So, You Want to Use C++ Modules... Cross-Platform?

Daniela Engert

Outline

- Modules Recap
- Compilers
- Modularization
- Build Systems
- Module Dependencies
- Demo
- Conclusion

ABOUT ME

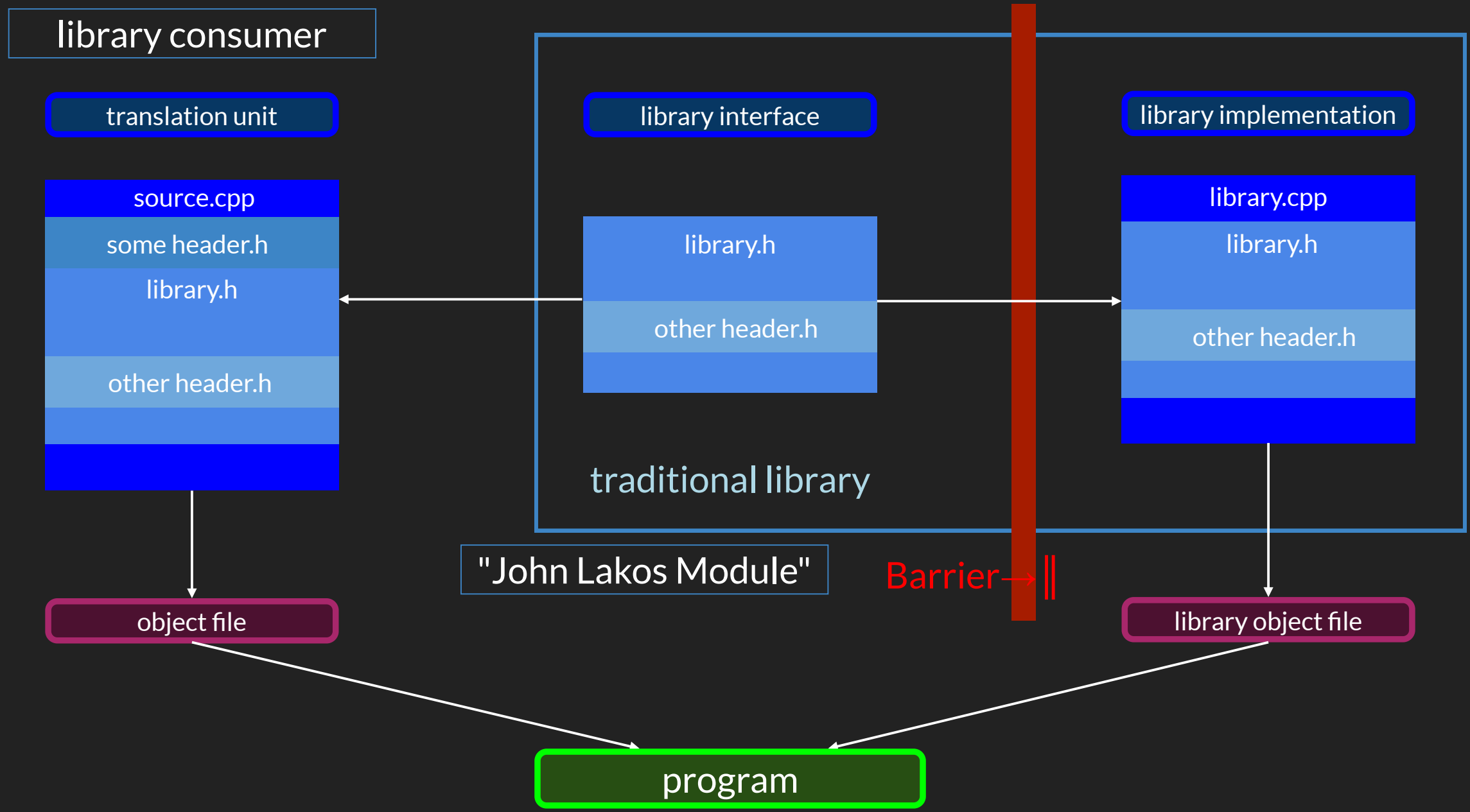
- Electrical engineer
- Build computers and create software for 40 years
- Develop hardware and software in the field of applied digital signal processing for 30 years
- Member of the C++ committee (learning novice) for 3 years (EWG, SG15)

