 2, `t` denotes an lvalue of type `T`, `ct` denotes a const lvalue of type `T`, `cp` denotes a const lvalue of type `typename T::promise_type`, `p` denotes an lvalue of type `typename T::promise_type`, and `h` denotes a value of type `coroutine_handle<>`.

Table 2 — io_runnable requirements

expression	return type	assertion/note pre/post-conditions
`ct.handle()`	`coroutine_handle<typename T::promise_type>`	***Returns:*** The typed coroutine handle for this task. Shall not exit via an exception.
`cp.exception()`	`exception_ptr`	***Returns:*** The exception captured during coroutine execution, or a null `exception_ptr` if no exception occurred. Shall not exit via an exception.
`t.release()`	`void`	***Effects:*** Releases ownership of the coroutine frame. After this call, the task object no longer destroys the frame upon destruction. Shall not exit via an exception. ***Postconditions:*** The task object is in a moved-from state.
`p.set_continuation(h)`	`void`	***Effects:*** Sets the coroutine handle to resume when this task reaches `final_suspend`. Shall not exit via an exception.
`p.set_environment(env)`	`void`	***Effects:*** Sets the `io_env` pointer that propagates executor, stop token, and allocator through the coroutine chain. Shall not exit via an exception. ***Preconditions:*** `env` points to an `io_env` whose lifetime exceeds that of the coroutine.

expression	return type	assertion/note pre/post-conditions
`p.result()`	***unspecified***	***Returns:*** The result value stored in the promise. ***Preconditions:*** The coroutine completed with a value (not an exception). ***Remarks:*** This expression is only required when `await_resume()` returns a non-void type.

3 [***Note:*** The `handle()` and `release()` methods enable launch functions to manage task lifetime directly. After `release()`, the launch function assumes responsibility for destroying the coroutine frame. ***— end note***]

10.3.3 Concept `executor` [ioawait.concepts.executor]

```
template<class E>
concept executor =
  is_nothrow_copy_constructible_v<E> &&
  is_nothrow_move_constructible_v<E> &&
  requires(E& e, E const& ce, E const& ce2, coroutine_handle<> h) {
    { ce == ce2 } noexcept -> convertible_to<bool>;
    { ce.context() } noexcept -> see-below;
    { ce.on_work_started() } noexcept;
    { ce.on_work_finished() } noexcept;
    { ce.dispatch(h) } -> same_as<coroutine_handle<>>;
    { ce.post(h) };
  };
```

1 A type `E` meets the `executor` requirements if it is nothrow copy and move constructible, and satisfies the semantic requirements below.

2 No comparison operator, copy operation, move operation, swap operation, or member functions `context`, `on_work_started`, and `on_work_finished` on these types shall exit via an exception.

3 The executor copy constructor, comparison operators, and other member functions defined in these requirements shall not introduce data races as a result of concurrent calls to those functions from different threads. The member function `dispatch` does not resume `h` directly; the caller is responsible for using the returned handle for symmetric transfer.

4 Let `ctx` be the execution context returned by the executor's `context()` member function. An executor becomes invalid when the first call to `ctx.shutdown()` returns. The effect of calling `on_work_started`, `on_work_finished`, `dispatch`, or `post` on an invalid executor is undefined. [***Note:*** The copy constructor, comparison operators, and `context()` member function continue to remain valid until `ctx` is destroyed. — ***end note***]

5 In Table 3, `x1` and `x2` denote (possibly const) values of type `E`, `mx1` denotes an xvalue of type `E`, `h` denotes a value of type `coroutine_handle<>`, and `u` denotes an identifier.

Table 3 — executor requirements

expression	return type	assertion/note pre/post-conditions
`E u(x1);`		Shall not exit via an exception. ***Postconditions:*** `u == x1` and `addressof(u.context()) == addressof(x1.context())`.
`E u(mx1);`		Shall not exit via an exception. ***Postconditions:*** `u` equals the prior value of `mx1` and `addressof(u.context())` equals the prior value of `addressof(mx1.context())`.
`x1 == x2`	`bool`	***Returns:*** `true` only if `x1` and `x2` can be interchanged with identical effects in any of the expressions defined in these type requirements. [***Note:*** Returning `false` does not necessarily imply that the effects are not identical. — ***end note***] `operator==` shall be reflexive, symmetric, and transitive, and shall not exit via an exception.
`x1 != x2`	`bool`	Same as `!(x1 == x2)`.
`x1.context()`	`execution_context&`, or `C&` where `C` is publicly derived from `execution_context`	Shall not exit via an exception. The comparison operators and member functions defined in these requirements shall not alter the reference returned by this function.
`x1.on_work_started()`	`void`	Shall not exit via an exception.
`x1.on_work_finished()`	`void`	Shall not exit via an exception. ***Preconditions:*** A preceding call `x2.on_work_started()` where `x1 == x2`.

expression	return type	assertion/note pre/post-conditions
`x1.dispatch(h)`	`coroutine_handle<>`	***Returns:*** A handle suitable for symmetric transfer. If the caller is already in the executor's context and inline execution is safe, returns `h` directly. Otherwise, queues `h` for later execution and returns `noop_coroutine()` . The caller must use the returned handle for symmetric transfer (e.g., return it from `await_suspend`). ***Synchronization:*** The invocation of `dispatch` synchronizes with the resumption of `h` .
`x1.post(h)`	`void`	***Effects:*** Queues `h` for later execution. The executor shall not block forward progress of the caller pending resumption of `h` . The executor shall not resume `h` before the call to `post` returns. ***Synchronization:*** The invocation of `post` synchronizes with the resumption of `h` .

