Migrating large codebases to C++ Modules

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Agenda

1. Motivation of C++ Modules
2. C++ Modules in ROOT
3. C++ Modules in CMSSW
4. CMS Performance Results
5. Conclusion

Motivation of C++ Modules

Motivation of C++ Modules

C++ Modules technology:

- Cache parsed header file information and avoid runtime header parsing
- Part of C++20 technical specification

Motivation of C++ Modules

```
#include <vector>
```

Motivation of C++ Modules

```
#include <vector>
```

Textual Include	Precompiled Headers (PCH)	Modules
✗ Expensive ✗ Fragile	✗ Inseparable	✓

Motivation of C++ Modules

```
#include "TVirtualPad.h"
#include <vector>
#include <set>

int main() {
…
```

original code

Preprocess

Textual Include

```
                                        ……
                                        ……
# 286 "/usr/include/c++/v1/vector" 
namespace std { inline namespace __
template <bool> class __vector_base
{
   __attribute__
((__visibility__("hidden"),
__always_inline__)) __vector_base_c
{}
                                        ……
# 394 "/usr/include/c++/v1/set" 3
namespace std {inline namespace __1
template <…> class set {
public:
    typedef _Key key_type;
                                        ……

int main {
                                        ……
```

TVirtualPad.h

mmon

vector

on()

set

one big file!

Parse

Compile

.o

Motivation of C++ Modules

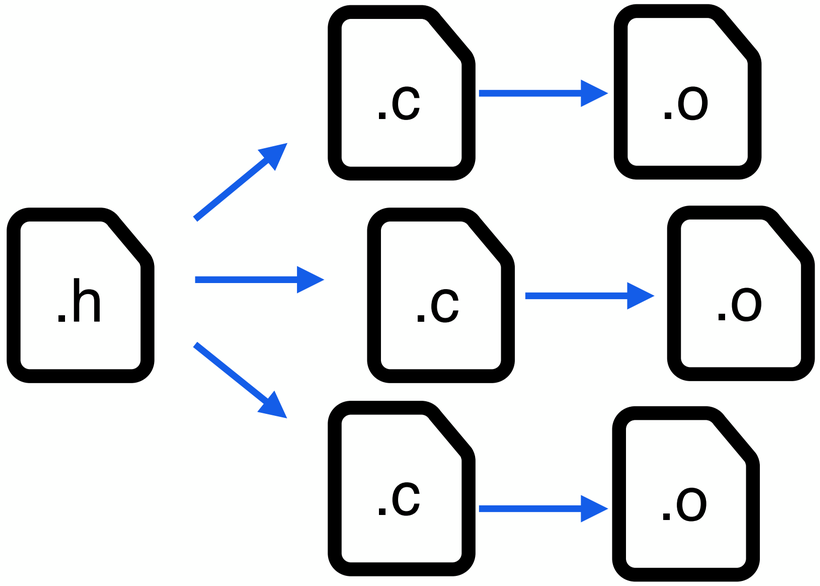
Textual Include

1. Expensive

   Reparse the same header

2. Fragile

   Name collisions



Rcpp library

```
#define PI 3.14
…
```

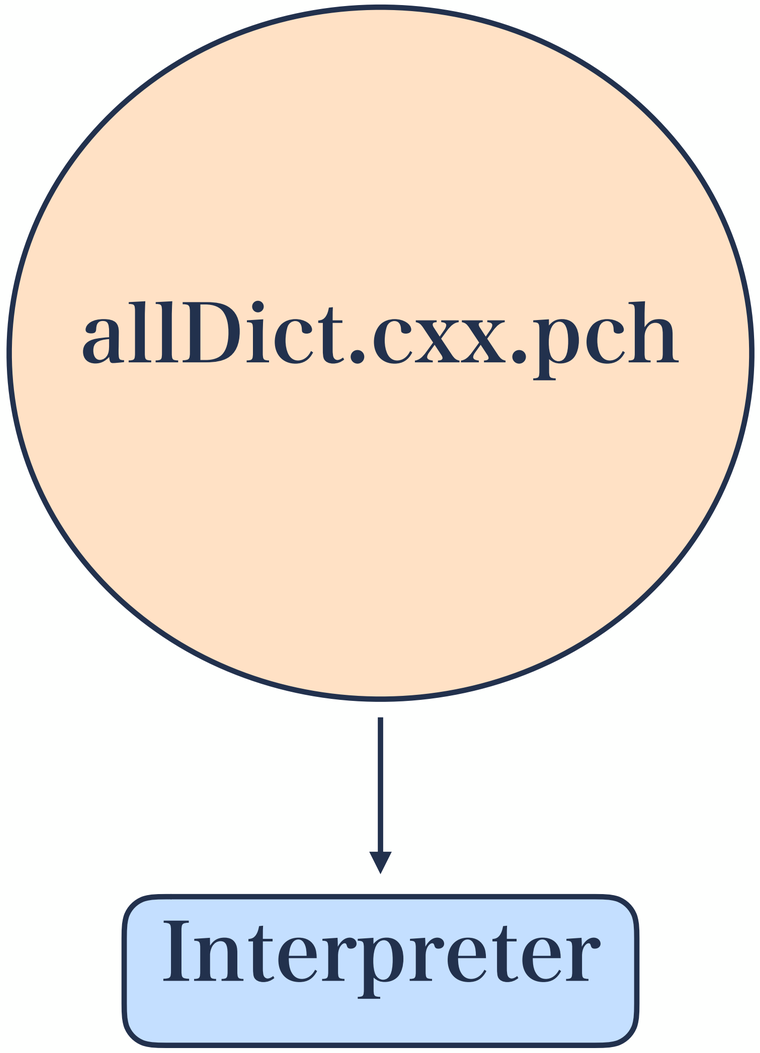
Users' code

```
#include <header.h>
                …
double PI = 3.14;
// => double 3.14 = 3.14;
```

