Build 'Em all with CMake

By Alexy Pellegrini

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About me

- Kitware Europe for 2+ years
- Kitware CMake trainer
- C++ dev
- Graphics programming
- Windows user
- Working on an LLVM backend for a VLIW processor designed by a friend

Kitware

Delivering Innovation

Kitware / Leader in AI & scientific open source solutions

Software development
Based on open source tools
300+ active projects worldwide

Sustained Growth
Since creation of the company
100% employee-owned

230 employees Worldwide
6 offices across USA/Europe

65% staff with PhD or Master
High Level customer expertise

20+ years of expertise
Kitware USA, 1998
Kitware Europe, 2010

Revenue 2020
$39M consolidated

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Customers / Various fields of application

Academics

70+ academic institutions worldwide

Government agencies

50+ government agencies and national laboratories

Commercial companies

Over 500 commercial customers

Medical

Image processing, multimodal visualization, image registration & segmentation, assisted surgery, custom software…

Energy

HPC, in-situ simulation, scientific visualisation, particle flow, fluid mechanics, ground exploration…

Intelligence

Scene analysis, big data analysis, scientific visualization, flow analysis…

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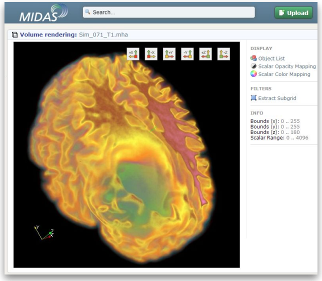
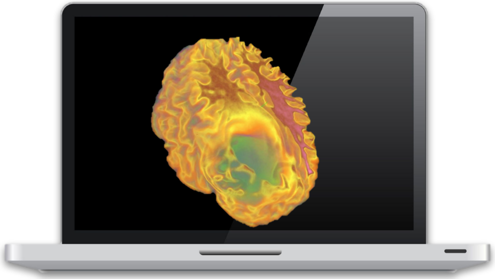
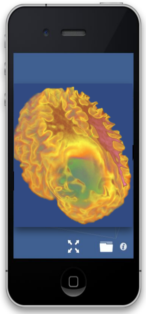
Applications / Universal Platforms



Web



Desktop



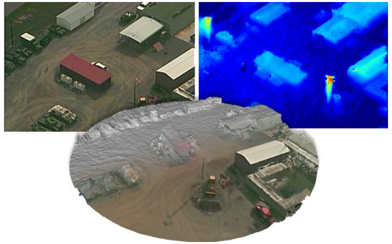
Mobile

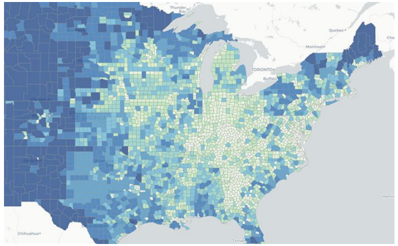
Cloud /HPC

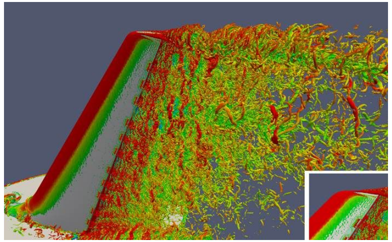
kitware Platforms

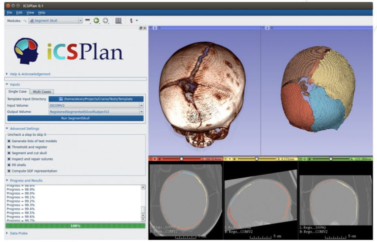
3D Slicer
ParaView
KWIVER
imstk
VTK
Pulse Physiology Engine
CMake
Resonant
tomviz
ITK

