NVIDIA

MODULES ARE COMING

Bryce Adelstein Lelbach

@blelbach

CUDA C++ Core Libraries Lead

ISO C++ Library Evolution Incubator Chair, ISO C++ Tooling Study Group Chair

#include <C++>

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MODULES ARE COMING

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CUDA C++ Core Libraries Lead

ISO C++ Library Evolution Incubator Chair, ISO C++ Tooling Study Group Chair

Modules are:

- A new compilation model for C++.
- A new way to organize C++ projects.

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Textual Inclusion

math.hpp

```
#pragma once

int square(int a);
```

math.cpp

```
#include “math.hpp”

int square(int a) { return a * a; }
```

main.cpp

```
#include “math.hpp”

int main() { return square(42); }
```

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Textual Inclusion

math.hpp

```
#pragma once

int square(int a);
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math.cpp

```
#include “math.hpp”

int square(int a) { return a * a; }
```

main.cpp

```
#include “math.hpp”

int main() { return square(42); }
```

Modular Import

math.cppm

```
export module math;

export int square(int a);
```

math.cpp

```
module math;

int square(int a) { return a * a; }
```

main.cpp

```
import math;

int main() { return square(42); }
```

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Modules will have a greater impact than any other feature added post C++-98.

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C++11's <thread> changes how…

… C++ code is written

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C++11's lambdas change how…

… C++ code is written

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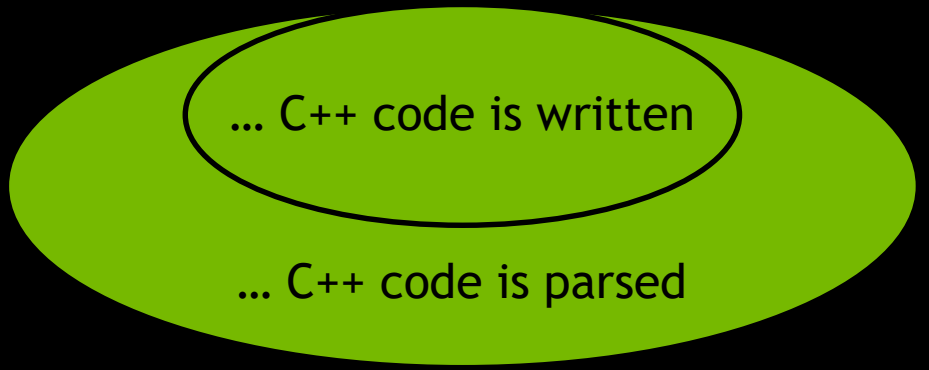
C++11's lambdas change how…



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C++20's modules change how…

… C++ code is written

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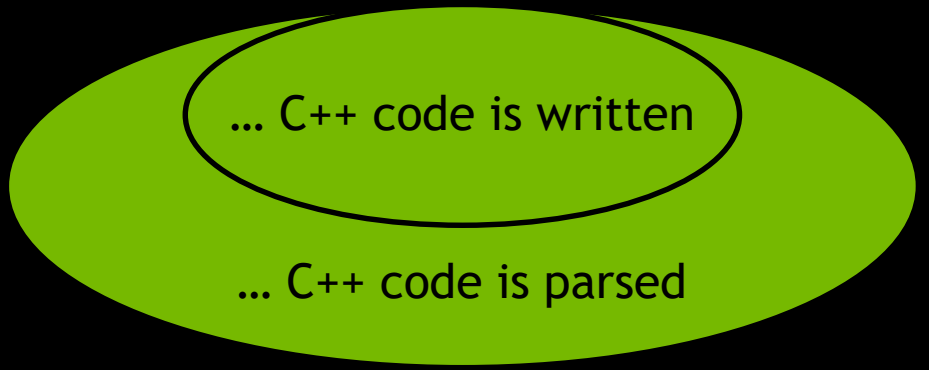
C++20's modules change how…



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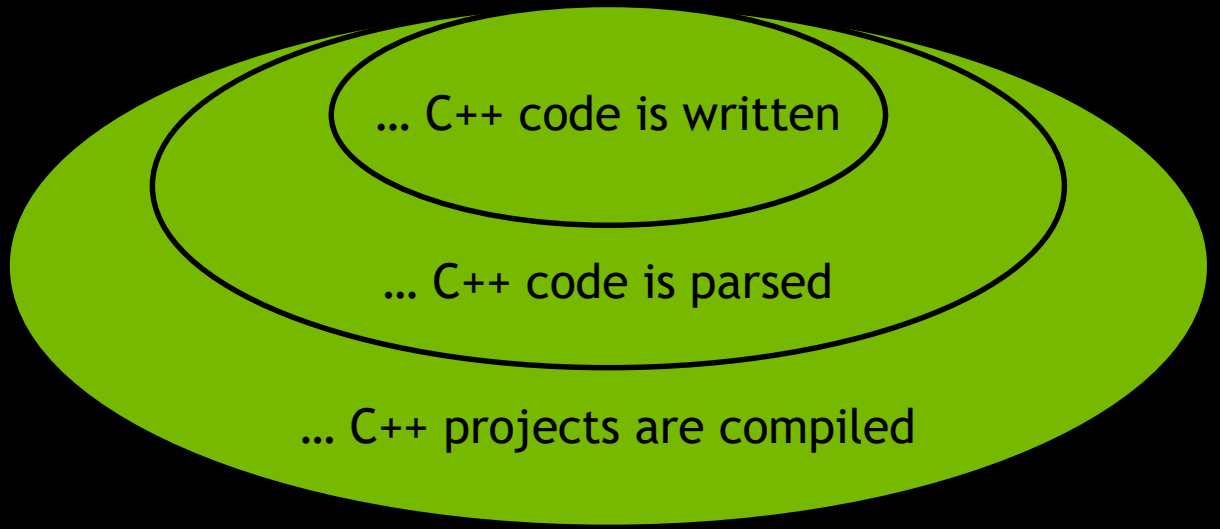
C++20's modules change how…



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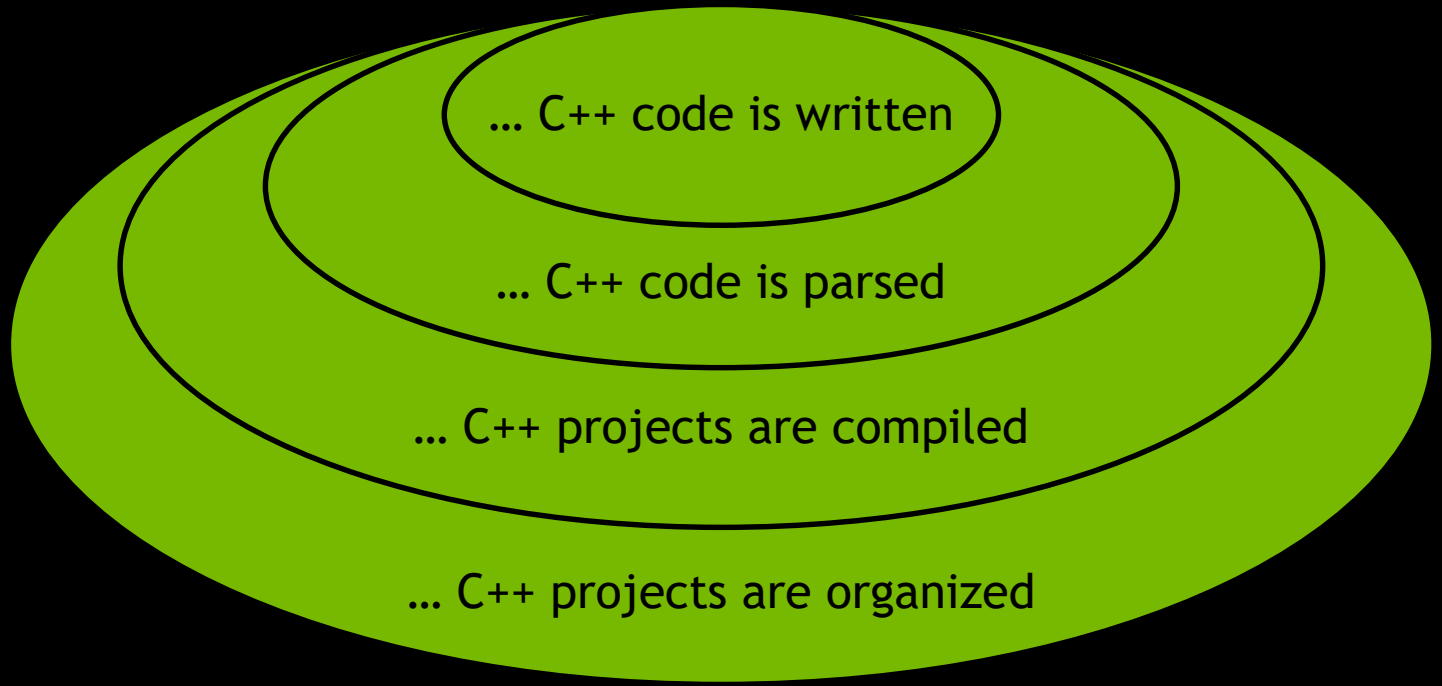
C++20's modules change how…



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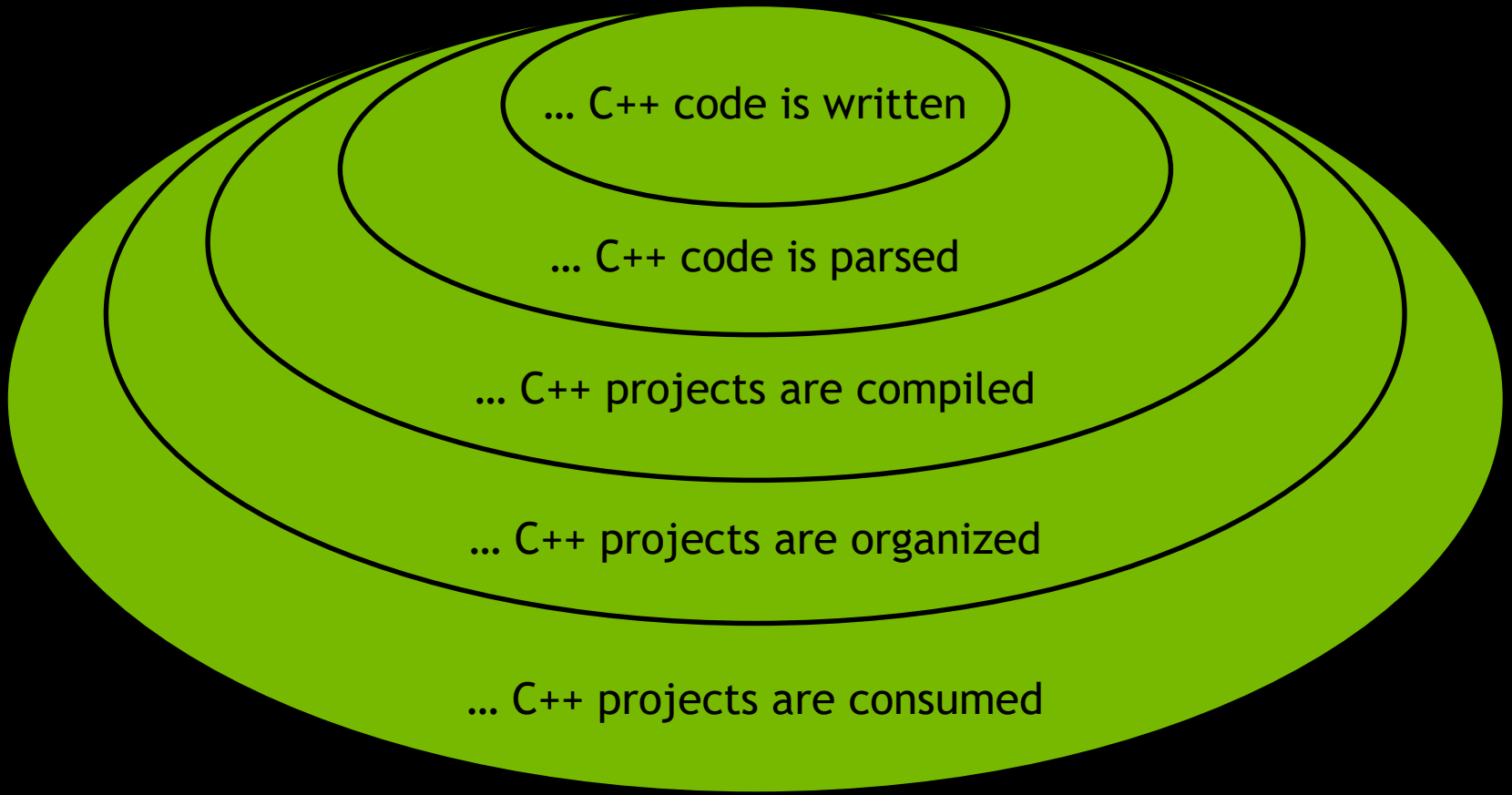
C++20's modules change how…



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Modules will have a greater impact than any other feature added post C++-98.

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Today's Compilation Model

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What is C++’s compilation model today?