6 [***Note:*** Unlike the Networking TS executor requirements, this concept operates on `coroutine_handle<>` rather than arbitrary function objects. This restriction enables zero-allocation dispatch in the common case and leverages the structural type erasure that coroutines already provide. The `dispatch` operation returns a `coroutine_handle<>` to enable symmetric transfer: the caller returns the handle from `await_suspend` , avoiding stack buildup. When the executor can run inline, it returns the handle directly; otherwise it posts to a queue and returns `noop_coroutine()` . — ***end note***]

10.3.4 Concept `execution_context` [ioawait.concepts.execctx]

```
template<class X>
concept execution_context =
  derived_from<X, std::execution_context> &&
  requires(X& x) {
    typename X::executor_type;
    requires executor<typename X::executor_type>;
    { x.get_executor() } noexcept -> same_as<typename X::executor_type>;
  };
```

1 A type `X` meets the `execution_context` requirements if it is publicly and unambiguously derived from `std::execution_context` , and satisfies the semantic requirements below.

2 In Table 4, `x` denotes a value of type `X` .

Table 4 — execution_context requirements

expression	return type	assertion/note pre/post-conditions
`X::executor_type`	type	A type meeting the `executor` requirements.
`x.get_executor()`	`X::executor_type`	***Returns:*** An executor object that is associated with the execution context. Shall not exit via an exception.
`x.~X()`		***Effects:*** Destroys all unexecuted function objects that were submitted via an executor object that is associated with the execution context.

3 [***Note:*** The destructor requirement ensures orderly cleanup—work queued but not yet executed does not leak or outlive its context. Types such as `io_context` and `thread_pool` satisfy this concept. ***— end note***]

10.4 Class `executor_ref` [ioawait.execref]

1 Class `executor_ref` is a type-erasing wrapper for executors satisfying the `executor` concept. It provides a uniform, non-templated interface for executor operations.

```
namespace std {
  class executor_ref {
    void const* ex_ = nullptr;                    // exposition only
    unspecified const* vt_ = nullptr;             // exposition only

  public:
    executor_ref() = default;
    executor_ref(executor_ref const&) = default;
    executor_ref& operator=(executor_ref const&) = default;

    template<executor E>
      executor_ref(E const& e) noexcept;

    explicit operator bool() const noexcept;
    bool operator==(executor_ref const&) const noexcept;

    execution_context& context() const noexcept;
    void on_work_started() const noexcept;
    void on_work_finished() const noexcept;
    coroutine_handle<> dispatch(coroutine_handle<> h) const;
    void post(coroutine_handle<> h) const;

    template<executor E> E const* target() const noexcept;
    template<executor E> E* target() noexcept;
  };
}
```

2 The class `executor_ref` satisfies `copy_constructible` and `equality_comparable`. Copies of an `executor_ref` refer to the same underlying executor.

3 [***Note:*** At two pointers in size, `executor_ref` is designed for efficient propagation through coroutine chains. The `dispatch` member returns a `coroutine_handle<>` for symmetric transfer, enabling zero-overhead resumption when executors match. — ***end note***]

10.4.1 `executor_ref` constructors [ioawait.execref.cons]

```
executor_ref() = default;
```

1 ***Postconditions:*** `bool(*this) == false`.

```
template<executor E>
  executor_ref(E const& e) noexcept;
```

2 ***Effects:*** Constructs an `executor_ref` that refers to `e`.

3 ***Postconditions:*** `bool(*this) == true`. `addressof(context())` equals `addressof(e.context())`.

4 ***Remarks:*** The behavior is undefined if `e` is destroyed or becomes invalid while `*this` or any copy of `*this` still exists. [***Note:*** In typical usage, the referenced executor is stored in a launch function's frame or a coroutine promise, which outlives all `executor_ref` copies propagated through the coroutine chain. — ***end note***]

10.4.2 `executor_ref` observers [ioawait.execref.obs]

```
explicit operator bool() const noexcept;
```

1 ***Returns:*** `true` if `*this` refers to an executor, otherwise `false`.

```
bool operator==(executor_ref const& other) const noexcept;
```

2 ***Returns:*** `true` if `*this` and `other` both refer to the same executor object (by address), or if both are empty. If both refer to executors of the same type, returns the result of the underlying executor's `operator==`. Otherwise `false`.

10.4.3 `executor_ref` operations [ioawait.execref.ops]

```
execution_context& context() const noexcept;
```

1 ***Preconditions:*** `bool(*this) == true`.

