CONTEMPORARY C++ IN ACTION

Daniela Engert - Meeting C++ 2022

Outline

- Prologue
- Motivation
- The Experiment
- Demo
- My Conclusion
- Epilogue

ABOUT ME

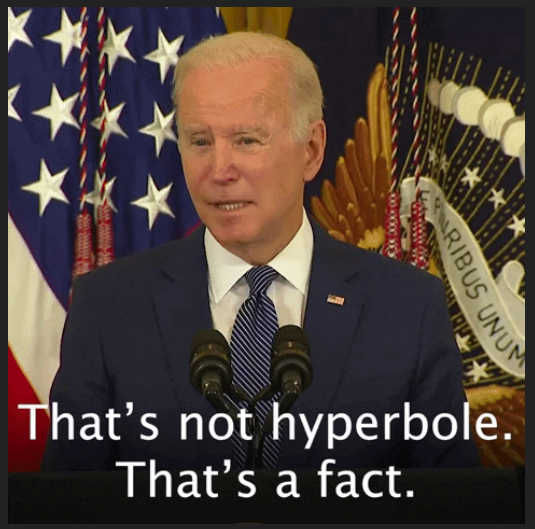
- Electrical engineer
- Build computers and create software for 40 years
- Develop hardware and software in the field of applied digital signal processing for 30 years
- Member of the C++ committee (learning novice) for 3 years (EWG, SG15)

- employed by 

Motivation

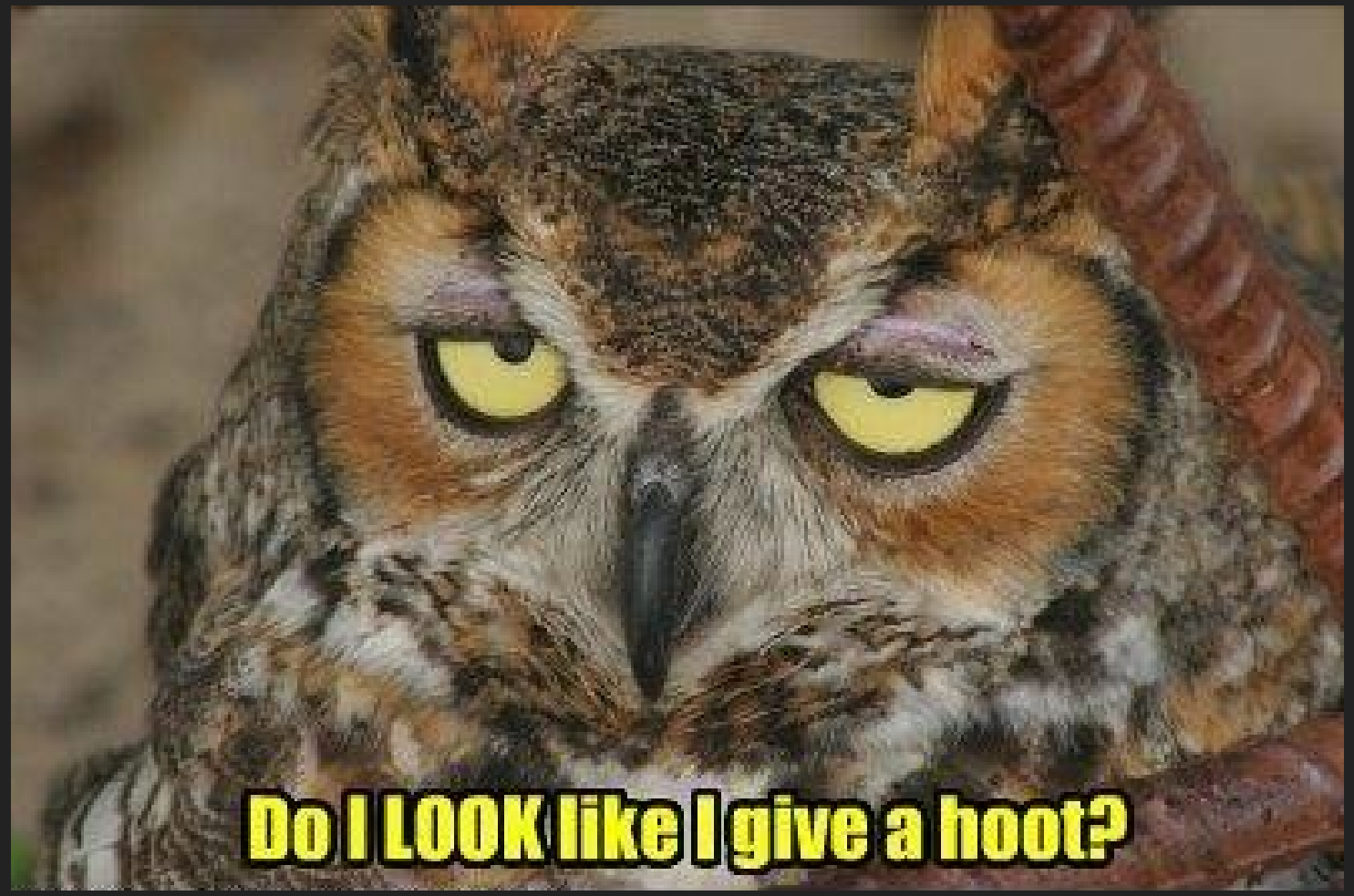
THIS IS AN EXPERIMENT

Whenever I encounter C++ in any media, there are at least some people very vocal about the "facts":



- C++ is dead!
- The committee cares only about nerds
- The committee cares only about library writers
- The committee is too slow and doesn't deliver
- The committee is too fast and delivers half-baked junk
- The committee is a bureaucratic bunch of troglodytes detached from reality
- C++ 03 is all you need. Everything beyond that is just syntactic sugar

IS THIS REALLY TRUE?