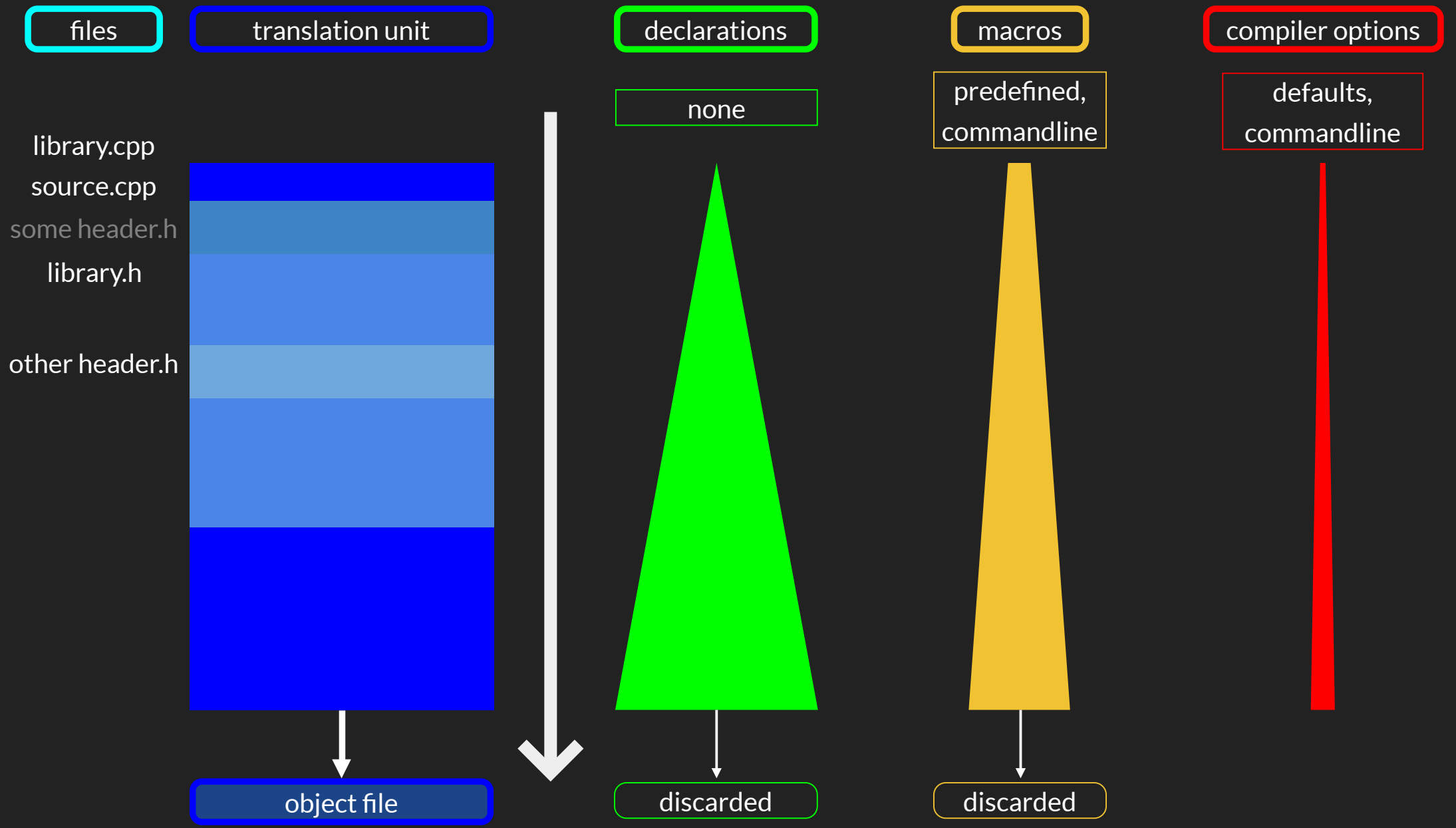
- employed by 

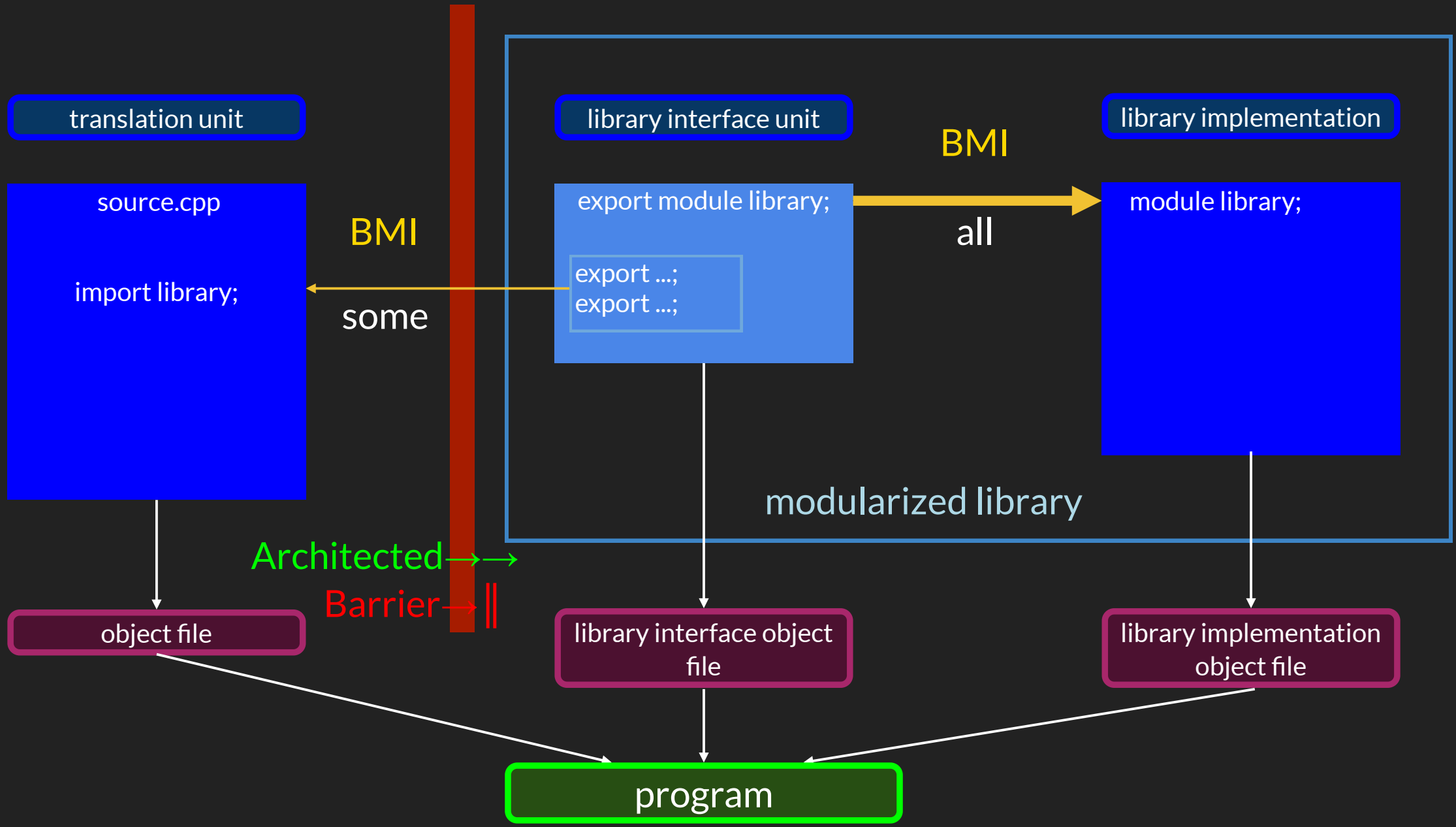
A recap of Modules

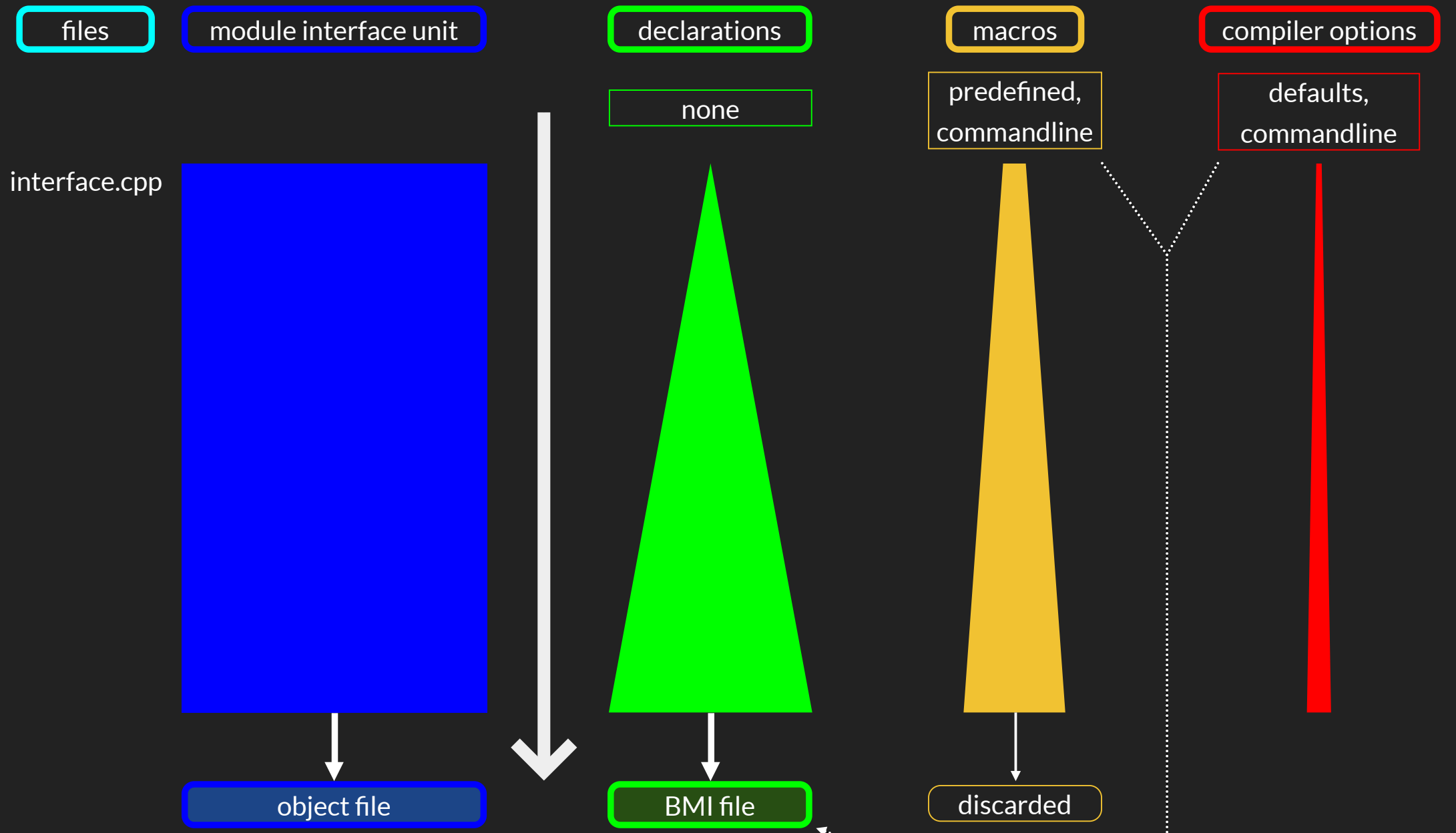
or

The shortest introduction to modules ever


library consumer
translation unit
source.cpp
some header.h
library.h
other header.h
library interface
library.h
other header.h
library implementation
library.cpp
library.h
other header.h
traditional library
"John Lakos Module"
Barrier
object file
library object file
program


files
translation unit
declarations
macros
compiler options
none
predefined, commandline
defaults, commandline
library.cpp
source.cpp
some header.h
library.h
other header.h
object file
discarded
discarded


translation unit
library interface unit
library implementation
BMI
source.cpp
import library;
BMI
some
export module library;
export ...;
export ...;
BMI
all
module library;
modularized library
Architected
Barrier
object file
library interface object file
library implementation object file
program


files
module interface unit
declarations
macros
compiler options
none
predefined, commandline
defaults, commandline
interface.cpp
object file
BMI file
discarded