2 ***Returns:*** A reference to the execution context of the referenced executor, as if by calling `e.context()` where `e` is the referenced executor.

```
void on_work_started() const noexcept;
```

3 ***Preconditions:*** `bool(*this) == true` .

4 ***Effects:*** Equivalent to `e.on_work_started()` where `e` is the referenced executor.

```
void on_work_finished() const noexcept;
```

5 ***Preconditions:*** `bool(*this) == true` . A preceding call to `on_work_started()` on `*this` or on an `executor_ref` that compares equal to `*this` .

6 ***Effects:*** Equivalent to `e.on_work_finished()` where `e` is the referenced executor.

```
coroutine_handle<> dispatch(coroutine_handle<> h) const;
```

7 ***Preconditions:*** `bool(*this) == true` . `h` is a valid, suspended coroutine handle.

8 ***Effects:*** Equivalent to `e.dispatch(h)` where `e` is the referenced executor.

9 ***Synchronization:*** The invocation of `dispatch` synchronizes with the resumption of `h` .

```
void post(coroutine_handle<> h) const;
```

11 ***Preconditions:*** `bool(*this) == true` . `h` is a valid, suspended coroutine handle.

12 ***Effects:*** Equivalent to `e.post(h)` where `e` is the referenced executor.

13 ***Synchronization:*** The invocation of `post` synchronizes with the resumption of `h` .

10.4.4 `executor_ref` target access [ioawait.execref.target]

```
template<executor E> E const* target() const noexcept;
template<executor E> E* target() noexcept;
```

1 ***Returns:*** If `*this` was constructed from an executor of type `E` , a pointer to the stored executor. Otherwise, `nullptr` .

2 ***Remarks:*** The returned pointer is invalidated when `*this` is destroyed or assigned to.

10.5 Class `execution_context` [ioawait.execctx]

1 Class `execution_context` is the base class for objects that manage a set of services and provide an execution environment for I/O operations. Derived classes typically provide platform-specific reactor integration (epoll, IOCP, io_uring, kqueue).

```
namespace std {
  class execution_context {
  public:
    class service;

    execution_context();
    execution_context(execution_context const&) = delete;
    execution_context& operator=(execution_context const&) = delete;
    ~execution_context();

    template<class T> bool has_service() const noexcept;
    template<class T> T* find_service() const noexcept;
    template<class T> T& use_service();
    template<class T, class... Args> T& make_service(Args&&... args);

    pmr::memory_resource* get_frame_allocator() const noexcept;
    void set_frame_allocator(pmr::memory_resource* mr) noexcept;

    template<class Allocator>
      requires (!is_pointer_v<Allocator>)
    void set_frame_allocator(Allocator const& a);

    template<class X> X const* target() const noexcept;
    template<class X> X* target() noexcept;

  protected:
    void shutdown() noexcept;
    void destroy() noexcept;
  };

  class execution_context::service {
  public:
    virtual ~service() = default;
  protected:
    service() = default;
    virtual void shutdown() = 0;
  };
}
```

2 Access to the services of an `execution_context` is via the function templates `use_service`, `make_service`, `find_service`, and `has_service`.

3 In a call to `use_service<Service>`, the type argument chooses a service from the set in the `execution_context`. If the service is not present, an object of type `Service` is created and added. A program can check if an `execution_context` contains a particular service with `has_service<Service>`.

4 Service objects may be explicitly added using `make_service<Service>`. If the service is already present, `make_service` throws an exception.

5 Once a service reference is obtained from an `execution_context` by calling `use_service` or `make_service`, that reference remains usable until a call to `destroy()`.

6 The functions `use_service`, `make_service`, `find_service`, and `has_service` do not introduce data races as a result of concurrent calls from different threads.

10.5.1 `execution_context` constructors and destructor [ioawait.execctx.cons]

```
execution_context();
```

1 ***Effects:*** Creates an object of class `execution_context` which contains no services. [***Note:*** An implementation may preload services of internal service types for its own use. — ***end note***]

```
~execution_context();
```

2 ***Effects:*** Destroys an object of class `execution_context`. Performs `shutdown()` followed by `destroy()`.

10.5.2 `execution_context` protected operations [ioawait.execctx.protected]

```
void shutdown() noexcept;
```

1 ***Effects:*** For each service object `svc` in the `execution_context` set, in reverse order of addition to the set, performs `svc->shutdown()`. For each service in the set, `svc->shutdown()` is called only once irrespective of the number of calls to `shutdown` on the `execution_context`.

```
void destroy() noexcept;
```

2 ***Effects:*** Destroys each service object in the `execution_context` set, and removes it from the set, in reverse order of addition to the set.

10.5.3 `execution_context` service access [ioawait.execctx.services]

```
template<class Service> bool has_service() const noexcept;
```

1 ***Returns:*** `true` if an object of type `Service` is present in `*this` , otherwise `false` .

```
template<class Service> Service* find_service() const noexcept;
```

2 ***Returns:*** A pointer to the service of type `Service` if present in `*this` , otherwise `nullptr` .

```
template<class Service> Service& use_service();
```

3 ***Effects:*** Let `Key` be `Service::key_type` if that ***qualified-id*** is valid and denotes a type, otherwise `Service` . If a service with key `Key` does not already exist in the `execution_context` set, creates an object of type `Service` , initialized as `Service(*this)` , and adds it to the set indexed under `Key` .