THE REALITY CHECK

To disadvantage myself as much as possible I committed myself on writing an application from scratch and implement something non-trivial using as many

- core language features
- standard library features
- 3rd-party libraries

that I've never used before (or failed at doing so). This includes

- C++23, coroutines, concepts, infinite ranges

Using the results of older, pre-2020 WG21 work is ok.

The objective: make them work together as smoothly as possible.

HENCE THE TITLE OF MY TALK

Contemporary C++ in Action

CONTEMPORARY C++ !

C++23 and

C++20 and

C++17 and

C++14 and

C++11

IN ACTION ?

I'm an engineer, and the demo application should contain all the engineery stuff that I deal with every day:

- data collection
- data processing
- data visualization
- near realtime networking
- library usage
- library creation
- interface design

The Experiment

Specification

Demo Code

THE SPECIFICATION

The server

- waits for clients to connect at any of a list of given endpoints
- when a client connects, observes a given directory for all files in there, repeats endlessly
- filters all GIF files which contain a video
- decodes each video into individual video frames
- sends each frame at the correct time to the client
- sends filler frames if there happen to be no GIF files to process

The client

- tries to connect to any of a list of given server endpoints
- receives video frames from the network connection
- presents the video frames in a reasonable manner in a GUI window

The application

- performs a clean shutdown from all inputs that the user can interact with
- handles timeouts and errors properly and performs a clean shutdown

DISCLAIMER

The following code

- contains significant amounts of C++23
- totally relies on C++20
- is following the  style

Allergy warning!

- There may be traces of compile-time programming
- Names are 🐫🐫cased and composed without underlines

CONVENTIONS

Where necessary, assume these *using directives* and *namespace alias definitions* to be present in the nearest surrounding scope.

```
using namespace std::chrono_literals;
using namespace std::string_view_literals;

namespace fs  = std::filesystem;
namespace rgs = std::ranges;
namespace vws = rgs::views;
```

- 'things' start with a capital letter
- 'things' of type kind (in particular *type aliases*) are prefixed with a lower-case 't'
- NSDM 'things' are postfixed with an underscore '_'
- predicate queries start with a lower-case letter
- actions start with a lower-case letter

THE LIBRARIES

Asio (https://think-async.com)

Semi-standardized, implements the 'Networking TS' (ISO/IEC TS 19216:2018)

provides asynchronous networking functions & an asynchronous execution framework

libav (https://ffmpeg.org)

Very popular open-source library to process virtually all media formats

SDL (https://www.libsdl.org)

A open-source library to handle multimedia I/O and minimal windowing, excels in simplicity

Two functions from the *in-house* codebase

- conversion from std::path to UTF-8 encoded narrow strings (not implementation-defined)
- command line options parser

C-LIBRARIES

libav and SDL are C libraries with heap-allocated objects and may therefore lead to

- manual memory management
- indeterminate responsibilites
- potential memory leaks
- potential memory retention
- accidental copying
- accidental sharing

So, instead of make them

```
// libav
AVCodecContext * pCodec;
avcodec_alloc_context3(&pCodec, ...);
avcodec_free_context(&pCodec);
```

```
// SDL
SDL_Window * pWindow = SDL_CreateWindow(...);
SDL_DestroyWindow(pWindow);
```

Value Types!

C_RESOURCE WRAPPER

Wrap these C objects to get proper C++ objects with

- constructors, destructors → well-defined lifetime
- uniqueness → no sharing, copying is prohibited
- constness → integrity
- independence → easy reasoning
- composability → create higher level abstractions

```
namespace libav {
using Codec =
    stdex::c_resource<AVCodecContext, avcodec_alloc_context3, avcodec_free_context>;
}
namespace sdl {
using Window = stdex::c_resource<SDL_Window, SDL_CreateWindow, SDL_DestroyWindow>;
}

void f() {
    libav::Codec MyCodec(...);
    sdl::Window  MyWindow(...);
}
```

VIDEO

```
// video frame generator
// wrap the libav (a.k.a. FFmpeg https://ffmpeg.org/) C API types and their
// assorted functions

namespace libav {
using Codec =
    stdex::c_resource<AVCodecContext, avcodec_alloc_context3, avcodec_free_context>;
using File =
    stdex::c_resource<AVFormatContext, avformat_open_input, avformat_close_input>;
using tFrame  = stdex::c_resource<AVFrame, av_frame_alloc, av_frame_free>;
using tPacket = stdex::c_resource<AVPacket, av_packet_alloc, av_packet_free>;

// frames and packets are reference-counted and always constructed non-empty
struct Frame : tFrame {
    [[nodiscard]] Frame() : tFrame(constructed){};
    [[nodiscard]] auto dropReference() { return Frame::guard<av_frame_unref>(*this); }
};
struct Packet : tPacket {
    [[nodiscard]] Packet() : tPacket(constructed){};
    [[nodiscard]] auto dropReference() { return Packet::guard<av_packet_unref>(*this); }
};
} // namespace libav
```

NETWORK - COMPOSED OPERATIONS

example: read with timeout

```
1  Thing {
2    socket S
3    timer T
4
5    timed_read(...)
6    callback_socket(...)
7    callback_timer(...)
8    return_result(...)
9    give_up()
10 }
```

Requirements:

- Things must live long enough, at least until all asynchronous operations have run to completion and the result is announced to the caller of timed_read.
- The ownership of Things must necessarily be shared between all asynchronous operations and the caller.
- Some mechanism must allow for cancellation even when no execution agent is acting on behalf of either operation.

