Meeting C++ 2019

MODULES

The Beginner's Guide

by Daniela Engert

ABOUT ME

- Diploma degree in electrical engineering
- For 40 years creating computers and software
- For 30 years developing hardware and software in the field of applied digital signal processing
- novice member of the C++ committee

- employed by GMH Prüftechnik GmbH · ND-Testing - Systems - Services

PRELUDE

The road towards modules

HIC HAROLD MARE NAVIGAVIT ET VELIS VENTO PLENIS VENIT IN TERRA

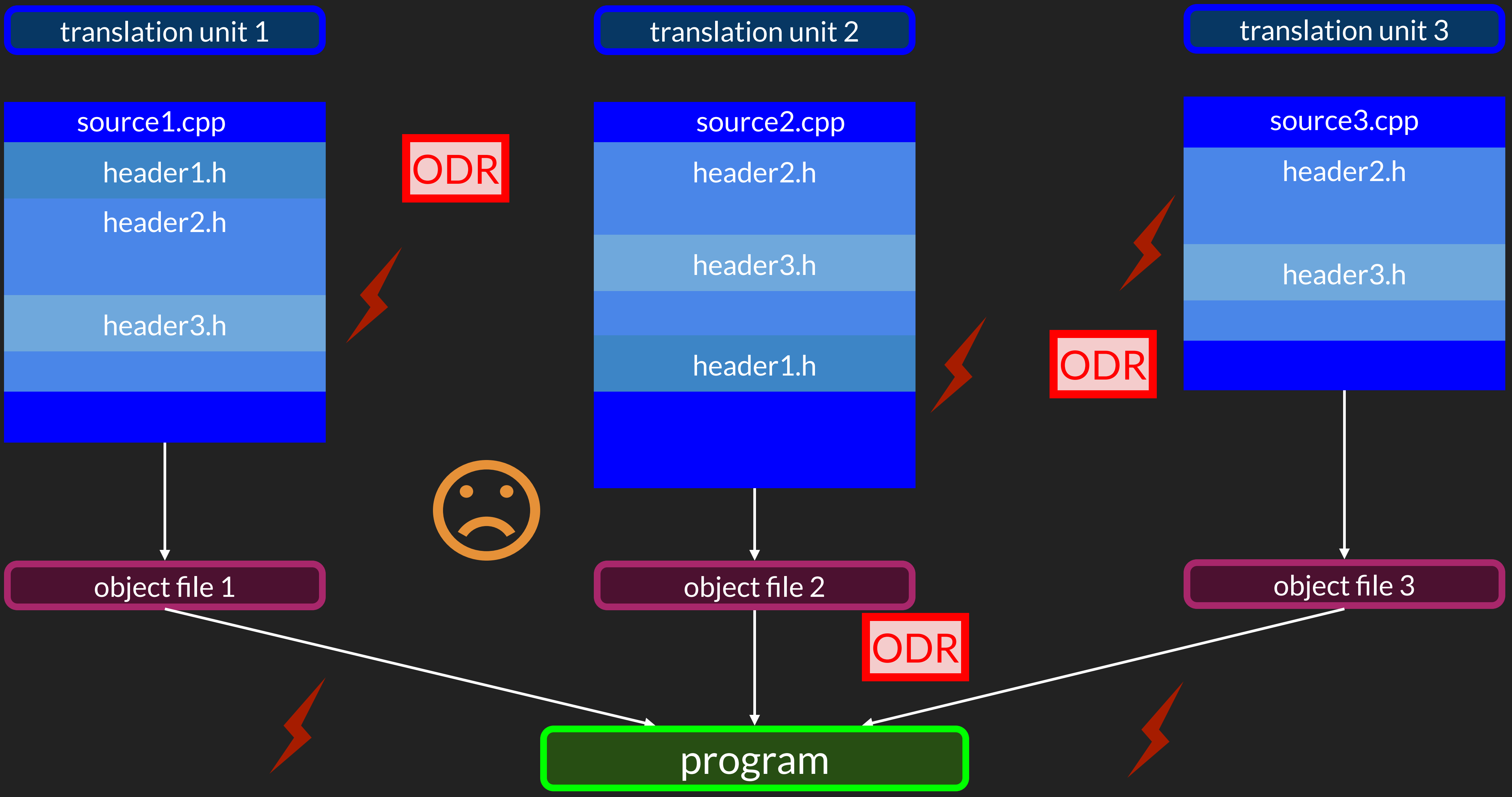
HAROLD: HIC APPREHENDIT: VVIDO: HAR

WHAT IS A PROGRAM?

The compilation model of C++ is inherited from C, and as such half a century old:

- The compiler processes just one single unit of program text individually in total isolation from all other program texts. This complete unit of program text is called a 'translation unit' (TU).
- The result of compiling a TU is a binary representation of machine instructions and associated meta information (e.g. symbols, linker instructions). This binary data is called an 'object file'.
- The linker takes all of the generated object files, interprets the meta information and puts all the pieces together into one final program. In the world of the C++ standard, the program is then to be executed by the 'abstract machine'. In reality, this is real hardware whose observable behaviour is supposed to be the same.

- If necessary, the preprocessor stitches multiple program text fragments together to form a complete TU ready for compilation. These code fragments are called 'source files' and 'header files'.
- A program text fragment is the unit of reuse in traditional C++.


translation unit 1
translation unit 2
translation unit 3
source1.cpp
header1.h
header2.h
header3.h
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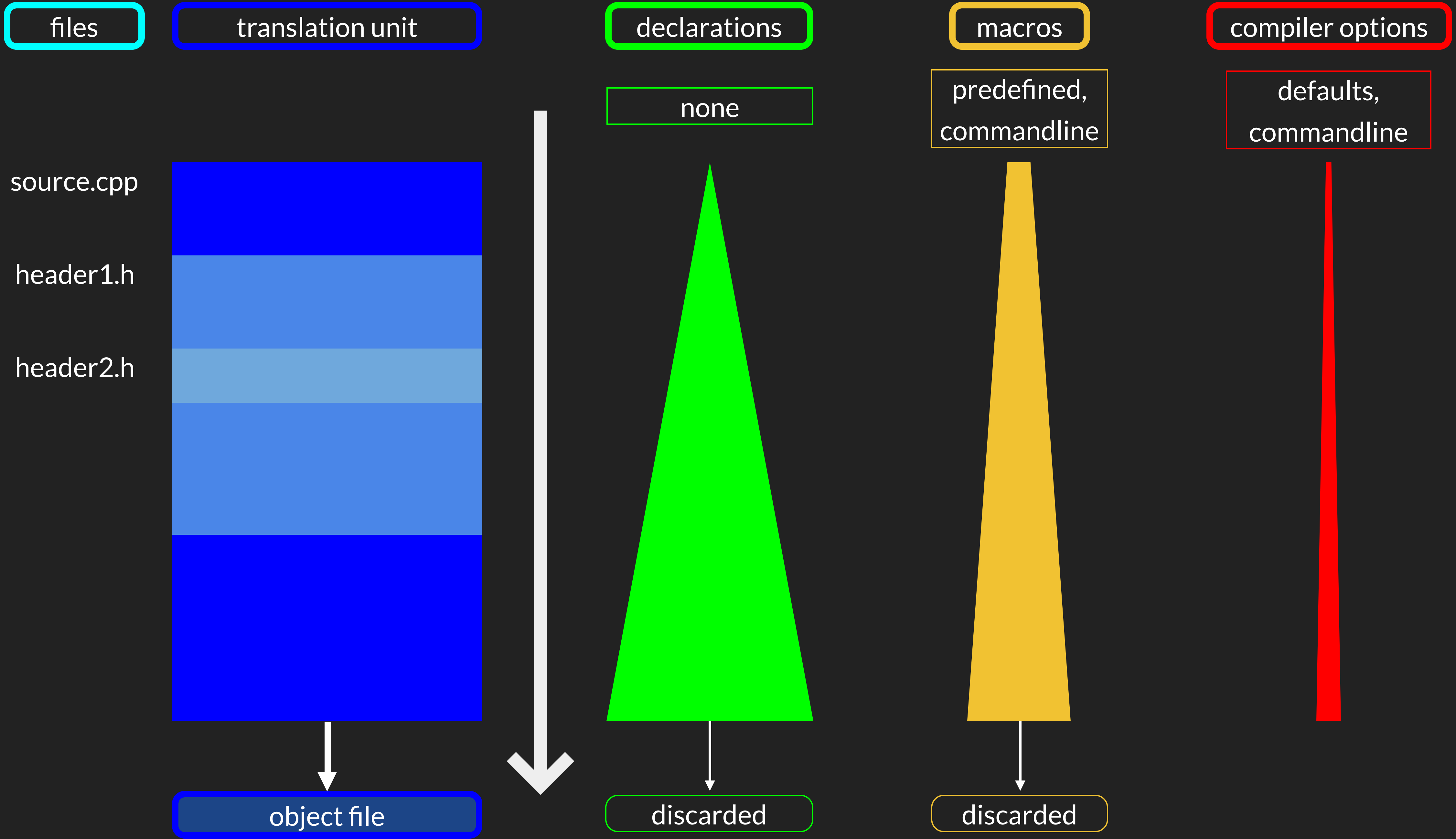
object file 1
object file 2
object file 3
program


files
translation unit
declarations
macros
compiler options
none
predefined, commandline
defaults, commandline
source.cpp
header1.h
header2.h
object file
discarded
discarded

THE MOTIVATION

Much less a problem in C, due to the nature of C++ and it's entities — in particular templates — much larger fractions of program text need to move from source files out into header files before being stitched back before compilation.

```cpp
#include <iostream> // tenths of thousands lines of code hide here!

int main() {
  std::cout << "Hello, world!";
}
```

On msvc 19.24, the total number of lines in this program is 53330.

