WG21 PROPOSAL

Coroutines for I/O

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Abstract

C++20 coroutines have five properties that, taken together, make them uniquely suited to asynchronous I/O: type erasure through `coroutine_handle<>`, customization through `promise_type`, stackless independently-resumable frames, symmetric transfer through `await_suspend`, and compiler-managed state that persists across suspension points. Each was designed for generality. Their conjunction yields something no single property suggests: the optimal basis for byte-oriented I/O.

We used C++20 coroutines directly for I/O - timers, sockets, DNS, TLS, HTTP - and observed what the language already provides. The protocol that emerged is the ***IoAwaitable***: a system for associating a coroutine with an executor, stop token, and frame allocator, and propagating this context forward through a coroutine chain to the operating system API boundary where asynchronous operations are performed.

Revision History

R1: March 2026 (pre-Croydon mailing)

- Added “Why Standardize” subsection to Section 1: committee record, tower of abstraction argument, P4133 cost/benefit analysis.
- Expanded implementation evidence in Section 3.
- Added Section 9 “Evidence Framework” addressing P4133 requirements: competing designs, case against standardization, decision record, domain coverage, post-adoption metrics, retrospective commitment, prediction registry.
- Editorial: fixed list formatting, code line wrapping, acknowledgements
- Expanded sequence diagram with explicit `set_environment`, `set_continuation`, and `handle.resume()` steps
- Renamed “Boost.Http” to “Http” in body and references
- Closed TLS spoilage gap in Section 5.4: intervening code between resume and child creation can overwrite the thread-local frame allocator. Introduced `safe_resume` save/restore protocol
- Added non-normative note to executor concept (Section 11.3.3) requiring event loop pump sites to save and restore TLS around `.resume()` calls
- Replaced `std::coroutine_handle<>` with `continuation` in the executor interface. The `continuation` struct embeds an intrusive list pointer, eliminating per-post heap allocation - the last steady-state allocation in the hot path

R0: March 2026 (pre-Croydon mailing)

- Initial version.

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1. Introduction

This paper is a research report drawn from working code: a complete coroutine-only networking library.

What we found 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 frame allocator policy out of coroutine signatures - yet it is the foundation from which a complete 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. For readers interested in how this model relates to other execution frameworks, see P4007R0 “Senders and Coroutines”[1] and P4014R0 “The Sender Sub-Language”[2].

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

Priorities

We adopted three priorities:

1. **Correctness.** Invariants are enforced at compile time.
2. **Ergonomics.** User-facing interfaces stay clean.
3. **Performance.** We benchmarked at every step.

What Matters

I/O applications share four requirements:

1. **The application decides executor policy.** A read operation should not need to know about executor policy.
2. **The application sends stop signals.** Stop signals propagate from the launch site to pending operations. The API builds on `std::stop_token`.
3. **The application decides frame allocation.** The allocator is a property of the coroutine chain, not of the operation.
4. **The execution context owns its I/O objects.** A socket knows its event loop. The call site does not.

Why Standardize

Networking has been a stated committee priority for nearly a decade. P0592R0 (2017)[13] listed networking as one of four primary C++20 priorities. P0592R2[13] elevated it to a “must-work-on-first” item for C++23. The 2021 LEWG polls[14][15] found weak consensus against the Networking TS async model as a general-purpose basis (5 SF, 10 WF, 6 N, 14 WA, 18 SA) and weak consensus that networking should be based on sender/receiver (17-11-10-4-6). P0592R5[13] dropped networking from C++26 priorities entirely: “The earlier direction/approach for Networking didn’t have consensus.” SG4 at Kona (November 2023) reached consensus that networking should use only a sender/receiver model. By 2025, SG4 declared the Networking TS “no longer relevant.” P3185R0[17] and P3482R0[18] proposed a TAPS-based direction that remains under review.

The committee is not asking whether to standardize networking. It has answered that question repeatedly, across three standard cycles, and the answer is yes. The open question is how. The coroutine-native approach described in this paper was not among the alternatives considered at the time of the Kona poll.

Every mature language ecosystem has a tower of networking abstractions. Python has Django and Flask. Go has `net/http` and everything built on it. Rust has tokio, hyper, and axum. JavaScript has Express and Next.js. These towers exist because each language has a standard or de facto standard networking foundation that every library builds upon.

C++ does not have this tower - and the ecosystem has had twenty years to build it. Boost.Asio[3] has been available since 2003. In over twenty years, the ecosystem has not produced a standard HTTP framework, a standard WebSocket library, or a web application framework. The `vcpkg` and Conan catalogs do not approach the depth of npm or pip for networking applications. The reason is not that C++ developers do not want these things. The reason is that there is no standard foundation to build them on. Every async I/O library invents its own model. An HTTP library built on one model cannot compose with a database library built on another. The tower cannot be built from incompatible foundations - and twenty years of evidence proves it.

Networking is where the tower starts. Sockets, DNS, TLS - these are the base layer. On top of them you build HTTP. On top of HTTP you build WebSocket, REST APIs, JSON-RPC. On top of those you build web frameworks, application servers, microservice toolkits. Each layer depends on the one below. Without a standard base layer, none of the layers above can be standard either.

The wrong foundation would be worse than none. Alternative coroutine task designs propagate the frame allocator through `allocator_arg_t` in every function signature (Section 5.2 demonstrates the damage). If such a design were standardized, every public interface of every library across the C++ ecosystem would carry allocator parameters unrelated to the library's purpose. That pollution would be permanent - standardized interfaces cannot be un-standardized. The ***IoAwaitable*** protocol solves this with thread-local propagation: the frame allocator is invisible to every coroutine except the launch site. Getting this right in the standard matters because getting it wrong in the standard is irreversible.