NETWORK - COMPOSED OPERATIONS

Callbacks with individual parameters

```
async_read(socket, data,     Callable(      error_code, size_t ));

timer::async_wait(      Callable(     error_code ));

// composition by (distributed) state-machine
```

```
async_read(S, data, [self](      error_code, size_t  result) {});

T.async_wait([self](      error_code  result) {});
```

NETWORK - COMPOSED OPERATIONS

Callbacks with packed parameters

```
async_read(socket, data,     Callable(tuple<error_code, size_t>));

timer::async_wait(      Callable(tuple<error_code>));

// composition by (distributed) state-machine
```

```
async_read(S, data, [self](tuple<error_code, size_t> result) {});

T.async_wait([self](tuple<error_code> result) {});
```

NETWORK - COMPOSED OPERATIONS

Return awaitables with packed parameters

```
async_read(socket, data) -> awaitable<tuple<error_code, size_t>>;

timer::async_wait() -> awaitable<tuple<error_code>>;

// composition t.b.d.
```

```
auto [error, transferred] = co_await async_read(S, data);

auto [error] = co_await T.async_wait();
```

NETWORK - COMPOSED OPERATIONS

Compose awaitables with automatic mutual cancellation

```
async_read(socket, data) -> awaitable<tuple1>;

timer::async_wait() -> awaitable<tuple2>;

operator||(awaitable<tuple1>, awaitable<tuple2>)
    -> awaitable<variant<tuple1, tuple2>>;
```

```
auto result = co_await (async_read(S, data) || T.async_wait());
```

NETWORK - COMPOSED OPERATIONS

```
Thing : enable_shared_from_this {
  socket S;
  timer T;
  some data;
  Callable callback;

  ... // more
  void timed_read(Callable);
  void callback_socket(...);
  void callback_timer(...);
  void return_result(...);
  void giveup()
};

// implementation here ...

// on the call site:
// create a shareable Thing
// think about lifetimes
// do something with result
```

```
auto timed_read(socket & S, timer & T, some & data) {
   return async_read(S, data) || T.async_wait();
}


auto f() {
    socket S;
    timer T;
    some data;

    T.expires_after(...);
    auto result = co_await timed_read(S, T, data);
    // do something with result
}
```

NETWORK - COMPOSED OPERATIONS

Chris Kohlhoff (creator of Asio):

this is

why ***C++20*** is the ***awesomest*** language for network programming

NETWORK - COMPOSED OPERATIONS

Flatten the composed result

```
async_read(socket, data) -> awaitable<tuple<error_code, size_t>>;

timer::async_wait() -> awaitable<tuple<error_code>>;

auto operator||(awaitable<tuple1>, awaitable<tuple2>)    // plus
flatten(variant<tuple1, tuple2>) -> expected<size_t, error_code>;
```

```
auto result =
    expect(co_await (async_read(S, data) || T.async_wait()));
```

NETWORK - COMPOSED OPERATIONS

me:

this is

why ***C++23*** is the ***even more awesomest*** language for network programming!

NETWORK

```
// Convenience types and functions to deal with the networking part of the
// Asio library https://think-async.com/Asio/

// The Asio library is also the reference implementation of the
// Networking TS (ISO/IEC TS 19216:2018, C++ Extensions for Library Fundamentals)
// Draft https://www.open-std.org/jtc1/sc22/wg21/docs/papers/2018/n4771.pdf
// plus P0958, P1322, P1943, P2444
// plus executors as decribed in P0443, P1348, and P1393

namespace aex = asio::experimental;
namespace net {

// basic networking types

// customize the regular Asio types and functions such that they can be
//  - conveniently used in await expressions
//  - composed into higher level, augmented operations

template <typename... Ts>
using tResult   = std::tuple<std::error_code, Ts...>;
using use_await = asio::as_tuple_t<asio::use_awaitable_t<>>;
using tSocket   = use_await::as_default_on_t<asio::ip::tcp::socket>;
using tAcceptor = use_await::as_default_on_t<asio::ip::tcp::acceptor>;
```

EXECUTORS

~~I will not talk~~

~~about executors~~

EXECUTION CONTEXTS

Asio provides this higher-level abstraction on top of executors as the primary interface for client code.

I will not talk about these.

Except for one feature:

User-definable services that can augment the ones provided by Asio

I add a "StopService" that gives access to a std::stop_source.

This makes the extended asio::io_service similar to a std::jthread.

And allows remote-controlled termination of asynchronous operations.