THE MOTIVATION

The invention of so called header-only libraries and their popularity emphasize this problem.

```cpp
#include <fmt/format.h>

int main() {
  fmt::print("Hello, world!");
}
```

On msvc 19.24, the total number of lines in this program is 75198.

THE PROBLEM

The duplication of work — the same header files are possibly compiled multiple times and most of the compiled output is later-on thrown away again by the linker — while creating the final program is growing ever more unsustainable.

In case of multiple definitions of the same linker symbol, the linker will decide which one will ultimately end up in the final program. Unfortunately, the linker is totally agnostic of language semantics, has no clue if duplicate symbols implement the same thing, and which one to pick. This choice is up to the implementation without any guarantees.

The difficulties in figuring out the actual meaning of code leads to errors (e.g. violations of the 'one definition rule') and unsatisfactory tooling.

THE OBJECTIVE

Increase efficiency:

- Avoid duplication of work
- Minimize the total effort that a compiler has to put into the creation of a program

Increase effectiveness:

- Make reasoning about pieces of code much less dependent on the context
- Leave less room for accidental mistakes
- Open the path to much richer tooling

ENTER MODULES

The new kid on the block

Coming soon in C++20 — already available today

AD BEL REM: ET IBI EVM: TENVIT:
VBI: HAROLD: ET VVIDO: PARABOLANT:
VBI: NVNTII: VVILLELMI: DVCIS: VENERVNT: ADVVIDONE
TVROLD

OVERVIEW

- A bit of history — how it came to be
- Modules 101 — basic concepts
- Modules level 2 — digging deeper
- Mo' Modules — the C++20 additions
- Pitfalls — beware!
- Implementation status — bumpy roads ahead ...
- From header to module — a reality check
- Transitioning to modules

THE HISTORY OF MODULES

how it came to be

VBI: VNVS: CLERICVS: ET ÆLFGYVA
HIC VVILLEM: DVX: ET EXERCITVS: EIVS: VENERVNT: AD MONTE MICHAELIS
ET HIC: TRANSIERVNT: FLVMEN: COSNONI
HIC: HAROLD: DVX: TRAHEBAT DE ARENA

TIMELINE

Modules have a history of more than 15 years now:

- 2004: Daveed Vandevoorde reveals his ideas of modules and sketches a syntax (N1736)
- 2012: WG21 SG2 (Modules) is formed
- 2012: Doug Gregor reports about the efforts of implementing modules in clang
- 2014: Gabriel Dos Reis and his co-authors show their vision of implementing Modules with actual language wording (N4214)
- 2017: implementations in clang (5.0) and msvc (19.1) become usable
- 2018: The Modules TS is finalized (N4720)
- 2018: a competing proposal of syntax and additional features is proposed by Google — the so called ATOM proposal (P0947)
- 2019: the Modules TS and ATOM merge (the first time that controlled fusion leads to a positive energy gain) (P1103)
- 2019: the fused Modules proposal is merged into the C++20 committee draft (N4810)

MODULES 101

the basics

IS: ET VENERVNT AD DOL: ET: CONAN: FVGA VERTIT:
AT: EOS:
HIC MILITES WILLELMI: DVCIS: PVGNANT: CONTRA DINANTES: ET: C
REDNES

OUR FIRST MODULE

Declares a module

interface unit

context sensitive

The name of this module

- multiple parts possible
  - separated by a dot
  - must be valid identifiers
  - do not clash with other identifiers
- can only be referred to in
  - module declaration
  - import declaration

not exported

- invisible outside the module

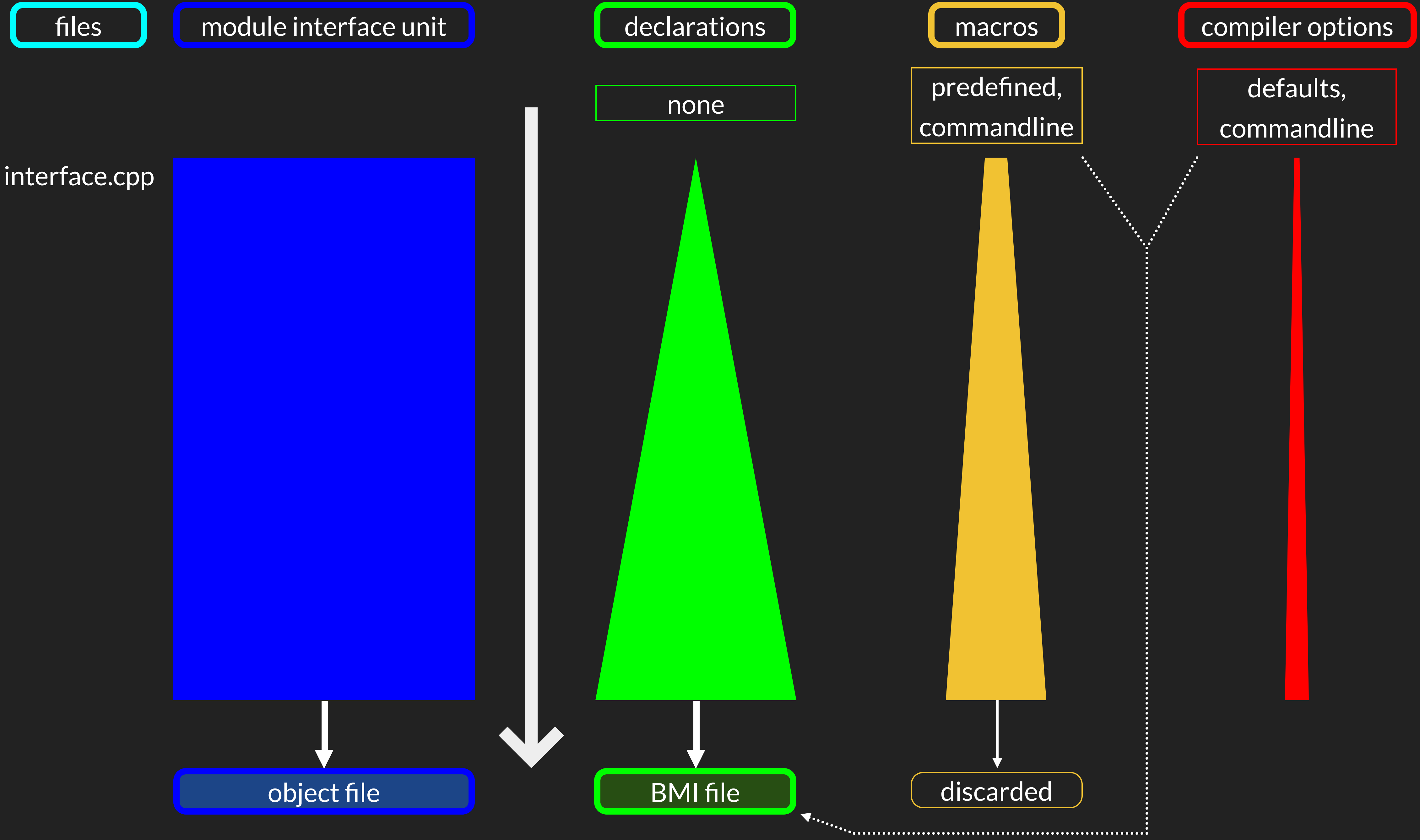
exported

the module interface

- visible outside the module by import

```cpp
export module my.first_module;

int foo(int x) {
  return x;
}

export
int e = 42;

export
int bar() {
  return foo(e);
}
```