Performance requires the frame allocator; ergonomics require TLS. The benchmarks in Section 2.3 show a 3.1x speedup over `std::allocator` and 1.28x over mimalloc. This performance is necessary for C++ to remain competitive with other language ecosystems for I/O workloads. But the performance is worthless if every route handler, every query function, every application-level coroutine must thread the allocator through its signature. The TLS mechanism delivers the performance without the ergonomic cost. Both parts - the frame allocator and the propagation mechanism - must be standardized together.

The specification is small: two concepts, one struct, one type-erased executor, two launch functions. This is the minimum a library needs to participate in the ecosystem. The implementer burden is proportionate. The cost of continued inaction is measured in standard cycles - three so far, each naming networking as a priority and each failing to deliver. Once this vocabulary is standard, any HTTP library, any WebSocket library, any database driver that satisfies the protocol can compose with any other. The tower becomes buildable.

2. Networking's Essentials

A socket read has **one implementation per platform**. The contract is specific: the coroutine suspends, a platform reactor performs the operation, and the coroutine resumes under the application's control.

The ***IoAwaitable*** protocol defines this contract. The executor resumes the coroutine according to the application's policy. The stop token propagates cancellation. The frame allocator controls coroutine memory. Every executor is bound to an execution context that owns the platform reactor and its I/O objects. Completions are delivered through the context the socket is registered with - a coupling inherent to every platform: IOCP, epoll, kqueue, io_uring.

2.1 The Executor

An allocator controls where objects live. An executor controls how coroutines resume. A minimal executor needs two operations: `dispatch` for continuations that can run inline, and `post` for work that must be deferred. The distinction matters for correctness: inline execution while holding a lock can deadlock. `dispatch` uses symmetric transfer to avoid stack buildup. Section 4 defines the concept and its semantics.

2.2 The `stop_token`

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

```
http_client -> http_request -> write -> write_some -> socket
```

The I/O object cancels the pending operation through the platform primitive: `CancelIoEx` on Windows, `IORING_OP_ASYNC_CANCEL` on Linux, `close()` on POSIX. The operation completes with an error and the coroutine chain unwinds normally. Cancellation is cooperative.

2.3 The Frame Allocator

A ***frame allocator*** is a `memory_resource` used exclusively for coroutine frame allocation. Coroutine frames follow a narrow pattern: sizes repeat, lifetimes nest, and deallocation order mirrors allocation order. A frame allocator exploits this pattern.

Every `co_await` may spawn new frames. Recycling frame allocators cache recently freed frames for immediate reuse:

Platform	Frame Allocator	Time (ms)	Speedup
MSVC	Recycling	1265.2	3.10x
MSVC	mimalloc	1622.2	2.42x
MSVC	`std::allocator`	3926.9	-
Apple clang	Recycling	2297.08	1.55x
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 frame allocator is 1.28x faster. Different deployments need different strategies - bounded pools, per-tenant budgets, allocation tracking - so the execution model must let the application choose. The frame allocator must be present at invocation time: `operator new` executes before the coroutine body. Section 5 examines the timing constraint and the solution.

2.4 Ergonomics

The executor, stop token, and frame allocator are infrastructure. They should be invisible to every coroutine except the launch site. When the developer needs control, the API should be obvious.

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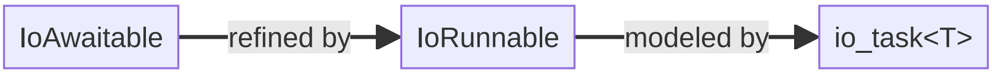
3. The Protocol: What Coroutines Need for I/O

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



> *To help readers understand how these requirements fit together, this paper provides the `io_awaitable_promise_base` CRTP mixin (Section 7) 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[5] implements the ***IoAwaitable*** protocol. Corosio[6], built on Capy, provides sockets, timers, TLS, and DNS resolution on multiple platforms. Both libraries are in active use and include unit tests covering protocol conformance, frame allocation, cancellation propagation, and cross-platform behavior. Corosio has been benchmarked on Linux (epoll, io_uring), Windows (IOCP), and macOS (kqueue). Http[8], an HTTP library built on Capy, ships as a compiled library with stable ABI, demonstrating that the single template parameter on `task<T>` enables separate compilation in practice. All three libraries are open-source, buildable with CMake, and available on GitHub. 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 frame 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* frame_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 frame 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:

```
template<typename Promise>
auto await_suspend(std::coroutine_handle<Promise> h) {
    auto& env = h.promise().get_env();
    // ...
}
```

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. The 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.