EXECUTOR

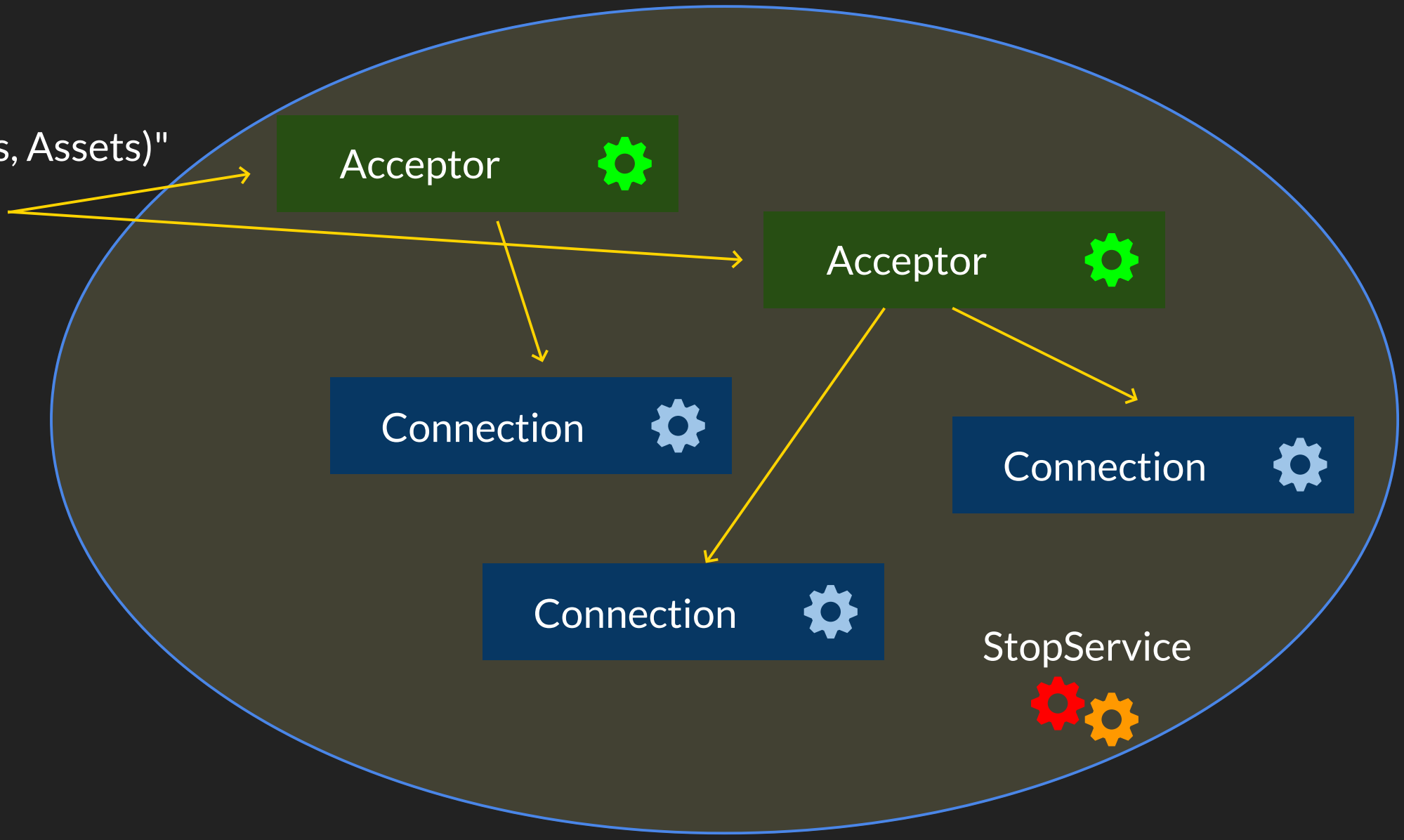
```
// Convenience types and functions to deal with the executor part of the
// Asio library https://think-async.com/Asio/

// The Asio library is also the reference implementation of the
// Networking TS (ISO/IEC TS 19216:2018, C++ Extensions for Library Fundamentals)
// Draft https://www.open-std.org/jtc1/sc22/wg21/docs/papers/2018/n4771.pdf
// plus P0958, P1322, P1943, P2444
// plus executors as decribed in P0443, P1348, and P1393

namespace executor {
template <typename T>
constexpr inline bool Unfortunate = false;

// an Asio service that holds an 'std::stop_source'.
// each service is unique in every instance of execution contexts!

using ServiceBase = asio::execution_context::service;
struct StopService : ServiceBase {
    using key_type = StopService;

    static asio::io_context::id id;

    using ServiceBase::ServiceBase;
```

SERVER

```
static constexpr auto SendTimeBudget = 100ms;

// start serving a list of given endpoints.
// each endpoint is served by an independent coroutine.

auto serve(asio::io_context & Context, net::tEndpoints Endpoints, const fs::path Source)
    -> net::tExpectSize {
    std::size_t NumberOfAcceptors = 0;
    auto Error = std::make_error_code(std::errc::function_not_supported);

    for (const auto & Endpoint : Endpoints) {
        try {
            executor::commission(Context, acceptConnections,
                                 net::tAcceptor{ Context, Endpoint }, Source);
            std::println("accept connections at {}", Endpoint.address().to_string());
            ++NumberOfAcceptors;
        } catch (const std::system_error & Ex) {
            Error = Ex.code();
        }
    }
    if (NumberOfAcceptors == 0)
        return std::unexpected{ Error };
    return NumberOfAcceptors;
```

SERVER - INDEPENDENT AGENTS ('ACTORS')

schedule
"serve(Endpoints, Assets)"
on IO context



CLIENT

```
static constexpr auto ReceiveTimeBudget = 2s;
static constexpr auto ConnectTimeBudget = 2s;

// connects to the server and starts the top-level video receive-render-present loop.
// initiates an application stop in case of communication problems.

[[nodiscard]] auto showVideos(asio::io_context & Context, gui::FancyWindow Window,
                              net::tEndpoints Endpoints) -> asio::awaitable<void> {
    net::tTimer Timer(Context);
    Timer.expires_after(ConnectTimeBudget);
    if (net::tExpectSocket Socket = co_await net::connectTo(Endpoints, Timer)) {
        co_await rollVideos(std::move(Socket).value(), std::move(Timer),
                            std::move(Window));
    }
    executor::StopAssetOf(Context).request_stop();
}

// present a possibly infinite sequence of video frames until the spectator
// gets bored or problems arise.

[[nodiscard]] auto rollVideos(net::tSocket Socket, net::tTimer Timer,
                              gui::FancyWindow Window) -> asio::awaitable<void> {
    const auto WatchDog = executor::abort(Socket, Timer);
```

GUI

```
// wrap the SDL (Simple Directmedia Layer https://www.libsdl.org/) C API types
// and their assorted functions

namespace sdl {
using Window   = stdex::c_resource<SDL_Window, SDL_CreateWindow, SDL_DestroyWindow>;
using Renderer = stdex::c_resource<SDL_Renderer, SDL_CreateRenderer, SDL_DestroyRenderer>;
using Texture  = stdex::c_resource<SDL_Texture, SDL_CreateTexture, SDL_DestroyTexture>;
} // namespace sdl

namespace gui {
struct tDimensions {
    uint16_t Width;
    uint16_t Height;
};

// the most minimal GUI
// capable of showing a frame with some decor for user interaction
// renders the video frames
struct FancyWindow {
    explicit FancyWindow(tDimensions) noexcept;

    void updateFrom(const video::FrameHeader &) noexcept;
    void present(video::tPixels) noexcept;
```