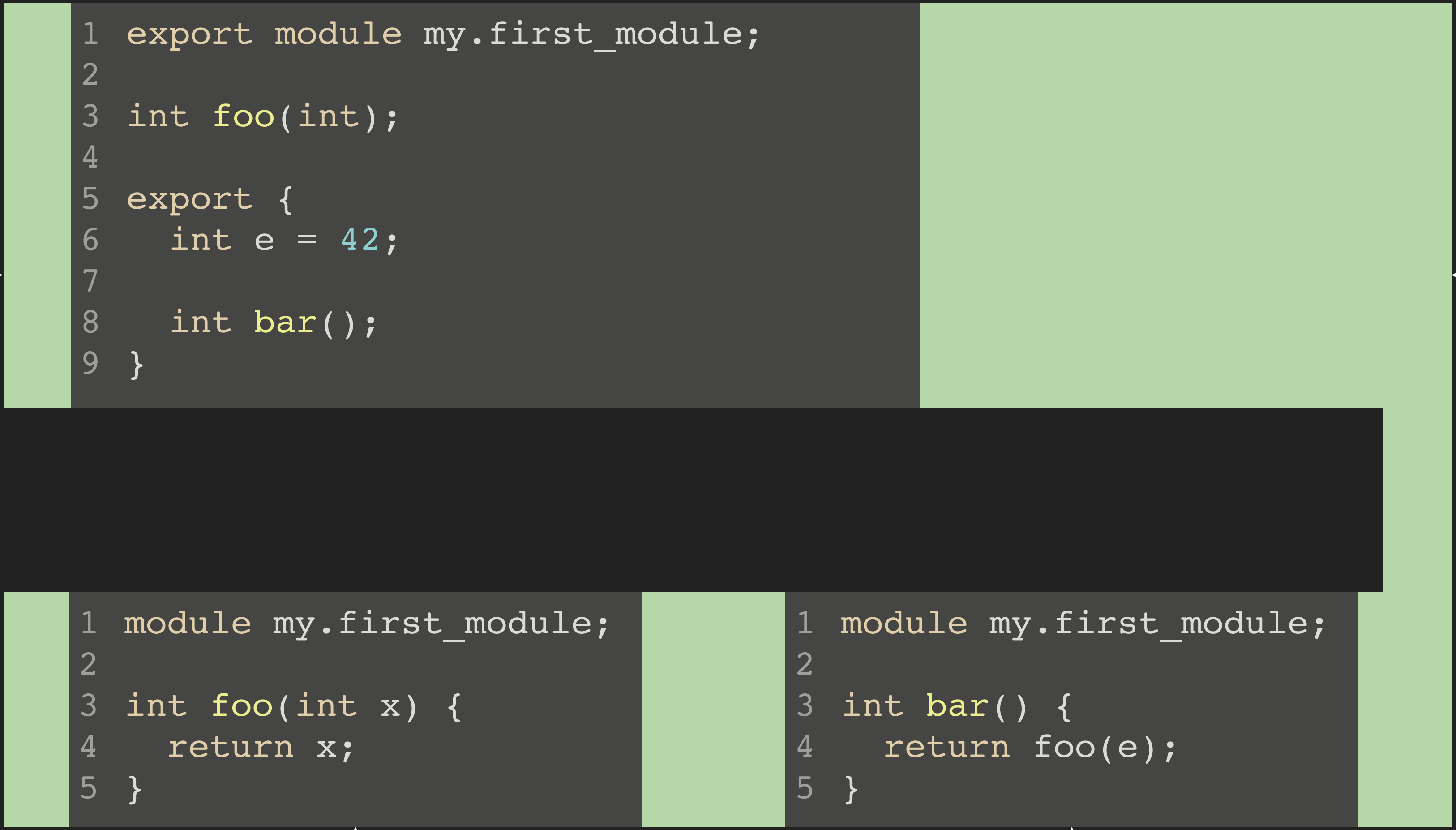
All exported entities have the same definition in all translation units!


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

SEPARATE INTERFACE FROM IMPLEMENTATION

module
interface unit

not a scope



```cpp
export module my.first_module;

int foo(int);

export {
  int e = 42;

  int bar();
}
```

module
purview

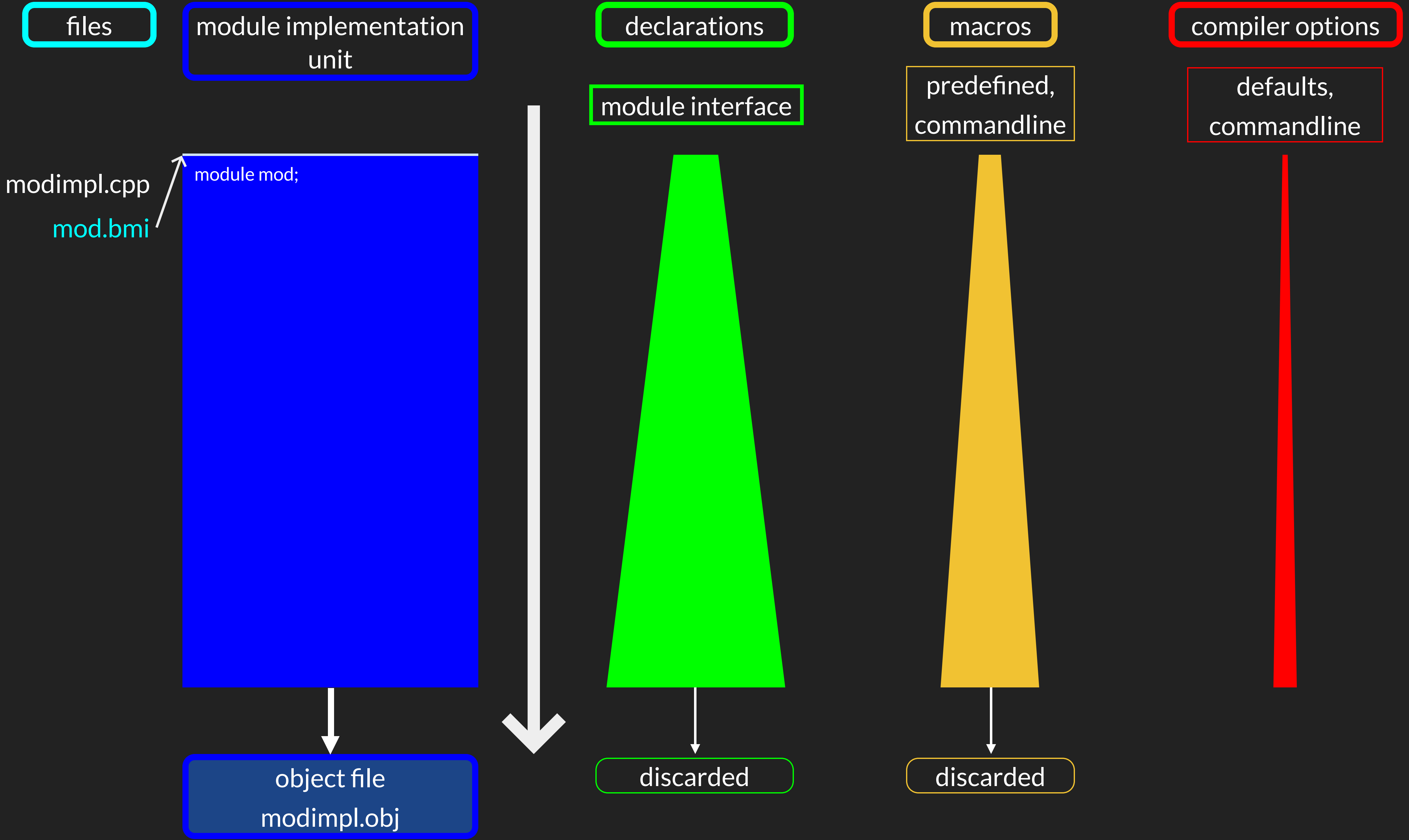
not a
namespace,
but a
separate
name
'universe'

module
implementation
units

```cpp
module my.first_module;

int foo(int x) {
  return x;
}
```

```cpp
module my.first_module;

int bar() {
  return foo(e);
}
```

all entities in the interface unit are implicitly visible in implementation units


files
module implementation unit
declarations
macros
compiler options
module interface
predefined, commandline
defaults, commandline
modimpl.cpp
mod.bmi
module mod;
object file modimpl.obj
discarded
discarded

USING THE MODULE

context sensitive

module name valid only in import declaration

import module

invisible

visible by import

```
import my.first_module;

int main() {
  foo(42); // sorry Dave!

  e = bar();
}
```