How do we organize C++ projects today?

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“The text of the program is kept in units called ***source files*** in this International Standard.”

[lex.separate] p1 s1

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"A source file together with all the headers and source files included via the preprocessing directive `#include`, less any source lines skipped by any of the conditional inclusion preprocessing directives, is called a ***translation unit***."

[lex.separate] p1 s2

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Kinds of Translation Units

	Example	Extension	Artifact	Notes
Non-Modular Unit	`#include "…"` …	`.cpp`	`.o`	

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"A ***program*** consists of one or more *translation units* linked together."

[basic.link] p1 s1

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“Previously translated *translation units* and instantiation units can be preserved individually or in libraries.”

[lex.separate] p2 s1

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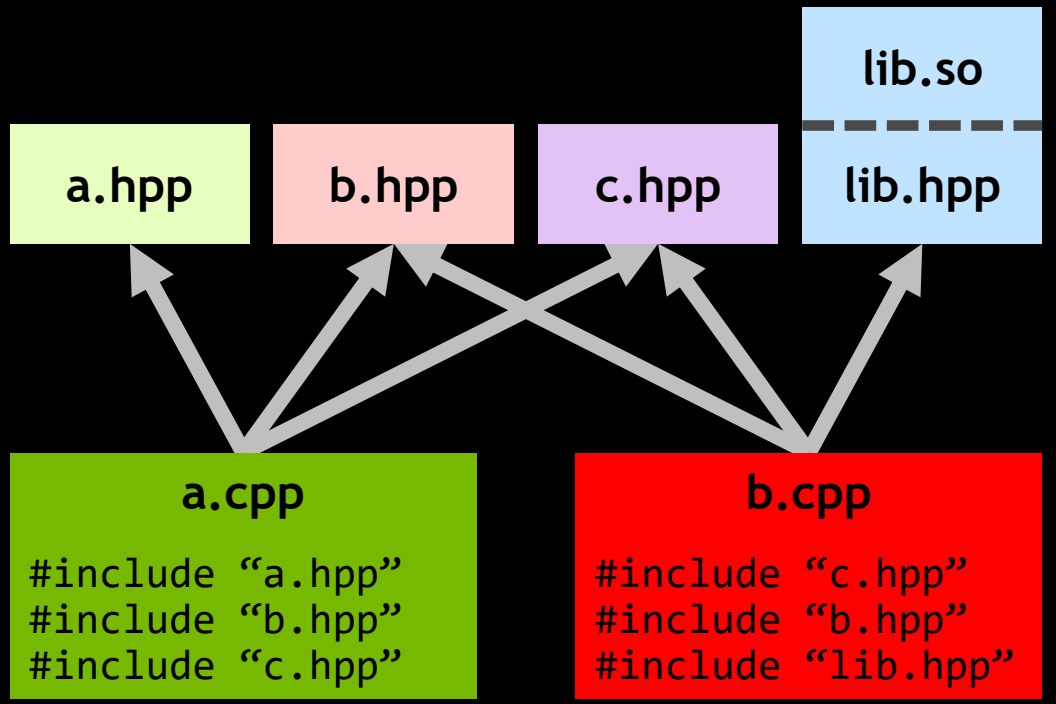
Textual Inclusion: Preprocess



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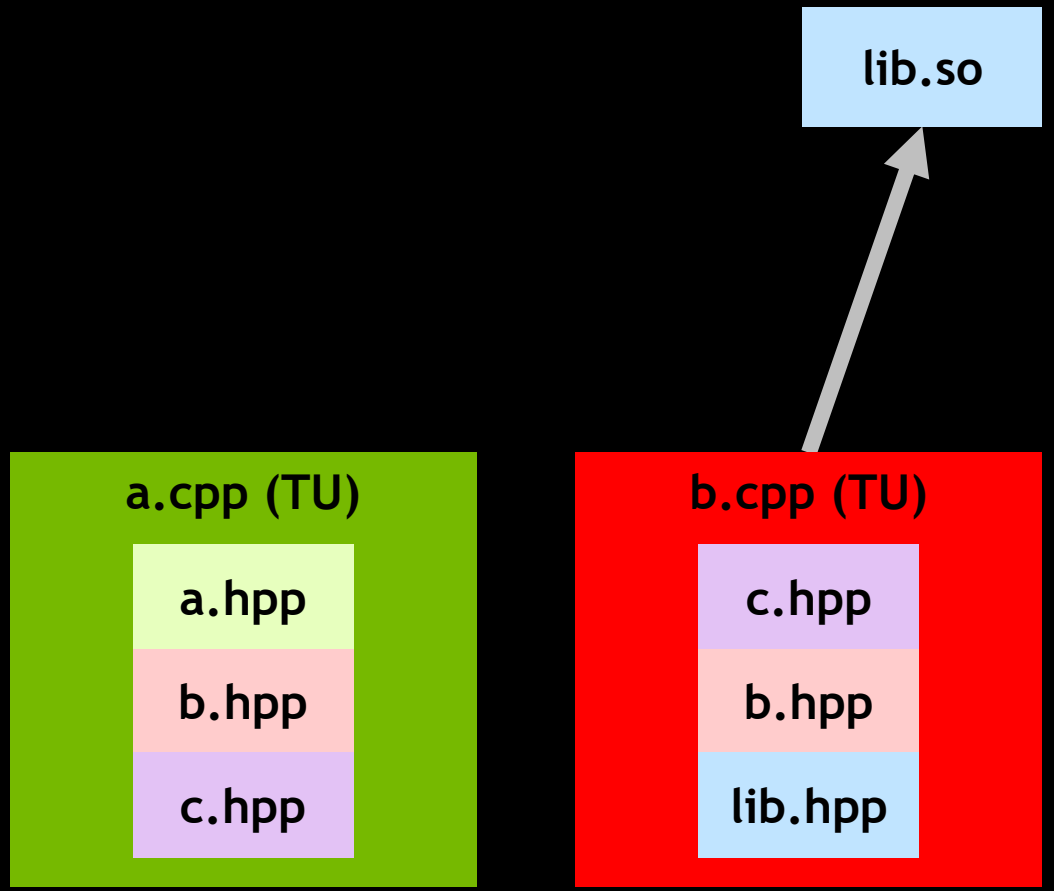
Textual Inclusion: Compile



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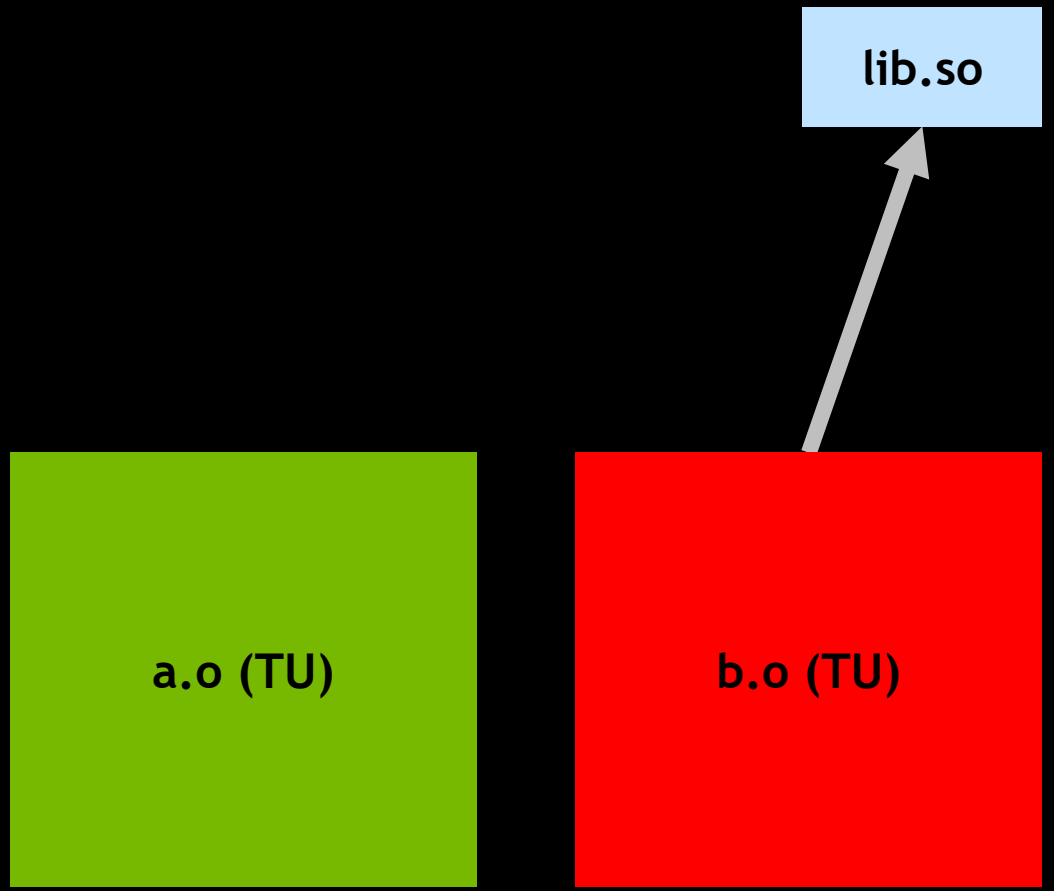
Textual Inclusion: Link



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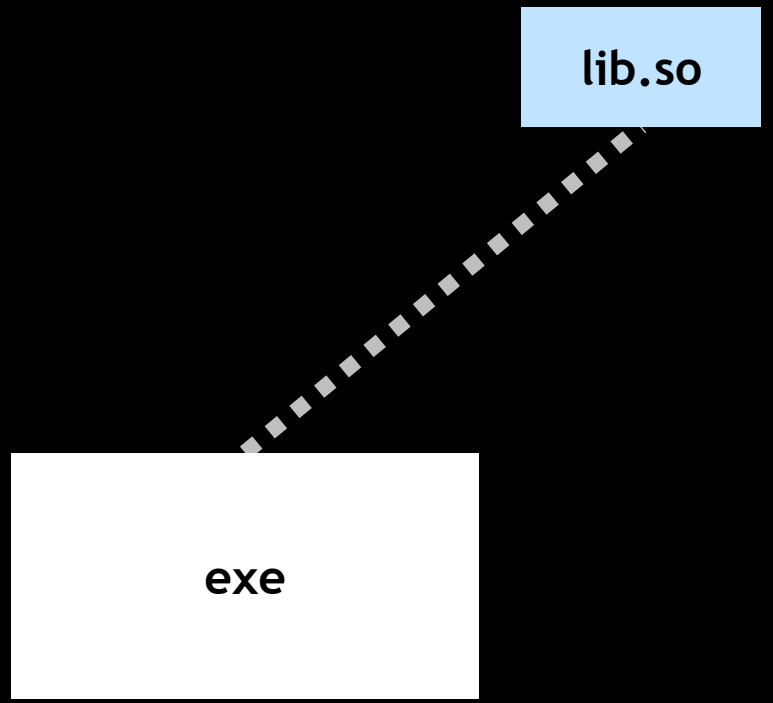
Textual Inclusion



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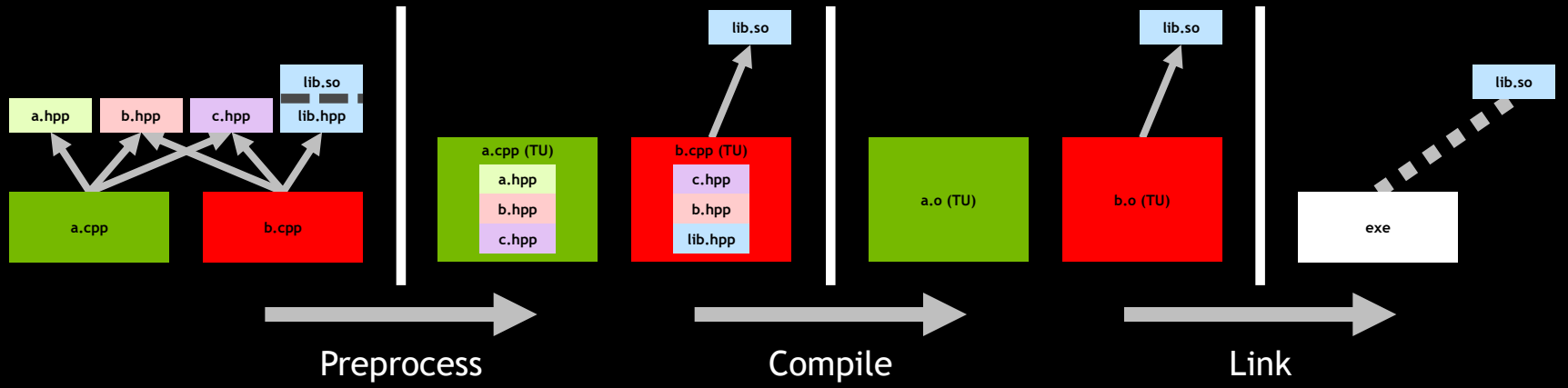
Textual Inclusion



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`#include` is problematic:

- Slow to compile.
- ODR violations.
- Lack of encapsulation.
- Cyclic dependencies.
- Order dependent.

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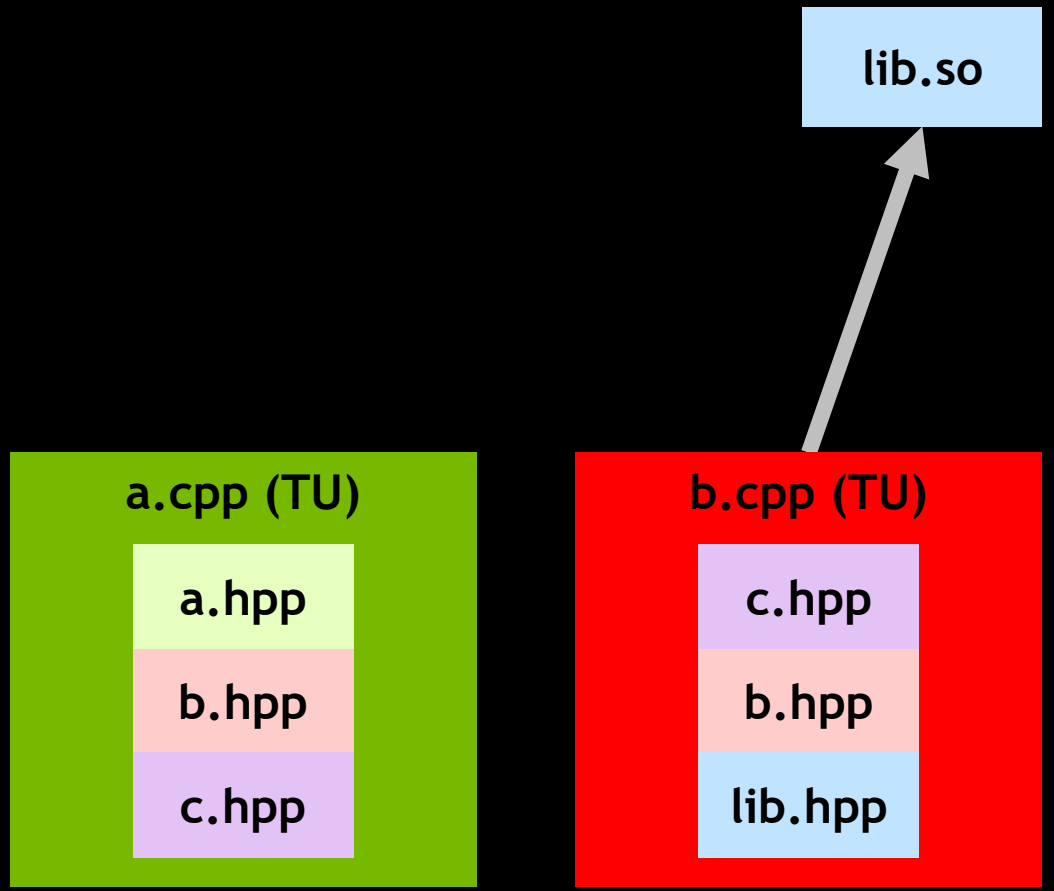
Textual Inclusion: Compile



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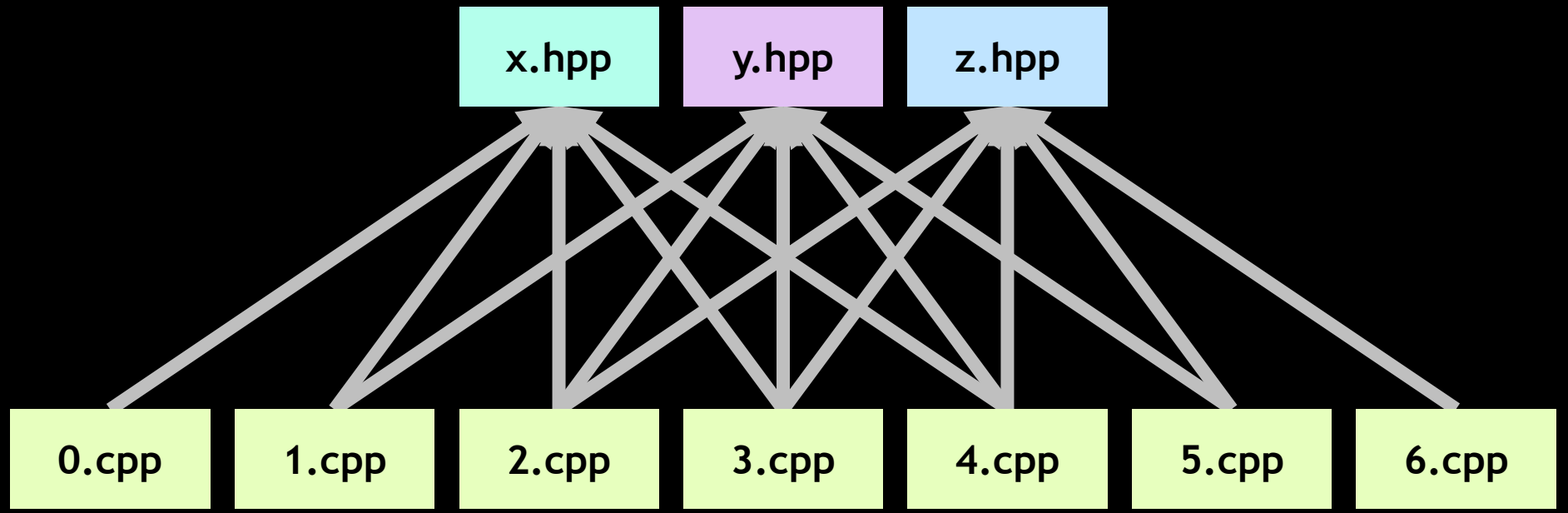
Textual Inclusion



Pro: Embarrassingly parallel.

Con: x.hpp, y.hpp, and z.hpp are compiled 7 times.

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`#include` is problematic:

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“There can be more than one definition of [an entity] in a program provided that no prior definition is necessarily reachable at the point where a definition appears, and provided the definitions satisfy the following requirements …”

[basic.def.odr] p12

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Ill formed, no diagnostic required

(IFNDR)

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tree_node.hpp