USER INTERACTION

```
namespace handleEvents {
static constexpr auto EventPollInterval = 50ms;

// watch out for an interrupt signal (e.g. from the command line).
// initiate an application stop in that case.

[[nodiscard]] auto fromTerminal(asio::io_context & Context) -> asio::awaitable<void> {
    asio::signal_set Signals(Context, SIGINT, SIGTERM);
    const auto WatchDog = executor::abort(Signals);

    co_await Signals.async_wait(asio::use_awaitable);
    executor::StopAssetOf(Context).request_stop();
}

// the GUI interaction is a separate coroutine.
// initiate an application stop if the spectator closes the window.

[[nodiscard]] auto fromGUI(asio::io_context & Context) -> asio::awaitable<void> {
    net::tTimer Timer(Context);
    const auto WatchDog = executor::abort(Timer);

    do {
        Timer.expires_after(EventPollInterval);
```

MAIN

```
static constexpr auto ServerPort        = net::Port{ 34567 };
static constexpr auto ResolveTimeBudget = 1s;

int main() {
    auto [MediaDirectory, ServerName] = caboodle::getOptions();
    if (MediaDirectory.empty())
        return -2;
    const auto ServerEndpoints =
        net::resolveHostEndpoints(ServerName, ServerPort, ResolveTimeBudget);
    if (ServerEndpoints.empty())
        return -3;

    asio::io_context ExecutionContext; // we have executors at home
    std::stop_source Stop;             // the mother of all stops
    const auto schedule = executor::makeScheduler(ExecutionContext, Stop);

    const auto Listening =
        schedule(server::serve, ServerEndpoints, std::move(MediaDirectory));
    if (not Listening)
        return -4;

    schedule(client::showVideos, gui::FancyWindow({ .Width = 1280, .Height = 1024 }),
        ServerEndpoints);
```

APPLICATION - ALL 'ACTORS'

schedule

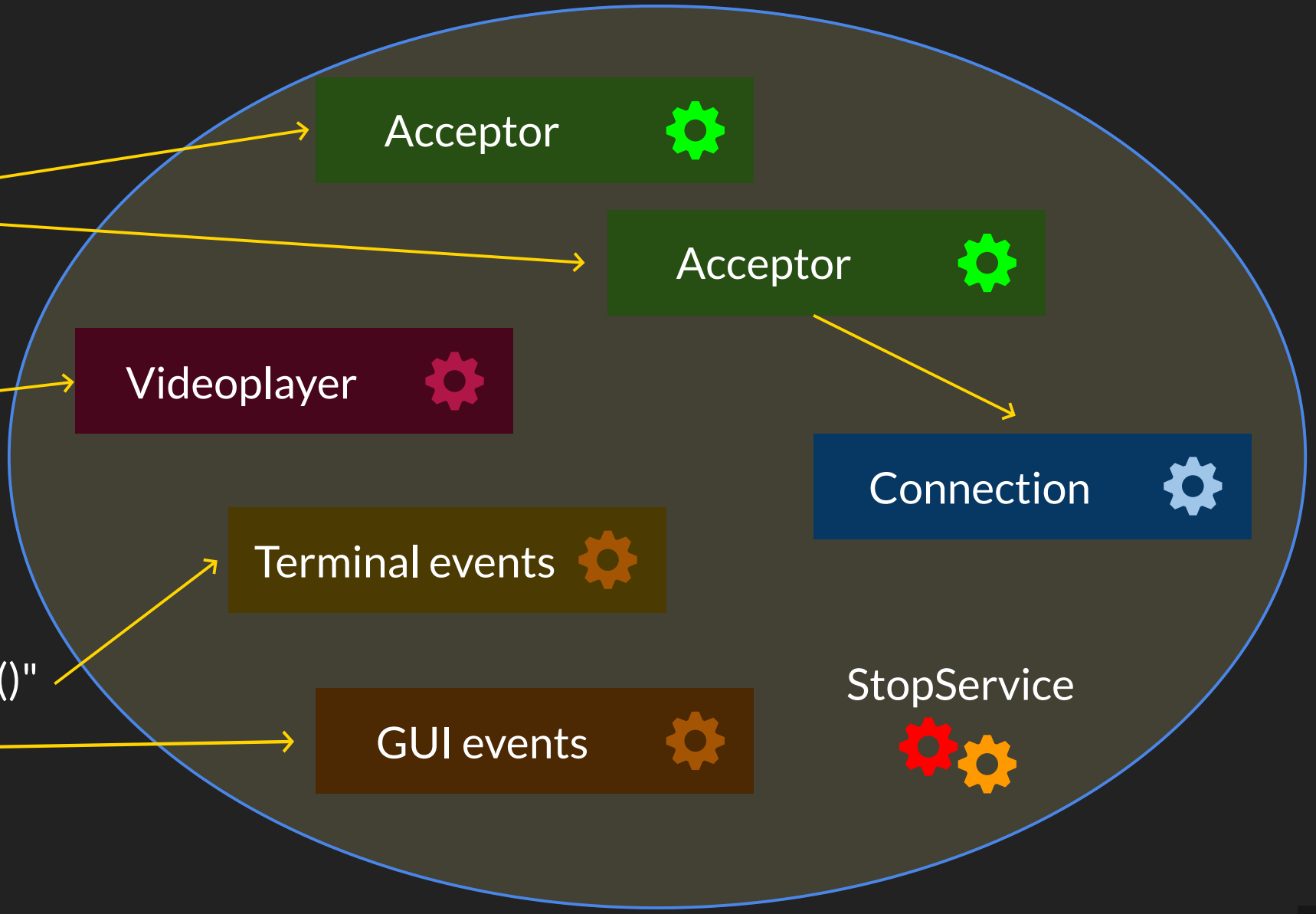
"server::serve(...)"