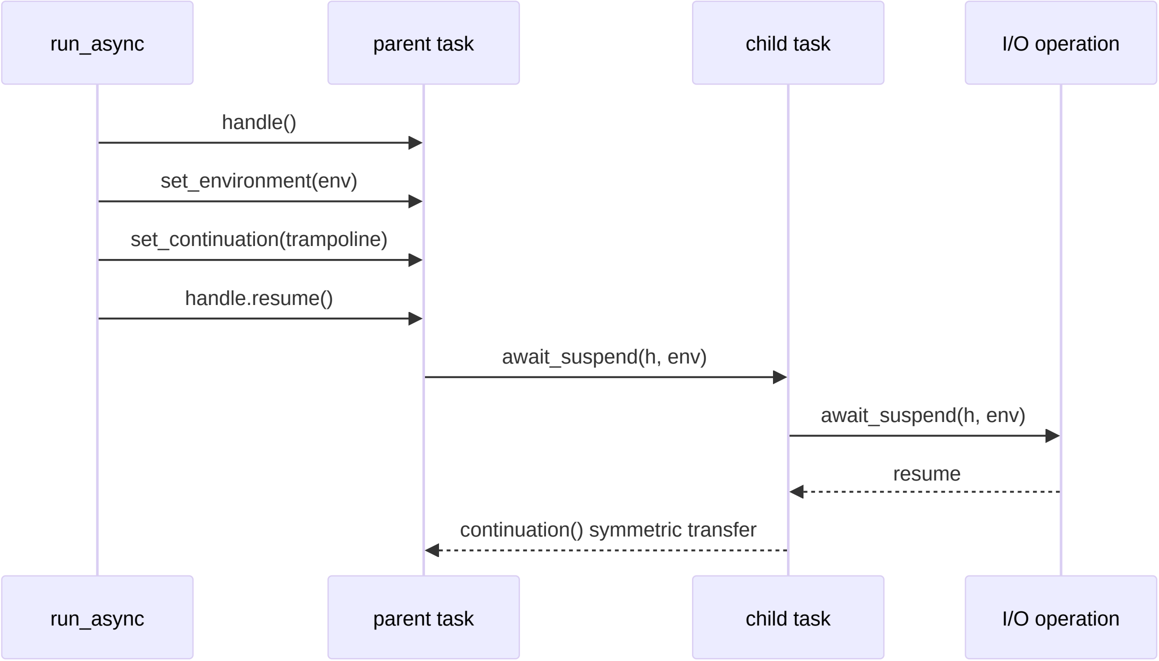
```
template<typename T>
concept IoRunnable =
    IoAwaitable<T> &&
    requires { typename T::promise_type; } &&
    requires( T& t, T const& ct,
              typename T::promise_type const& cp,
              typename T::promise_type& p )
    {
        { ct.handle() } noexcept
            -> std::same_as< 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 frame 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 frame allocator propagation (read TLS)

Example implementation:

```
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 (Section 7) 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(continuation& c) const;
    void post(continuation& c) 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 [7] - 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 `c.h` directly for immediate resumption. Otherwise it queues the continuation via its intrusive `next_` pointer 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 cancellation signals
- `alloc` frame allocator 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, frame 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. Still, it is 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 frame 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 frame 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();
    continuation c{ task.handle() };
    ex.post( c );
}
```

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

---

4. Executor concept

Terminology note. We use the term ***Executor*** intentionally. An executor controls how coroutines resume: `dispatch` for inline continuations via symmetric transfer, `post` for deferred execution. The concept is tailored to I/O's requirements: strand serialization, I/O completion contexts, and thread affinity. This terminology honors Christopher Kohlhoff's executor model in Boost.Asio[3], which established the foundation for modern C++ asynchronous I/O.

The executor's `dispatch` and `post` operations accept a `continuation` - a lightweight struct that pairs a `coroutine_handle<>` with an intrusive linked-list pointer:

```
struct continuation
{
    std::coroutine_handle<> h;
    continuation* next_ = nullptr;
};
```

The embedded `next_` pointer allows executors to queue continuations without allocating a separate node for each posted item - eliminating the last steady-state allocation in the hot path. A `continuation` is passed by reference; the caller guarantees address stability for the duration of the queue residency. In coroutine code this invariant is satisfied automatically: I/O awaitables embed their `continuation` and are alive for the duration of the suspension.

```
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, continuation c ) {
        { 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( c ) } -> std::same_as< std::coroutine_handle<> >;
        { ce.post(c) };
    };
```

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 does not know where the coroutine may suspend

This structural erasure is often lamented as overhead, but it is an opportunity. In this 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` accepts a `continuation&` and returns a `std::coroutine_handle<>` for symmetric transfer. If the caller is already in the executor's context, `dispatch` returns `c.h` directly. Otherwise, the continuation is queued via its intrusive `next_` pointer 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 `safe_resume()` at the event loop pump level (Section 5.4), which saves and restores the thread-local frame allocator around the `.resume()` call.

Unlike general-purpose executors that accept templated callables, `dispatch` and `post` accept only `continuation&` - this is a coroutine-only model. A continuation is two pointers: a coroutine handle and an intrusive list node. 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[3].

```
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 frame allocator is specified at the launch site. Since every launcher requires an ***Executor***, the execution context naturally coordinates frame allocation policy. The default frame 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 Frame Allocator

Achieving high performance levels with coroutines demands frame allocator customization, yet frame allocator propagation presents a unique challenge. Unlike executors and stop tokens, which can be injected at suspension points via `await_transform`, the frame 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 - `await_transform`, explicit method calls, post-construction configuration - 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 a frame allocator. The standard pattern uses `std::allocator_arg_t` as a tag to mark the allocator parameter:

```
// Free function: frame 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 frame 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 frame allocator through its signature, even if it never uses it directly. The frame 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 frame 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 frame 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 frame 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 frame 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 frame 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 frame 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: **frame allocator customization happens at launch sites**, not within coroutine algorithms. Functions like `run_async` and `run` accept frame allocator parameters because they represent application policy decisions. Coroutine algorithms do not need to "allocator-hop" - they simply inherit whatever frame allocator the application has established.

The approach:

1. **Receive the frame 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 frame allocator lives in the launch coroutine's frame. Because coroutine parameter lifetimes extend until final suspension, the frame allocator remains valid for the entire operation chain.

4. **Propagate through thread-locals.** Before any child coroutine is invoked, the current frame 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 frame 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 frame
// 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 frame allocator faithfully (via set before
// invoking child coroutines) so that downstream frames can
// use it.

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

    // Store frame allocator pointer at end of frame for correct deallocation
    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 ) {
    // Read the frame allocator pointer from the end of the frame
    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));
}
```

`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 frame 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 frame allocator controls ***where*** a frame's memory comes from, not what the coroutine does. However, a conforming awaitable must still propagate the frame 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 frame 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 frame allocator.