Areas of expertise / Built on open source









Computer Vision

Data and Analytics

Scientific Computing

Medical Computing

Software Solutions

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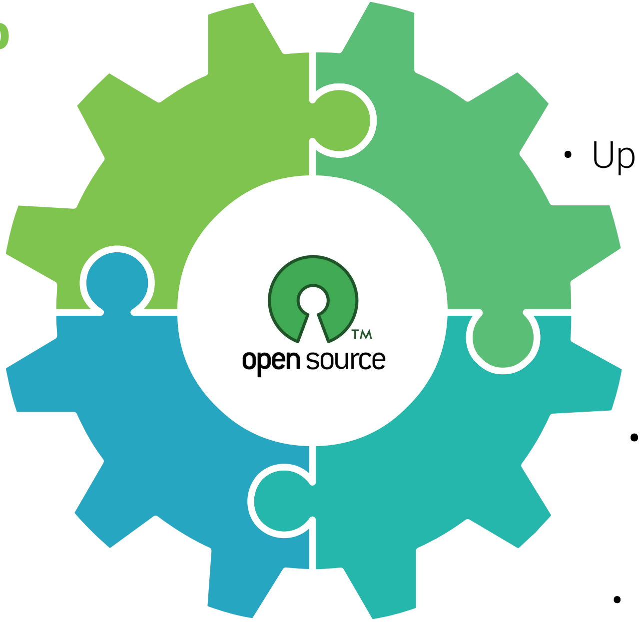
Open Source Benefits / Shifting Power

Source code ownership

- Source code ownership
- Integration with commercial software solutions

Cost effectiveness

- No license fee
- No vendor lock-in
- Shared maintenance costs



Flexibility and Agility

- Continuous development
- Up to date with new technologies
- Ability to customize and fix

Security

- Robust software and libraries
- Transparency
- Community effort
- Open Innovation mitigates risk

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Kitware / Services

TRAINING

SUPPORT

DEVELOPMENT

GRANT COLLABORATION

Delivering Innovation

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Why CMake

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What is CMake?

- CMake is the cross-platform, open-source build system generator that **lets you use the native development tools** you love the most.

- It's a **build system generator**

- It **takes plain text files as input** that describe your project and **produces project files** or make files for use with a wide variety of native development tools.

- **Family of Software Development Tools**
  - Build = CMake Test = CTest/CDash Package = CPack

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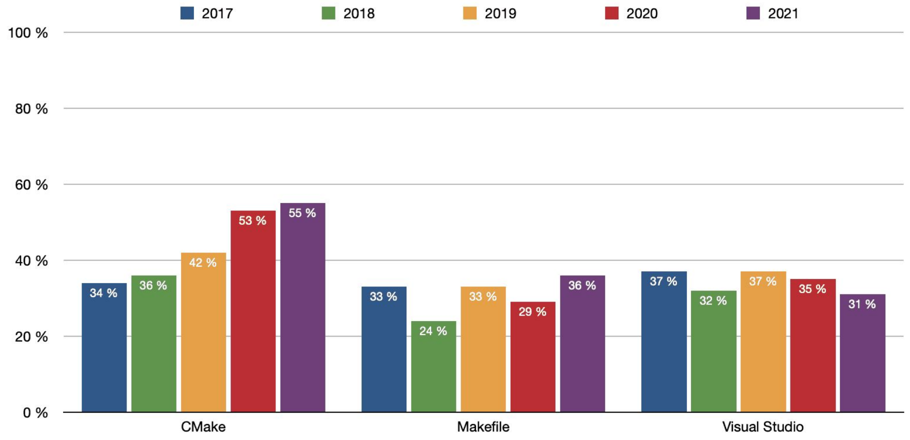
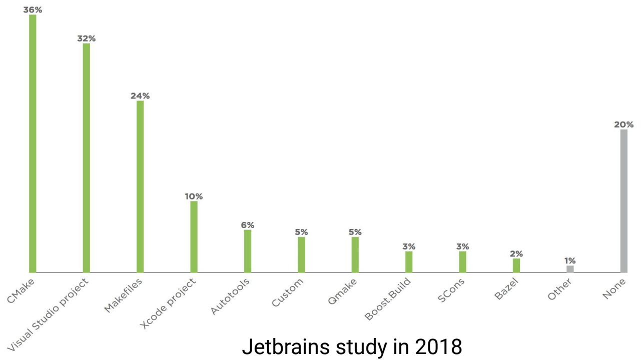
CMake is the most popular C++ build tool at 55%