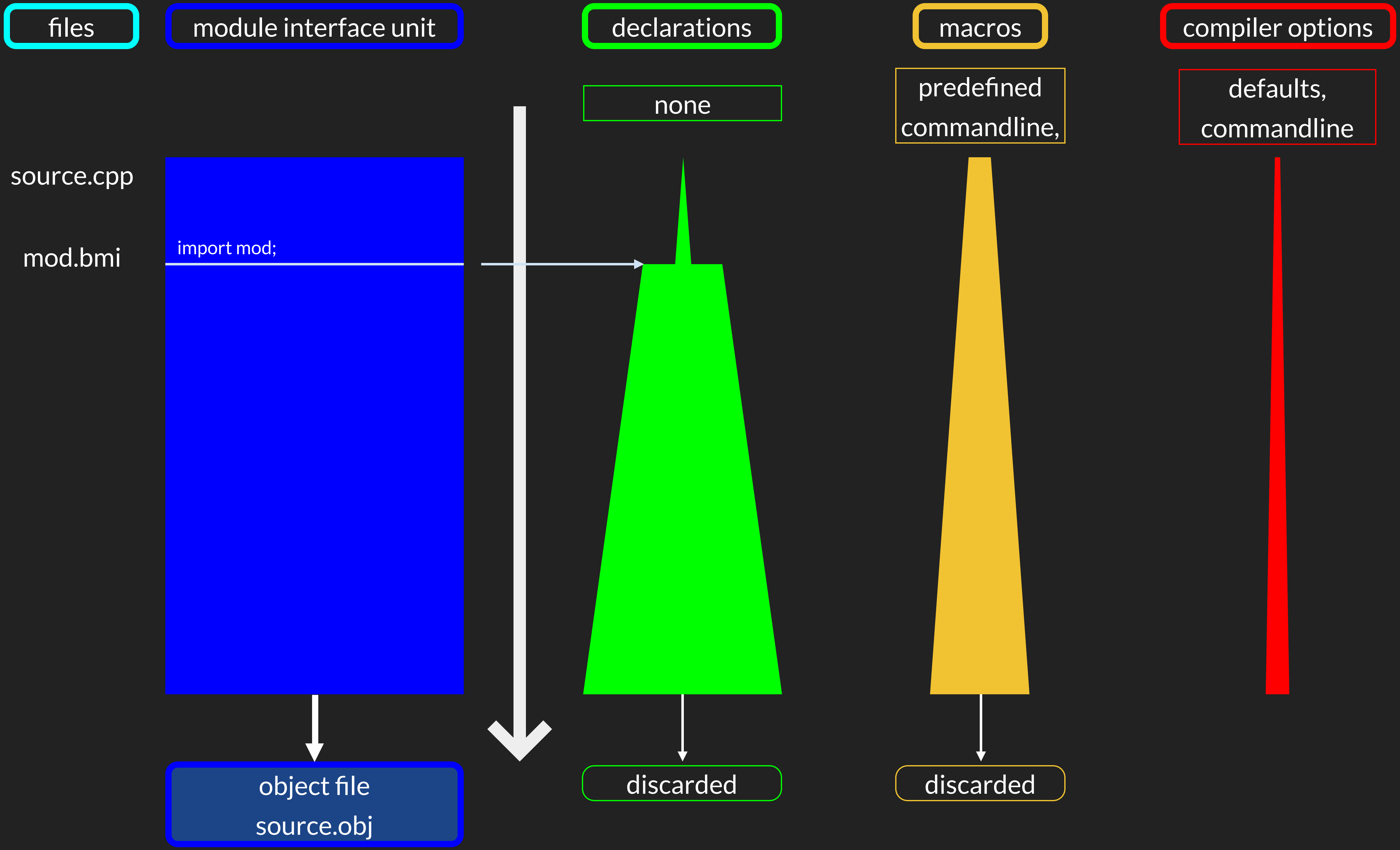
does not compile,

name 'foo' is not available for lookup

imports are cheap

imports of named modules exhibit only architected side effects

import order is irrelevant


files
module interface unit
declarations
macros
compiler options
none
predefined commandline,
defaults, commandline
source.cpp
mod.bmi
import mod;
object file source.obj
discarded
discarded

USING HEADERS

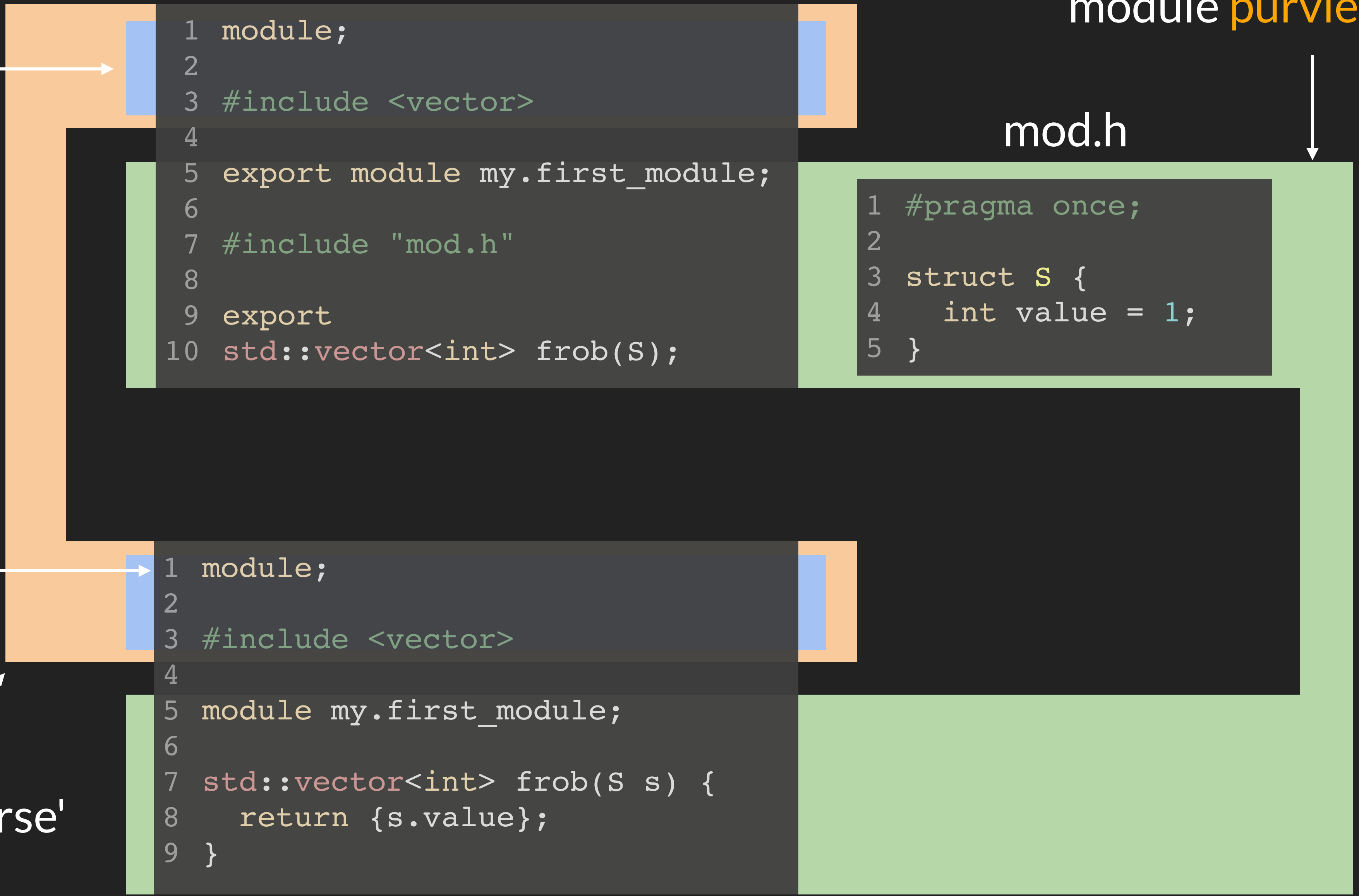
global module fragment

- no declarations
- only preprocessor directives

module declaration without a name

global module default name 'universe'

module purview



```cpp
module;

#include <vector>

export module my.first_module;

#include "mod.h"

export
std::vector<int> frob(S);
```

mod.h

```cpp
#pragma once;

struct S {
  int value = 1;
}
```

```cpp
module;

#include <vector>

module my.first_module;

std::vector<int> frob(S s) {
  return {s.value};
}
```

NAME ISOLATION

```cpp
export module my.first_module;

int foo();

export namespace A {

int bar() {
  return foo();
}

} // namespace A
```

← no clash →

same namespace ::A, exports its name and contents of this namespace part

```cpp
export module your.best_stuff;

int foo();

namespace A {

export int baz() {
  return foo();
}

} // namespace A
```