An important distinction: other coroutine libraries that use thread-local storage for frame allocation set it once globally, so all coroutine chains share the same frame allocator for the lifetime of the program. Our approach is per-chain. Each launch site can choose a different frame allocator, and that frame allocator is scoped to the specific chain it launches. When a chain suspends for I/O, another chain with a different frame allocator can run without interference. When the first chain resumes, the window mechanism restores its frame allocator before any child coroutines are created. This is how frame 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
}
```

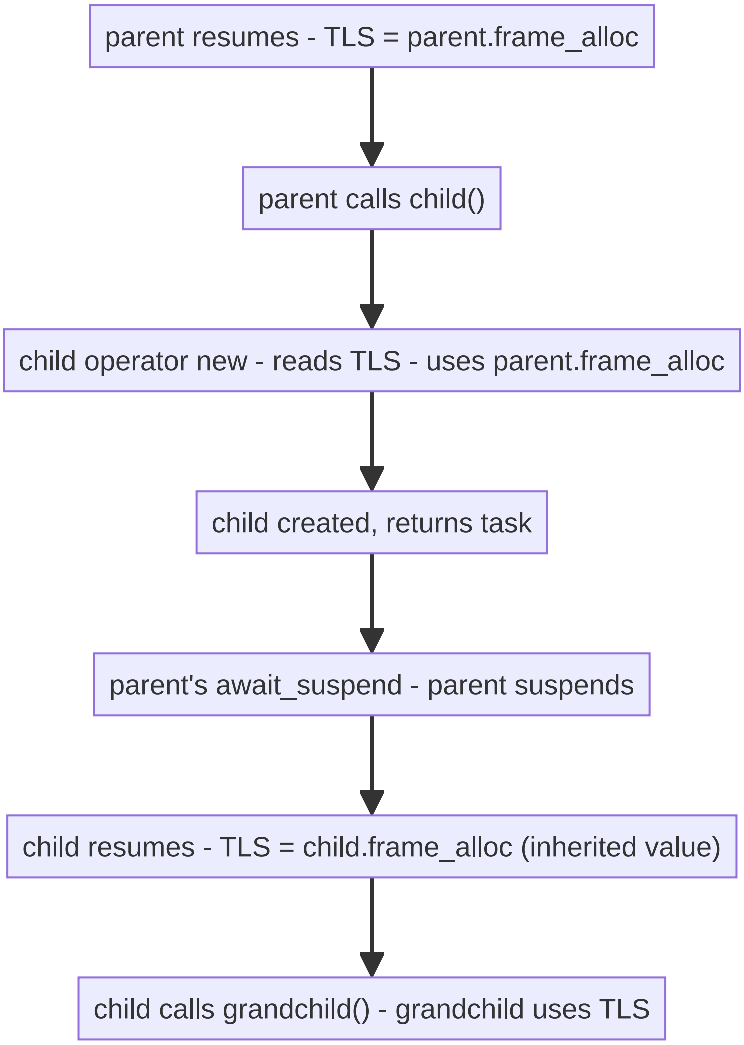
When `child()` is called: 1. `parent` coroutine is **actively executing** (not suspended) 2. `child()`'s `operator new` is called 3. `child()`'s frame is created 4. `child()` returns task 5. THEN `parent` suspends

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 frame allocator while it is 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 frame allocator. When `child()` is called, TLS is already pointing to `parent` 's frame allocator. The flow:



This is safe because:

- TLS is only read in `operator new` - no other code path inspects the thread-local frame 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`. Executor event loops preserve this invariant by saving and restoring TLS around each `.resume()` call (see "Intervening Code and TLS Spoilage" below)
- Thread migration is handled: when a coroutine suspends on thread A and resumes on thread B, the `await_resume` path writes the correct frame 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 frame allocator from a pointer embedded in the frame footer, not from TLS. A frame can be destroyed on any thread

Intervening Code and TLS Spoilage

The analysis above covers the direct case: `co_await child()` is the first expression after resume. Consider instead:

```
task<void> parent()
{
    foo();
    co_await child();
}
```

Between `await_resume` (which sets TLS) and `child()`'s `operator new` (which reads TLS), `foo()` executes. If `foo()` resumes a coroutine from a different chain on this thread - by pumping a dispatch queue, running nested event loop work, or calling `.resume()` on a foreign handle - that coroutine's `await_resume` overwrites TLS with its own frame allocator. When `foo()` returns and `child()` is called, `operator new` reads the wrong value.

The consequence is not memory corruption. `operator delete` reads the frame allocator from the frame footer, not from TLS. A frame allocated from the wrong resource is deallocated from the correct one. The program produces correct results with the wrong allocation strategy for some frames. But a user who passes a `monotonic_buffer_resource` to `run_async` expects every frame in that chain to use it. Silent allocation from a different resource violates that expectation.

The fix is a save/restore protocol at every `.resume()` call site:

```
inline void
safe_resume(std::coroutine_handle<> h) noexcept
{
    auto* saved = get_current_frame_allocator();
    h.resume();
    set_current_frame_allocator(saved);
}
```

Every executor event loop and strand dispatch loop saves TLS before resuming a coroutine handle and restores it after the coroutine suspends and `.resume()` returns. TLS now behaves like a stack: each nested resume pushes a frame allocator; when `.resume()` returns, the previous value is restored. The cost is one pointer save and one pointer restore per `.resume()` call - two TLS accesses, negligible compared to the cost of resuming a coroutine.

Two `.resume()` sites intentionally do not use `safe_resume`:

1. **Symmetric transfer workarounds.** When a coroutine calls `.resume()` as a substitute for symmetric transfer (to work around compiler codegen bugs), the calling coroutine is about to suspend unconditionally. When it later resumes, `await_resume` restores TLS from the promise's stored environment. Save/restore here would add overhead on every suspension with no benefit.

2. **Launch function wrappers.** `run_async`'s internal wrapper saves TLS in its constructor and restores it in its destructor, bracketing the entire task lifetime. The `.resume()` inside the wrapper occurs within this bracket.

The burden falls on executor and strand authors - the same people who write promise types, `await_transform`, and `operator new` overloads. They write `safe_resume` once, and every application developer who writes a coroutine body benefits without knowing it exists.

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 - by `await_resume` from the coroutine side, and preserved by `safe_resume` from the event loop side - 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 frame 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 frame 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_->frame_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 frame allocator outlives every frame that uses it - not by convention, but by the structural nesting of coroutine lifetimes.

The ***IoAwaitable*** model performs the lookup before the frame is created - the one point in time where it can actually work. Any mechanism that delivers the allocator after coroutine invocation arrives too late by definition.

---

6. The Ergonomics of Type Erasure

C++20 coroutines allocate a frame for every invocation. The frame stores local variables, awaitables, and intermediate state across suspension points. For I/O coroutines, this allocation is unavoidable: Heap Allocation eLision Optimization (HALO) cannot apply when frame lifetime depends on an external event.

The allocation we cannot avoid buys the type erasure we need.

6.1 Coroutine Frames as Type Erasure

A socket, an SSL context, an HTTP parser, a database connection - all live inside a coroutine frame. The caller sees `task<Response>`. The coroutine body goes in a `.cpp` file; the header exposes the signature. Every type behind the frame boundary is hidden from the caller's type system. This is the foundation of ABI stability for coroutine-based libraries.

6.2 Type-Erased Streams

This research produced `any_read_stream`, a type-erased wrapper for any type satisfying the `ReadStream` concept (complete listing in Appendix B). It is not part of the ***IoAwaitable*** protocol, 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`.

Http[8], an HTTP library built on Capy, works entirely in terms of type-erased streams. It reads requests, parses headers, dispatches to route handlers, and sends responses without knowing whether the underlying transport is a TCP socket, a TLS connection, or a test harness. The HTTP library depends on Capy's type-erased abstractions. It ships as a compiled library with stable ABI.

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 frame allocator, or the stop token in the public interface. Libraries built on ***IoAwaitable*** ship as compiled binaries. P4007R0[1] Section 6.4 examines why alternative designs require a second template parameter and what the ecosystem's response has been.

6.4 Ergonomic Impact

An HTTP server has dozens of route handlers. A database layer has query functions. A WebSocket handler has message processors. Application developers write these, not framework experts.

With ***IoAwaitable***, the executor, frame allocator, and stop token propagate automatically. The developer writes 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;
}
```

---

7. 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 frame 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 frame allocator pointer stored via `memcpy` at the end of each frame for correct deallocation. Bypasses virtual dispatch for the recycling frame 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.

---

8. Conclusion

We asked what happens when networking requirements drive the design of a coroutine execution model. The protocol that emerged is small, and we could not find anything to remove from it without losing function. Every language feature it depends on - `coroutine_handle<>`, `promise_type`, `await_suspend`, compiler-managed state - is part of C++20.

The abstractions that succeed in C++ are narrow. Iterators capture traversal. Allocators capture memory strategy. Each serves a broad category by focusing on one set of requirements. I/O asynchrony is one such category. GPU computing is another. Each deserves a model that fits.

For I/O, the basis is already in the language.

A reference implementation is available as Capy[5], with networking provided by Corosio[6]. A self-contained demonstration is on Compiler Explorer (https://godbolt.org/z/Wzrb7McrT)[10].

These libraries arose from use-case-first development with a simple mandate: use C++20 coroutines directly for I/O and observe what the language provides. Every design decision emerged from implementing the solution. 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.

---

9. Evidence Framework

This section addresses the structured evidence requirements described in P4133R0 "What Every Proposal Must Contain"[11].

The protocol described in this paper was not designed top-down from theory. It was discovered bottom-up from working code. We started from an empty directory - an empty `.cpp` file, an empty `.hpp` file - with nothing inherited and no existing framework assumed. We added one thing at a time: a coroutine, then an executor, then a stop token, then a frame allocator. At each step we added exactly what the next use case demanded and nothing more. The result is the smallest abstraction from which nothing can be removed and still remain functional. Every design decision recorded below was forced by this process - not chosen from a menu of options but discovered as the only thing that worked. The evidence is the code itself.

9.1 Competing Designs

Four alternative approaches address the same problem space. Each has genuine advantages. We present each at its strongest before explaining why ***IoAwaitable*** is preferred for I/O.

Sender/receiver (P2300R10[12]). The committee-adopted framework for structured asynchronous execution. Its advantages are real: generality across I/O, GPU, and parallel workloads; a formal algebra of sender composition; strong structured-concurrency guarantees; and significant investment from NVIDIA, Meta, and Bloomberg. For domains that require DAG-shaped execution graphs - GPU kernel fusion, heterogeneous compute pipelines, complex parallel algorithms - sender/receiver provides machinery that ***IoAwaitable*** does not attempt. Where sender/receiver is weakest is in the I/O-specific properties that drive this paper: it requires a second template parameter on the task type (making separate compilation and ABI stability difficult), it does not define a frame allocator propagation mechanism, and the sender composition algebra adds conceptual weight that I/O coroutines - which are sequential by nature - do not use. P4007R0[1] and P4014R0[2] examine this relationship in detail.