4 ***Returns:*** A reference to the service indexed under `Key` .

5 ***Remarks:*** The reference returned remains valid until a call to `destroy()` . [***Note:*** The `key_type` mechanism allows a derived service to replace a base service in the lookup table. This enables service implementations to be swapped without changing the lookup key. — ***end note***]

```
template<class Service, class... Args> Service& make_service(Args&&... args);
```

6 ***Preconditions:*** A service with the same key does not already exist in the `execution_context` set. The key is `Service::key_type` if that ***qualified-id*** is valid and denotes a type, otherwise `Service` .

7 ***Effects:*** Creates an object of type `Service` , initialized as `Service(*this, forward<Args>(args)...)` , and adds it to the `execution_context` set.

8 ***Returns:*** A reference to the new service.

9 ***Throws:*** `std::invalid_argument` if a service with the same key is already present in the set.

10 ***Remarks:*** The reference returned remains valid until a call to `destroy()` .

10.5.4 `execution_context` frame allocator [ioawait.execctx.alloc]

```
pmr::memory_resource* get_frame_allocator() const noexcept;
```

1 ***Returns:*** The memory resource set via `set_frame_allocator` . The default value is implementation-defined and shall not be null. [***Note:*** A quality implementation uses a recycling allocator for coroutine frames. ***- end note***]

2 ***Remarks:*** This function provides the default allocator for coroutine frames launched with executors from this context when no allocator is specified at the launch site.

```
void set_frame_allocator(pmr::memory_resource* mr) noexcept;
```

3 ***Effects:*** Sets the memory resource to be returned by subsequent calls to `get_frame_allocator()` .

4 ***Remarks:*** This function does not affect coroutine frames that have already been allocated.

```
template<class Allocator>
  requires (!is_pointer_v<Allocator>)
void set_frame_allocator(Allocator const& a);
```

5 ***Effects:*** Wraps `a` in a `pmr::memory_resource` and sets it as if by calling `set_frame_allocator(mr)` where `mr` is a pointer to the wrapper. The wrapper is owned by the `execution_context` and remains valid until the next call to `set_frame_allocator` or until the `execution_context` is destroyed.

6 ***Mandates:*** `Allocator` satisfies the ***Cpp17Allocator*** requirements. `Allocator` is copy constructible.

7 [***Note:*** The frame allocator is a quality of implementation concern. A conforming implementation may ignore the allocator parameter entirely, and programs should still behave correctly. The allocator mechanism is provided to enable performance optimizations such as thread-local recycling pools or bounded allocation strategies, but correct program behavior must not depend on a specific allocation strategy being used. — ***end note***]

10.5.5 `execution_context` target access [ioawait.execctx.target]

```
template<class X> X const* target() const noexcept;
template<class X> X* target() noexcept;
```

1 ***Returns:*** If `*this` is of dynamic type `X` (or a type publicly derived from `X`), a pointer to `*this` cast to `X`. Otherwise, `nullptr`.

2 ***Remarks:*** `X` shall be publicly and unambiguously derived from `execution_context`.

10.5.6 Class `execution_context::service` [ioawait.execctx.service]

```
class execution_context::service {
public:
  virtual ~service() = default;
protected:
  service() = default;
  virtual void shutdown() = 0;
};
```

1 A class is a service if it is publicly and unambiguously derived from `execution_context::service`.

2 A service's `shutdown` member function shall destroy all copies of function objects that are held by the service.

10.6 Launch functions [ioawait.launch]

1 Launch functions bootstrap execution context into a coroutine chain. They are the bridge between non-coroutine code and the `io_awaitable` protocol.

10.6.1 Function template `run_async` [ioawait.launch.async]

```
template<executor Ex, class... Args>
  unspecified run_async(Ex ex, Args&&... args);
```

1 ***Returns:*** A callable object `f` such that the expression `f(task)` is valid when `task` satisfies `io_runnable`.

2 ***Effects:*** When `f(task)` is invoked:

- (2.1) Sets the thread-local frame allocator to the allocator specified in `Args`, or to `ex.context().get_frame_allocator()` if no allocator is specified.
- (2.2) Evaluates `task` (which allocates the coroutine frame using the thread-local allocator).
- (2.3) Calls `task.handle().promise().set_environment(io_env{ex, token, alloc})` where `token` is the stop token specified in `Args`, or a default-constructed `stop_token` if none is specified, and `alloc` is the allocator specified in `Args`, or `nullptr` if none is specified.
- (2.4) Calls `task.handle().promise().set_continuation(h)` where `h` is a coroutine handle for the trampoline that will process completion.
- (2.5) Sets up completion handling: if completion handlers are specified in `Args`, arranges for them to be invoked when `task` completes.
- (2.6) Calls `task.release()` to transfer ownership.
- (2.7) Resumes the coroutine via the executor.