```
#pragma once

template <typename T>
struct tree_node {
  T value;
  std::vector<tree_node*> children;
 #ifdef DEBUG
  tree_node* parent;
 #endif
};
```

a.cpp

```
#define DEBUG
#include “tree_node.hpp”

// …
```

b.cpp

```
#include “tree_node.hpp”

// …
```

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`#include` is problematic:

- Slow to compile.
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- Cyclic dependencies.
- Order dependent.

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a.hpp

```
#pragma once

namespace c {
 struct A {
  private:
   template <typename T>
   void impl();
 };

 namespace detail::unsupported {
  template <typename T>
  void __please_dont_use();
 }
}
```

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`#include` is problematic:

- Slow to compile.
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- Order dependent.

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a.hpp

```
#pragma once
#include “b.hpp”

struct Y;
struct X { Y* y; };
```

b.hpp

```
#pragma once
#include “a.hpp”

struct X;
struct Y { X* x; };
```

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`#include` is problematic:

- Slow to compile.
- ODR violations.
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- Cyclic dependencies.
- Order dependent.

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a.hpp

```
#pragma once

struct S { /* … */ };
```

b.hpp

```
#pragma once

void foo(S s);
```

c.cpp

```
#include “a.hpp”
#include “b.hpp”
```

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a.hpp

```
#pragma once

struct S { /* … */ };
```

b.hpp

```
#pragma once

void foo(S s);
```

c.cpp

```
#include “a.hpp”
#include “b.hpp”
```

d.cpp

```
#include “b.hpp”
#include “a.hpp”
```

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`#include` is problematic:

- Slow to compile.
- ODR violations.
- Lack of encapsulation.
- Cyclic dependencies.
- Order dependent.

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Using Modules

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Textual Inclusion