Boost.Asio completion handlers (Boost.Asio[3]). The most widely deployed C++ async I/O model, with over twenty years of production use. Its advantages are maturity, extensive documentation, and a large existing codebase. It supports coroutines through completion tokens. The 2021 LEWG polls[15] found weak consensus against the Networking TS async model as a general-purpose basis (5 SF, 10 WF, 6 N, 14 WA, 18 SA), primarily due to concerns about composability, error handling between work submission and continuation invocation[16], and unsuitability for GPU workloads. For I/O specifically, the Asio model remains capable, but the completion-token mechanism requires each call site to specify how it will be consumed, and the absence of a standard frame allocator propagation mechanism forces either `allocator_arg_t` signature pollution or reliance on `shared_ptr` for lifetime management.

Pure coroutine libraries (cppcoro, libcoro). These provide coroutine task types and synchronization primitives without a formal protocol. Their advantage is simplicity - a task type, a scheduler, and nothing else. The limitation is that each library defines its own model. An HTTP library built on cppcoro cannot compose with a database driver built on libcoro. Without a shared protocol, each library is an island.

Do nothing. Leave coroutine I/O execution models to the ecosystem. The advantage is zero standardization cost and maximum freedom for library authors. The disadvantage is twenty years of evidence: Boost.Asio[3] has been available since 2003. In that time, the ecosystem has not produced a standard HTTP framework, a standard WebSocket library, or a web application framework comparable to what other language ecosystems provide. Each C++ networking library builds on a different async model. The higher layers of the abstraction tower - the layers that application developers need - have not emerged because the foundation is not shared.

9.2 Case Against Standardization

The strongest argument against standardization: Capy, Corosio, and Http already exist as open-source libraries. Any project that needs ***IoAwaitable*** can depend on them directly. The protocol relies on thread-local storage, which may not be available or performant on all target platforms. The two-call launch syntax (`run_async(ex)(task())`) is a workaround for a language limitation in `operator new` timing. The design is young - the first implementation is months old, not years.

Each point deserves a direct response.

"The ecosystem can deliver this." It has not. Boost.Asio has been available for over twenty years. In that time, the C++ ecosystem has not produced the tower of abstractions that every other major language ecosystem enjoys. There is no Django of C++. There is no standard HTTP framework. The `vcpkg` and Conan catalogs do not approach the depth of npm or pip for networking applications. The reason is that every C++ networking library is an island - each builds on a different async model, so they cannot compose. The ecosystem cannot converge on a common vocabulary without standardization, because the entire point of a vocabulary is that everyone can depend on it being there. Twenty years of evidence is sufficient to conclude that the ecosystem alone will not produce a shared foundation.

"Thread-local storage is problematic." Section 5.5 addresses the TLS concerns directly. 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. Thread migration is handled: every resume path restores TLS from the heap-stable `io_env` before the coroutine body continues. The standard library already accepted this approach: `std::pmr::get_default_resource()` is a process-wide thread-local allocator channel, adopted in C++17. For platforms without thread-local storage, implementations may use whatever mechanism is available - the interface is two free functions, not a language feature.

"The two-call syntax is a workaround." It is. The syntax exists because `operator new` executes before the coroutine body, and no mechanism exists to inject the frame allocator after invocation. A future language change could eliminate the need. But the alternative - threading `allocator_arg_t` through every coroutine signature in every library across the ecosystem - is worse, and that damage would be permanent if standardized. The two-call syntax is localized to launch sites. Application-level coroutines never see it.

"The design is young." The protocol is young. The patterns it captures are not. Type-erased executors, stop-token cancellation, and per-chain frame allocation have been refined across years of networking library development. The protocol is small because it was distilled from experience, not because it is incomplete. What matters is whether the protocol is correct - and three deployed libraries across multiple platforms provide that evidence.

9.3 Decision Record

Each major design decision was forced by the bottom-up development process described above. This section consolidates the rationale, documents trade-offs, and states conditions for revisiting.

Two-argument `await_suspend(coroutine_handle<>, io_env const*)` (Section 3.1). The only signature that makes protocol violations a compile error. A non-compliant awaitable produces a compile-time failure when a compliant coroutine's `await_transform` calls the two-argument form. The alternative - templating on the promise type - compiles silently when mismatched and produces runtime errors. ***Trade-off:*** the signature is non-standard; existing awaitables must be adapted. ***Revisit if:*** the language gains a mechanism for statically verifying awaitable-promise compatibility without a custom `await_suspend` signature.

Thread-local frame allocator propagation (Sections 5.2-5.5). The only mechanism that respects `operator new` timing without polluting coroutine signatures with `allocator_arg_t`. The frame allocator must be available before the coroutine frame exists. Standard approaches (parameter threading, post-construction injection) arrive too late. ***Trade-off:*** relies on thread-local storage; introduces a non-obvious propagation path. ***Revisit if:*** the language gains a mechanism to inject allocator context into `operator new` without function parameters.

Type-erased `executor_ref` (Section 3.3). The only way to keep `task<T>` at one template parameter. Alternatives that preserve the executor type in the task type produce `task<T, Executor>`, which prevents separate compilation and ABI stability. The vtable cost is one pointer indirection - roughly 1-2 nanoseconds - negligible for I/O operations. ***Trade-off:*** type information is lost behind the erasure boundary. ***Revisit if:*** the overhead proves measurable relative to I/O latency in a validated benchmark.