3 ***Remarks:*** `Args` may include:

- A `stop_token` to propagate cancellation signals.
- An allocator satisfying the ***Allocator*** requirements, or a `pmr::memory_resource*`, used to allocate all coroutine frames in the chain.
- A completion handler invoked with the task's result value upon successful completion.
- An error handler invoked with `exception_ptr` if the task completes with an exception.

4 ***Synchronization:*** The call to `run_async(ex, args...)(task)` synchronizes with the invocation of the completion handler (if any) and with the resumption of the task coroutine.

5 [***Note:*** The two-call syntax `run_async(ex)(task())` is required because of coroutine allocation timing. The outer expression `run_async(ex)` must complete—returning the callable and establishing the thread-local allocator—before `task()` is evaluated. This ordering is guaranteed by [expr.call] in C++17 and later: "The postfix-expression is sequenced before each expression in the expression-list." — ***end note***]

6 [***Example:***

```
// Basic launch
run_async(ioc.get_executor())(my_task());

// With stop token and allocator
run_async(ex, source.get_token(), my_allocator)(my_task());

// With completion handlers
run_async(ex,
    [](int result) { /* handle success */ },
    [](exception_ptr ep) { /* handle error */ }
)(compute_value());
```

— end example]

10.6.2 Function template `run` [ioawait.launch.run]

```
template<executor Ex, class... Args>
  unspecified run(Ex ex, Args&&... args);

template<class... Args>
  unspecified run(Args&&... args);
```

1 ***Returns:*** A callable object `f` such that the expression `f(task)` is valid when `task` satisfies `io_runnable`, and returns an awaitable object `a`.

2 ***Effects:*** When `f(task)` is invoked:

- (2.1) Sets the thread-local frame allocator to the allocator specified in `Args`, or inherits the caller's allocator if none is specified.
- (2.2) Evaluates `task` (which allocates the coroutine frame using the thread-local allocator).
- (2.3) Returns an awaitable `a` that stores the executor (if provided), stop token (if provided), and the task.

3 ***Effects:*** When `a` is awaited via `co_await a`:

- (3.1) The child task is bound to executor `ex` (if provided) or inherits the caller's executor.
- (3.2) The stop token from `Args` is propagated to `task`, or the caller's stop token is inherited if none is specified.
- (3.3) The child task executes on the bound executor.
- (3.4) Upon completion, the caller resumes on its original executor (via `dispatch` for symmetric transfer when executors differ, or direct continuation return when they match).

- (3.5) The result of `co_await a` is the result of `task`.

4 ***Preconditions:*** The expression appears in a coroutine whose promise type satisfies `io_runnable`.

5 ***Remarks:*** `Args` may include:

- A `stop_token` to override the caller's stop token.
- An allocator satisfying the ***Allocator*** requirements, or a `pmr::memory_resource*`, used for coroutine frame allocation.

6 ***Remarks:*** When no executor is provided, the task inherits the caller's executor directly, enabling zero-overhead symmetric transfer on completion.

7 ***Synchronization:*** The suspension of the caller synchronizes with the resumption of `task`. The completion of `task` synchronizes with the resumption of the caller.

8 [***Note:*** Like `run_async`, `run` uses the two-call syntax `run(ex)(task())` to ensure proper frame allocation ordering. ***— end note***]

9 [***Example:***

```
task<int> parent() {
    // Child runs on worker_ex, but completion returns here
    int result = co_await run(worker_ex)(compute_on_worker());
    co_return result * 2;
}

task<void> with_custom_token() {
    std::stop_source source;
    // Child inherits caller's executor, uses different stop_token
    co_await run(source.get_token())(cancellable_work());
}
```

— end example]

10.7 Namespace `this_coro` [ioawait.thiscoro]

```
namespace std::this_coro {
  struct environment_tag {};
  inline constexpr environment_tag environment{};
}
```

1 The `this_coro` namespace provides tag objects that can be awaited within a coroutine to retrieve execution context information without suspension.

10.7.1 `this_coro::environment` [ioawait.thiscoro.environment]

```
inline constexpr environment_tag environment;
```

1 When awaited via `co_await this_coro::environment` inside a coroutine whose promise type satisfies `io_runnable`:

2 ***Returns:*** A pointer to the `io_env` bound to the current coroutine, as would be returned by `promise.environment()`.

3 ***Remarks:*** This operation never suspends. The promise's `await_transform` intercepts the `environment_tag` type and returns an immediate awaiter where `await_ready()` returns `true`.

4 ***Preconditions:*** `set_environment` has been called on the promise.

5 [***Example:***

```
task<void> cancellable_work() {
    auto env = co_await this_coro::environment;

    for (int i = 0; i < 1000; ++i) {
        if (env->stop_token.stop_requested())
            co_return;  // Exit gracefully
        co_await process_chunk(i);
    }
}
```

— end example]

10.8 Threading and synchronization [ioawait.sync]

1 Unless otherwise specified, it is safe to call `const` member functions of the classes defined in this clause concurrently from multiple threads.