```
#include “foo.hpp”
```

Modular Import

```
import foo;
```

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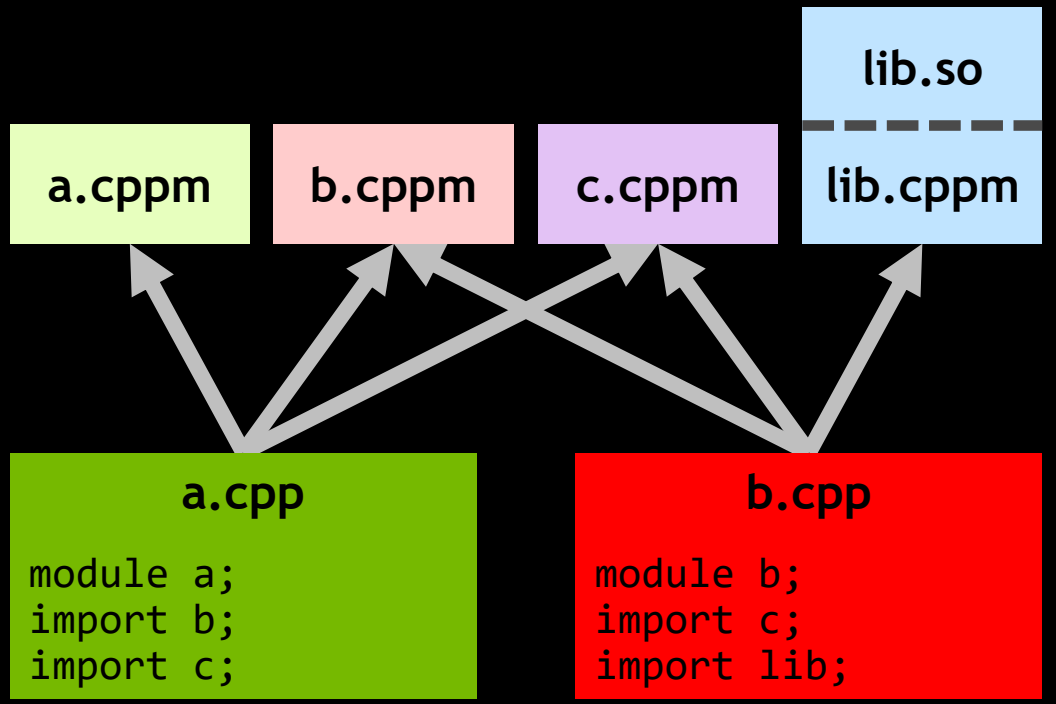
Modular Import



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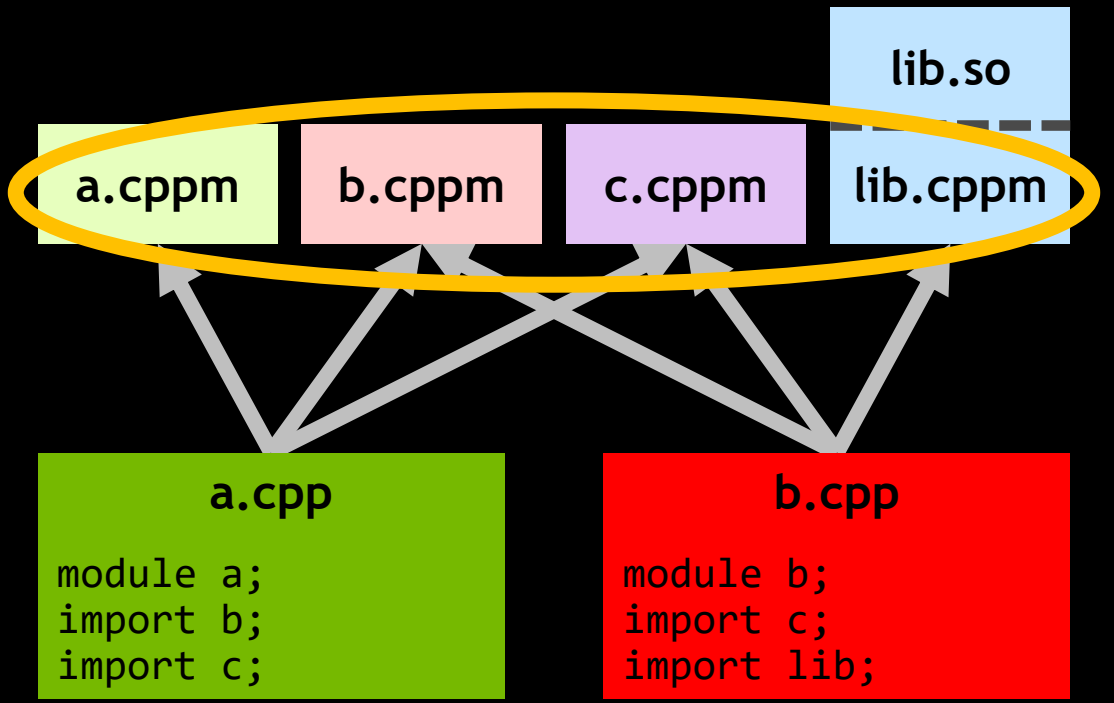
Modular Import



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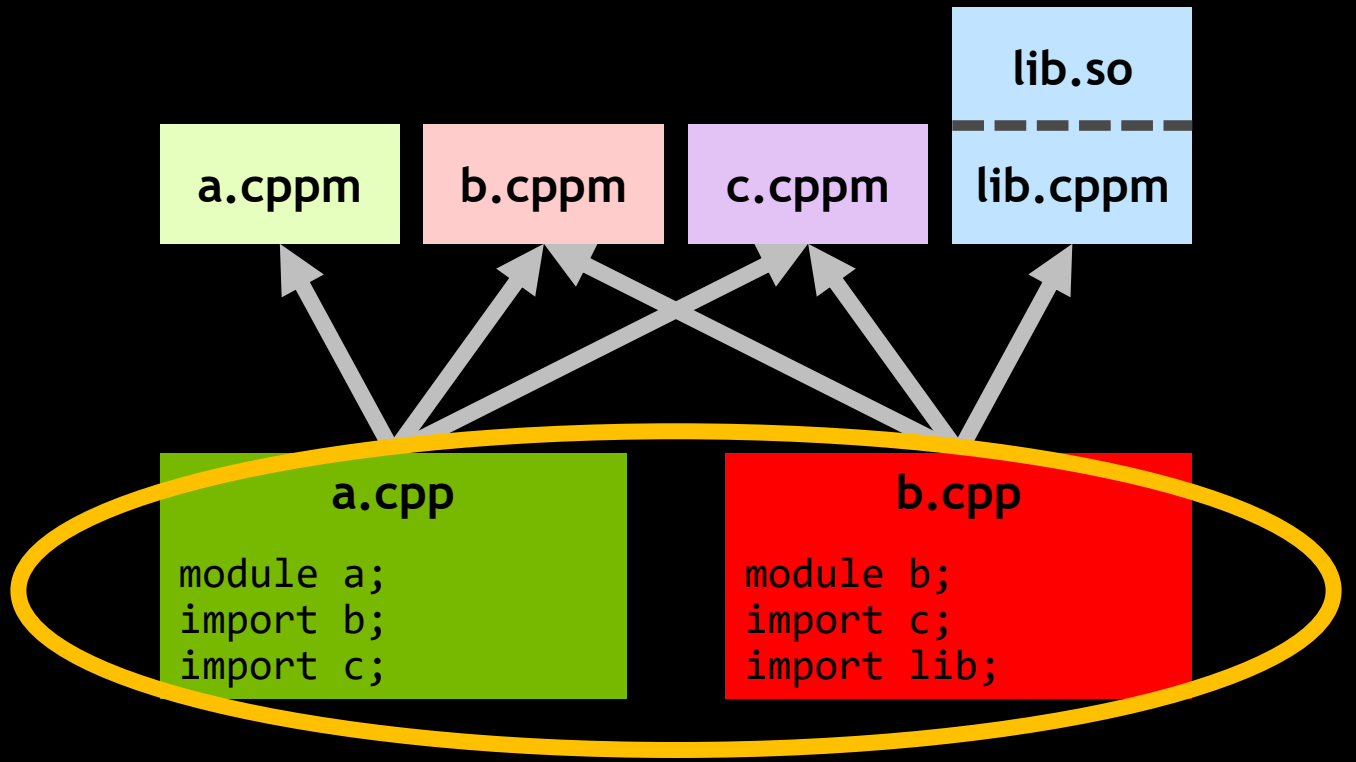
Modular Import



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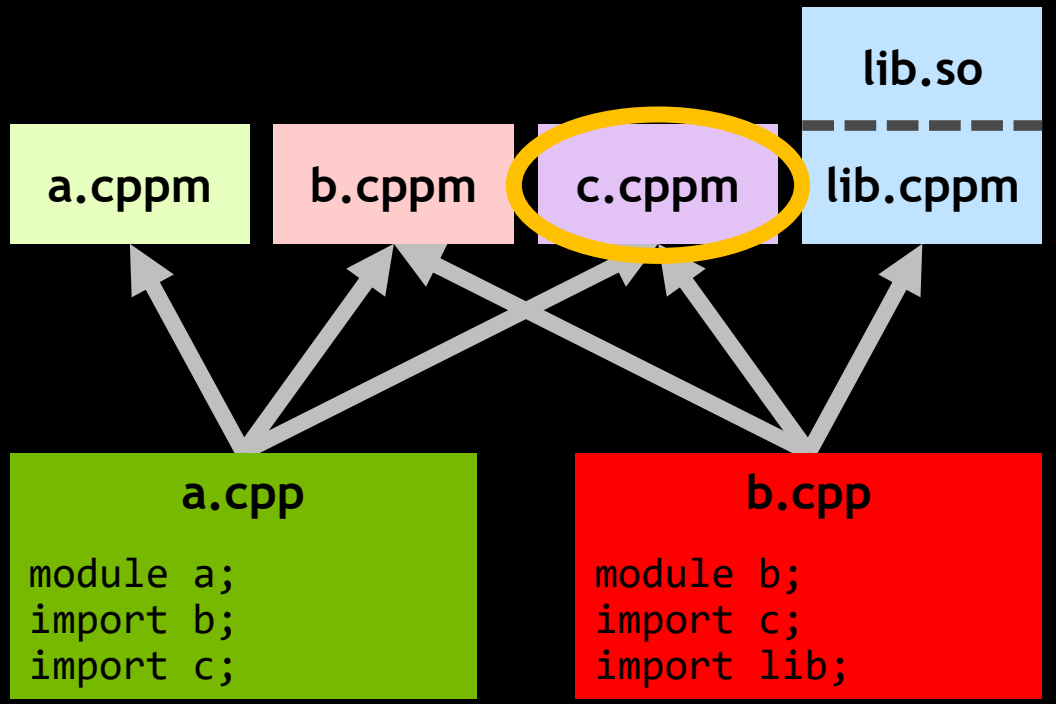
Modular Import



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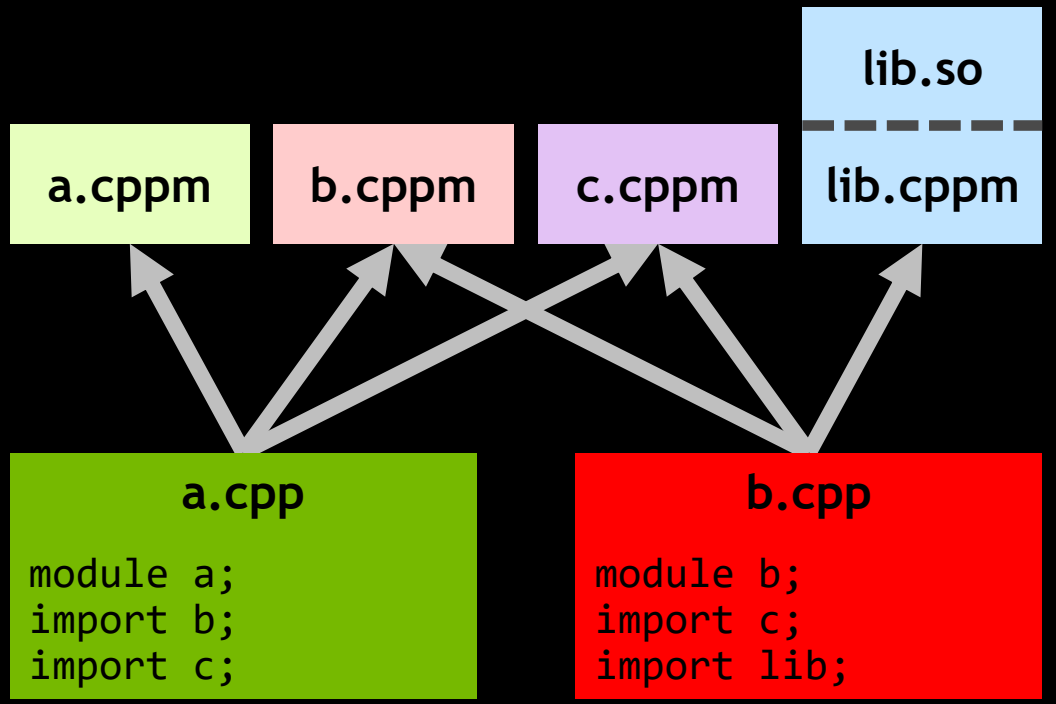
Modular Import: Precompile



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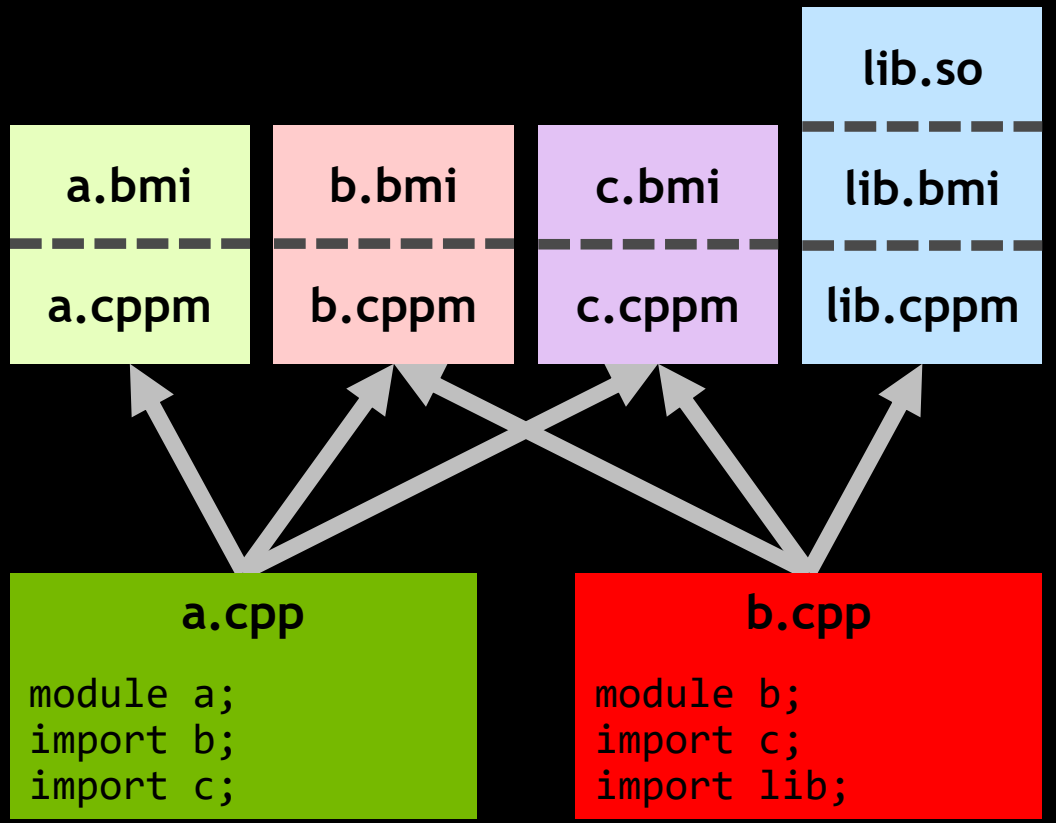
Modular Import: Preprocess



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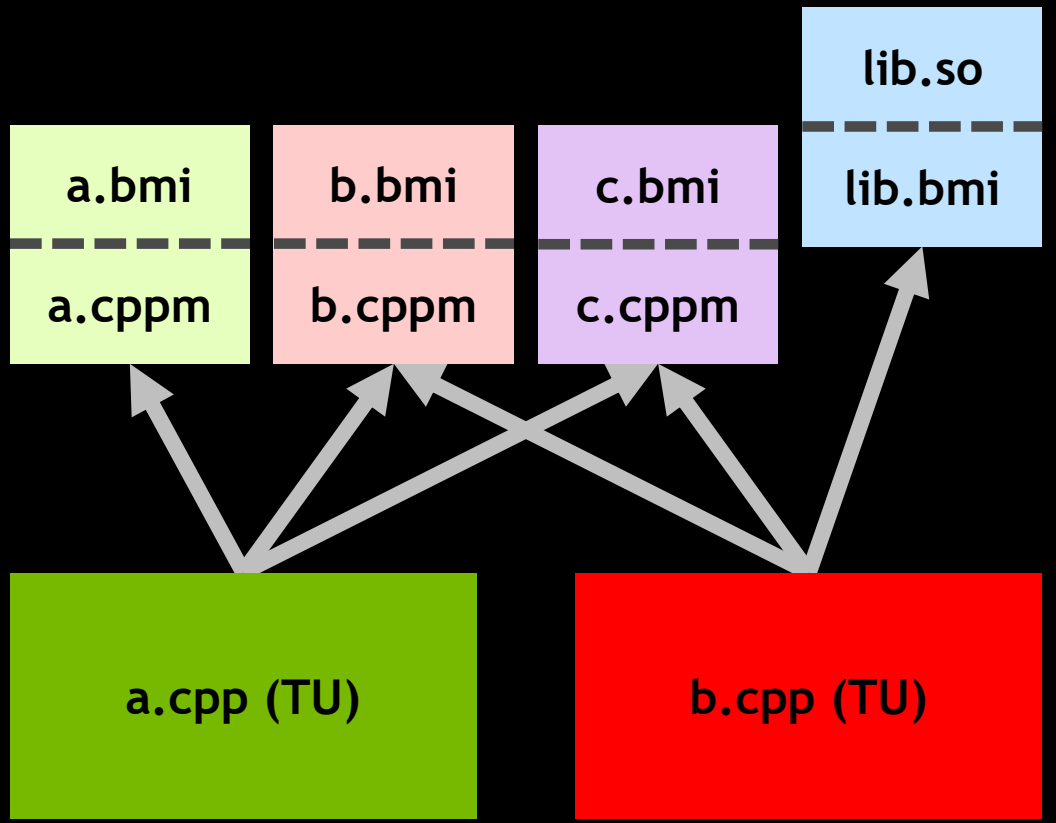
Modular Import: Compile



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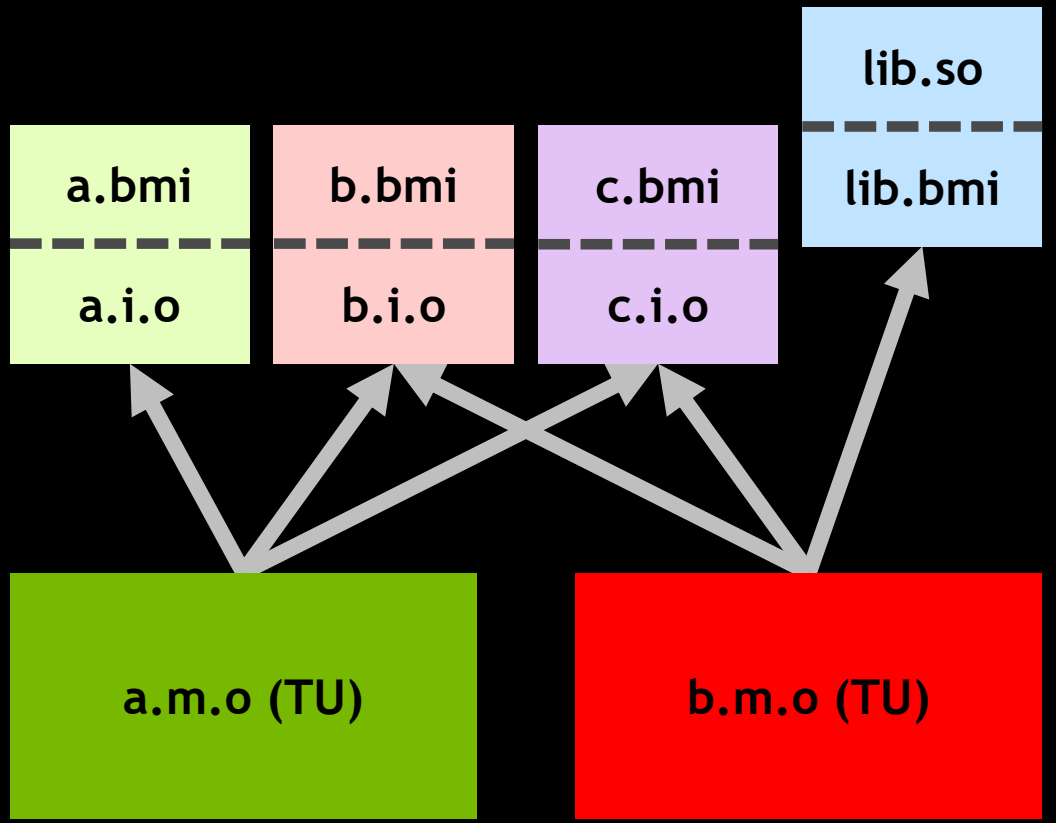
Modular Import: Link