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

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

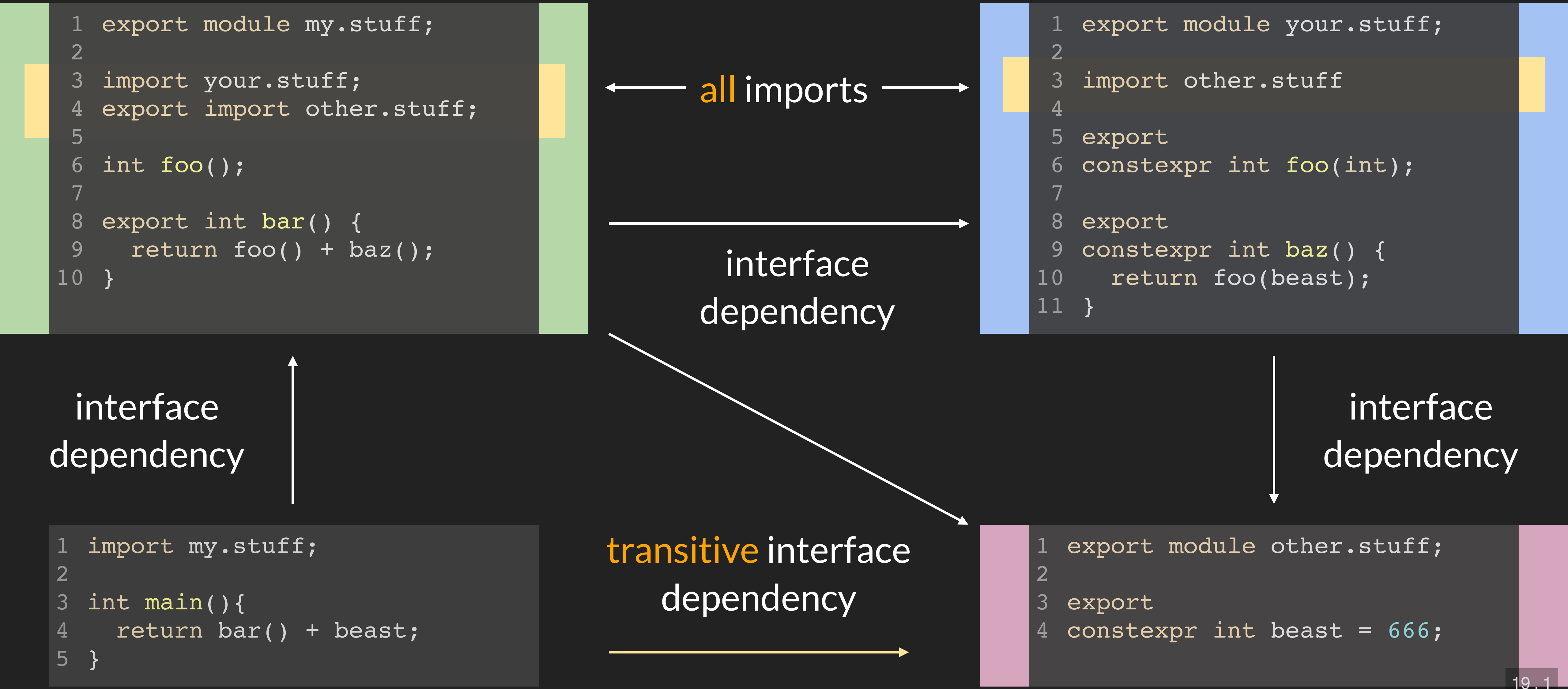
```cpp
import my.first_module;
import your.best_stuff;

using namespace A;

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

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

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

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

IMPORT & EXPORT

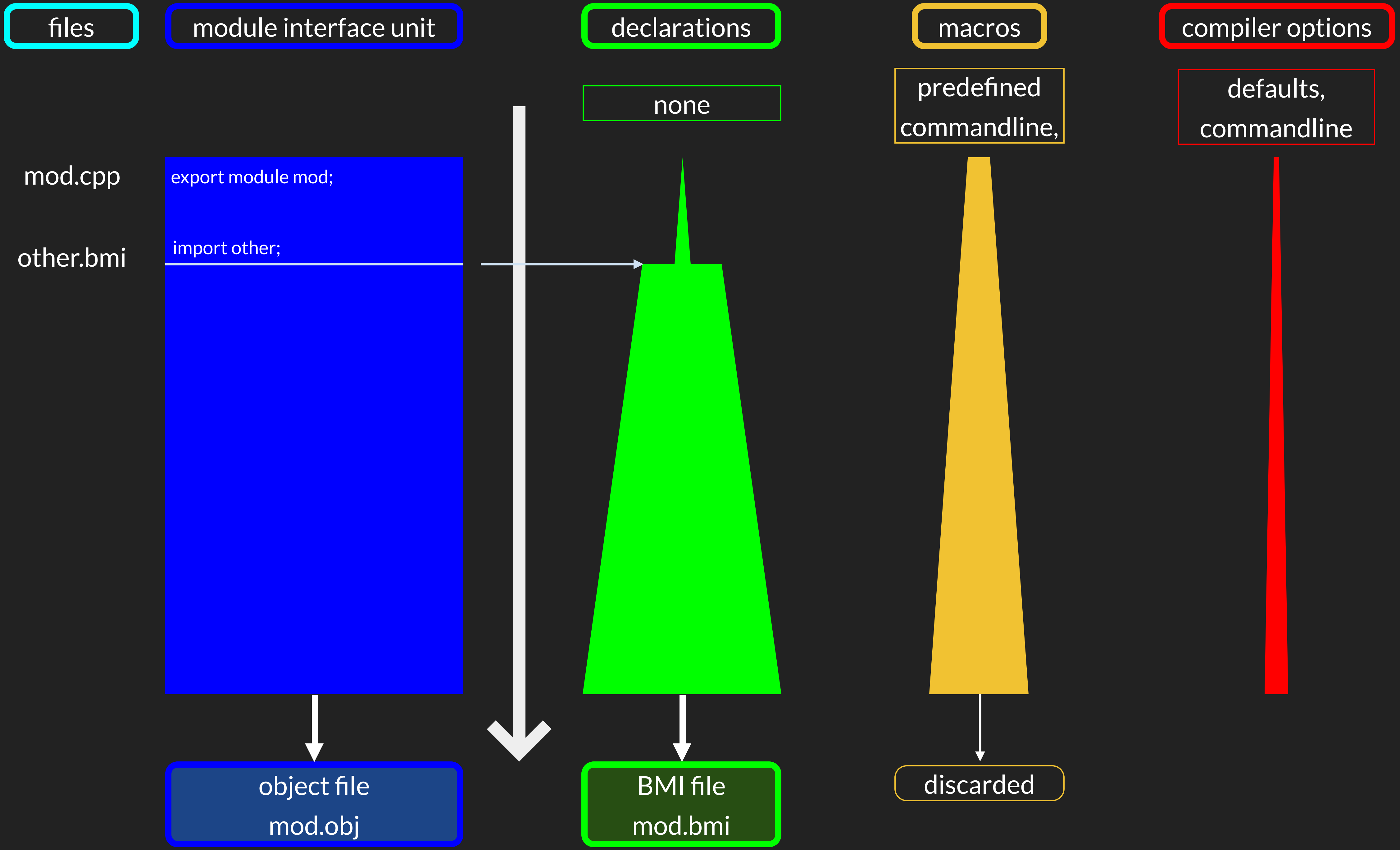


```
export module my.stuff;

import your.stuff;
export import other.stuff;

int foo();

export int bar() {
  return foo() + baz();
}
```

```
export module your.stuff;

import other.stuff

export
constexpr int foo(int);

export
constexpr int baz() {
  return foo(beast);
}
```

```
import my.stuff;

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

```
export module other.stuff;

export
constexpr int beast = 666;
```


files
module interface unit
declarations
macros
compiler options
none
predefined commandline,
defaults, commandline
mod.cpp
other.bmi
export module mod;
import other;
object file mod.obj
BMI file mod.bmi
discarded

EXPORTABLE GOODS

All kinds of C++ entities can be exported that

- have a name
- have external linkage

Corollary: names with internal linkage or no linkage cannot be exported

Names of namespaces containing export declarations are implictly exported as well

The export declaration

- must also introduce the name
- or be a using declaration eventually referring to an entity with external linkage
- includes all semantic properties known at this point

An export group must not contain declarations that cannot be exported, e.g. a static_assert or an anonymous namespace

SYNTAX GOTCHAS

comments and empty lines before module declaration are ok

```
// ok

export module my.first_module;
```

```
// ok
module;
```

-DMODULE="module"

```
MODULE my.first_module;
```

```
MODULE ;
```

doesn't compile

the module declaration must not be the result of macro expansion

-DMODULE="module ;"

```
MODULE
```

-DMODULE="export module"

```
MODULE my.first_module;
```

FIRST GUIDELINES

- think about taking advantage of the structured module naming scheme
- mirror the subparts of the module name in top-level namespaces
- think about mirroring this in the file system layout and file naming as well
- prefer a modularized standard library over standard library headers

- use #includes within the module purview very carefully — only if you really need to
- never #include standard library headers within the module purview!

```
module;

#include <standard library header>
#include "library not ready for modularization"
...

export module top.middle.bottom;

import modularized.standard.library.component;
import std; // it's probably a cheap, simple option
import other.modularized.library;
...

#include "module internal header" // beware!

non-exported declarations;
...

export namespace top {
  namespace middle {
    namespace bottom {

    exported declarations;
    ...
}}}
```

MODULES LEVEL 2

digging deeper

HIC WILLELM VENIT: BAGIAS
UBI HAROLD: SACRAMENTUM: FECIT: WILLELMO DUCI:
HIC HAROLD: DUX:
REVERSUS: EST
AD ANGLICAM: TERRAM: ET

[TAKE-OUTS]

- Visibility of names: invisible names from a foreign TU become visible by means of export and import
- Reachability of declarations: the collected semantic properties associated with exported entities along the dependency chain of imported module interface units become available to the compiler
- module linkage: like external linkage but applies to declarations in the module purview (mangling)
- language linkage: a way to re-attach names to the global module

```cpp
auto make() {
  // the semantic properties
  // of struct S are reachable
  // from the point of its
  // declaration

  struct S{ int i = 0; };
  return S{};
}

static_assert(
  is_default_constructible_v<
    decltype(make())>);
```

```cpp
module mine;

extern "C++" int foo(); // external linkage, C++ language linkage, attached to global module
extern "C" int var;     // external linkage, C language linkage,   attached to global module

int bar(); // module linkage, C++ language linkage, attached to module 'mine'
int jot;   // module linkage, C++ language linkage, attached to module 'mine'
```