2 The execution context, executor, and coroutine handle types do not introduce data races when used according to their documented requirements.

3 Synchronization between asynchronous operations follows the “synchronizes with” relationship defined in [intro.multithread]:

- (3.1) A call to `executor::dispatch` or `executor::post` synchronizes with the resumption of the submitted coroutine handle.
- (3.2) The suspension of a coroutine at a `co_await` expression synchronizes with the resumption of that coroutine.
- (3.3) The completion of a child coroutine (at final suspension) synchronizes with the resumption of the parent coroutine.

4 [***Note:*** These synchronization guarantees ensure that modifications made by one coroutine before suspension are visible to the code that resumes it. ***— end note***]

Acknowledgements

This paper builds on the foundational work of many contributors to C++ asynchronous programming:

Chris Kohlhoff for Boost.Asio, which has served the C++ community for over two decades and established many of the patterns we build upon—and some we consciously depart from. The executor model in this paper honors his pioneering work.

Lewis Baker for his work on C++ coroutines, the Asymmetric Transfer blog series, and his contributions to P2300 and P3826. His explanations of symmetric transfer and coroutine optimization techniques directly informed our design.

Dietmar Kühl for P2762 and P3552, which explore sender/receiver networking and coroutine task types. His clear articulation of design tradeoffs—including the late-binding problem and cancellation overhead concerns—helped crystallize our understanding of where the sender model introduces friction for networking.

The analysis in this paper is not a critique of these authors’ contributions, but rather an exploration of whether networking’s specific requirements are best served by adapting to general-purpose abstractions or by purpose-built designs.

Appendix A: Understanding Asynchronous I/O

Not every committee member or library reviewer works with network programming daily, and the challenges that shape I/O library design may not be immediately obvious from other domains. This appendix provides the background needed to evaluate the design decisions in the paper. The concepts presented here draw heavily from Christopher Kohlhoff's pioneering work on Boost.Asio, which has served the C++ community for over two decades, and from Gor Nishanov's C++ coroutines that now enable elegant expression of asynchronous control flow.

A.1 The Problem with Waiting

Network I/O operates on a fundamentally different timescale than computation. A CPU executes billions of instructions per second; reading a single byte from a local network takes microseconds, and from a remote server, milliseconds. The disparity is stark:

Operation	Approximate Time
CPU instruction	0.3 ns
L1 cache access	1 ns
Main memory access	100 ns
Local network round-trip	500 µs
Internet round-trip	50-200 ms

When code calls a blocking read on a socket, the thread waits—doing nothing—while the network delivers data. During a 100ms network round-trip, a modern CPU could have executed 300 billion instructions. Blocking I/O wastes this potential.

```
// Blocking I/O: thread waits here
char buf[1024];
ssize_t n = recv(fd, buf, sizeof(buf), 0);  // Thread blocked
process(buf, n);
```

For a single connection, this inefficiency is tolerable. For a server handling thousands of connections, it becomes catastrophic.

A.2 The Thread-Per-Connection Trap

The natural response to blocking I/O is to spawn a thread per connection. Each thread blocks on its own socket; while one waits, others make progress.

```
void handle_client(socket client) {
    char buf[1024];
    while (auto [ec, n] = client.read_some(buf); !ec) {
        process(buf, n);
    }
}

// Spawn a thread for each connection
for (;;) {
    socket client = accept(listener);
    std::thread(handle_client, std::move(client)).detach();
}
```

This works—until it doesn't. Each thread consumes memory (typically 1MB for the stack) and creates scheduling overhead. Context switches between threads cost thousands of CPU cycles. At 10,000 connections, you have 10,000 threads consuming 10GB of stack space, and the scheduler spends more time switching between threads than running actual code.

The C10K problem—handling 10,000 concurrent connections—revealed that thread-per-connection doesn't scale. Modern servers handle millions of connections. Something else is needed.

A.3 Event-Driven I/O

The solution is to invert the relationship between threads and I/O operations. Instead of one thread per connection, use a small number of threads that multiplex across many connections. The operating system provides mechanisms to wait for ***any*** of a set of file descriptors to become ready:

- **Linux:** `epoll` — register interest in file descriptors, wait for events
- **Windows:** I/O Completion Ports (IOCP) — queue-based completion notification
- **BSD/macOS:** `kqueue` — unified event notification

These mechanisms enable the **proactor pattern**: instead of blocking until an operation completes, you ***initiate*** an operation and receive notification when it finishes. The thread is free to do other work in the meantime.

```
io_context ioc;
socket sock(ioc);
sock.open();

// Initiate an async operation - returns immediately
auto [ec] = co_await sock.connect(endpoint(ipv4_address::loopback(), 8080));
// Execution resumes here when the connection completes
```

The `io_context` is the heart of this model. It maintains a queue of pending operations and dispatches completions as they arrive from the OS. Calling `ioc.run()` processes this queue:

```
io_context ioc;
// ... set up async operations ...
ioc.run();  // Process completions until no work remains
```

A single thread calling `run()` can service thousands of connections. For CPU-bound workloads, multiple threads can call `run()` on the same context, processing completions in parallel.