(primary) module interface unit

global module fragment

- no declarations
- only preprocessor directives

```
1  module;
2
3  #include <vector>
4
5  export module my.first_module;
6
7  export import other.module;
8  #include "mod.h"
9  constexpr int beast = 666;
10
11 export std::vector<int> frob(S);
```

standard library

platform library, etc.

```
1  // mod.h
2  #pragma once;
3
4  struct S {
5    int value = 1;
6  }
```

exported

"exportedness" applies to names

The name of this module can be referred to only in

- module declaration
- import declaration

module implementation unit

module declaration without a name

```
1  module;
2
3  #include <vector>
4
5  module my.first_module;
6
7  std::vector<int> frob(S s) {
8    return {s.value + beast};
9  }
```

module purview

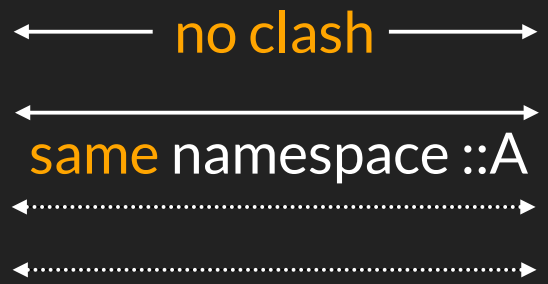
global module fragment

default name 'domain'

- not a namespace
- separate name 'domain'

NAME ISOLATION

```
export module mod1;

int foo(); // module linkage

export namespace A { // external l.

int bar() { // external linkage
  return foo();
}

} // namespace A
```




```
export module mod2;

int foo(); // module linkage

namespace A { // external link.

export int baz() { // external link
  return foo();
}

} // namespace A
```

name '::foo' is attached to module 'mod1', i.e. '::foo@mod1',

exported name '::A::bar' is also attached to the module

```
import mod1;
import mod2;

using namespace A;

int main(){
  return bar() + baz();
}
```

name '::foo' is attached to module 'mod2', i.e. '::foo@mod2',

exported name '::A::baz' is also attached to the module

namespace name '::A' is attached to the global module, as it is oblivious of module boundaries

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 PMIF	fully isolated
Primary Module Interface	✅	✅		✅	🟡	❌	✅	✅	✅
Mod. Implementation unit	❌	❌	✅	✅	🟡	❌	❌	❌	✅
Interface partition	❌	✅	❌	✅	🟡	❌	✅	✅	✅ !
Internal partition	❌	❌	❌	✅	🟡	❌	✅	🔶	✅ ⚠️
Private module fragment		❌		✅		❌		❌	✅
Header unit	✅	✅		❌	✅	✅	✅	❌	❌ !!‍🕳️

✅ unconditionally 🟡 if a GMF exists in the TU 🔶 if TU's BMI is (transitively) imported into the PMIF

Compilers


REGE AM:- HIC PORTATVR:CORPVS:EADWARDI:REGIS:AD:ECCLESIAM:SCI
PETRI APLI
HIC EADWARDVS:REX
INTECTO:ALLOQVIT:FIDE LES:-
HIC DEDERVNT:HAROLDO:
CORO NA: REGIS
HIC RE
REX:AN
SIDET:HAROLD
GLORVM:
STIGANT
ARChi EPS
ET HIC: DEFVNCTVS
EST

COMPILER SUPPORT AND SPECIFICS

- supported features
- completeness
- file extensions for modular translation units
  - preferred
  - others allowed
- compiler flags for compiling
  - named modules
  - header units

as advertised and / or documented ⚠️

LANGUAGE / LIBRARY FEATURES

	gcc / libstdc++	clang / libc++	msvc / ms stl
Syntax specification	C++20 -fmodules-ts 🙄	≤ 8.0: Modules TS ≥ 15.0: C++20	≤ 19.22: Modules TS ≥ 19.23: C++20
Named modules	✅ partial	✅ partial	✅
Module partitions	✅ partial	✅ partial	✅
Header units	✅	✅	✅
Private mod. fragment	⛔	✅	✅
Name attachment	✅ strong model	✅ strong model	✅ strong model
#include → import	✅	✅	✅
__cpp_modules	🟨 201810L 🤨	⛔	✅ 201907L
Modularized std library	⛔	🟨 partial, experimental	✅

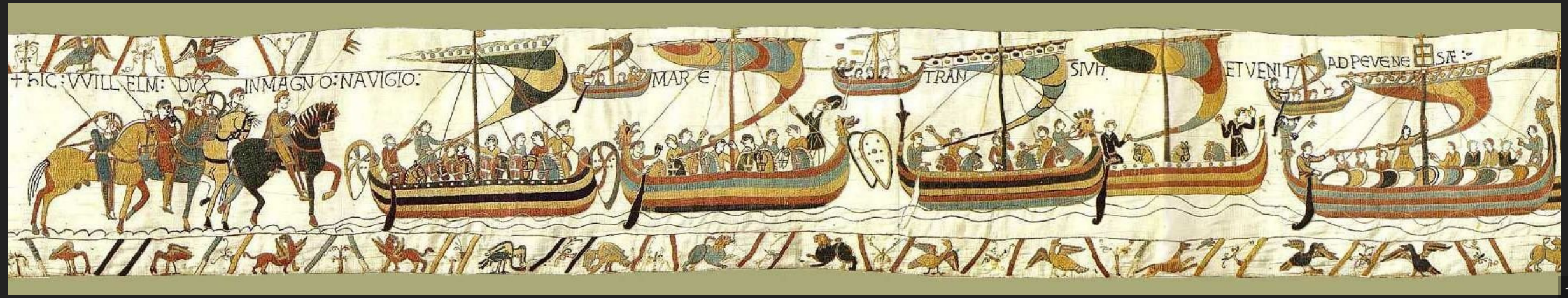
BMI CONSISTENCY - COMPILER FLAGS

- msvc:
  - pretty lenient
  - fastmath, execution encoding, RTTI, exception handling
  - warnings, can be suppressed -> ODR violations possible
- clang:
  - very strict, an unspecified set of flags matters, language flags matter, release/debug doesn't matter -> ODR violations possible
  - not overridable, warnings can be suppressed 🤦
- gcc:
  - no documentation

FILE NAMING - EXTENSIONS

- clang:
  - all extensions possible, given -x c++-module option
  - preferred: .cppm (ccm, cxxm, c++m), infers -x c++-module
  - header units: -x c++-header, -x c++-user-header, or -x c++-system-header
- gcc:
  - all extensions possible, give -x c++ option
  - preferred: .cpp (cc, cp, cxx, c++), infers -x c++
  - header units: -x c++-header, -x c++-user-header, or -x c++-system-header
- msvc:
  - all extensions possible, given proper /interface or /internalPartition, and /TP
  - preferred: .ixx for all sources that contribute to the interface of a module, infers /interface
  - header units: /exportHeader with optional header type qualification

Modularizing traditional libraries



ARGPARSE

argparse.hpp, C++17, single-file, header-only, portable

```
#include <algorithm>
#include <any>
... more standard library headers

namespace argparse {

namespace details {
... const variables, classes, and functions, some templated
}

... enums, operator&()

class ArgumentParser;

class Argument {
... many variables, classes, and functions, many templated
};

class ArgumentParser {
... many variables, classes, and functions, many templated
};

} // namespace argparse
```

ARGPARSE

argparse.ixx, naïve modularization using wholesale export

```
export module argparse; // module interface declaration [module.unit]/2

#include <algorithm>
#include <any> // ... more standard library headers

namespace argparse {

namespace details { // not exported -> invisible, but reachable!
}

export { // export declaration sequence [module.interface]/1
... enums, operator&()

class ArgumentParser;

class Argument {
};

class ArgumentParser {
};

} // export
} // namespace argparse
```

ARGPARSE

often better: explicit single export declarations

```
export module argparse;

#include <algorithm>
#include <any> // ... more standard library headers

namespace argparse {

namespace details { // not exported -> invisible, but reachable!
}

export enum class nargs_pattern { optional, any, at_least_one };
export enum class default_arguments : unsigned int { ... };
export inline default_arguments operator&(const default_arguments &a,
                                          const default_arguments &b) { ... }

export class ArgumentParser;

export class Argument {
};

class ArgumentParser { // no export keyword!
};
} // namespace argparse
```