Jetbrains study 2017-2021

- **Job openings requiring CMake experience, June, 2022:**
  - Indeed.com: 900 jobs at Tesla Motors, DCS Corp, Mindsource, Quanergy, …
  - LinkedIn.com: >600 jobs at Samsung, Johnson Controls, Apple, Uber, Toyota, Microsoft ...



Jetbrains study in 2018

- **Bryce Adelstein Lelbach**, the chair of Standard C++ Library Evolution group, in his talk “What Belongs In The C++ Standard Library?” at C++Now in 2022, stated that **we actually have a standard build system! It’s CMake.**

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C++ modules

include vs import

Headers and sources

- The classic approach:
  - **Header files**: **declarations, template/inline code**
  - **Source files**: **definitions**

Example: foo.hpp and foo.cpp

```cpp
// foo.hpp
#ifndef FOO_HPP
#define FOO_HPP
int foo(int i);
#endif
```

```cpp
// foo.cpp
int foo(int i) {
    return i * 42;
}
```

Example: foo usage

```cpp
// main.cpp
#include "foo.hpp"
int main() {
    return foo(4);
}
```

Preproc →

```cpp
// main.cpp
int foo(int i);
int main() {
    return foo(4);
}
```

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File types of classic approach

File	Example	Artifact	Notes

Headers (.hpp)	`#ifndef X`
	`#define X`
	…
	`#endif`
		(None)	Never built, only copied into translation units using #include

Source (.cpp)	`#include "x.hpp"` …	Object file (.obj)	Translation Units

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Issues with headers: Textual inclusion

- **Increase compile-time (headers parsed multiple times)**
  - Reduce as much as possible headers content
- **No encapsulation, preprocessor leaks…**
  - PIMPL pattern, avoid defines in headers, impl namespace
- **#includes order matters**
  - May break randomly

C++ modules (since C++20): include vs import

- **Textual inclusion is replaced with semantic import**
- **Only exported symbols are visible!**
  - No macro leak, no need for “impl” namespace…
- **Header-Source replaced by:**
  - **1: “Module Interface Unit”**
  - N >= 0: “Module Implementation Unit”

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Example: foo.cppm (.ixx, .mpp, .mxx, .cmi)

```
// foo.cppm
export module foo;
export int foo(int i) {
    return i * 42;
}
```

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Example: foo usage

```cpp
// main.cpp
import foo;
int main() {
    return foo(4);
}
```

File types of modules

File	Example	Artifact	Notes
Module interface unit (.cppm)	`export module x;` `…`	Built Module Interface (.pcm) Object file (.obj)	One per module
Module implementation unit (.cppm)	`module x;` `…`	Object file (.obj)	Optional, contains definitions
Non-module unit (.cpp)	`import x;`	Object file (.obj)	"Classic" Translation Units

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Built Module Interface

The artifact created by a compiler to represent a module unit or header unit. The format [...] is **implementation specific** and holds C++ entities, which can be represented in the form of compiler specific data structures (e.g. ASTs), machine code or any intermediate representation chosen by the implementer.

File extension: .pcm (Clang) | **.gcm** (GCC) | **.ifc** (MSVC)

Built Module Interface

In short:

- **`import foo` looks for foo's BMI** (e.g. `foo.pcm`)
- This file contains the **module definition**

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Issues with headers solved by modules

- Increase compile-time (headers parsed multiple times)
  - **Prebuilt representation used directly!**
- No encapsulation, preprocessor leaks…
  - **Explicit export, preprocessor is local to module units!**
- #includes order matters
  - **Imports order does not matter!**