A.4 Completion Handlers and Coroutines

Early asynchronous APIs used callbacks to handle completions:

```
// Callback-based async (traditional style)
socket.async_read(buffer, [](error_code ec, size_t n) {
    if (!ec) {
        // Process data, then start another read...
        socket.async_read(buffer, [](error_code ec, size_t n) {
            // More nesting...
        });
    }
});
```

This “callback hell” inverts control flow, making code hard to follow and debug. Error handling becomes scattered across nested lambdas. State must be explicitly captured and managed.

C++20 coroutines restore sequential control flow while preserving the efficiency of asynchronous execution:

```
// Coroutine-based async (modern style)
task<> handle_connection(socket sock) {
    char buf[1024];
    for (;;) {
        auto [ec, n] = co_await sock.read_some(buf);
        if (ec)
            co_return;
        co_await process_data(buf, n);
    }
}
```

The `co_await` keyword suspends the coroutine until the operation completes, then resumes execution at that point. The code reads sequentially, but executes asynchronously. The `task<>` return type represents a coroutine that can be awaited by a caller or launched independently.

A.5 The Execution Context

I/O objects must be associated with an execution context that manages their lifecycle and delivers completions. A `socket` created with an `io_context` is registered with that context's platform reactor (epoll, IOCP, etc.). This binding is physical—the socket's file descriptor is registered with specific kernel structures.

```
io_context ioc;
socket sock(ioc);  // Socket bound to this context
sock.open();

// The socket's completions will be delivered through ioc
auto [ec] = co_await sock.connect(endpoint);
```

This binding has implications: - A socket cannot migrate between contexts - Completions are delivered to the context that owns the socket - The context must remain alive while operations are pending

The `io_context` abstracts platform differences. On Windows, it wraps an I/O Completion Port. On Linux, it wraps epoll (or io_uring). Application code remains portable while the implementation leverages platform-specific optimizations.

A.6 Executors

An **executor** determines where and how work runs. It answers: when an async operation completes, which thread should run the completion handler? Should it run immediately, or be queued for later?

```
auto ex = ioc.get_executor();
```

The executor provides two fundamental operations:

`dispatch` — Run work immediately if safe, otherwise queue it. When the I/O context thread detects a completion, it typically dispatches the waiting coroutine inline for minimal latency.

`post` — Always queue work for later execution. Use this when you need a guarantee that the work won't run until after the current function returns—for example, when holding a lock.

```
// Dispatch: may run inline
ex.dispatch(continuation);

// Post: always queued
ex.post(new_work);
```

The distinction matters for correctness. Dispatching while holding a mutex could cause the completion handler to run immediately, potentially deadlocking if it tries to acquire the same mutex. Posting guarantees the handler runs later, after the lock is released.

A.7 Strands: Serialization Without Locks

When multiple threads call `ioc.run()`, completions may execute concurrently. If two coroutines access shared state, you need synchronization. Mutexes work but introduce blocking—the very thing async I/O tries to avoid.

A **strand** provides an alternative: it guarantees that handlers submitted through it never execute concurrently, without using locks.

```
strand my_strand(ioc.get_executor());

// Entire coroutine runs serialized through the strand
run_async(my_strand)(handle_connection(sock));
```

Handlers on a strand execute in FIFO order, one at a time. Multiple strands can make progress concurrently on different threads, but within a single strand, execution is sequential. This enables safe concurrent access to connection state without explicit locking.

A.8 Cancellation

Long-running operations need a way to stop gracefully. A connection might timeout. A user might close a window. A server might be shutting down.

C++20's `std::stop_token` provides cooperative cancellation:

```
std::stop_source source;
std::stop_token token = source.get_token();

// Launch a coroutine with a stop token
run_async(ex, token)(long_running_operation());

// Later, request cancellation
source.request_stop();
```

The stop token propagates through the coroutine chain. At the lowest level, I/O objects observe the token and cancel pending operations with the appropriate OS primitive (`CancelIoEx` on Windows, `IORING_OP_ASYNC_CANCEL` on Linux). The operation completes with an error, and the coroutine can handle it normally.

Cancellation is cooperative—no operation is forcibly terminated. The I/O layer requests cancellation, the OS acknowledges it, and the operation completes with an error code. This keeps resource cleanup predictable and avoids the hazards of abrupt termination.

A.9 Moving Forward

With these fundamentals in hand—event loops, executors, strands, and cancellation—you have the conceptual vocabulary to understand the design decisions in the sections that follow. These patterns form the bedrock of modern C++ networking: high-performance servers and responsive client applications build on some combination of non-blocking I/O, completion handlers, and execution contexts [14].

If you're eager to experiment, the Corosio library implements these concepts in production-ready code. It provides sockets, timers, TLS, and DNS resolution—all built on the coroutine-first model we'll explore in depth. The Boost.Asio documentation and its many community tutorials offer additional paths to hands-on learning. Building a simple echo server or chat application is one of the best ways to internalize how these pieces fit together.

The rest of this paper examines what an execution model looks like when these networking requirements drive the design from the ground up.