COMPILE IT

Clang 16.0.4

```
// -std=c++2b      : C++23
// -fmodule-output : compile module interface (or partition) -> generate BMI module-name.pcm
// -c              : create object file, too
// -x c++-module   : input is C++ module

clang++ -std=c++2b -fmodule-output -c -x c++-module argparse.ixx


->  doesn't compile


In file included from argparse.ixx:32:
In file included from /include/c++/13.1.0/algorithm:60:
In file included from /include/c++/13.1.0/bits/stl_algobase.h:65:
In file included from /include/c++/13.1.0/bits/stl_iterator_base_types.h:71:
/include/c++/13.1.0/bits/iterator_concepts.h:72:12: error: declaration of 'iterator_traits' in module
      argparse follows declaration in the global module
    struct iterator_traits;
           ^
/include/c++/13.1.0/bits/cpp_type_traits.h:470:29: note: previous declaration is here
  template<typename> struct iterator_traits;

more errors to follow
```

COMPILE IT

gcc 13.1.0

```
// -std=c++2b             : C++23
// -fmodules-ts           : enable C++ 20 modules
// (deduced from content) : module interface -> generate BMI
// -x c++                 : input is C++

g++ /c -std=c++2b -fmodules-ts -x c++ argparse.ixx

  -> doesn't compile


In file included from /include/c++/13.1.0/bits/stl_algobase.h:59,
                 from /include/c++/13.1.0/algorithm:60,
                 from argparse.ixx:32:
/include/c++/13.1.0/bits/c++config.h: In function 'void std::__terminate()':
/include/c++/13.1.0/bits/c++config.h:321:10: error: block-scope extern declaration 'void std::terminate()' not
  321 |     void terminate() _GLIBCXX_USE_NOEXCEPT __attribute__ ((__noreturn__));
      |          ^~~~~~~~~
In file included from /include/c++/13.1.0/bits/stl_iterator_base_types.h:71,
                 from /include/c++/13.1.0/bits/stl_algobase.h:65:
/include/c++/13.1.0/bits/iterator_concepts.h: At global scope:
/include/c++/13.1.0/bits/iterator_concepts.h:72:12: error: cannot declare 'struct std::iterator_traits< <templ
   72 |     struct iterator_traits;
      |            ^~~~~~~~~~~~~~~
In file included from /include/c++/13.1.0/bits/stl_algobase.h:61:
/include/c++/13.1.0/bits/cpp_type_traits.h:470:29: note: declared here
```

COMPILE IT

MSVC 14.36

```
// /std:c++latest : C++23
// /interface     : compile a module interface (or partition) -> generate BMI
// /TP            : input is C++

cl /c /EHsc /std:c++latest /interface /TP argparse.ixx

  ->  compiles and creates BMI argparse.ifc + object file argparse.obj


argparse.ixx(32): warning C5244: '#include <algorithm>' in the purview of module 'argparse'
  appears erroneous.
  Consider moving that directive before the module declaration,
  or replace the textual inclusion with 'import <algorithm>;'.

more warnings to follow
```

FIX IT

introduce the GMF and place the standard library headers there

```
// at most comments or white space lines here !
module; // introduce the so-called global module fragment [module.global.frag]

// put all your #includes here that come from the traditional,
// non-modular code that lives in the global module

// *all* of them, pretty please! 😺

#include <algorithm>
#include <any> //
... all the other library headers

export module argparse; // module interface declaration [module.unit]/2

// no more *traditional* #includes

namespace argparse {
...
```

FIX IT (MODERN ALTERNATIVE)

replace the standard library #includes with the C++23 modularized standard library

```
export module argparse; // module interface declaration [module.unit]/2
// the module purview (in this TU) starts here

// this is also the so-called module preamble at the very beginning of the purview,
// before the *first declaration* (other than import) in the module purview

// *all* imports must be placed here
import std; // import pp-directive [cpp.import]/4 -> declaration [module.import]

// no more *traditional* #includes
// other #includes are still allowed

namespace argparse {
...
```

COMPILE IT

Clang 16.0.4

```
// -fmodule-output=<name>=<BMI path> : generate BMI at given location

clang++ -std=c++2b -fmodule-output=$(BMIpath)/argparse.pcm -c -x c++-module argparse.ixx

  ->  compiles and creates BMI argparse.pcm + object file argparse.o
```

gcc 13.1.0

```
g++ -c -std=c++2b -fmodules-ts -x c++ argparse.ixx

  -> compiler crashes

argparse.ixx:57:8: internal compiler error: Segmentation fault
   57 | export module argparse;
      |        ^~~~~~
```

MSVC 14.36

```
cl /c /EHsc /std:c++latest /interface /TP argparse.ixx

  ->  compiles and creates BMI argparse.ifc + object file argparse.obj
```

TEST IT

Modules have 2 interfaces:

- Compiling the module excercises only the internal, module-facing part.
- Never forget to test the consumer-facing part of the interface!

```
import argparse;

int main(int argc, char *argv[]) {
  argparse::ArgumentParser program("test");
  program.add_argument("--foo").implicit_value(true).default_value(false);

  auto unknown_args = program.parse_known_args(argc, argv);

  if (program.is_used("--foo"))
    return program.get<bool>("--foo");
}
```

TEST IT

Clang 16.0.4

```
// -fmodule-file=<name>=<BMI path> : associate module name with BMI (a.k.a. module mapper)
//
// alternatively
//
// -fprebuilt-module-path=<directory> : search for BMI module-name.pcm in given directory

clang++ -std=c++2b -fmodule-file=argparse=argparse.pcm main.cpp argparse.o

  -> fails to compile

In module 'argparse' imported from main.cpp:1:
/include/c++/13.1.0/bits/stl_algo.h:1945:19: error: invalid operands to binary expression
      ('__gnu_cxx::__normal_iterator<std::basic_string<char> *, std::vector<std::basic_string<char>>>'
      '__gnu_cxx::__normal_iterator<std::basic_string<char> *, std::vector<std::basic_string<char>>>')
      if (__first != __last)
          ~~~~~~~ ^  ~~~~~~
/include/c++/13.1.0/bits/stl_algo.h:4894:12: note: in instantiation of function template specializatio
      'std::__sort<__gnu_cxx::__normal_iterator<std::basic_string<char> *, std::vector<std::basic_stri
      __gnu_cxx::__ops::_Iter_comp_iter<(lambda at argparse.ixx:387:41)>>' requested here
      std::__sort(__first, __last, __gnu_cxx::__ops::__iter_comp_iter(__comp));
           ^
argparse.ixx:386:10: note: in instantiation of function template specialization
      'std::sort<__gnu_cxx::__normal_iterator<std::basic_string<char> *, std::vector<std::basic_string
      at argparse.ixx:387:41)>' requested here
    std::sort(
```

TEST IT

MSVC 14.36

```
// /reference <name>=<BMI path> : associate module name with BMI (a.k.a. module mapper)
//
// alternatively
//
// /ifcSearchDir <directory> : search for BMI module-name.ifc in given directory

cl /EHsc /std:c++latest /reference argparse=argparse.ifc main.cpp argparse.obj


  ->  fails to compile

argparse.ixx(388): error C2676: binary '<': 'const _T2' does not define this operator or a conversion
        with
        [
            _T2=std::basic_string<char,std::char_traits<char>,std::allocator<char>>
        ]
\include\algorithm(7929): note: see reference to function template instantiation 'auto argparse::Argum
        with
        [
            _T2=std::basic_string<char,std::char_traits<char>,std::allocator<char>>,
            _T3=std::basic_string<char,std::char_traits<char>,std::allocator<char>>
        ]
\include\algorithm(8053): note: see reference to function template instantiation '_BidIt std::_Inserti
        with
        [
            _BidIt=std::basic_string<char,std::char_traits<char>,std::allocator<char>> *
```

DECLARATION PRUNING

Declarations from the GMF undergo special treatment. From the C++ standard document [module.global.frag]/4:

> *A declaration D in a global module fragment of a module unit is discarded if D is not decl-reachable from any declaration in the declaration-seq of the translation-unit.*

> *[Note 3: A discarded declaration is neither reachable nor visible to name lookup outside the module unit, nor in template instantiations whose points of instantiation are outside the module unit, even when the instantiation context includes the module unit. — end note]*

In other words:

You need to provide the missing declarations and definitions by either #including the related header files or other means like import std !

P2191 elaborates on this topic and the problems associated with it.

TEST IT AGAIN

```
#include <any>    // required by clang          😮
#include <string> // required by clang & msvc   😢

import argparse;

int main(int argc, char *argv[]) {
  argparse::ArgumentParser program("test");
  program.add_argument("--foo").implicit_value(true).default_value(false);

  auto unknown_args = program.parse_known_args(argc, argv);

  if (program.is_used("--foo"))
    return program.get<bool>("--foo");
}
```

Both compilers succeed and create an executable 🎉

But also 🤯😱😮😢

THERE'S MORE ...