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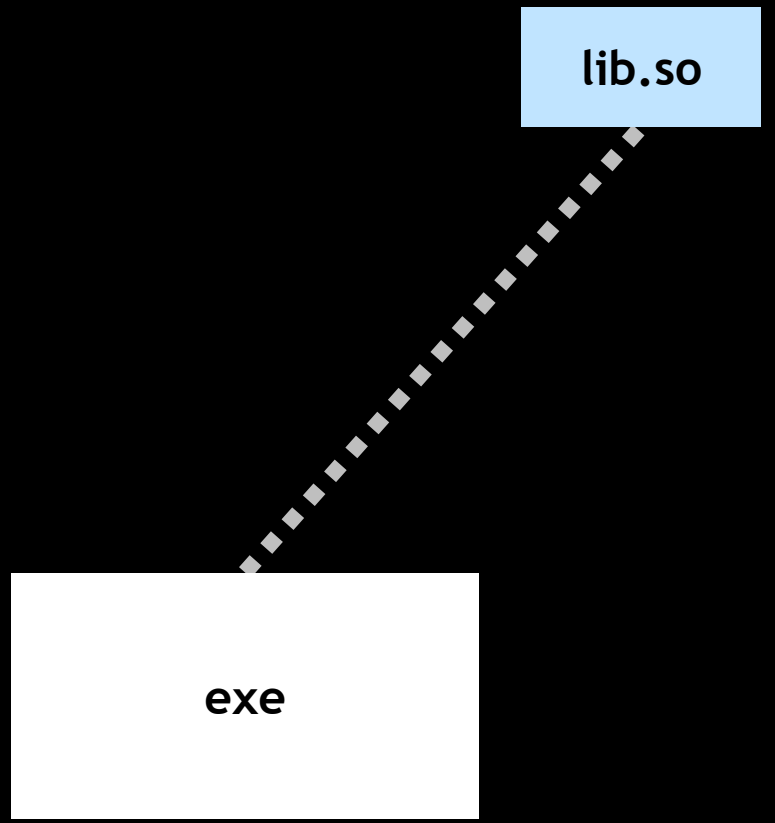
Modular Import



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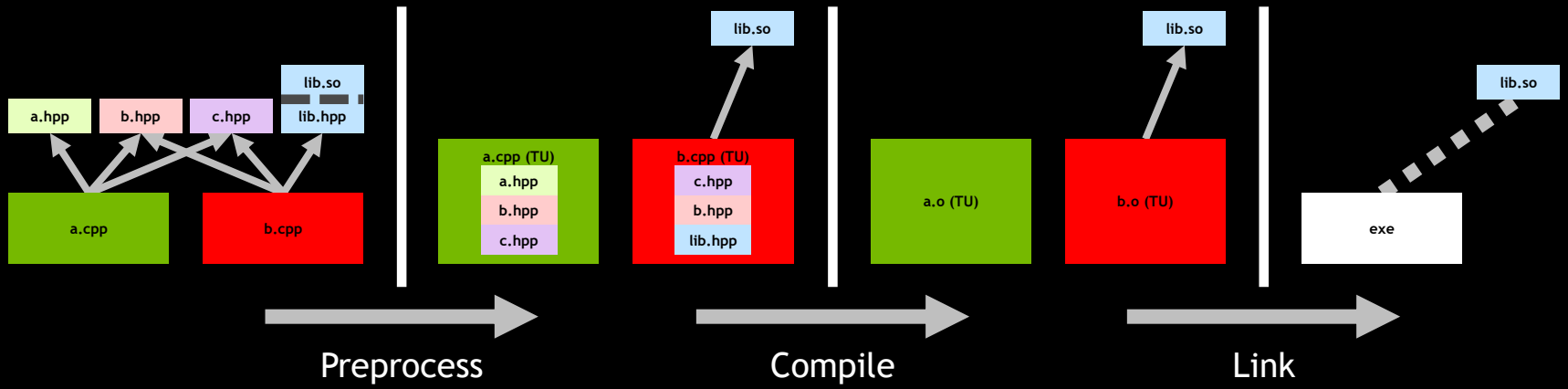
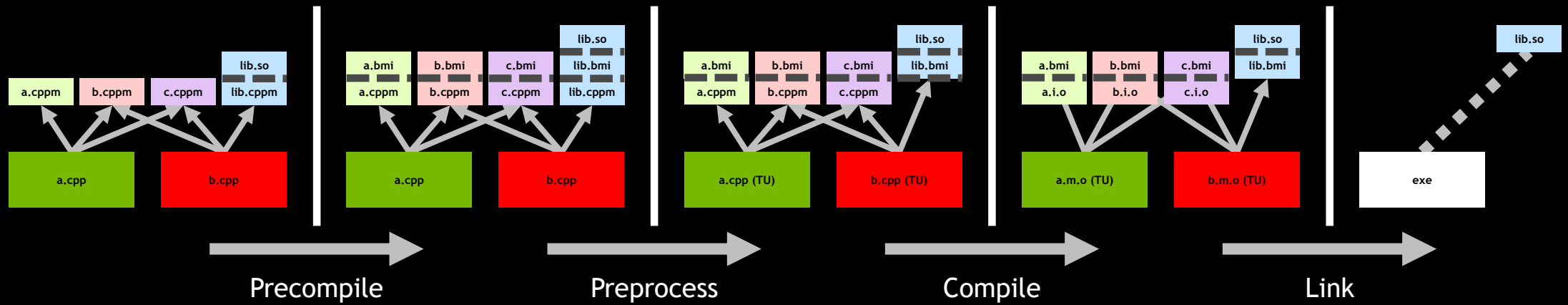
Textual Inclusion



Modular Import



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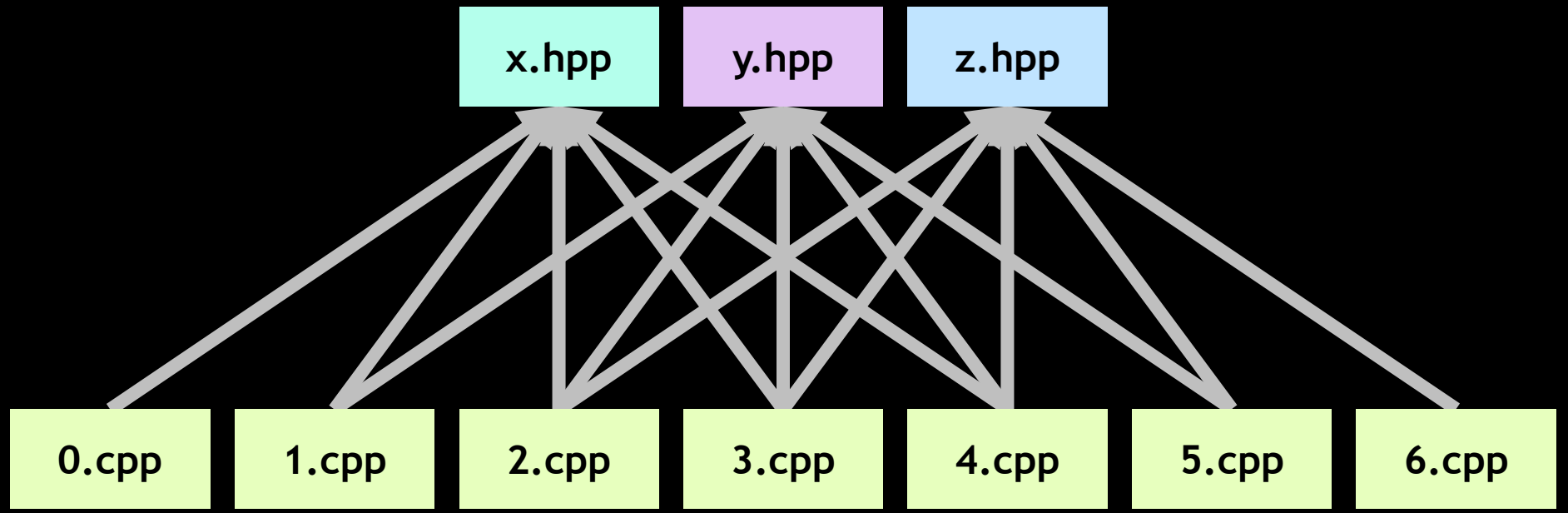
Textual Inclusion



Pro: Embarrassingly parallel.

Con: x.hpp, y.hpp, and z.hpp are compiled 7 times.

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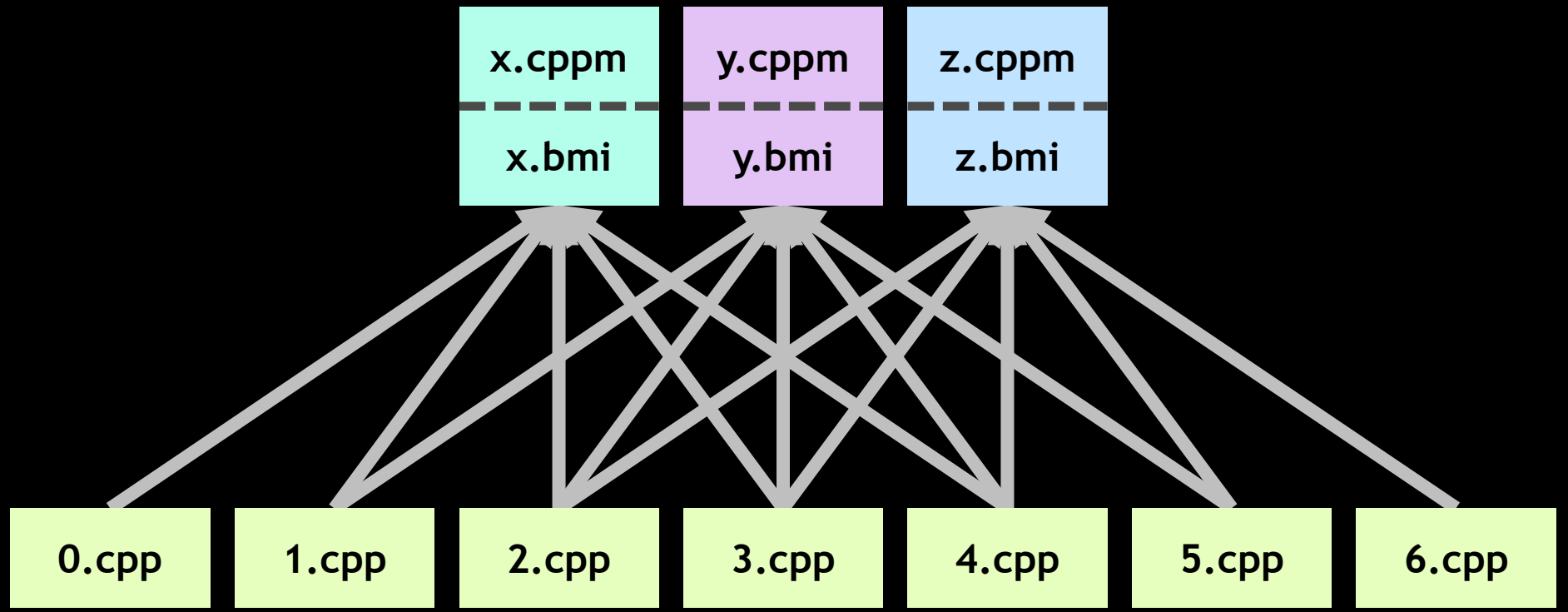
Modular Inclusion



Pro: x.cppm, y.cppm, and z.cppm are precompiled once.

Con: Not embarrassingly parallel.

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Kinds of Translation Units

	Example	Extension	Artifact	Notes
Non-Modular Unit	`#include "…"` …	`.cpp`	`.o`	
Module Interface Unit	`export module …;` …	`.cppm`	`.bmi` `.o`	Exactly one per module.
Module Implementation Unit	`module …;` …	`.cpp`	`.o`	

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Textual Inclusion