"client::showVideos(...)"

"handleEvents::fromTerminal()"

"handleEvents::fromGUI()"

on the IO context



std::generator

std::expected

std::println

std::stop_source

std::stop_token

std::stop_callback

std::span

ranges

views

concepts

requires-expressions

coroutines

structured bindings

fold expressions

compile-time decisions

compile-time functions

compile-time reflection

value types

strong types

compiler-generated closure types

compiler-generated state-machines

one more compositional aspect

source code composition

MAIN (AGAIN)

```
/* ================================================================================
The server

 - waits for clients to connect at anyone of a list of given endpoints
 - when a client connects, observes a given directory for all files in there,
   repeating this endlessly
 - filters all GIF files which contain a video
 - decodes each video file into individual video frames
 - sends each frame at the correct time to the client
 - sends filler frames if there happen to be no GIF files to process

The client

 - tries to connect to anyone of a list of given server endpoints
 - receives video frames from the network connection
 - presents the video frames in a reasonable manner in a GUI window

The application

 - watches all inputs that the user can interact with for the desire to end
   the application
 - handles timeouts and errors properly and performs a clean shutdown if needed
================================================================================*/
```

MODULE STRUCTURE

Besides the main translation unit 'main.cpp', there are

compiled in project:

- 8 named modules:
  - executor
  - gui
  - net
  - the.whole.caboodle
  - video

  - client
  - server
  - events

- 1 cross-project header unit
  - c_resource

precompiled and cached:

- 4 named modules from external libraries:
  - asio
  - boost.program_options
  - libav
  - sdl

- the modularized C++23 standard library
  - compiled from msvc open-source
  - + std::generator
  - + std::print
  - + std::start_lifetime_as

MODULE TU TYPES & FEATURES

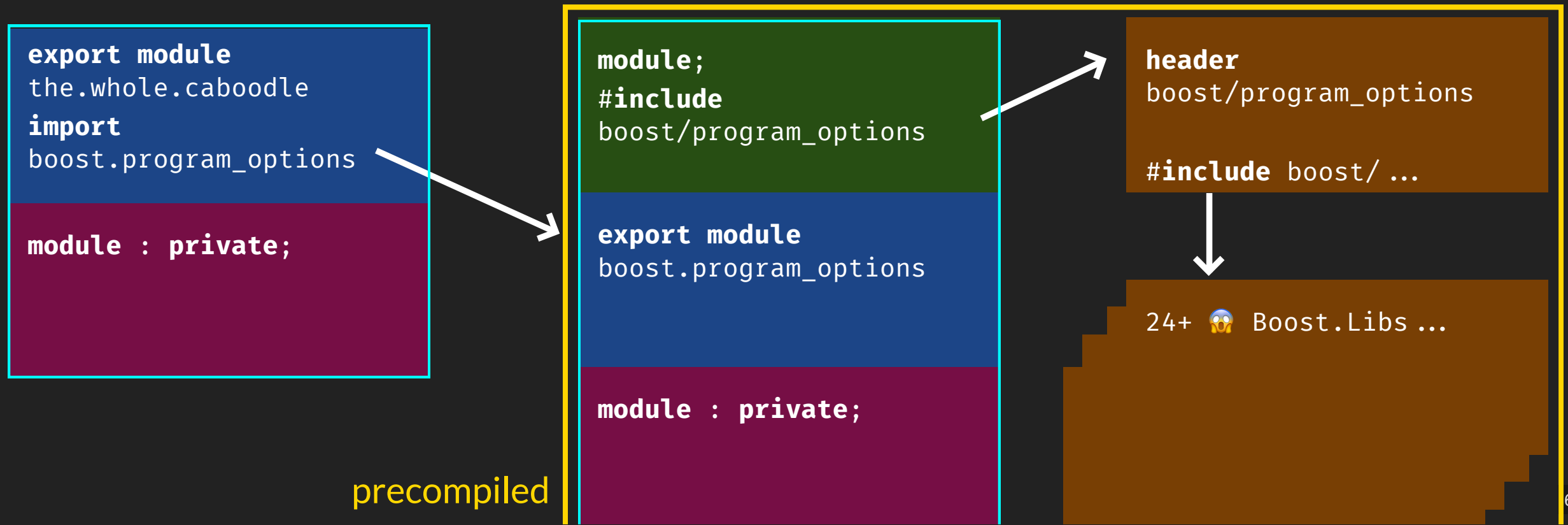
	Defines interface	contributes to interface	implicitly imports interface	part of module purview	part of global module	exports MACROs	creates BMI	contributes to BMI	fully isolated
Interface unit	✅	✅		✅	❌		✅	✅	✅
Implementation unit			✅	✅	❌				✅
Interface partition		✅		✅	❌		✅	✅	✅
Internal partition				✅	❌		✅	❌	✅
Private module fragment				✅					✅
Header unit	✅	✅			✅	✅	✅	✅	

✅ unconditionally ❌ if a GMF exists in the TU / if TU's BMI is imported into the primary module interface

MODULE THE.WHOLE.CABOODLE

Consists of only the primary module interface unit (PMIU)