New issues created by modules

- **Build order of modules units matters**
  - Need the “BMI” build artifact to import a module
- **Build parallelism is lower**
  - Dependencies are stronger (per-file)
  - Mitigated by the fact that each translation unit is faster

Other features

- **Partition units**
  - Enable splitting modules in multiple files
- **Header units (not supported by CMake, yet)**
  - Translation units synthesized from headers
  - `import <header>` don't have access to macros defined before import declaration
- **Global module fragment**
  - Fragment where we can use classic includes in modules

Other features (example)

```
module; // global module fragment
#define NOMINMAX
#include <Windows.h> // have access to NOMINMAX
export module foo:math; // partition
import <algorithm>; // private header unit
export int min(int a, int b) {
    return std::min(a, b); // OK
}
```

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Building modules

LLVM support

Of C++ modules

Clang Module Support

Main module proposal → P1103R3

Fixes and clarifications about parsing, linkage, semantics, interactions with preprocessor…

P1103R3	Clang 15
P1766R1 (DR)	Clang 11
P1811R0	No
P1703R1	Subsumed by P1857
P1874R1	Clang 15
P1979R0	No
P1779R3	Clang 15
P1857R3	No
P2115R0	Partial
P1815R2	Partial
P2615R1 (DR)	No
P2788R0 (DR)	No

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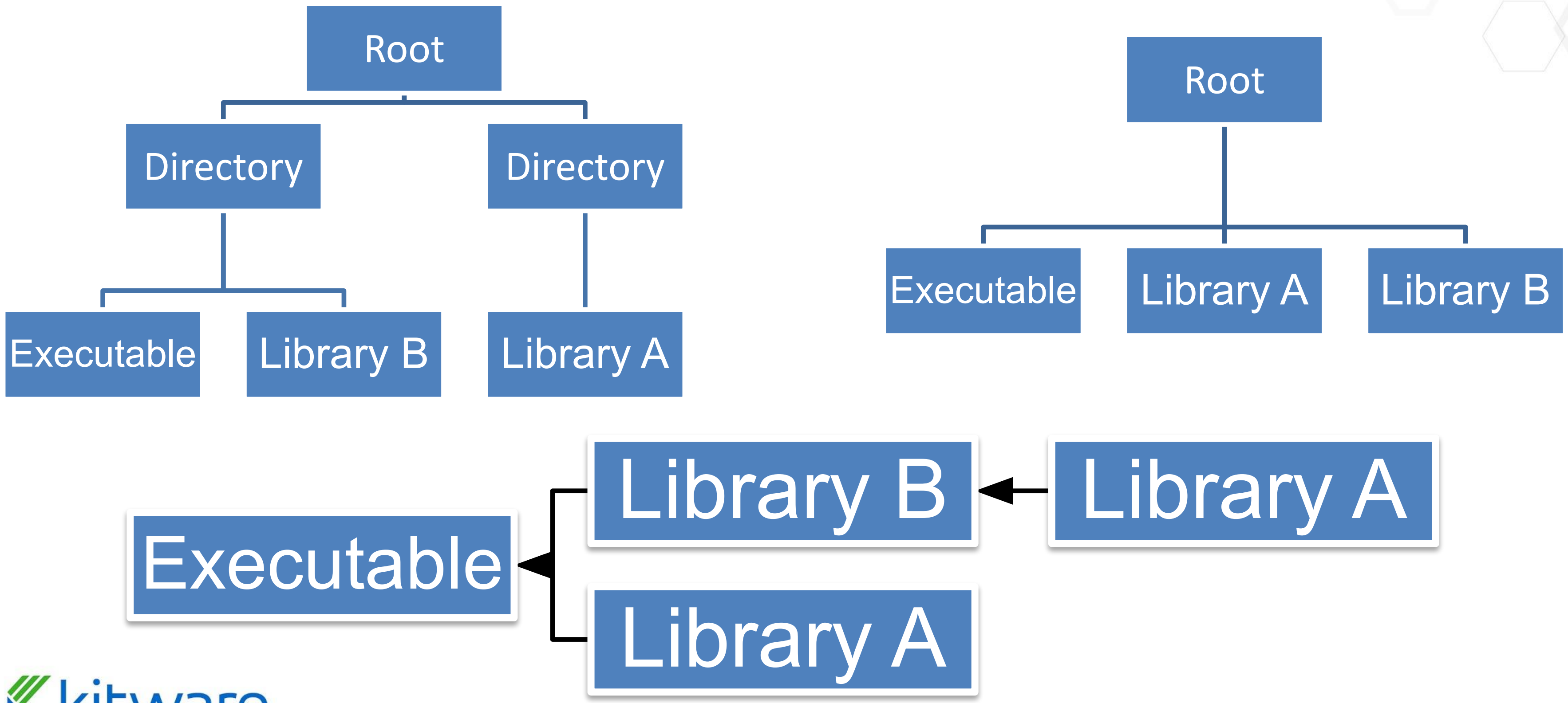
Clang Scan Deps