```
#include <foo.hpp>
#include “foo.hpp”
```

Modular Import

```
import foo;
import <foo.hpp>;
import “foo.hpp”;
```

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Importable headers:

- Most C++ standard library headers*.
- Some system headers.
- Headers you proclaim importable†.

* C standard library headers (`<cfoo>`, `<foo.h>`) are not required to be importable.

† Today, the mechanism for indicating importability is implementation defined (see P1905).

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assert.h

```
#ifdef NDEBUG
#define assert(condition) ((void)0)
#else
#define assert(condition) /* … */
#endif
```

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cstddef

```
namespace std { /* ... */ }
#define NULL /*see definition*/
#define offsetof(P, D) /*see definition*/
```

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```
import <foo>;
```

Ill-formed if foo is not importable.

Your implementation defines the set of importable headers.

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Your Code

```
#include <vector>
#include <iostream>

// …
```

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Your Code

```
#include <vector>
#include <iostream>

// …
```

Compiler Interpretation

Include Translation: Implementations are free to interpret #includes of importable headers as imports.

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Kinds of Translation Units

	Example	Extension	Artifact	Notes
Non-Modular Unit	`#include "…"` `…`	`.cpp`	`.o`	
Header Unit	`// Created by:` `import <…>;`	`.hpp`	`.bmi` `.o`	
Module Interface Unit	`export module …;` `…`	`.cppm`	`.bmi` `.o`	Exactly one per module.
Module Implementation Unit	`module …;` `…`	`.cpp`	`.o`	

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Textual Inclusion

Interfaces (headers) are not translation units; they are expanded into translation units.

Modular Import

Interfaces are translation units.

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Modules are not translation units.

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Writing Modules

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```
import boost.spirit;
import ctre;
import blas.level1;
```

Module names are dot-separated identifiers.

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```
import boost.spirit;
import ctre;
import blas.level1;
```

Module names are dot-separated identifiers.
Dots in module names have no semantic meaning.

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```
module a;
// …
module b;
// …
```

Only one module declaration per translation unit.

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```
export module a;
// …
export module b;
// …
```

Only one module declaration per translation unit.

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Module Unit Structure

```
export module …;
import …;
…
```

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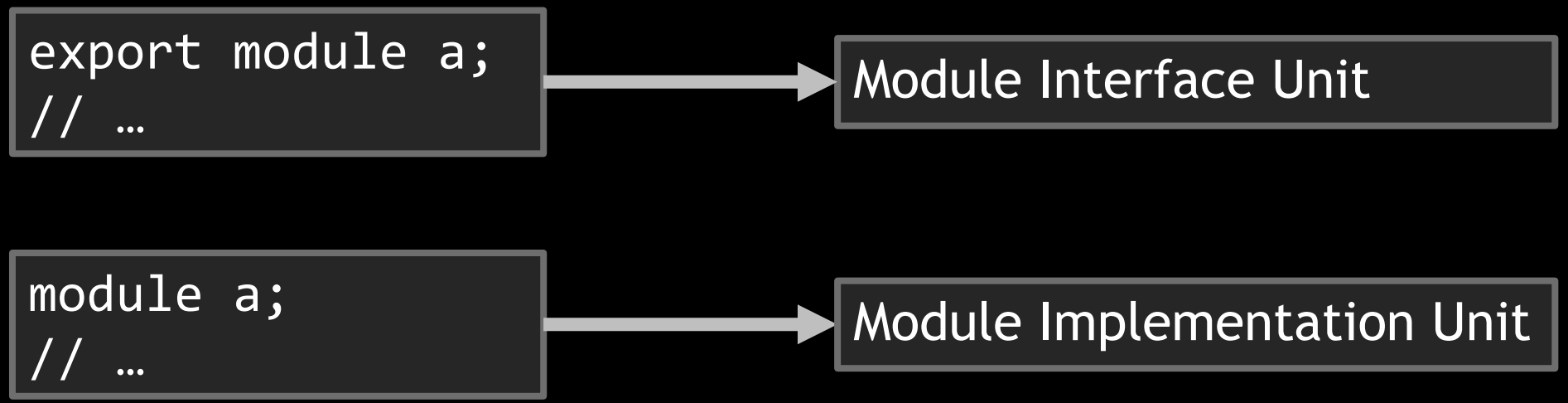

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```
export declaration

export {
  declaration …
}
```

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```
export void f();

export int i{0};

export struct A;

export using B = A;

export using std::any;
```

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```
export {
  void f();
  struct A;
  int i{0};
}
```

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```
export template <typename T>
T square(T t) { return t * t; }
```

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```
export template <typename T>
struct is_const : false_type {};

export template <typename T>
struct is_const<T const> : true_type {};
```

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```
export namespace foo { struct A; }

namespace foo { struct B; }
```

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```
export namespace foo { struct A; }

namespace foo { struct B; }
```

Only `foo::A` is exported.

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```
export import a;
```

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square.cppm

```
export module math.square;

export template <typename T>
T square(T a) { return a * a; }
```

add.cppm

```
export module math.add;

export template <typename T>
T add(T a, T b) { return a + b; }
```

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square.cppm

```
export module math.square;

export template <typename T>
T square(T a) { return a * a; }
```

add.cppm

```
export module math.add;

export template <typename T>
T add(T a, T b) { return a + b; }
```

math.cppm

```
export module math;

export import math.square;
export import math.add;
```

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a.cppm

```
export module a;

struct S { int m; };
export S foo();
```

main.cpp

```
import a;

int main() {
  auto s0 = foo();
  s0.m = 42;
}
```

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a.cppm

```
export module a;

struct S { int m; };
export S foo();
```

main.cpp

```
import a;

int main() {
  auto s0 = foo();
  s0.m = 42;

  S s1{};
}
```

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a.cppm

```
export module a;

struct S { int m; };
export S foo();
```

main.cpp

```
import a;

int main() {
  auto s0 = foo();
  s0.m = 42;

  decltype(foo()) s1{};
}
```

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Visible: In scope, can be named.

Reachable: In scope, not necessarily namable.

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a.cppm

```
export module a;

struct S { int m; };
export S foo();
```

main.cpp

```
import a;
```

In `main.cpp`:

- `S` is reachable.
- `foo` is reachable and visible.

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Modules enable true encapsulation.

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Textual Inclusion

a.hpp

```
#pragma once

struct foo { /* … */ };
```

b.hpp

```
#pragma once

void bar(foo f);
```

main.cpp

```
#include “a.hpp”
#include “b.hpp”
```

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Textual Inclusion

a.hpp

```
#pragma once

struct foo { /* … */ };
```

b.hpp

```
#pragma once

void bar(foo f);
```

main.cpp

```
#include “a.hpp”
#include “b.hpp”
```

Modular Import

a.cppm

```
export module a;

export struct foo { /* … */ };
```

b.cppm

```
export module b;

export void bar(foo f);
```

main.cpp

```
import a;
import b;
```

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Textual Inclusion

a.hpp

```
#pragma once

struct foo { /* … */ };
```

b.hpp

```
#pragma once

void bar(foo f);
```

main.cpp

```
#include “a.hpp”
#include “b.hpp”
```

Modular Import

a.cppm

```
export module a;

export struct foo { /* … */ };
```

b.cppm

```
export module b;

export void bar(foo f);
```

main.cpp

```
import a;
import b;
```

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Textual Inclusion

a.hpp

```
#pragma once

// Implementation detail/not part of the API.
template <typename T>
T id(T t) { return t; }
```

b.hpp

```
#pragma once

// Implementation detail/not part of the API.
template <typename T>
struct id { using type = T; };
```

main.cpp

```
#include “a.hpp”
#include “b.hpp”
```

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Textual Inclusion

a.hpp

```
#pragma once

// Implementation detail/not part of the API.
template <typename T>
T id(T t) { return t; }
```

b.hpp

```
#pragma once

// Implementation detail/not part of the API.
template <typename T>
struct id { using type = T; };
```

main.cpp

```
#include “a.hpp”
#include “b.hpp”
```

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Textual Inclusion

a.hpp

```
#pragma once

namespace a {
 template <typename T>
 T id(T t) { return t; }
}
```

b.hpp

```
#pragma once

namespace b {
 template <typename T>
 struct id { using type = T; };
}
```

main.cpp

```
#include “a.hpp”
#include “b.hpp”
```

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Textual Inclusion

a.hpp

```
#pragma once

namespace a::detail {
 template <typename T>
 T id(T t) { return t; }
}
```

b.hpp

```
#pragma once

namespace b::detail {
 template <typename T>
 struct id { using type = T; };
}
```

main.cpp

```
#include “a.hpp”
#include “b.hpp”
```

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Textual Inclusion

a.hpp

```
#pragma once

namespace a::detail {
 template <typename T>
 T __dont_use_id(T t) { return t; }
}
```

b.hpp

```
#pragma once

namespace b::detail {
 template <typename T>
 struct __dont_use_id { using type = T; };
}
```

main.cpp

```
#include “a.hpp”
#include “b.hpp”
```

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Textual Inclusion

a.hpp

```
#pragma once

namespace a::detail {
 template <typename T>
 T __dont_use_id(T t) { return t; }
}
```

b.hpp

```
#pragma once

namespace b::detail {
 template <typename T>
 struct __dont_use_id { using type = T; };
}
```

main.cpp

```
#include “a.hpp”
#include “b.hpp”
```

Modular Import

a.cppm

```
export module a;

template <typename T>
T id(T t) { return t; }
```

b.cppm

```
export module b;

template <typename T>
struct id { using type = T; };
```

main.cpp

```
import a;
import b;
```

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No more `detail/impl` namespaces.

No more uglifying identifiers.

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Kinds of Linkage

	Example	Visible From	Notes

External Linkage	`extern void foo();`
	`export void bar();`
	`extern int i{};`
	`export bool b{};`
		Other translation units.	

Module Linkage	`struct S;`
	`int foo();`
	`int i{};`
		This module.	In non-modular units, entities with module linkage have external linkage.

Internal Linkage	`static void foo();`
	`static int i{};`
	`bool const b{};`
	`namespace { /* … */ }`
		This translation unit.	

No Linkage	`int main() {`
	`  int i{};`
	`}`
		This scope.	

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Non-header-unit never expose macros.

```
import foo;         // No macros brought in.
import <foo.hpp>; // Macros brought in.
import “foo.hpp”; // Macros brought in.
```

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a.cppm

```
export module a;

#define foo int
```

main.cpp

```
import a;

foo f{};
```

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a.cppm

```
export module a;

#define foo int
```

main.cpp

```
import a;

foo f{};
```

The definition of `foo` isn't brought in by the `import`.

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a.hpp

```
#pragma once

#define foo int
```

main.cpp

```
import <a>;

foo f{};
```

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a.hpp

```
#pragma once

#define foo int
```

main.cpp

```
import <a>;

foo f{};
```

The definition of `foo` is brought in by the `import`.

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Modules never see the definition of programmatic macros defined in other modules.

Programmatic macros == `#define FOO`

Non-programmatic macros == `-DFOO`

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a.cppm

```
export module a;

export struct foo{};
```

main.cpp

```
#define foo bar
import a;
#undef foo

foo f{};
```

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a.cppm

```
export module a;

export struct foo{};
```

main.cpp

```
#define foo bar
import a;
#undef foo

foo f{};
```

The definition of `foo` isn't seen by the imported module.

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a.cppm

```
export module a;

#if defined(DEBUG)
  // …
#else
  // …
#endif
```

main.cpp

```
#define DEBUG
import a;
```

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a.cppm

```
export module a;

#if defined(DEBUG)
  // …
#else
  // …
#endif
```

main.cpp

```
#define DEBUG
import a;
```

The definition of DEBUG isn’t seen by the imported module.

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a.hpp

```
#pragma once

#if defined(DEBUG)
  // …
#else
  // …
#endif
```

main.cpp

```
#define DEBUG
import <a>;
```

The definition of DEBUG isn’t seen by the imported header-unit.

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Programmatic macros are:

- Never seen by modules.
- Never exported from non-header-unit modules.

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With modules we no longer have to defend names:

- No more `detail/impl` namespaces.
- No more uglifying identifiers.