Appendix B: `any_read_stream`

This appendix provides the complete listing of `any_read_stream`, a type-erased wrapper for any type satisfying the `ReadStream` concept. It is not proposed for standardization - it is included to demonstrate what the ***IoAwaitable*** protocol enables. The implementation is from the Capy library.

The vtable dispatches through the two-argument `await_suspend(coroutine_handle<>, io_env const*)`, preserving ***IoAwaitable*** protocol compliance across the type erasure boundary. Awaitable storage is preallocated at construction time, so steady-state read operations involve zero allocation.

```
class any_read_stream
{
    struct vtable;

    template<ReadStream S>
    struct vtable_for_impl;

    void* stream_ = nullptr;
    vtable const* vt_ = nullptr;
    void* cached_awaitable_ = nullptr;
    void* storage_ = nullptr;
    bool awaitable_active_ = false;

public:
    ~any_read_stream();

    any_read_stream() = default;
    any_read_stream(any_read_stream const&) = delete;
    any_read_stream& operator=(any_read_stream const&) = delete;

    any_read_stream(any_read_stream&& other) noexcept
        : stream_(std::exchange(other.stream_, nullptr))
        , vt_(std::exchange(other.vt_, nullptr))
        , cached_awaitable_(std::exchange(
              other.cached_awaitable_, nullptr))
        , storage_(std::exchange(other.storage_, nullptr))
        , awaitable_active_(std::exchange(
              other.awaitable_active_, false))
    {
    }

    any_read_stream&
    operator=(any_read_stream&& other) noexcept;

    // Owning construction
    template<ReadStream S>
        requires (!std::same_as<std::decay_t<S>,
                                any_read_stream>)
    any_read_stream(S s);

    // Reference construction
    template<ReadStream S>
    any_read_stream(S* s);

    bool has_value() const noexcept
    {
        return stream_ != nullptr;
    }

    explicit operator bool() const noexcept
    {
        return has_value();
    }

    template<MutableBufferSequence MB>
    auto read_some(MB buffers);
};

// vtable: one per concrete stream type
struct any_read_stream::vtable
{
    void (*construct_awaitable)(
        void* stream, void* storage,
        std::span<mutable_buffer const> buffers);
    bool (*await_ready)(void*);
    std::coroutine_handle<> (*await_suspend)(
        void*, std::coroutine_handle<>,
        io_env const*);
    io_result<std::size_t> (*await_resume)(void*);
    void (*destroy_awaitable)(void*) noexcept;
    std::size_t awaitable_size;
    std::size_t awaitable_align;
    void (*destroy)(void*) noexcept;
};

// vtable instantiation for a concrete ReadStream
template<ReadStream S>
struct any_read_stream::vtable_for_impl
{
    using Awaitable = decltype(
        std::declval<S&>().read_some(
            std::span<mutable_buffer const>{}));

    static void construct_awaitable_impl(
        void* stream, void* storage,
        std::span<mutable_buffer const> buffers)
    {
        auto& s = *static_cast<S*>(stream);
        ::new(storage) Awaitable(s.read_some(buffers));
    }

    static constexpr vtable value = {
        &construct_awaitable_impl,
        +[](void* p) {
            return static_cast<Awaitable*>(p)
                ->await_ready();
        },
        +[](void* p, std::coroutine_handle<> h,
            io_env const* env) {
            return static_cast<Awaitable*>(p)
                ->await_suspend(h, env);
        },
        +[](void* p) {
            return static_cast<Awaitable*>(p)
                ->await_resume();
        },
        +[](void* p) noexcept {
            static_cast<Awaitable*>(p)->~Awaitable();
        },
        sizeof(Awaitable),
        alignof(Awaitable),
        +[](void* p) noexcept {
            static_cast<S*>(p)->~S();
        }
    };
};

// read_some returns an IoAwaitable that dispatches
// through the vtable
template<MutableBufferSequence MB>
auto
any_read_stream::read_some(MB buffers)
{
    struct awaitable
    {
        any_read_stream* self_;
        mutable_buffer_array<max_iovec> ba_;

        bool await_ready()
        {
            self_->vt_->construct_awaitable(
                self_->stream_,
                self_->cached_awaitable_,
                ba_.to_span());
            self_->awaitable_active_ = true;
            return self_->vt_->await_ready(
                self_->cached_awaitable_);
        }

        std::coroutine_handle<>
```

```
            await_suspend(
                std::coroutine_handle<> h,
                io_env const* env)
            {
                return self_->vt_->await_suspend(
                    self_->cached_awaitable_, h, env);
            }

            io_result<std::size_t>
            await_resume()
            {
                struct guard {
                    any_read_stream* self;
                    ~guard() {
                        self->vt_->destroy_awaitable(
                            self->cached_awaitable_);
                        self->awaitable_active_ = false;
                    }
                } g{self_};
                return self_->vt_->await_resume(
                    self_->cached_awaitable_);
            }
        };
        return awaitable{this,
            mutable_buffer_array<max_iovec>(buffers)};
    }
```

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