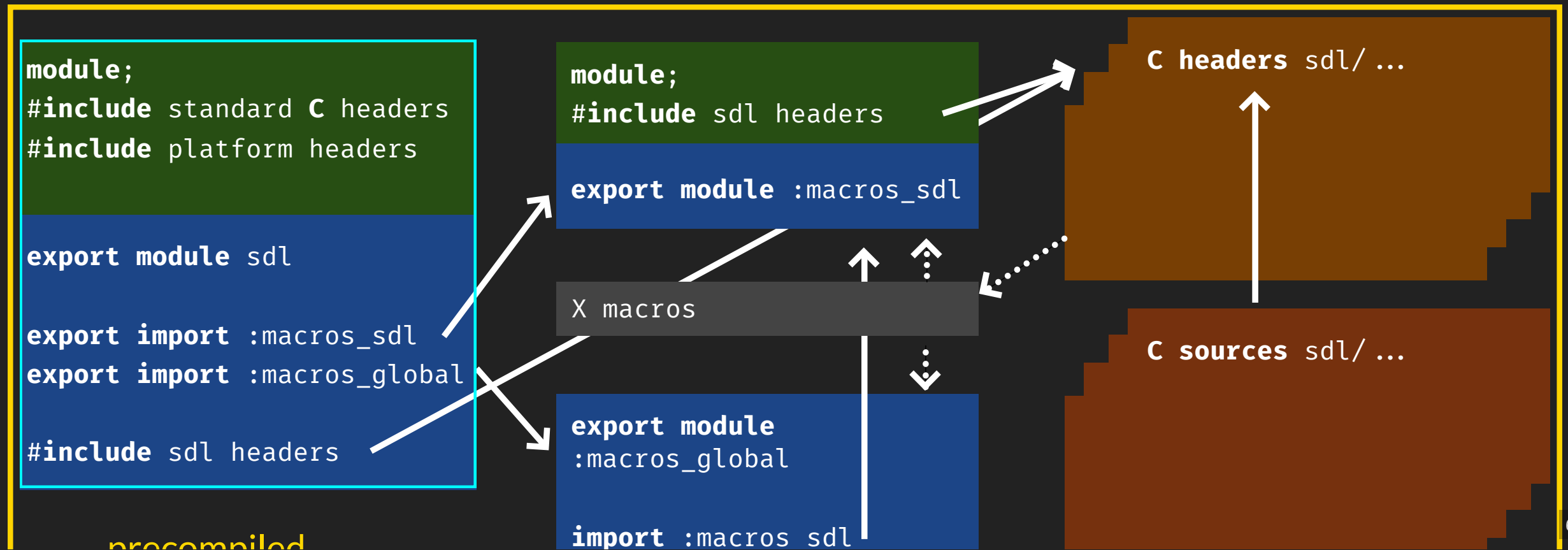
- exports 2 function declarations
- the full implementation is in the private module fragment (PMF)
- imports module boost.program_options



MODULE SDL

A multi-part module compiled as a static library that contains

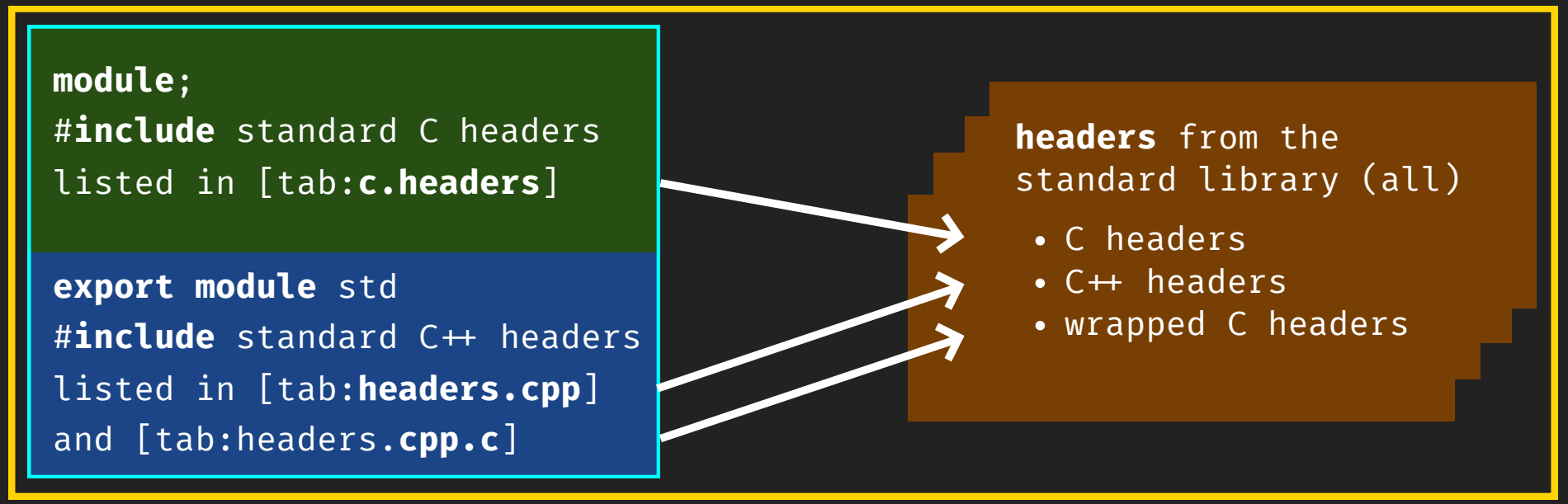
- a global module fragment with all headers that must not be attached to the module
- the module purview with all exported interfaces
- the implementation, compiled separately with C semantics