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Bug ID:	2547402
Date:	3/6/2019 2:56:55 PM
Synopsis:	CUB: NAMD defines WARP_ANY as a macro, which conflicts with CUB
Module:	CUDA - C++ Core Libraries - Thrust

```
281  /**
282   * Warp any
283   */
284  __device__  __forceinline__ int WARP_ANY(int predicate, unsigned int member_mask)
285  {
286  #ifdef CUB_USE_COOPERATIVE_GROUPS
287      return __any_sync(member_mask, predicate);
288  #else
289      return ::__any(predicate);
290  #endif
291  }
```

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```
#define _LIBCPP_NO_EXCEPTIONS
import <vector>;
```

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```
#define _LIBCPP_NO_EXCEPTIONS
import <vector>;
```

The definition of _LIBCPP_NO_EXCEPTIONS isn't seen by <vector>.

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```
#define _LIBCPP_NO_EXCEPTIONS
#include <vector>
```

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```
#define _LIBCPP_NO_EXCEPTIONS
#include <vector>
```

If include translation occurs here,
the definition of `_LIBCPP_NO_EXCEPTIONS` isn't seen by `<vector>`.

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```
#define NDEBUG
#include <cassert>

// For `readlink`.
#define _XOPEN_SOURCE
#include <unistd.h>
```

How do we deal with non-modular headers?

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Textual Inclusion

a.hpp

```
#pragma once
#define NDEBUG
#include <cassert>

// …
```

Modular Import

a.cppm

```
export module a;
#define NDEBUG
import <cassert>;

// …
```

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Textual Inclusion

a.hpp

```
#pragma once
#define NDEBUG
#include <cassert>

// …
```

Modular Import

a.cppm

```
export module a;
#define NDEBUG
#include <cassert>

// …
```

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Module Unit Structure

```
module;
#pp-directive …;
export module …;
import …;
…
```

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Textual Inclusion

a.hpp

```
#pragma once
#define NDEBUG
#include <cassert>

// …
```

Modular Import

a.cppm

```
module;
#define NDEBUG
#include <cassert>
export module a;

// …
```

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```
module;
#include <boost/circular_buffer>
export module boost.circular_buffer;
namespace boost {
  export using ::boost::circular_buffer;
}
```

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Modules are order independent.

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```
import a;
import b;
```

==

```
import b;
import a;
```

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Modules cannot have cycles.

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Textual Inclusion

a.hpp

```
#pragma once
#include “b.hpp”

struct Y;
struct X { Y* y; };
```

b.hpp

```
#pragma once
#include “a.hpp”

struct X;
struct Y { X* x; };
```

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Textual Inclusion

a.hpp

```
#pragma once
#include “b.hpp”

struct Y;
struct X { Y* y; };
```

b.hpp

```
#pragma once
#include “a.hpp”

struct X;
struct Y { X* x; };
```

Modular Import

a.cppm

```
export module a;
import b;

struct Y;
export struct X { Y* y; };
```

b.cppm

```
export module b;
import a;

struct X;
export struct Y { X* x; };
```

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Textual Inclusion

a.hpp

```
#pragma once
#include “b.hpp”

struct Y;
struct X { Y* y; };
```

b.hpp

```
#pragma once
#include “a.hpp”

struct X;
struct Y { X* x; };
```

Modular Import

a.cppm

```
export module a;
import b;

struct Y;
export struct X { Y* y; };
```

b.cppm

```
export module b;
import a;

struct X;
export struct Y { X* x; };
```

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Modular Import

a.cppm

```
export module a;

struct Y;
export struct X { Y* y; };
```

b.cppm

```
export module b;

struct X;
export struct Y { X* x; };
```

main.cpp

```
import a;
import b;
```

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How do we break cycles?

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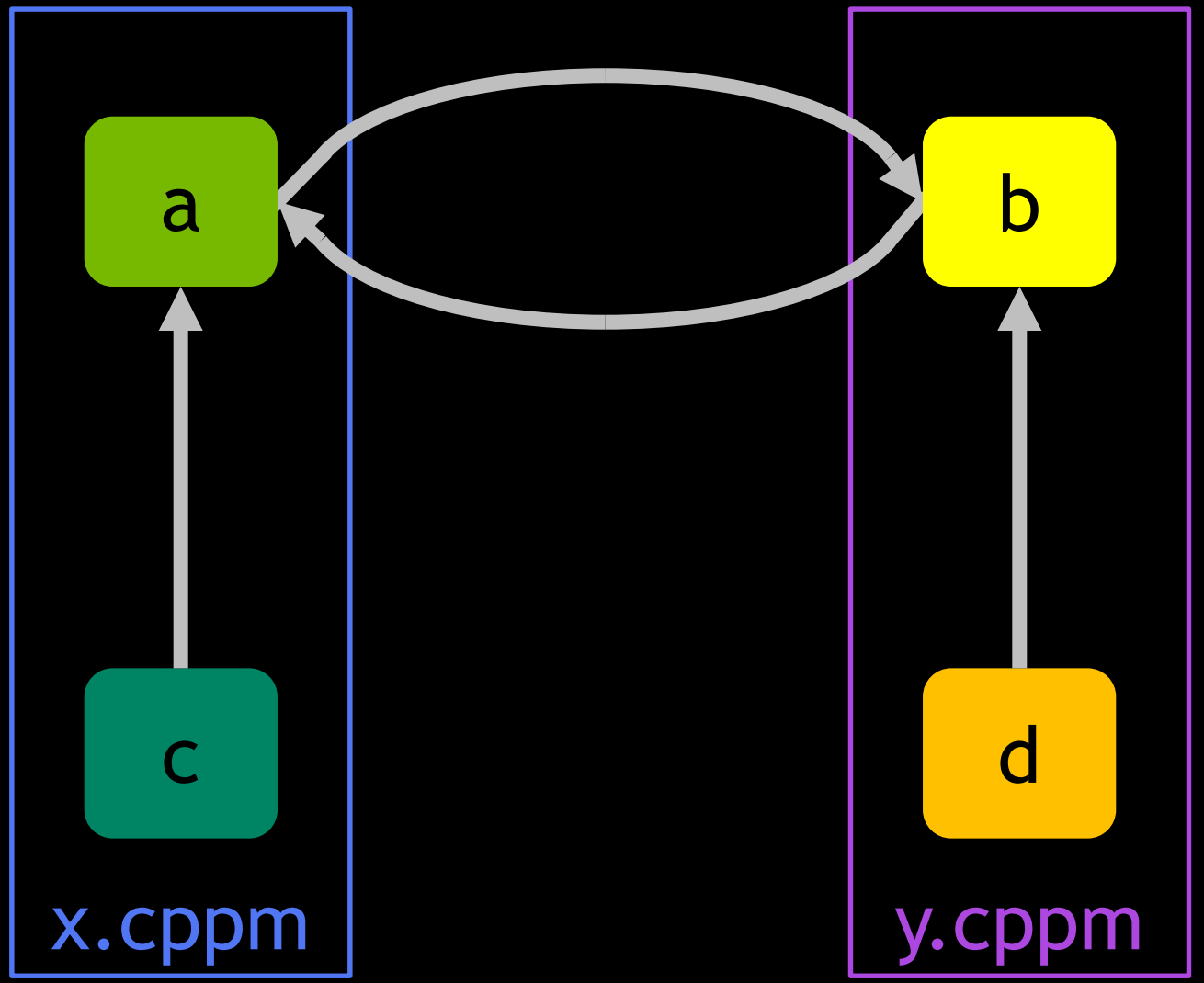

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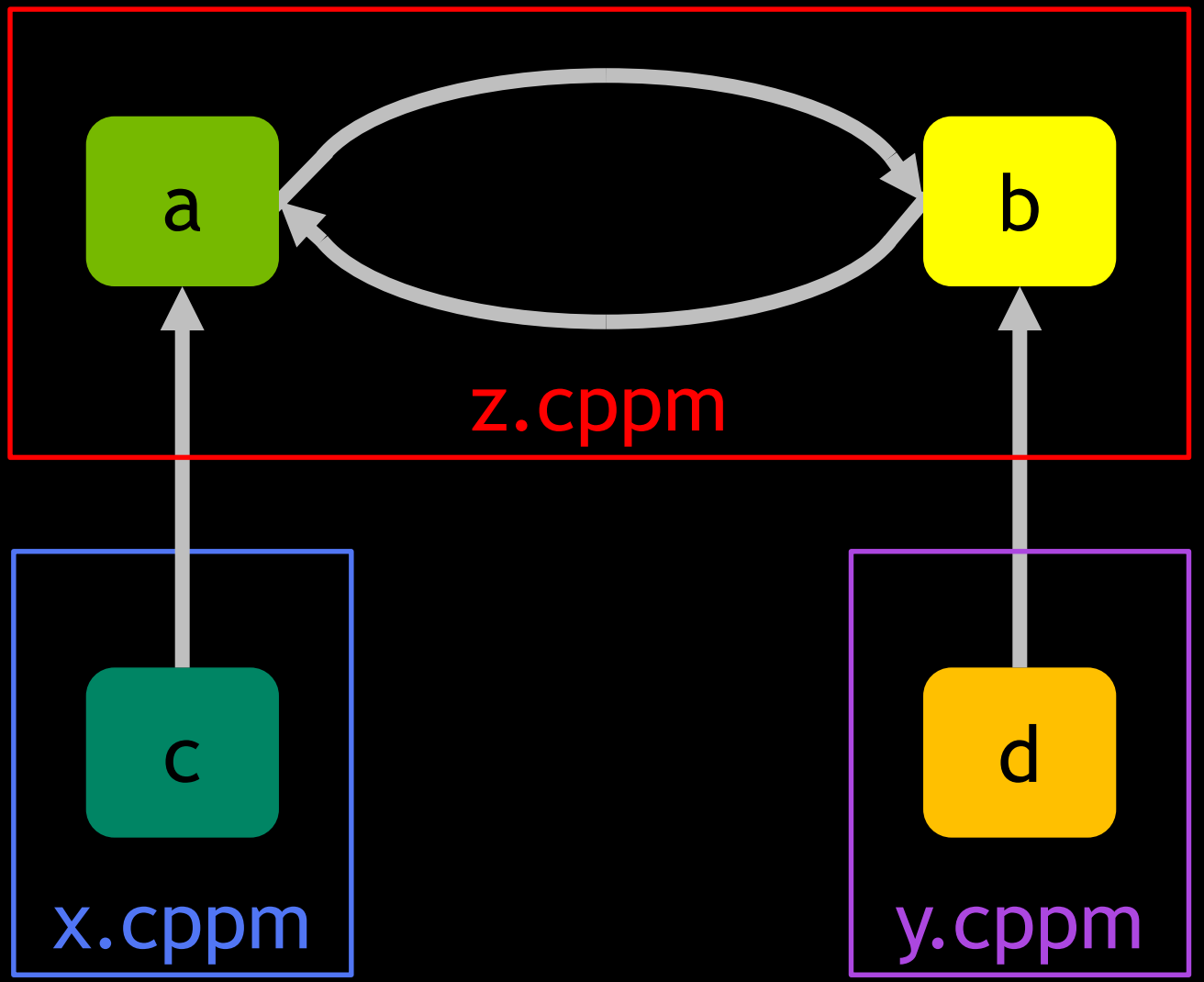

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Breaking cyclic dependencies:

- Is difficult to automate.
- May require major structural changes.

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Modules own their declarations.

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Modular Import

a.cppm

```
export module a;

struct Y;
export struct X { Y* y; };
```

b.cppm

```
export module b;

struct X;
export struct Y { X* x; };
```

main.cpp

```
import a;
import b;
```

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You can not forward declare an entity
that lives in another module.

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Textual Inclusion

a.hpp

```
#pragma once

void foo();
```

a.cpp

```
#include “a.hpp”

void foo() { /* … */ }
```

b.cpp

```
#include “a.hpp”

static void foo() { /* … */ }
```

Modular Import

a.cppm

```
export module a;

export void foo();
```

a.cpp

```
module a;

void foo() { /* … */ }
```

b.cpp

```
import a;

static void foo() { /* … */ }
```

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Textual Inclusion

a.hpp

```
#pragma once

void foo();
```

a.cpp

```
#include “a.hpp”

void foo() { /* … */ }
```

b.cpp

```
#include “a.hpp”

static void foo() { /* … */ }
```

Modular Import

a.cppm

```
export module a;

export void foo();
```

a.cpp

```
module a;

void foo() { /* … */ }
```

b.cpp

```
import a;

static void foo() { /* … */ }
```

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a.cppm

```
export module a;

export void foo();
```

b.cppm

```
export module b;

export void foo();
```

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a.cppm

```
export module a;

export void foo();
```

b.cppm

```
export module b;

export void foo();
```

Ill formed, no diagnostic required (IFNDR).

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Modules can be contained in one file.

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Textual Inclusion

math.hpp

```
#pragma once

template <typename T>
T square(T a) { return a * a; }
```

main.cpp

```
import square;

int main() { return square(42); }
```

Modular Import

math.cppm

```
export module math;

export template <typename T>
T square(T a) { return a * a; }
```

main.cpp

```
import math;

int main() { return square(42); }
```

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Textual Inclusion

a.hpp

```
#pragma once

struct pimpl;
```

a.cpp

```
#include “a.hpp”

struct pimpl { /* … */ };
```

Modular Import

a.cppm

```
export module a;

export struct pimpl;
```

a.cpp

```
module a;

struct pimpl { /* … */ };
```

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Textual Inclusion

a.hpp