`io_env` passed by pointer (Section 3.1). The launch function owns the `io_env`. Every coroutine in the chain borrows it. Pointer semantics make this ownership model explicit and make accidental copies difficult. ***Trade-off:*** nullable pointer; requires documentation of lifetime invariant. ***Revisit if:*** a reference-based alternative can enforce the same ownership semantics without adding a nullable state.

`execution_context` as a base class (Section 4.3). I/O objects need the platform reactor, not the executor. A socket registers with epoll, IOCP, or kqueue through the execution context, not through the executor. The executor is a lightweight handle; the context owns the reactor and its services. ***Trade-off:*** virtual `shutdown()` in the service base class; runtime polymorphism in the service registry. ***Revisit if:*** a compile-time service mechanism can provide the same ordered-shutdown guarantees.

9.4 Domain Coverage

The ***IoAwaitable*** protocol has been validated in the following I/O domains through deployed implementations:

Domain	Implementation	Platform coverage
TCP/UDP sockets	Corosio[6]	Linux (epoll, io_uring), Windows (IOCP), macOS (kqueue)
TLS	Corosio[6]	All supported platforms via OpenSSL
DNS resolution	Corosio[6]	All supported platforms
HTTP/1.1	Http[8]	All supported platforms
Timers	Corosio[6]	All supported platforms

Domains not yet validated:

- **Embedded/real-time** - thread-local storage may be unavailable or expensive; bounded-memory frame allocators need testing
- **File I/O** - completion patterns differ from socket I/O; the protocol should apply but has not been demonstrated
- **Database I/O** - query-response patterns differ from byte-stream I/O
- **Game engines** - custom job systems with different scheduling constraints
- **GPU compute** - explicitly deferred to sender/receiver; see P4007R0[1]

9.5 Post-Adoption Metrics

The following measurable criteria define successful adoption:

1. **Implementation breadth.** At least two major standard library implementations (libstdc++, libc++, or MSVC STL) ship a conforming ***IoAwaitable*** implementation within two releases of the standard that adopts it.
2. **Library adoption.** At least three independently developed I/O libraries adopt the ***IoAwaitable*** protocol within five years of standardization.

3. **Interoperability.** At least one demonstrated case of two independently developed libraries (e.g., an HTTP library and a database driver) composing through the protocol without glue code.
4. **Frame allocator robustness.** The thread-local frame allocator mechanism produces correct behavior on all three major platforms without platform-specific workarounds.
5. **Developer comprehension.** Developer surveys or conference feedback show that the two-call launch syntax and the TLS propagation mechanism are understood by a majority of C++ developers who use coroutines for I/O.

9.6 Retrospective Commitment

We commit to a retrospective at two standard releases or six years after standardization, whichever comes first. The retrospective must answer:

1. Did major implementations ship? If not, what blocked them?
2. Did independent libraries adopt the protocol? If not, what prevented interoperability?
3. Did the thread-local frame allocator mechanism prove robust across platforms?
4. Did the two-call launch syntax prove acceptable to users, or did workarounds proliferate?
5. Did the single template parameter on `task<T>` remain sufficient as the ecosystem grew?
6. Did the vtable overhead of `executor_ref` remain negligible relative to I/O latency?
7. What design limitations emerged in practice that were not anticipated?

9.7 Prediction Registry

#	Prediction	Criterion	Revisit
1	The ***IoAwaitable*** protocol is sufficient for all byte-oriented I/O domains	Implementation attempts in file I/O, database I/O, and IPC succeed without protocol extensions	+3 years
2	The thread-local frame allocator achieves within 10% of benchmarked performance on all platforms	Benchmark comparison on libstdc++, libc++, MSVC STL	+2 releases
3	The two-call launch syntax does not become a barrier to adoption	Developer survey shows >60% find it acceptable or transparent	+3 years
4	The vtable overhead of `executor_ref` remains below 5% of total I/O operation cost	Microbenchmark on representative workloads across platforms	+2 releases

#	Prediction	Criterion	Revisit
5	The single template parameter on `task<T>` remains sufficient for the ecosystem	No widely adopted library requires a second template parameter for environment or executor type	+5 years
6	At least three independent libraries adopt the protocol within five years	Count of libraries on vcpkg/Conan that declare ***IoAwaitable*** conformance	+5 years

---

10. Suggested Straw Polls

SG4 polled at Kona (November 2023) on P2762R2 "Sender/Receiver Interface For Networking"[9]:

> ***"Networking should support only a sender/receiver model for asynchronous operations; the Networking TS's executor model should be removed"***
>
> | *SF* | *F* | *N* | *A* | *SA* |
> |---|---|---|---|---|
> | *5* | *5* | *1* | *0* | *1* |
>
> *Consensus.*

The approach described in this paper - a coroutine-native I/O model using C++20 language features - was not among the alternatives considered.

Poll 1. A coroutine-native I/O model is a distinct approach from both the Networking TS executor model and the sender/receiver model.

Poll 2. New research into coroutine-native I/O, not available at the time of the Kona poll, warrants consideration.

---

11. Thoughts on Wording

> ***Non-normative note.*** *The wording below is not primarily intended for standardization. Its purpose is to demonstrate how a use-case-first design produces a lean specification footprint, and to show how compact an execution model becomes when designed specifically for I/O workloads.*

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

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

  // [ioawait.cont], struct continuation
  struct continuation;

  // [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 ExecutionContext = 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{};
  }
}
```

11.2 Struct `io_env` [ioawait.env]

```
namespace std {
  struct io_env {
    executor_ref executor;
    stop_token stop_token;
    pmr::memory_resource* frame_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 `frame_allocator` member, when non-null, identifies the memory resource used for coroutine frame allocation in the chain. A null value indicates that no frame allocator was specified at the launch site; the implementation is free to use any allocation strategy.