MO' MODULES

the C++20 additions

HIC EADWARDVS:REX
IN LECTO:ALLOQVIT:FIDELES:
REGE
HIC PORTATVR:CORPVS:EADWARDI:REGIS:AD:ECCLESIAM:SCI
PETRI APLI
ET HIC: DEFVNCTVS EST
HIC DEDERVNT:HAROLDO:CORONA:REGIS
HIC RESIDET:HAROLD REX:ANGLORVM:
STIGANT ARCHIEPS

[TAKE-OUTS]

Refined types of module TUs specified in the C++20 draft:

- module interface partitions: must be re-exported through the primary module interface unit
- module implementation partitions: these do not implicitly import the primary interface unit
- the private module fragment: available only in case of single-file modules

These module unit types are currently mostly not available in implementations

HEADER MODULES

Header modules are generated from header files without tampering them:

- compiled through compilation phases 1 … 7 like a normal source file
- all declarations are implicitly exported
- all declarations are attached to the global module
- must not contain a module declaration
- do not have a module name
- export their macro definitions and deletions from the end of translation phase 4
- taint translation phase 4 of the importing translation unit beyond the point of the import declaration until the end of the TU

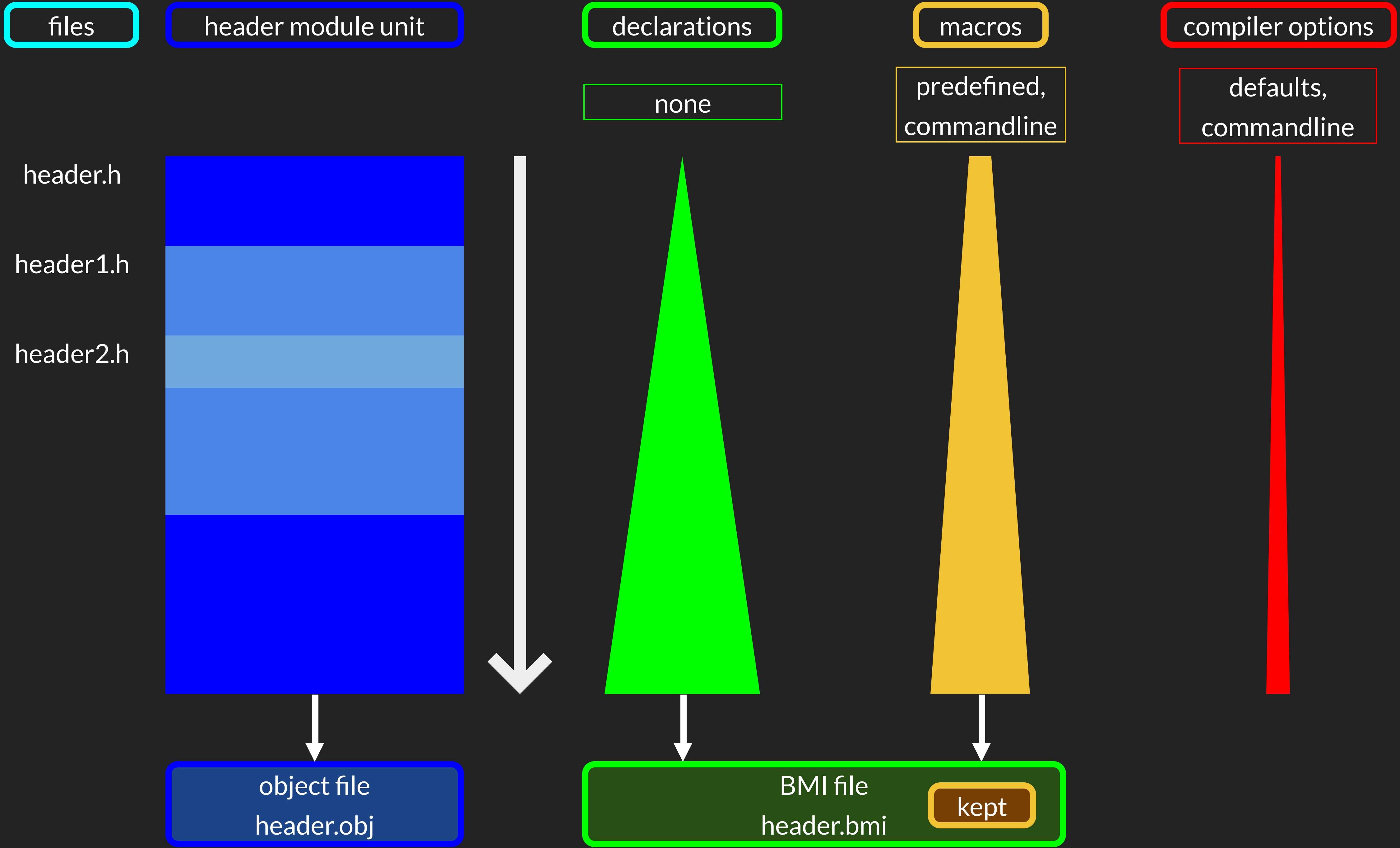
```cpp
#include <vector>
#include "importable.h"
```

$\xrightarrow{\text{manual}}$

```cpp
import <vector>;
import "importable.h";
```

$\leftarrow$ no module name

The import of an unnamed header file requires special syntax: the BMI of the compiled header module is nominated like an #include nominates a header file


files
header module unit
declarations
macros
compiler options
none
predefined,
commandline
defaults,
commandline
header.h
header1.h
header2.h
object file
header.obj
BMI file
header.bmi
kept

SANE PRECOMPILED HEADERS

Header modules have the same properties as precompiled headers:

- make all of their declarations visible in the importing TU like the equivalent #includes do
- affect macro definitions in the importing TU like the equivalent #includes do

The benefits of importing header modules over including header files:

- importing compiled declarations is faster — like precompiled headers
- limited isolation: the compilation context is not affected by the point of #include

But beware:

- header guards have no effect on the compilation of a header module!

LIMITATIONS OF HEADER MODULES

Not every header file can be compiled into a header module, only so called "importable headers" can

- the definition of an importable header and the resulting set of importable headers is implementation defined
- the C++ standard guarantees that all standard library headers — but not the wrapped C ones — are importable headers
- other header files can be assumed to be accepted as importable headers by an implementation if they behave reasonably well (e.g. no X-macros)

- Compiling importable headers into header modules requires special incantations of the compiler
- nominating header modules in import declarations with #include syntax require support from the build system to locate the BMIs

ONE MORE THING

The C++ standard allows special support for header modules

- in case of C++ standard standard library headers — and only those —
- #include directives are automatically turned into import declarations nominating the same C++ standard library header

```cpp
#include <vector>
#include <string>
```

$\xrightarrow[\text{implicit}]{}$

```cpp
import <vector>;
import <string>;
```

- the support of this functionality is an optional feature of an implementation
- if available, it offers immediate benefits without changing the code base at all

🤩 this is probably the 😎 feature of header modules 😀

PITFALLS

beware!

+HIC: WILLELM: DUX INMAGNO: NAVIGIO: MARE TRANSIVIT ET VENIT AD PEVENESÆ:

THINGS TO TAKE CARE OF

- mistaking module names as namespace names — modules do not establish a namespace
- calls from exported inline function bodies that call into functions with internal linkage that are not available in the importing TU
  - exported inline functions
  - inline member functions from exported classes
- incomplete treatment of module interface units as translation units
  - missing compilation into an object file
  - missing linking the object file into the final program
- precompiled headers or force-included headers (/FI or -include) may no longer be available due to syntactic restrictions
- semantic deviations because of compiler bugs (transitional)

IMPLEMENTATION STATUS

bumpy roads ahead ...

HIC:COQVITVR:CARO
ET HIC: MINISTRAVERVNT
MINISTRI
HIC FECERVNT: PRANDIVM:
ET HIC EPISCOPVS:CIBV:ET POTV: BENEDICIT
ODO:EPS:
WILLELM:
ROTBERT:
ISTE IVSSIT: VT FODERETVR:CASTELLVM:AT:HESTENGA CEASTRA

LANGUAGE / LIBRARY FEATURES

	gcc (branch)	clang	msvc
Syntax specification	C++20	<= 8.0: Modules TS >= 9.0: TS and C++20	<= 19.23: Modules TS >= 19.24: C++20 ⚠
Named modules	✅	✅	✅
Module partitions	✅	⛔	⛔
Header modules	❎ (undocumented)	❎ (undocumented)	❎ (undocumented)
Private mod. fragment	⛔	✅ (in C++20 mode)	⛔
Name attachment	(✅)	(✅)	⛔
#include → import	⛔	⛔	⛔
__cpp_modules	201810L ⚠	⛔	⛔
Modularized std library	⛔	⛔	(✅)

BUILD SYSTEMS

Build systems with support for modules are rare

- build2
  - supports clang, gcc, and msvc
  - predefines macro __cpp_modules
- more ?