MODULE STD

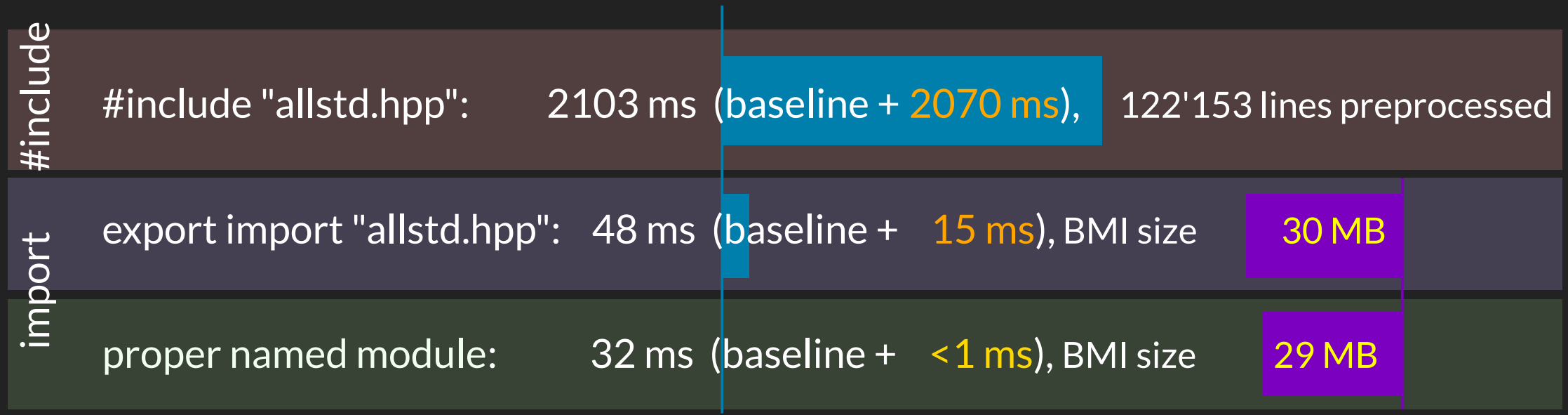
A single-file module compiled as a static lib that contains

- a global module fragment with all headers that must not be attached to the module
- the module purview with all exported interfaces



STANDARD LIBRARY USAGE SCENARIOS

```
#include "allstd.hpp"   // make the complete API of the
import std;             // C++ standard library visible

int main {}             // but don't use it
```



DEMO CODE TIME

My Conclusion

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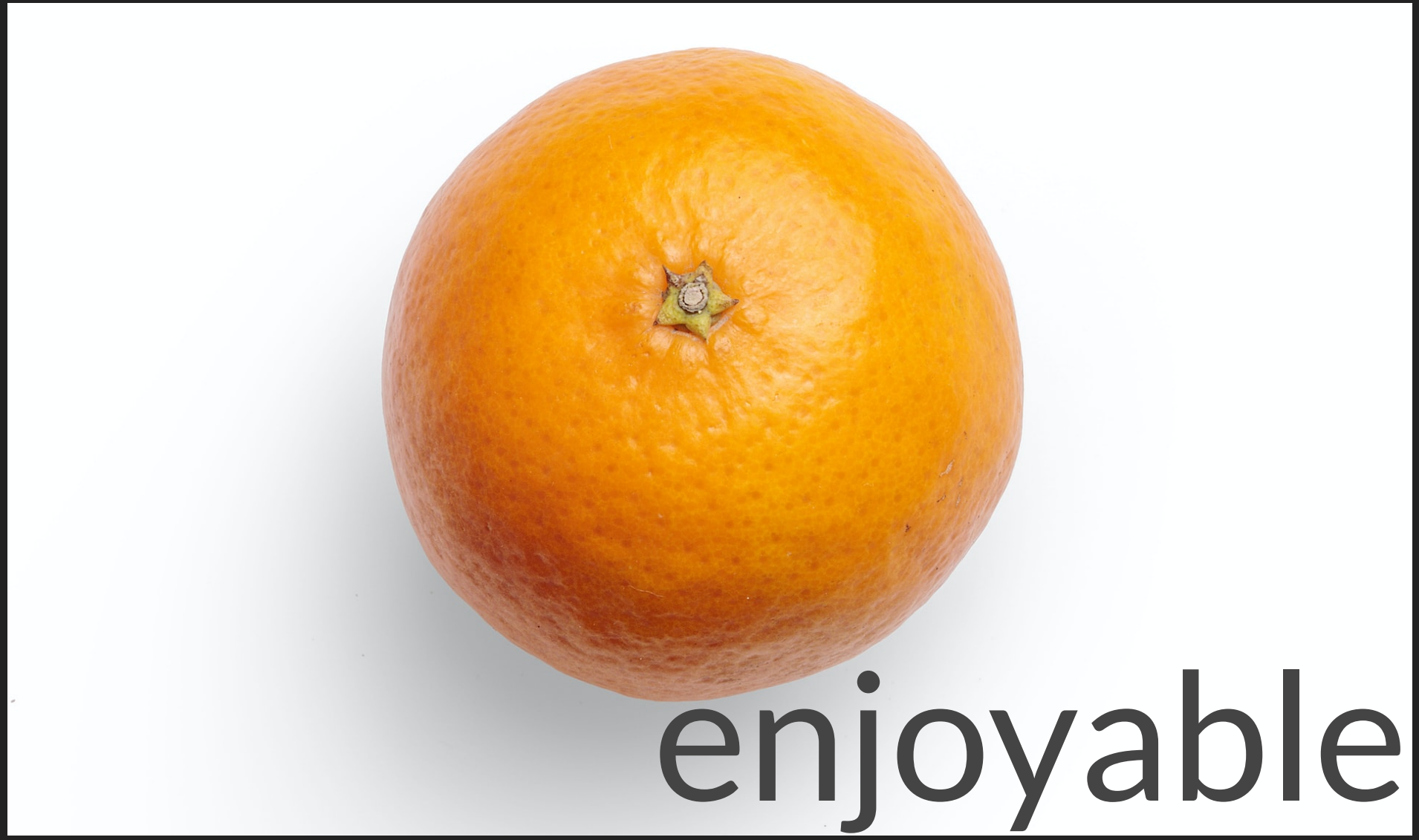

Epilogue

RESOURCES

- Talking Async Ep1: Why C++20 is the Awesomest Language for Network Programming
- Talking Async Ep2: Cancellation in depth
- Demo code github.com/DanielaE/CppInAction
- Asio module github.com/DanielaE/asio/tree/module
- SDL module github.com/DanielaE/SDL/tree/module
- augmented open source Microsoft STL github.com/DanielaE/STL/tree/my-stl

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