- Command line tool to scan module dependencies without full tokenizer for faster scan
- Added in LLVM 16
- JSON format defined by P1689R5

CMake concepts

Small reminders

Usage requirements (Modern CMake)



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Usage requirements (Modern CMake)

PRIVATE: Only *this* target will use it

INTERFACE: Only *consuming targets* use it

PUBLIC: PRIVATE + INTERFACE

$<BUILD_INTERFACE>: When this target is being built

$<INSTALL_INTERFACE>: After this target has been installed

Consuming target: `target_link_libraries`

File sets (target_sources)

```
add_library(foo STATIC)
target_sources(foo PUBLIC
   FILE_SET name
   TYPE CXX_MODULES
   FILES files...
)
```

Compile features

```
~~set(CMAKE_CXX_STANDARD 20)~~
~~add_library(foo STATIC)~~

add_library(foo STATIC)
target_compile_features(foo PUBLIC cxx_std_20)
```

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CMake support

Using the Ninja build system

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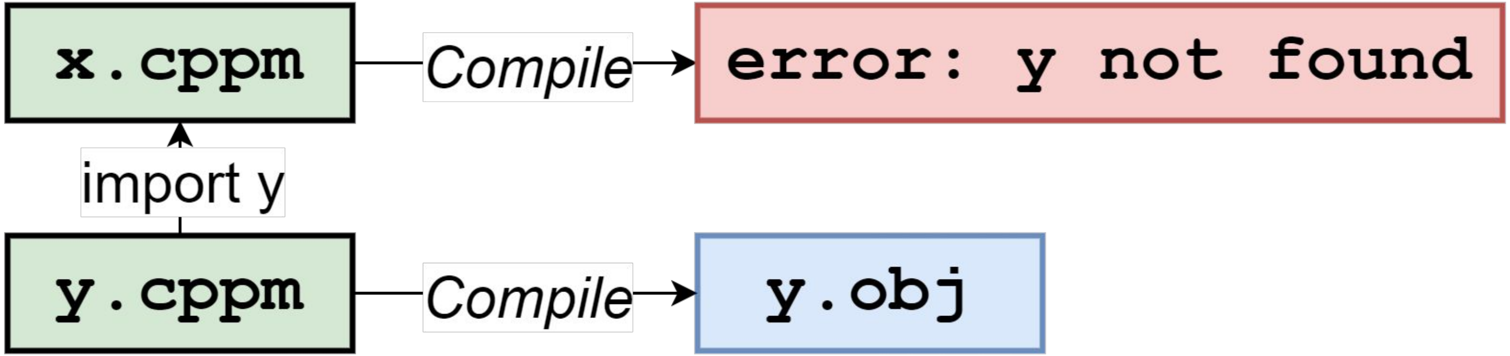
Building modules with CMake (wrong way)

```
# x.cppm imports y.cppm
add_library(foo STATIC y.cppm x.cppm)
target_compile_features(foo PUBLIC cxx_std_20)
```

Building modules with CMake

Build may fail due to missing dependency!