11.2a Struct `continuation` [ioawait.cont]

```
namespace std {
  struct continuation {
    coroutine_handle<> h;
    continuation* next_ = nullptr;
  };
}
```

1 The struct `continuation` is the schedulable unit in the executor interface. It pairs a coroutine handle with an intrusive linked-list pointer, allowing executors to queue continuations without per-post heap allocation.

2 A `continuation` is passed to `dispatch` and `post` by reference. The caller guarantees that the `continuation` object has a stable address and remains alive for the duration of the queue residency. [***Note:*** In coroutine code, this invariant is satisfied automatically. I/O awaitables embed a `continuation` and are alive for

the duration of the suspension. Combinator and trampoline state outlive the child coroutines they manage. ***- end note***]

3 Both members are public. The `h` member holds the coroutine handle to resume. The `next_` member is used by executor implementations for intrusive queue linkage.

11.3 Concepts [ioawait.concepts]

11.3.1 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***]

11.3.2 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.

expression	return type	assertion/note pre/post-conditions
`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 frame 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.
`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***]

11.3.3 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, continuation c) {
    { ce == ce2 } noexcept -> convertible_to<bool>;
    { ce.context() } noexcept -> see-below;
    { ce.on_work_started() } noexcept;
    { ce.on_work_finished() } noexcept;
    { ce.dispatch(c) } -> same_as<coroutine_handle<>>;
    { ce.post(c) };
  };
```

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 `c.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`, `c` denotes an lvalue of type `continuation`, 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`.
`x1.dispatch(c)`	`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 `c.h` directly. Otherwise, queues `c` for later execution via its intrusive `next_` pointer and returns `noop_coroutine()`. The caller must use the returned handle for symmetric transfer (e.g., return it from `await_suspend`). ***Preconditions:*** `c` has a stable address that remains valid until the continuation is dequeued and resumed. ***Synchronization:*** The invocation of `dispatch` synchronizes with the resumption of `c.h`.

expression	return type	assertion/note pre/post-conditions
`x1.post(c)`	`void`	***Effects:*** Queues `c` for later execution via its intrusive `next_` pointer. The executor shall not block forward progress of the caller pending resumption of `c.h`. The executor shall not resume `c.h` before the call to `post` returns. ***Preconditions:*** `c` has a stable address that remains valid until the continuation is dequeued and resumed. ***Synchronization:*** The invocation of `post` synchronizes with the resumption of `c.h`.

6 [***Note:*** Unlike the Networking TS executor requirements, this concept operates on `continuation&` rather than arbitrary function objects. The `continuation` struct embeds an intrusive list pointer, enabling executors to queue work without per-post heap allocation. 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 `c.h` directly; otherwise it queues the continuation and returns `noop_coroutine()`. ***- end note***]

7 [***Note:*** When an execution context's event loop dequeues a `coroutine_handle<>` for resumption, it should save the thread-local frame allocator before calling `h.resume()` and restore it afterward. This ensures that a resumed coroutine cannot spoil the frame allocator of the coroutine that was executing on the same thread before the event loop iteration. A convenience function `safe_resume` encapsulates this protocol (Section 5.4). Failure to save and restore does not cause memory corruption - `operator delete` reads the frame allocator from the frame footer - but can cause frames to be allocated from the wrong memory resource. ***- end note***]

11.3.4 Concept `ExecutionContext` [ioawait.concepts.execctx]

```
template<class X>
concept ExecutionContext =
  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 `ExecutionContext` 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 - ExecutionContext 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***]

11.4 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(continuation& c) const;
    void post(continuation& c) 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***]

11.4.1 `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***]

11.4.2 `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`.

11.4.3 `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(continuation& c) const;
```

7 ***Preconditions:*** `bool(*this) == true` . `c.h` is a valid, suspended coroutine handle. `c` has a stable address that remains valid until the continuation is dequeued and resumed.

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

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

```
void post(continuation& c) const;
```

10 ***Preconditions:*** `bool(*this) == true` . `c.h` is a valid, suspended coroutine handle. `c` has a stable address that remains valid until the continuation is dequeued and resumed.

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

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

11.4.4 `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.

11.5 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.

11.5.1 `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()` .

11.5.2 `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.

11.5.3 `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()`.

11.5.4 `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 frame allocator for coroutine frames. ***- end note***]

2 ***Remarks:*** This function provides the default frame allocator for coroutine frames launched with executors from this context when no frame 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 frame allocator parameter entirely, and programs should still behave correctly. The frame 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 frame allocation strategy being used. ***- end note***]

11.5.5 `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`.

11.5.6 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.

11.6 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.

11.6.1 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 frame allocator specified in `Args`, or to `ex.context().get_frame_allocator()` if no frame allocator is specified.
- (2.2) Evaluates `task` (which allocates the coroutine frame using the thread-local frame 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 frame 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.
- A frame 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 frame 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 frame 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***]

11.6.2 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 frame allocator specified in `Args` , or inherits the caller's frame allocator if none is specified.
- (2.2) Evaluates `task` (which allocates the coroutine frame using the thread-local frame 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.
- A frame 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]

11.7 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.

11.7.1 `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***]

11.8 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 continuation's 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***]

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 (true) {
        auto [ec, n] = client.read_some(buf);
        if (ec) break;
        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 does not. 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[4] - handling 10,000 concurrent connections - revealed that thread-per-connection does not 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:

```cpp
// 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:

```cpp
// 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 will not 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.

If you are eager to experiment, the Corosio[6] 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[3] 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[5] 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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