The test code was carefully chosen to sidestep issues still lurking in the non-exported namespace 'details':

- unqualified name lookup that
  - (unwittlingly) invokes ADL and at least reduces compilation throughput
  - can lead to lookup failures in 2nd-phase name lookup of templates that are instantiated outside the module
- declarations with internal linkage that may cause a so-called exposure of TU-local entities [basic.link]/14

The latter is particularily damning [basic.link]/17:

> *If a (possibly instantiated) declaration of, or a deduction guide for, a non-TU-local entity in a module interface unit (outside the private-module-fragment, if any) or module partition is an exposure, the program is ill-formed. Such a declaration in any other context is deprecated.*

FIXING THESE PROBLEMS

```
--- a/argparse.ixx
+++ b/argparse.ixx
@@ namespace details { // namespace for helper methods
@@ -128,8 +133,6 @@

-namespace {
-
 template <typename T> constexpr bool standard_signed_integer = false;
 template <> constexpr bool standard_signed_integer<signed char> = true;
 template <> constexpr bool standard_signed_integer<short int> = true;
 template <>
 constexpr bool standard_unsigned_integer<unsigned long long int> = true;

-} // namespace
-
 constexpr int radix_8 = 8;
 constexpr int radix_10 = 10;
 constexpr int radix_16 = 16;

 template <typename T>
 constexpr bool standard_integer =
-    standard_signed_integer<T> || standard_unsigned_integer<T>;
+    details::standard_signed_integer<T> || details::standard_unsigned_integer<T>;

 template <class F, class Tuple, class Extra, std::size_t... I>
 constexpr decltype(auto)
@@ -226,14 +226,14 @@ inline auto do_from_chars(std::string_vi
```

ASIO

≈6 MB source text in 673 files, ported to many compilers and platforms

-> single-TU module with the module "trinity", i.e. GMF, purview, PMF

```
module;
#include "asio-gmf.h" // all the platform- and compiler-specific includes

export module asio;

#ifdef ASIO_ATTACH_TO_GLOBAL_MODULE
extern "C++" { // [module.unit]/7.2.2, detach all exported entities from
#endif         // module 'asio' and attach them to the global module

export {     // export all of the Asio headers wholesale,
             // without exception, they all must have *external* linkage!
#include "asio.hpp"

#include "asio/ts/buffer.hpp"
... more Networking TS headers

#include "asio/experimental/awaitable_operators.hpp"
... more "experimental" headers

#if defined(ASIO_USE_SSL)
#  include <asio/ssl.hpp>
#endif
} // export
```

ASIO - GMF

The list of included headers (and its dependencies) *must* be complete! Clang's or gcc's compiler option -MD is your friend 😊

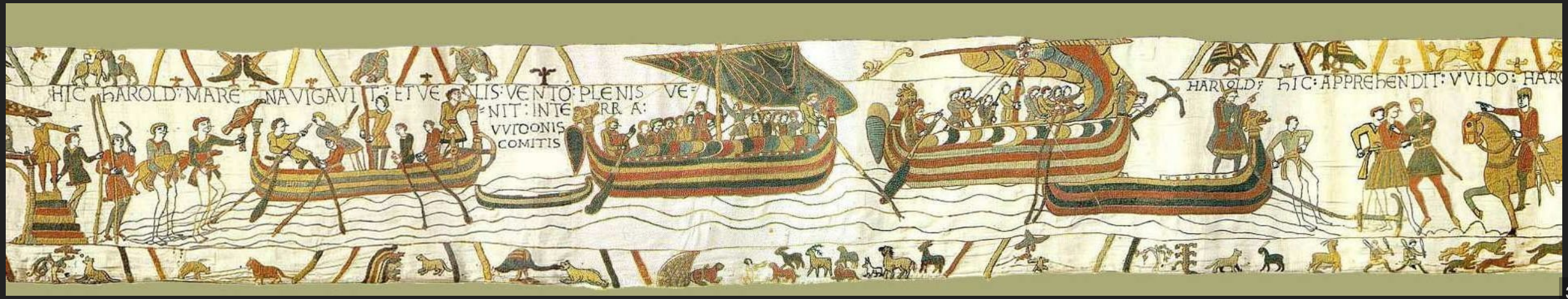
```
#pragma once
#define ASIO_STANDALONE // sorry, Boost-ified Asio is not yet supported

#if defined(_WIN32) and __has_include(<SDKDDKVer.h>)
#   include <SDKDDKVer.h>
#endif

#if defined(ASIO_HEADER_ONLY)
#   error "ASIO_HEADER_ONLY" makes no sense with this module
#endif

#if !defined(ASIO_SEPARATE_COMPILATION)
#   define ASIO_SEPARATE_COMPILATION
#endif

#if !defined(ASIO_DISABLE_BUFFER_DEBUGGING) && !defined(ASIO_ENABLE_BUFFER_DEBUGGING)
#   define ASIO_DISABLE_BUFFER_DEBUGGING
#endif

#define ASIO_NO_DEPRECATED
#define ASIO_MODULE

#include <asio/detail/config.hpp>
```

ASIO - DEPENDENCIES

Clang's or gcc's compiler option -MD, or msvc's equivalent, is your friend 😊

```
/asio/module/asio.ixx
/asio/module/asio-gmf.h
/include/SDKDDKVer.h
/asio/include/asio/detail/config.hpp
/include/c++/13.1.0/version
/include/winapifamily.h
/include/c++/13.1.0/algorithm
/include/c++/13.1.0/bits/stl_algobase.h
/include/c++/13.1.0/bits/functexcept.h
/include/c++/13.1.0/bits/exception_defines.h
/include/c++/13.1.0/bits/cpp_type_traits.h
/include/c++/13.1.0/ext/type_traits.h
/include/c++/13.1.0/ext/numeric_traits.h
/include/c++/13.1.0/bits/stl_pair.h
/include/c++/13.1.0/type_traits
/include/c++/13.1.0/bits/move.h
/include/c++/13.1.0/bits/utility.h
/include/c++/13.1.0/compare
/include/c++/13.1.0/concepts
/include/c++/13.1.0/bits/stl_iterator_base_types.h
/include/c++/13.1.0/bits/iterator_concepts.h
/include/c++/13.1.0/bits/ptr_traits.h
/include/c++/13.1.0/bits/ranges_cmp.h
/include/c++/13.1.0/bits/stl_iterator_base_funcs.h
```

Build systems



BUILD SYSTEMS

There are a few build systems with some support for C++ modules

In alphabetical order:

- build2 (by Boris Kolpackov, build2.org)
  - claims to support all TU types
  - currently supports only gcc,
    formerly also Clang and msvc
  - module dependency scanner ?
- CMake (by Kitware, CMake.org)
  - supports all named module TU types
  - no support for header units
  - supports Clang 16+, msvc 19.32+, and self-built gcc 13.1 with a patch ⚠️
  - does module dependency scanning (required)
  - manual dependency specifications are tedious and hard

BUILD SYSTEMS

- Evoke (by Peter Bindels, GitHub)
  - clang only (for modules)
  - documentation is lacking

- MSBuild (by Microsoft, since toolset 16.28, Visual Studio)
  - msvc only (for modules)
  - supports all TU types
  - supports and prefers automatic module dependency scanning
  - manual module depency specifications are possible
  - extensive documentation

BUILD SYSTEMS

- xmake (community driven, xmake.io)
  "A cross-platform build utility based on Lua"
  - claims to support all C++ module TU types
  - supports all compilers
  - no documented module dependency scanning facility
  - documentation is lacking

some might even consider

- make
  - bring your own build rules, f.e. like Bloomberg's P2473
  - module dependency scanning might be implementable

CMAKE 3.26

CMake 3.25 (3.26 recommended) introduces *experimental* support (link) using modules with

- Clang (16.0 or newer)
- MSVC (19.34 or newer)

These compilers can produce dependency scanning results according to the specification described in P1689 (discussed in WG21 SG15 'Tooling')

The 'experimental' tag is deemed to be removed as soon as a future gcc release implements this as well. Until then you can build your own gcc with a patch by Kitware applied.

Tip: use the Ninja generator (Ninja 1.10 or newer), the Visual Studio generator is fine, too.

CMAKE FILESETS

The new, experimental APIs are opt-in by setting

```
set(CMAKE_EXPERIMENTAL_CXX_MODULE_CMAKE_API "2182bf5c-ef0d-489a-91da-49dbc3090d2a")
```

and compiling with C++20 or newer.