FROM HEADER TO MODULE

A reality check

ET·VENERVNT
AD PRELIVM: CON TRA: HAROL DVM:REGE: HIC: V VILLELM:DVX INTERROGAT:VITAL: ASIVI DISSET EXER CI TV
HAROLDI

CONVERTING AN EXISTING LIBRARY

Use a library from our in-house production codebase and check out what it takes to transform it into a named module.

Library "libGalil":

- wraps and augments a vendor provided C-library that implements low-level network communication with its 'Digital Motion Controller'
- adds higher level functions and error handling on top of it

CONVERTING AN EXISTING LIBRARY

- the OEM provides 2 headers, a link library and a DLL
- we add 4 more headers and 2 source files

The consumable artifacts after compiling the 2 source files are

- a static library
- a single header file with the C++ API

The actual interface is a single class plus some enums within a unique namespace.

THE HEADER API

The header "DmcDevice.h" exposing the API looks quite unsuspicious ...

```
#pragma once
#include <boost/asio/ts/net.hpp>
#include <boost/filesystem/path.hpp>
#include <boost/signals2.hpp>
#include <meerkat/semaphores.hpp>
#include <atomic>
#include <chrono>
#include <memory>
#include <string>
#include <string_view>
#include <system_error>
#include <vector>

namespace libGalil {

... // some enums used in member function parameters and return values

namespace detail {
... // 2 small classes used as non-static data members in the class below
}

class DmcDevice {
...
};
}
```

THE MODULE API

Turn this into the primary module interface unit "DmcDevice.cpp" of module "libGalil"

```
module;                  // the global module fragment starts here
#include <boost/asio/ts/net.hpp>
#include <boost/filesystem/path.hpp>
#include <boost/signals2.hpp>
...
#include <string>
#include <string_view>
#include <system_error>
#include <vector>
                         // the global module fragment ends here
export module libGalil;  // the module purview starts here

namespace libGalil {     // entity 'namespace libGalil' implicitly exported
export {                 // make enums visible outside of module
... // some enums used in member function parameters and return values
}

namespace detail {       // not mentioned anywhere in the exported entities
...                      // totally hidden
}

export class DmcDevice { // make class name visible
...                      // and its contents reachable
};
}
```

BUILD THE BMI

Compile the primary module interface just like any other translation unit. Depending on the compiler this might require compiler flags to nudge it to treat the source file as an module interface.

MSVC 14.24 greeted me with this:

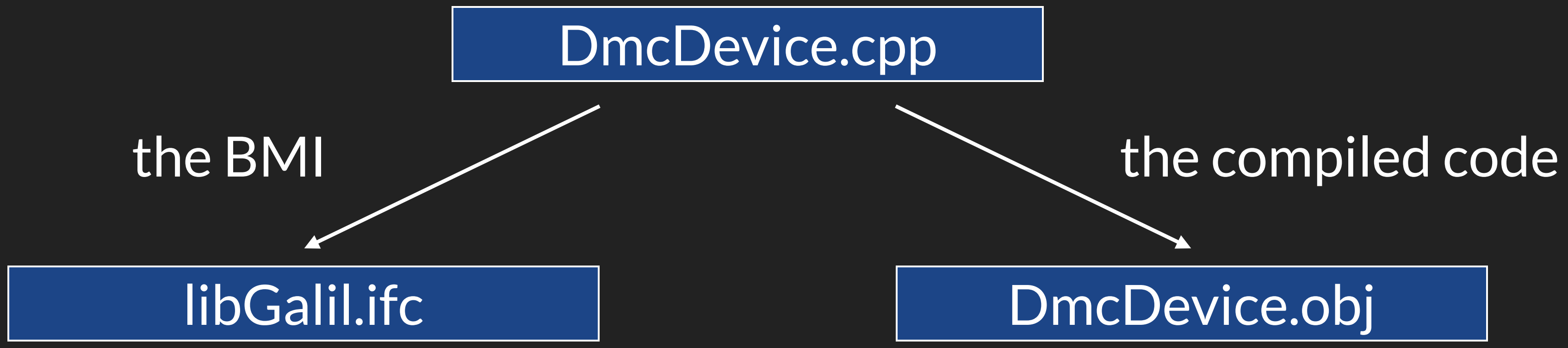
```
DmcDevice.cpp(295,1): fatal error C1001: An internal error has occurred in the compiler.

DmcDevice.cpp(295,1): fatal error C1001: (compiler file 'msc1.cpp', line 1523)

DmcDevice.cpp(295,1): fatal error C1001:  To work around this problem, try simplifying or changing the

program near the locations listed above.

...

DmcDevice.cpp(295,1): fatal error C1001: INTERNAL COMPILER ERROR in 'C:\...\CL.exe'

Done building project "libGalil.vcxproj" -- FAILED.
```

At least it processed the source up to the last line, Clang 10 didn't even get that far.

BUILD THE BMI (TAKE 2)

As it turns out, there is some problem in a Boost library that both Boost.Filesystem and Boost.Signals2 depend on.

After modifying two member functions in a functionally identical or equivalent way I got rid of both Boost library includes, and at least MSVC compiles the module interface unit.



BUILD THE IMPLEMENTATION

As before, transforming the source file "DmcDeviceImpl.cpp" into a module implementation unit is straight-forward:

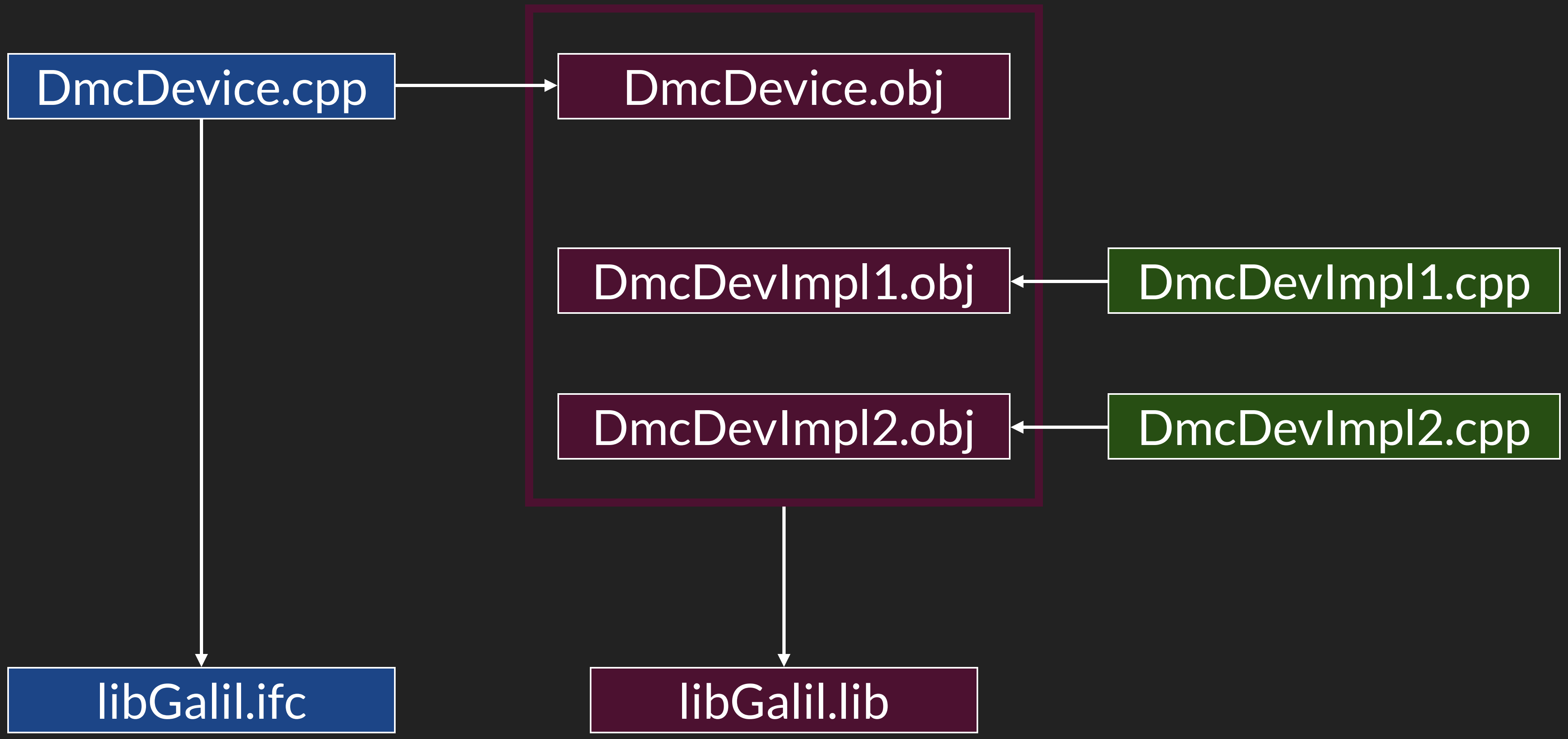
```
#include "DmcDevice.h"

#include "gclibo.h"
#pragma comment(lib, "gclib")

#include "expected.h"
#include <boost/signals2/signal.hpp>
#include <boost/algorithm/string.hpp>
#include <boost/filesystem.hpp>
#include <boost/filesystem/fstream.hpp>
#include <boost/asio/ts/net.hpp>
#include <fmt/format.h>
#include <meerkat/ping.hpp>
#include <meerkat/makeIpEndpoint.hpp>
#include <algorithm>
#include <cassert>
#include <chrono>
#include <memory>
#include <system_error>

... lots of code
```