```
#pragma once

struct pimpl;
```

a.cpp

```
#include “a.hpp”

struct pimpl { /* … */ };
```

Modular Import

a.cppm

```
export module a;

export struct pimpl;

module : private;

struct pimpl { /* … */ };
```

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Module Unit Structure

```
module;
#pp-directive …;
export module …;
import …;
…
module : private;
…
```

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Modules can be split across multiple files.

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square.cppm

```
export module math.square;

export template <typename T>
T square(T a) { return a * a; }
```

add.cppm

```
export module math.add;

export template <typename T>
T add(T a, T b) { return a + b; }
```

math.cppm

```
export module math;

export import math.square;
export import math.add;
```

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square.cppm

```
export module math:square;

export template <typename T>
T square(T a) { return a * a; }
```

add.cppm

```
export module math:add;

export template <typename T>
T add(T a, T b) { return a + b; }
```

math.cppm

```
export module math;

export import :add;
export import :square;
```

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math_vector.cppm

```
export module math.vector;
export import :dot_product;
float sqrt(float x);
```

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math_vector.cppm

```
export module math.vector;
export import :dot_product;
float sqrt(float x);
```

math_vector_dot_product.cppm

```
export module math.vector:dot_product;
import :sum_squares;
import <span>;
export float vector_norm(std::span<float> x) {
  return sqrt(sum_squares(x));
}
```

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math_vector.cppm

```
export module math.vector;
export import :dot_product;
float sqrt(float x);
```

math_vector_dot_product.cppm

```
export module math.vector:dot_product;
import :sum_squares;
import <span>;
export float vector_norm(std::span<float> x) {
  return sqrt(sum_squares(x));
}
```

math_vector_sum_squares.cpp

```
module math.vector:sum_squares;
import <span>;
import <algorithm>;
export float sum_squares(std::span<float> x) {
  return std::transform_reduce(x);
}
```

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math_vector.cppm

```
export module math.vector;
export import :dot_product;
float sqrt(float x);
```

math_vector_dot_product.cppm

```
export module math.vector:dot_product;
import :sum_squares;
import <span>;
export float vector_norm(std::span<float> x) {
  return sqrt(sum_squares(x));
}
```

math_vector_sum_squares.cpp

```
module math.vector:sum_squares;
import <span>;
import <algorithm>;
float sum_squares(std::span<float> x) {
  return std::transform_reduce(x);
}
```

math_vector.cpp

```
module math.vector;
float sqrt(float x) { /* ... */ }
```

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Kinds of Translation Units

	Example	Extension	Artifact	Notes
Non-Modular Unit	`#include "…"` `…`	`.cpp`	`.o`	
Header Unit	`// Created by:` `import <…>;`	`.hpp`	`.bmi` `.o`	
Module Interface Unit	`export module …;` `…`	`.cppm`	`.bmi` `.o`	Exactly one per module.
Module Implementation Unit	`module …;` `…`	`.cpp`	`.o`	
Module Partition Interface Unit	`export module …:…;` `…`	`.cppm`	`.bmi` `.o`	
Module Partition Implementation Unit	`module …:…;` `…`	`.cpp`	`.o`	

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Modules do not force a file layout on you.

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Modules are not translation units.

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`#include` is problematic:

- Slow to compile.
- ODR violations.
- Lack of encapsulation.
- Cyclic dependencies.
- Order dependent.

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Modules are coming:

- Modules will bring substantial algorithmic build throughput improvements.
- Modules offer true encapsulation which will eliminate many structural challenges with writing C++ at scale.
- Transitioning to modules will not be free.

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Ecosystem Impact

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math.hpp

```
#pragma once

int square(int a);
```

math.cpp

```
#include “math.hpp”

int square(int a) { return a * a; }
```

How are headers found?

- Not specified by the standard.
- In practice, all implementations assume a mapping between file names and #includes.
- The file is searched for in a set of include paths.

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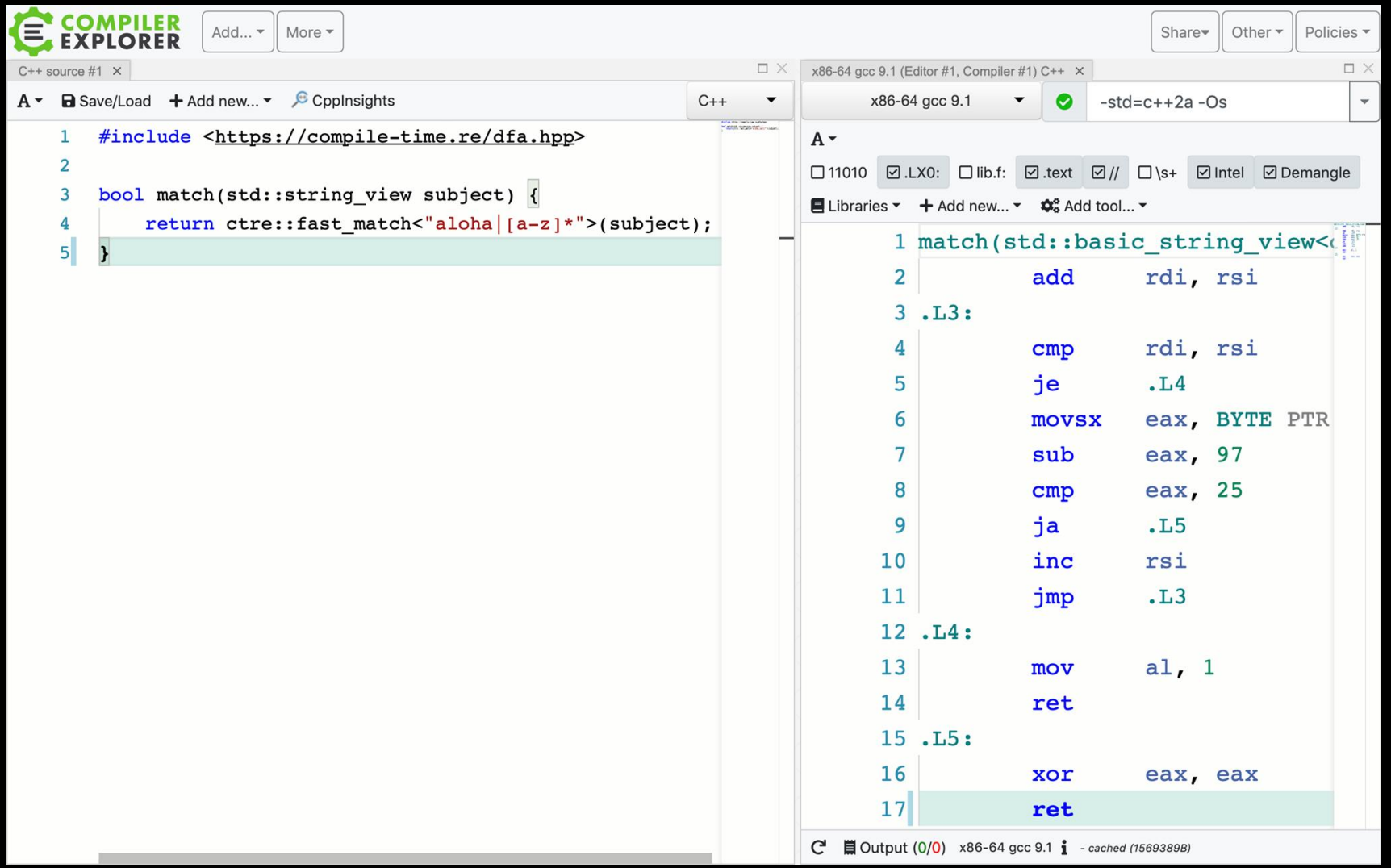

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bar.cppm

```
export module foo;

// …
```

How are modules found?

- Not specified by the standard.
- Unlike headers, modules are programmatically named.
- A file name <-> module name mapping is not straightforward.
  - Modules have to be precompiled.
  - Partitions span multiple files.

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Strategies for Module Lookup

- (Fast) Dependency Scanner.
- Assume File Name == Module Name and Search.
- Explicit Mapping.
- Client/Server Mapper.

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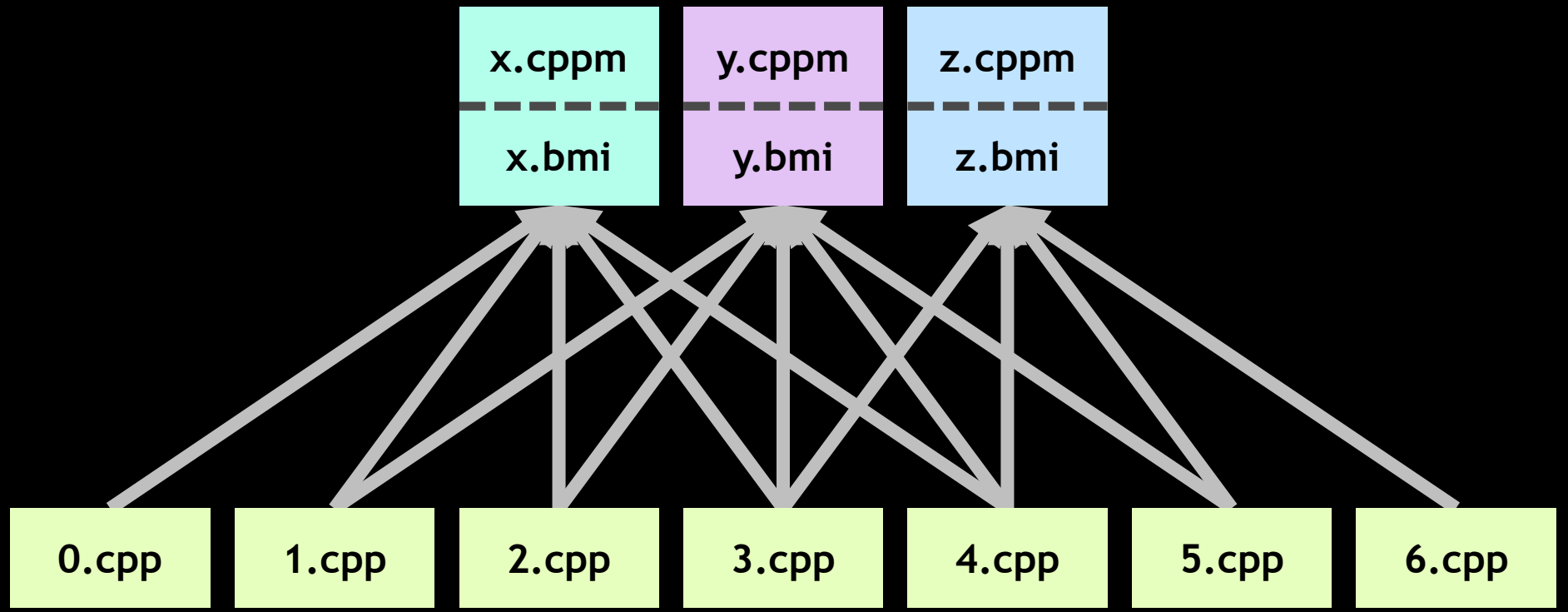
Implicit Precompilation is Problematic



If precompilation is implicit and builds are parallel, how do we decide who builds the BMIs?

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Implicit Precompilation is Problematic

Assuming the existence of fast dependency scanners, you can implicitly discover what BMIs need to be built.

This comes with a cost, however; you'll need to do this scanning as an additional pass prior to compilation.

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Module Recipes

- BMIs are built with a certain set of compiler options and global macro definitions (the module recipe).
  - Ex: GCC 7.3, -O3, -DDEBUG
- The BMI may only be used when compiling with the same set of compiler options and global macro definitions.
- Tools need to either interface with the compiler and read BMIs, or be able to build BMIs of their own using the module recipe.
- Module lookup isn't just a matter of mapping a module name to a module interface unit (MIU) + a BMI. It's mapping a module name + module recipe to a MIU + a BMI.

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Guidelines for BMI Redistribution

- BMIs are built with a certain set of compiler options and global macro definitions (the module recipe).
- The source for module interface units (MIUs) must always be distributed.
- BMIs may be distributed as an optimization alongside MIU sources.
- BMIs must be distributed with module recipes to allow tools to rebuild BMIs if needed.

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Tools can no longer rely on simple lookup mechanism (include directories and header file names) to understand C++ projects.

Tools must be able to either consume BMIs or rebuild BMIs using module recipes.

Dependency scanning now requires a C++ parser, not just a C preprocessor.

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C++ Ecosystem Technical Report

(P1688, P1838)

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C++ Ecosystem Technical Report:

- Packaging Modules (P1767).
- Module Mapping (P1302, P1484).
- Module Naming (P1634).
- Module Transition Path.
- Module Recipes (P1788).
- Built Module Interface (BMI) Distribution (P1788).
- Dependency Scanning (P1689, P1857).

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C++ Ecosystem Technical Report Metadata Formats:

- Package Manifest Format (P1767).
- Dependency Format (P1689).
- Module Recipe Format (P1788).

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Modules are coming:

- Modules will bring substantial algorithmic build throughput improvements.
- Modules offer true encapsulation which will eliminate many structural challenges with writing C++ at scale.
- Transitioning to modules will not be free.

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Modules are a team effort.

Thanks to everyone involved!

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