Module TU sources need to be indicated a such by grouping the target sources into different *file sets* like so:

```
 1 add_library(demo)
 2
 3 target_sources(demo
 4   PRIVATE ${non-modular-TUs} ${module-implementation-TUs} # consume BMIs
 5   PRIVATE
 6     FILE_SET moduleunits TYPE CXX_MODULES     # those create BMIs
 7       FILES ${module-interface-TUs} ${module-internal-partition-TUs}
 8     FILE_SET headerunits TYPE CXX_MODULE_HEADER_UNITS # still TODO 😢
 9       FILES ${header-unit-TUs}                # those create BMIs, too!
10 )
```

CMAKE MODULE DEPENDENCIES

With some true dedication, you technically can describe the dependency between BMI creation and BMI consumption in CMake syntax. I do that in the module test suite of the {fmt} library. But that's brittle, limited to the most simple cases, 100% manual in all aspects, and therefore not scalable.

CMake's true support for C++ modules revolves around (dynamic) dependency discovery:

- implementation-supplied module depency scanners
- a standard-defined dependency report for each module
- module maps created and supplied to compiler invocations by CMake
- build-node processors with dynamic dependency re-evaluation (Ninja, MSBuild)

```
set(CMAKE_EXPERIMENTAL_CXX_MODULE_CMAKE_API "2182bf5c-ef0d-489a-91da-49dbc3090d2a")
set(CMAKE_EXPERIMENTAL_CXX_MODULE_DYNDEP 1) # enable (dynamic) dependency scanning
set(CMAKE_CXX_EXTENSIONS OFF)               # required with Clang
```

CMAKE MODULE PREREQUISITES

In summary, CMake support for C++ modules requires

- a sufficiently recent CMake
- sufficiently recent compiler toolsets with supported commandlines (Clang, MSVC)
- dependency scanners that report according to P1983 (Clang 16+, MSVC 19.34+)
- sufficiently recent build processors (Ninja, MSBuild)
- opt-in into the experimental APIs
- opt-in into dependency scanning
- using FILE_SETs

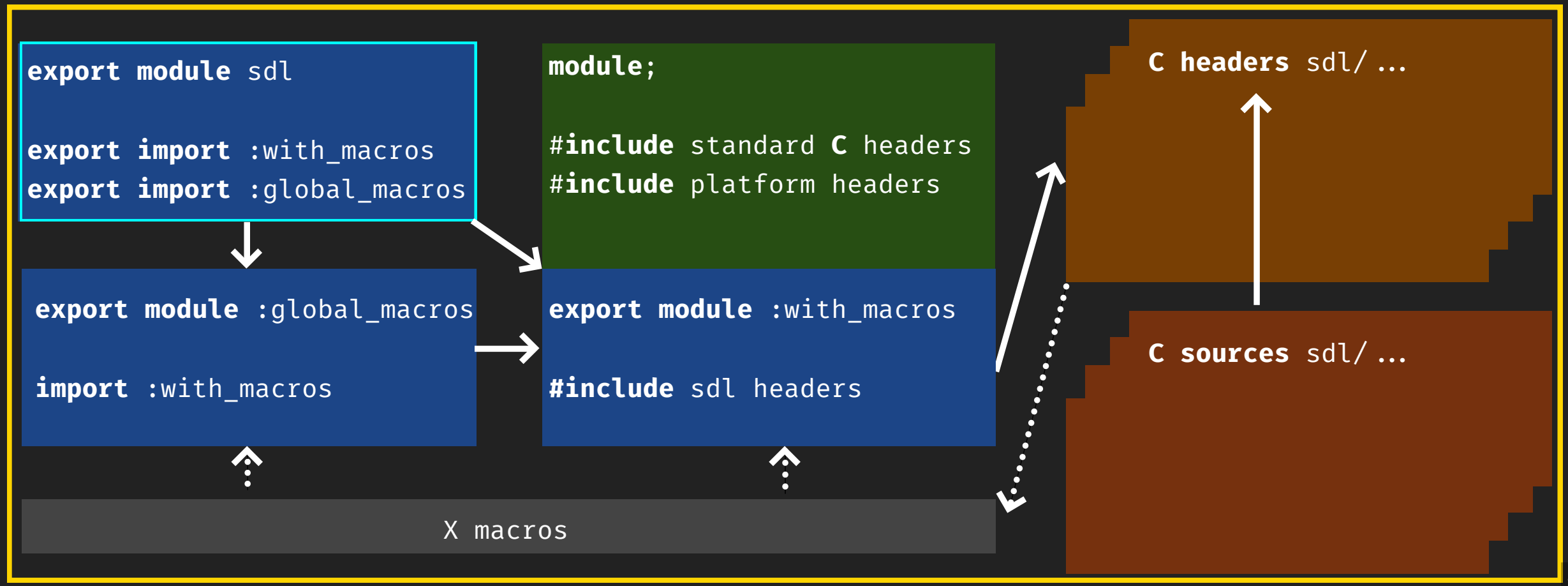
to build and use named modules.

Header units are completely unsupported.

Module dependencies

MODULE DEPENDENCY SCANNING

Let's look at module 'sdl', a static C library with a C++ module interface, composed from a primary module interface and two module interface partitions.



MODULE DEPENDENCY SCANNING

The result is a static library with unmangled "C" symbols that can be used

- with traditional #include of the original headers
- with imports of the 'sdl' module interface

```
add_library(sdl STATIC)

set(module_dir module)
file(GLOB module_interface_files ${SDL2_SOURCE_DIR}/${module_dir}/*.ixx)

target_sources(sdl
  PUBLIC
    FILE_SET modules TYPE CXX_MODULES
      BASE_DIRS ${module_dir}           # the module interface,
      FILES ${module_interface_files}   # all found module TUs
  PRIVATE
    ${SOURCE_FILES}                     # the C library implementation
)
```

MODULE DEPENDENCY REPORT

The report from scanning interface partition 'sdl:global_macros' generated by Clang:


```
{
  "revision": 0,
  "rules": [
    {
      "primary-output": "SDL/CMakeFiles/sdl.dir/module/sdl2-global-macros.ixx.obj",
      "provides": [
        {
          "logical-name": "sdl:global_macros",
          "is-interface": true,
          "source-path": "SDL/module/sdl2-global-macros.ixx"
        }
      ],
      "requires": [
        {
          "logical-name": "sdl:with_macros"
        }
      ]
    }
  ],
  "version": 1
}
```

MODULE DEPENDENCY REPORT

and the one created by MSVC, with some additional information, but basically the same:

```
{
  "version": 1,
  "revision": 0,
  "rules": [
    {
      "primary-output": "SDL/CMakeFiles/sdl.dir/module/sdl2-global-macros.ixx.obj",
      "outputs": [
        "bld-msvc/vc140.pdb"
      ],
      "provides": [
        {
          "logical-name": "sdl:global_macros",
          "source-path": "sdl/module/sdl2-global-macros.ixx",
          "is-interface": true
        }
      ],
      "requires": [
        {
          "logical-name": "sdl:with_macros"
        }
      ]
```

MODULE MAPS

CMake generates module maps from the reports.

Clang:

```
-x c++-module
-fmodule-output=SDL/CMakeFiles/sdl.dir/sdl-global_macros.pcm
-fmodule-file=sdl:with_macros=SDL/CMakeFiles/sdl.dir/sdl-with_macros.pcm
```

MSVC:

```
-interface
-ifcOutput SDL/CMakeFiles/sdl.dir/sdl-global_macros.ifc
-reference sdl:with_macros=SDL/CMakeFiles/sdl.dir/sdl-with_macros.ifc
```

These are fed to the compilers to compile the module unit.