You can start the build multiple times until it works :)



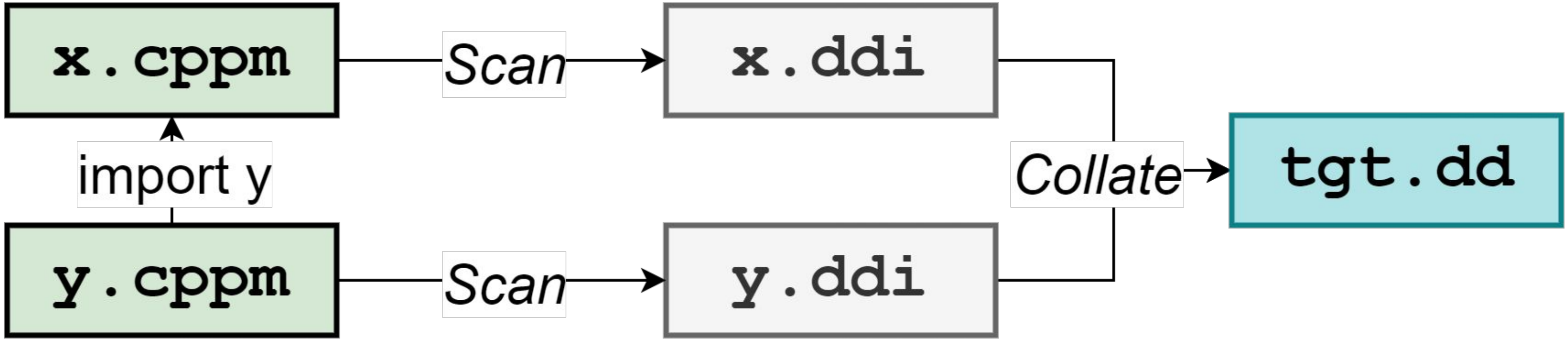
Building modules with CMake (good way)

```
add_library(foo STATIC)
target_compile_features(foo PUBLIC cxx_std_20)
target_sources(foo PUBLIC
    FILE_SET modules TYPE CXX_MODULES FILES
    y.cppm x.cppm
)
```

Building modules with CMake

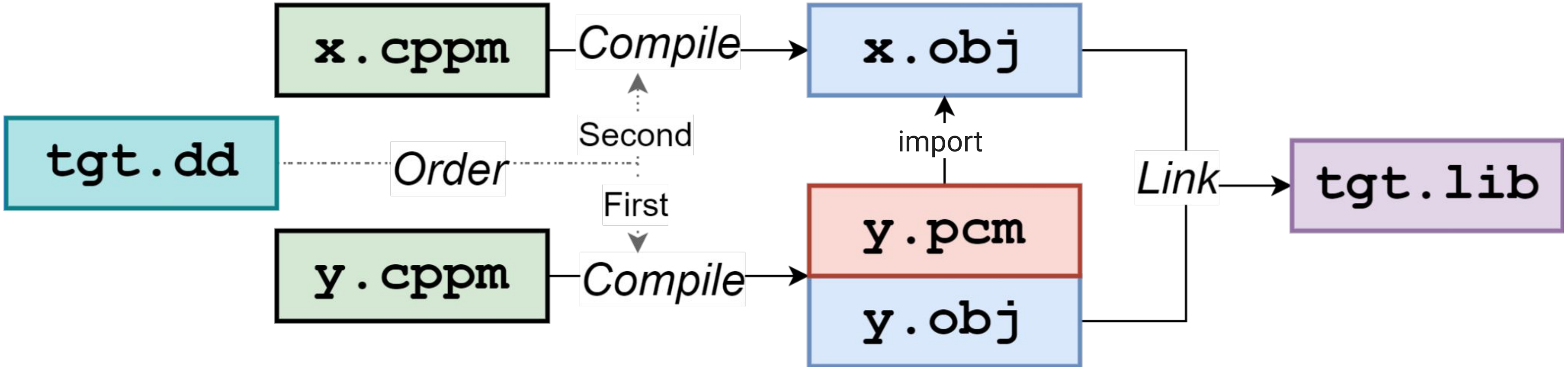
For each target, scan module units dependencies.