BUILD THE IMPLEMENTATION

just declare the global module fragment and the module itself

```
module;                        // the global module fragment starts here
                               // the import of the module interface is implicit!
#include "gclibo.h"
#pragma comment(lib, "gclib")

#include "expected.h"
#include <boost/signals2/signal.hpp>
#include <boost/algorithm/string.hpp>
#include <boost/filesystem.hpp>
#include <boost/filesystem/fstream.hpp>
#include <boost/asio/ts/net.hpp>
#include <fmt/format.h>
#include <meerkat/ping.hpp>
#include <meerkat/makeIpEndpoint.hpp>
#include <algorithm>
#include <cassert>
#include <chrono>
#include <memory>
#include <system_error>
                               // the global module fragment ends here
module libGalil;               // the module purview starts here

... lots of code
```

BUILD THE LIBRARY



USE THE MODULE

```cpp
#include <libGalil/DmcDevice.h>

int main() {
  libGalil::DmcDevice("192.168.55.10");
}
```

457440 lines after preprocessing

151268 non-blank lines

1546 milliseconds to compile

becomes

```cpp
import libGalil;

int main() {
  libGalil::DmcDevice("192.168.55.10");
}
```

5 lines after preprocessing

4 non-blank lines

62 milliseconds to compile

The compile time was taken on a Intel Core i7-6700K @ 4 GHz using msvc 19.24.28117, average of 100 compiler invocations after preloading the filesystem caches.

The time shown is the **additional** time on top of compiling an empty main function.

TRANSITIONING TO MODULES

My Assessment

THE PROS

Immediate benefits:

- improved control over API surfaces, better isolation
- improved control over overload-sets
- improved control over argument dependent lookup
- lower probability of unconscious one-definition rule violations
- no macros intruding from other source code
- no macros escaping into other source code
- smaller compilation context
- better local reasoning about source code

Future benefits:

- new tooling opportunities
- improved compile times, faster development cycles
- increased developer satisfaction

THE CONS

Current roadblocks:

- limited compiler availability
- limited feature support
- limited compiler stability
- major implementation bugs
- mostly missing modularized standard library implementations
- severely limited support by build systems
- hardly any support in IDEs or code editors
- all but missing documentation

Long-term costs:

- longer build-dependency chains

MY RECOMMENDATIONS

- start experimenting with simple examples to get familiar with the new syntax and features
- stick with the feature set as described in the Modules TS (i.e. no module partitions, no header modules) before exploring the less-well supported C++20 module language features
- use the C++20 syntax from the beginning
- use a simple build tool like 'make' (or even simpler) to start with as little friction as possible
- or use a build system with support for modules (e.g. build2) to focus your efforts on learning modules rather than fighting with the build environment
- be prepared to run into problems with your compiler. There will be crashes, miscompiles, or even totally misleading compiler messages
- be resilient to frustration and persevere
- feel happy while becoming confident in using modules as a great language feature to structure your codebase and manage API surfaces

RESOURCES

Papers

- Modules in C++, 2004, Daveed Vandevoorde
- Modules, 2012, Doug Gregor
- A Module System for C++, 2014, Gabriel Dos Reis, Mark Hall, Gor Nishanov
- C++ Modules TS, 2018, Gabriel Dos Reis
- Another take on Modules, 2018, Richard Smith
- Merging Modules, 2019, Richard Smith
- C++20 Draft

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Images: Bayeux Tapestry, 11th century, world heritage

source: WikiMedia Commons, public domain

QUESTIONS?

Ceterum censeo ABI esse frangendam

VISIBILITY OF NAMES

- as soon as a named entity is declared within a given scope, it may become subject to name lookup
- name lookup finds only names that are visible, i.e. the name is not hidden
- the visibility of a particular named entity is not a static property but the result of
  - the point and scope of its first declaration
  - the point and scope from where it is looked-up
  - the lookup rules
    - regular, unqualified lookup
    - qualified lookup
    - argument dependent lookup

```cpp
auto make() {
  // struct S has no linkage
  // name 'S' is invisible
  // from other scopes
  struct S{ int i = 0; };
  return S{};
}
```

- without modules, total invisibility of entities with linkage is impossible
- moving declarations from headers into modules makes them totally invisible
- exporting names from a module and importing them controls the extent to which names become visible in the importing translation unit

REACHABILITY OF DECLARATIONS

the reachability of a declaration is orthogonal to the visibility of the declared name

- each visible declaration is also reachable
- not all reachable declarations are also visible

```cpp
auto make() {
  // the semantic properties
  // of struct S are reachable
  // from the point of its
  // declaration
  struct S{ int i = 0; };
  return S{};
}

static_assert(
  is_default_constructible_v<
    decltype(make())>);
```

the set of semantic properties associated with a reachable declaration depends on the point within a TU

- after the declaration
- after the definition

when a named entity is exported from a module, then

- the name becomes visible
- the declaration becomes reachable with the set of properties known at this point
- all declarations referred to from the exported declaration become reachable, too!

LINKAGE

linkage determines the relationship between named entities within scopes of

- a single translation unit
- multiple translation units

non-modular C++ knows three kinds of linkage

- no linkage: entities at function block scope are not related to any other entities with same name. They live in solitude within this scope
- internal: entities at namespace or class scope that are not related to any entities with the same name in other TUs. There may be multiple of them in the program
- external: entities that are related to entities with the same name in all other TUs. They are the same thing and there is only one incarnation in the final program

Modules add a fourth kind of linkage

- module linkage: effectively the same as external linkage, but confined to TUs of the same module

MODULE LINKAGE

module linkage

- applies to names attached to named modules
- requires different mangling of linker symbols
- exhibits the same linker behavior as external linkage does to linker symbols from names attached to the global module

therefore, each named module opens a new, separate linker symbol domain

- external-linkage names attached to the global, unnamed module are decorated with no additional name part
- module-linkage names attached to a named module become decorated with an additional name part derived from the module name

LANGUAGE LINKAGE

C++ knows two kinds of language linkage that apply to function types, functions and variables with external linkage

- C++ language linkage — this is the default
- C language linkage

the language linkage affects (at least) the mangling of external-ish names

in addition to that, declarations within a linkage specification in the purview of a module attach the declared names to the global module

```cpp
module mine;

extern "C++" int foo(); // external linkage, C++ language linkage, attached to global module
extern "C" int var;     // external linkage, C language linkage,   attached to global module

int bar(); // module linkage, C++ language linkage, attached to module 'mine'
int jot;   // module linkage, C++ language linkage, attached to module 'mine'
```

MODULE PARTITIONS

module partition → contributing to interface

- must be exported through the primary module interface unit
- may be imported into other TUs of this module

```cpp
export module my.stuff : part;

export {
  template <typename T>
  struct S {
    S(T x) { /* ... */ }
    operator int() const { /* ... */ }
  };

  int func(auto x) { return S{x}; }
}
```

← partition name must be unique within module

primary module interface →

- constitutes the full module interface

```cpp
export module my.stuff;

export import : part;

export
int foo();
```

← no module name

MODULE PARTITIONS

module partition not contributing to interface

- not visible outside of module
- may be imported into other TUs of this module
- do not implicitly import the module interface
- may replace module-internal #includes

```cpp
module my.stuff : forward;

template <typename T>
struct S;
```

partition names must be unique within module

```cpp
module my.stuff : impl;

import : forward;

template <typename T>
struct S {
  S(T x) { /* ... */ }
  operator int() const { /* ... */ }
};
```

no module name

PRIVATE MODULE FRAGMENT

module interface partition →

- must be the only, single translation unit of this module

private module fragment →

- no exports
- definitions not reachable from outside of module

```cpp
export module cute.little.skunk;

template <typename T>
struct S {
  S(T x) { /* ... */ }
  operator int() const {
    return foo(*this);
  }
};

module : private;

int foo(auto x) {
  // do something with x
  // resulting in y
  return y;
}
```

← partition name

must be 'private'

COMPATIBILITY (BONUS)

Add a shim header "DmcDevice.h" like this after renaming the 'old' header file:

```cpp
#pragma once
#if __cpp_modules >= 201907
import libGalil;
#else
#include "DmcDevice.hh"
#endif
```

Now, all users of the library will benefit from modularization as soon as their compiler is capable of C++ modules even without any code changes.

```cpp
#include <libGalil/DmcDevice.h>

int main() {
  libGalil::DmcDevice("192.168.55.10");
}
```