The demo code

MAIN

```
/* ================================================================
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
```

MAIN - DEPENDENCIES 1ST LEVEL


```
{
  "revision": 0,
  "rules": [
    {
      "primary-output": "Demo-App/CMakeFiles/demo.dir/main.cpp.obj",
      "requires": [
        {
          "logical-name": "std"
        },
        {
          "logical-name": "asio"
        },
        {
          "logical-name": "executor"
        },
        {
          "logical-name": "gui"
        },
        {
          "logical-name": "net"
        },
        {
          "logical-name": "the.whole.caboodle"
        },
        {
          "logical-name": "client"
        },
        {
          "logical-name": "events"
        },
        {
          "logical-name": "server"
        }
      ]
    }
  ],
  "version": 1
}
```

MAIN - DEPENDENCIES LAST LEVEL


```
{
    "modules" :
    {
        "client" : "Demo-App/CMakeFiles/demo.dir/client.pcm",
        "events" : "Demo-App/CMakeFiles/demo.dir/events.pcm",
        "executor" : "Demo-App/CMakeFiles/demo.dir/executor.pcm",
        "gui" : "Demo-App/CMakeFiles/demo.dir/gui.pcm",
        "net" : "Demo-App/CMakeFiles/demo.dir/net.pcm",
        "server" : "Demo-App/CMakeFiles/demo.dir/server.pcm",
        "the.whole.caboodle" : "Demo-App/CMakeFiles/demo.dir/the.whole.caboodle.pcm",
        "video" : "Demo-App/CMakeFiles/demo.dir/video.pcm",
        "video:decoder" : "Demo-App/CMakeFiles/demo.dir/video-decoder.pcm",
        "video:decoder.pipeline" : "Demo-App/CMakeFiles/demo.dir/video-decoder.pipeline.pcm",
        "video:frame" : "Demo-App/CMakeFiles/demo.dir/video-frame.pcm"
    },
    "references" :
    {
        "argparse" :
        {
            "path" : "argparse/CMakeFiles/argparse.dir/argparse.pcm"
        },
        "asio" :
        {
            "path" : "asio/asio/CMakeFiles/asio.dir/asio.pcm"
        },
        "client" :
        {
            "path" : "Demo-App/CMakeFiles/demo.dir/client.pcm"
        },
        "events" :
        {
            "path" : "Demo-App/CMakeFiles/demo.dir/events.pcm"
        },
        "executor" :
        {
            "path" : "Demo-App/CMakeFiles/demo.dir/executor.pcm"
        },
        "gui" :
```

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 header (because reasons 🙄)
  - c_resource.hpp

taken as an dependency:

- 4 named modules from external libraries:
  - asio
  - argparse
  - libav
  - sdl
- the modularized C++23 standard library
  - compiled from the platform C++ library
  - + polyfill.hpp
    - std::generator (P2502 reference impl.)
    - std::print (partial)
    - std::start_lifetime_as (partial)

APPLICATION - ALL 'ACTORS'

schedule

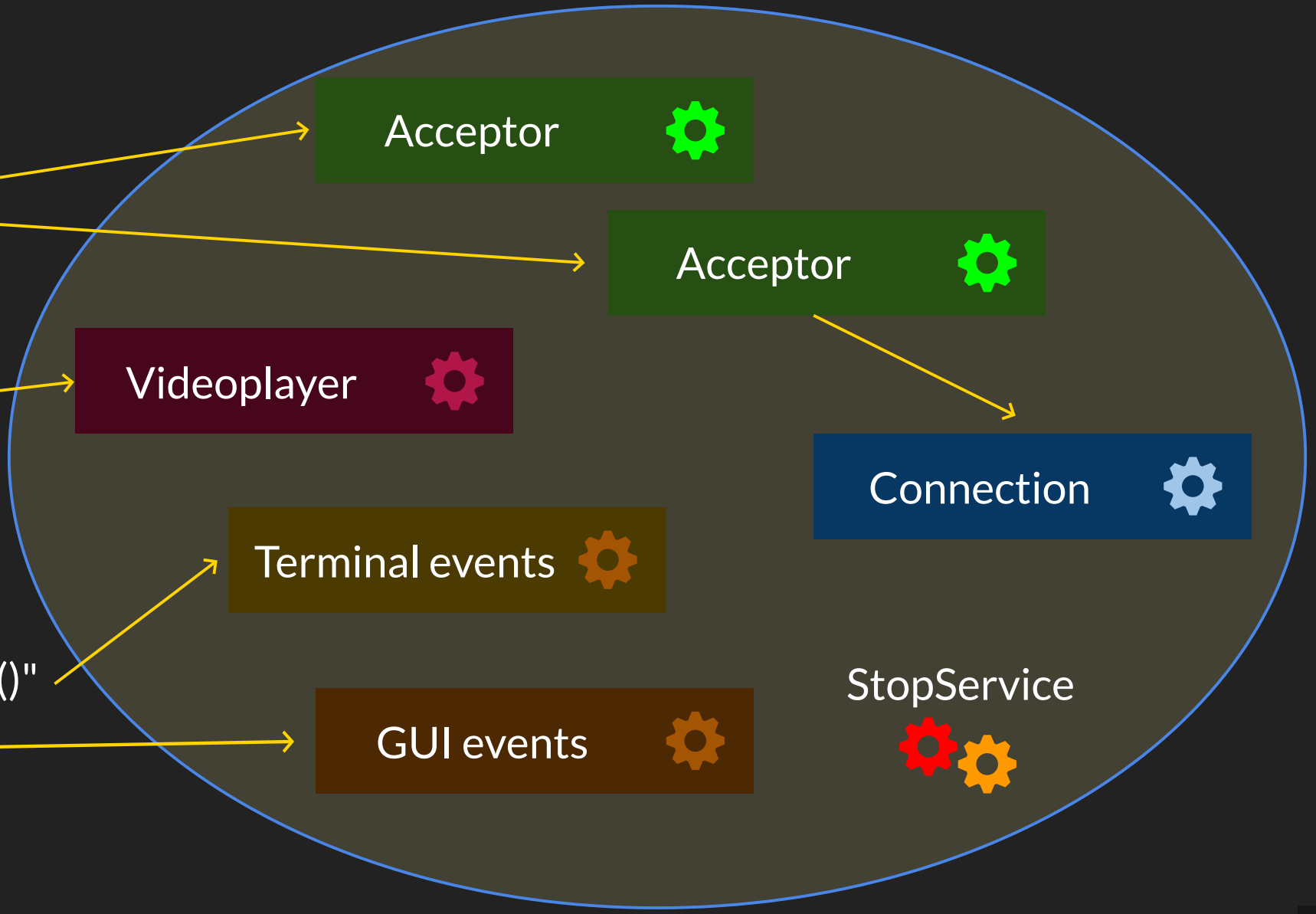
"server::serve(...)"

"client::showVideos(...)"

"handleEvents::fromTerminal()"

"handleEvents::fromGUI()"