Then collate them into a single, per-target, file.



Building modules with CMake

Build system use this file to know the right build order



Build output example

Scan	[1/6] Scanning y.cppm for CXX dependencies
	[2/6] Scanning x.cppm for CXX dependencies
Collate	[3/6] Generating CXX dyndep file CXX.dd
Build	[4/6] Building CXX object y.cppm.obj
	[5/6] Building CXX object x.cppm.obj
Link	[6/6] Linking CXX static library foo.lib

Build output example (verbose)

Scan

```
[1/6] clang-scan-deps -format=p1689 -- clang -O0 -std=c++20 y.cppm -c -o CMakeFiles\foo.dir\y.cppm.obj -MT CMakeFiles\foo.dir\y.cppm.obj.ddi -MD -MF CMakeFiles\foo.dir\y.cppm.obj.ddi.d > CMakeFiles\foo.dir\y.cppm.obj.ddi
[2/6] clang-scan-deps -format=p1689 -- clang -O0 -std=c++20 x.cppm -c -o CMakeFiles\foo.dir\x.cppm.obj -MT CMakeFiles\foo.dir\x.cppm.obj.ddi -MD -MF CMakeFiles\foo.dir\x.cppm.obj.ddi.d > CMakeFiles\foo.dir\x.cppm.obj.ddi
```

Collate

```
[3/6] cmake -E cmake_ninja_dyndep --tdi=CMakeFiles\foo.dir\CXXDependInfo.json --lang=CXX --modmapfmt=clang --dd=CMakeFiles/foo.dir/CXX.dd @CMakeFiles/foo.dir/CXX.dd.rsp
```

Build

```
[4/6] clang -O0 -std=c++20 -MD -MT CMakeFiles/foo.dir/y.cppm.obj -MF CMakeFiles\foo.dir\y.cppm.obj.d @CMakeFiles\foo.dir\y.cppm.obj.modmap -o CMakeFiles/foo.dir/y.cppm.obj -c C:/dev/eurollvm/y.cppm
[5/6] clang -O0 -std=c++20 -MD -MT CMakeFiles/foo.dir/x.cppm.obj -MF CMakeFiles\foo.dir\x.cppm.obj.d @CMakeFiles\foo.dir\x.cppm.obj.modmap -o CMakeFiles/foo.dir/x.cppm.obj -c C:/dev/eurollvm/x.cppm
```

Link

```
[6/6] llvm-ar qc foo.lib  CMakeFiles/foo.dir/y.cppm.obj CMakeFiles/foo.dir/x.cppm.obj
```

Importing modules ?

Exporting modules

```
install(TARGETS foo
    EXPORT footargets
    FILE_SET modules DESTINATION include
)
```

Build output (importing foo in another project)

Scan	`[1/6] Scanning foo.cppm for CXX dependencies`
Collate	`[2/6] Generating CXX dyndep file foo.dir/CXX.dd`
Scan	`[3/6] Scanning main.cpp for CXX dependencies`
Collate	`[4/6] Generating CXX dyndep file test.dir/CXX.dd`
Build BMI	`[5/7] Building CXX object foo.dir/foo.bmi`
Build	`[6/7] Building CXX object test.dir/main.cpp.obj`
Link	`[7/7] Linking CXX executable test.exe`

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Build output (importing foo in another project)

The module interface unit is precompiled once to generate the BMI

```
[5/7] clang++ -O0 -std=gnu++20 --precompile
[…] -o foo.dir/foo.bmi -c …/include/foo.cppm
```

import foo -> foo.bmi

Link against prebuilt foo.lib/a

Questions ?

- Kitware blog on CMake support of modules
- P2473R: Distributing C++ Module Libraries
- CMake Header Units support
- CMake 3.28 Release Notes