on the IO context



DEMO CODE TIME

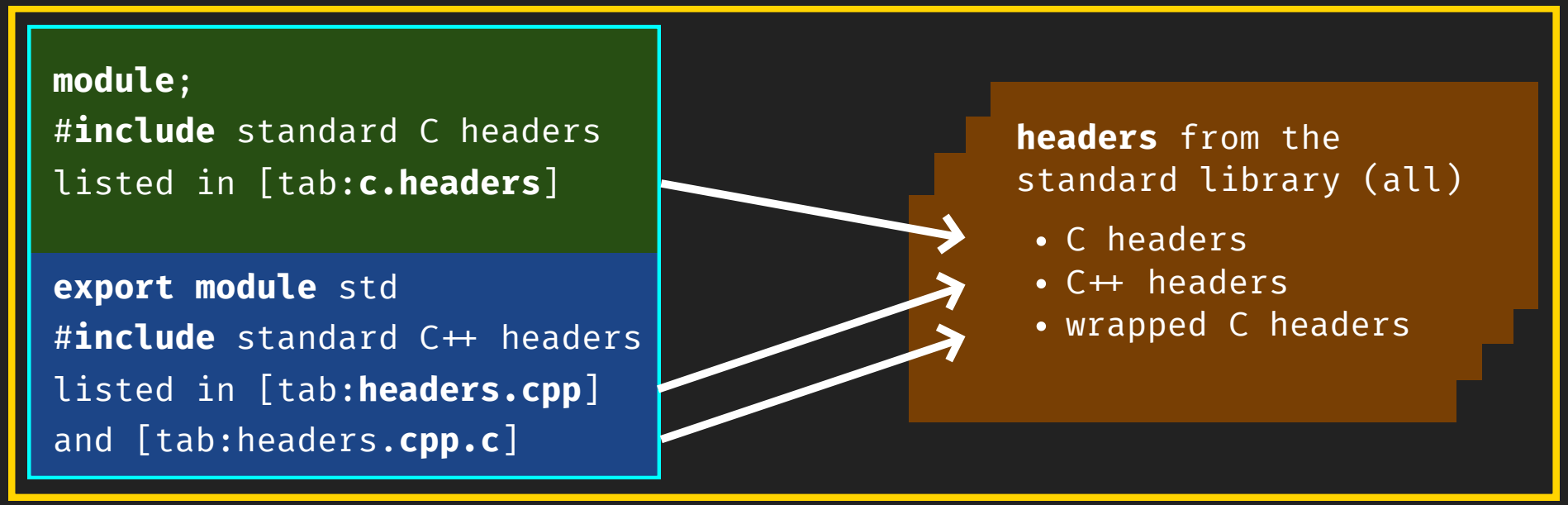
Conclusion


ET:VENERVNT
AD PRELIVM: CON TRA: HAROL DVM:REGE HIC : V VILLELM:DVX INTERROGAT:VITAL: SIVI DISSET
HAROLDI

MODULE STD

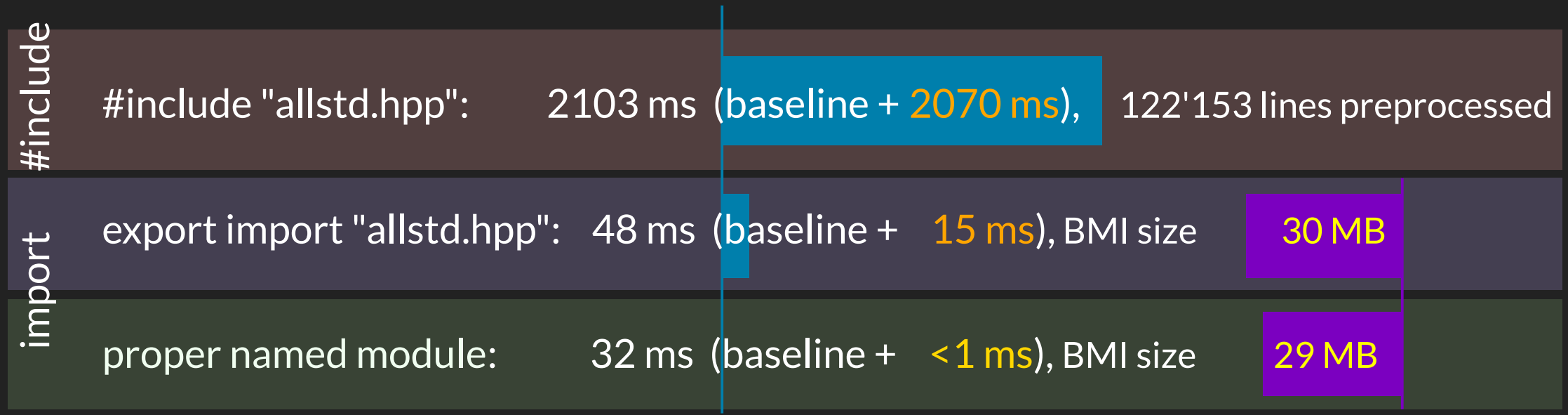
A single-file module compiled as a static lib that contains

- 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
```



{FMT} USAGE SCENARIOS

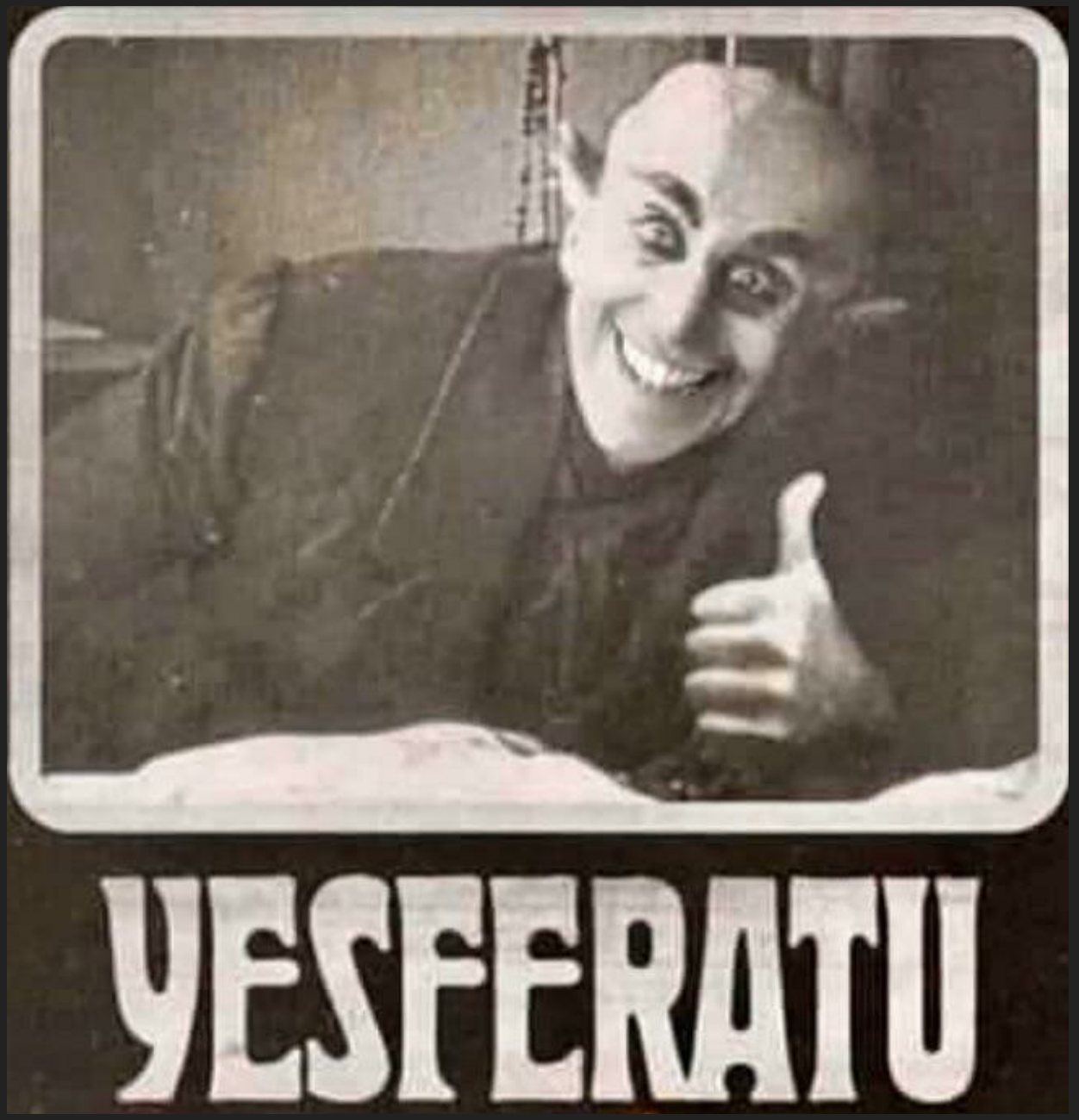
THE FINAL COMPARISON RESULT

```
#include <fmt/*.h>  // provide the *full* API
import <fmt/*.h>    // provide the *full* API
import fmt;         // provide the *full* API
```

#include	#include (header-only):	1599 ms	(baseline + 1568 ms), 90'431 lines preprocessed
	#include (static library):	1422 ms	(baseline + 1391 ms), 88'576 lines preprocessed
	Mod. STL (header-only):	658 ms	(baseline + 627 ms), 10'249 code lines
	Mod. STL (static library):	430 ms	(baseline + 399 ms), 8'038 code lines
import	import (header-only):	160 ms	(baseline + 129 ms), BMI size 117 MB
	import (static library):	155 ms	(baseline + 124 ms), BMI size 91 MB
	named module:	31 ms	(baseline + <1 ms), BMI size 8 MB

This is the way!

128'431 lines preprocessed


YESFERATU

RESOURCES

- Modules in C++, 2004, Daveed Vandevoorde N1736
- C++ Modules TS, 2018, Gabriel Dos Reis N4720
- C++26 draft eel.is/c++draft, the latest available draft standard text
- Demo code github.com/DanielaE/CppInAction
- Asio module github.com/DanielaE/asio/tree/module
- SDL module github.com/DanielaE/SDL/tree/module
- STL module github.com/DanielaE/std.module/tree/module

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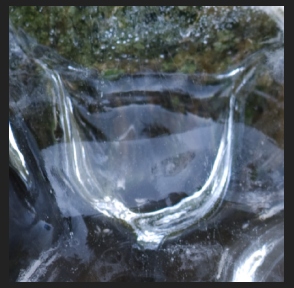

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QUESTIONS?

Ceterum censeo ABI esse frangendam