Motivation of C++ Modules

PCH (Precompiled Headers)

1. Storing precompiled header information (same as modules)
2. Stored in one big file
   - Inseparable

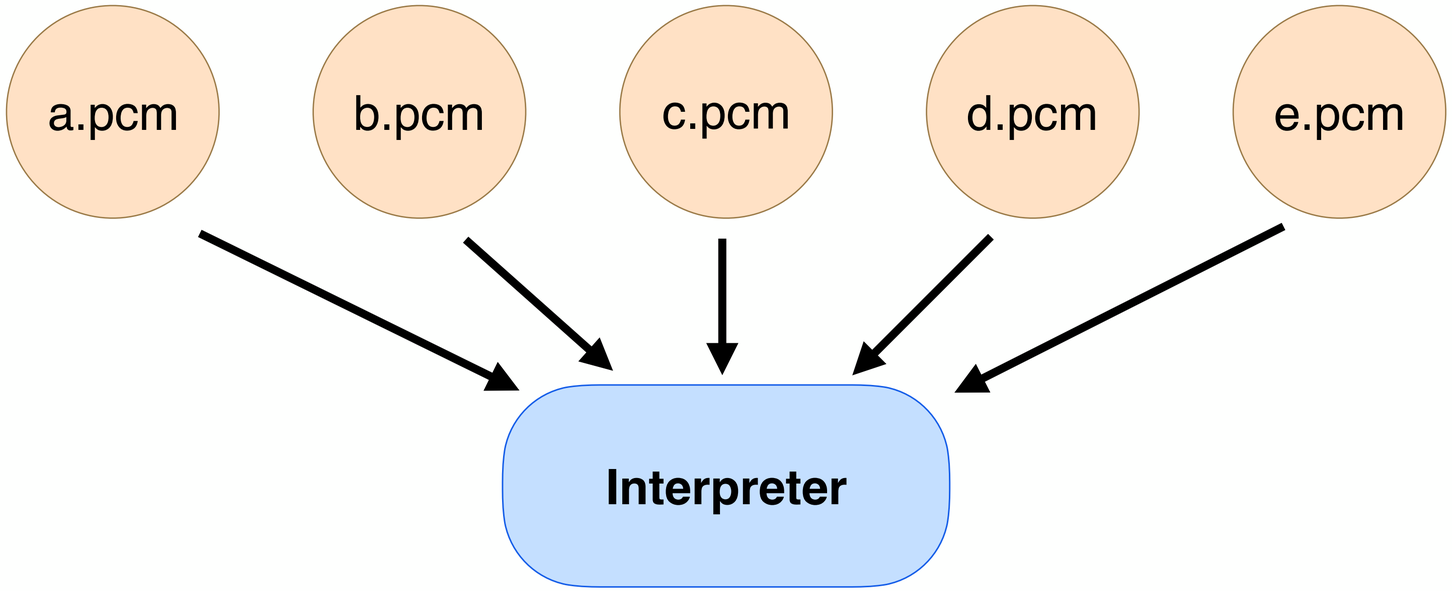


Motivation of C++ Modules

Modules

- Pre compiled **PCM files** contain header information
- PCMs are **separated**

Each PCM file (a.pcm) corresponds to a library (liba.so)



Motivation of C++ Modules

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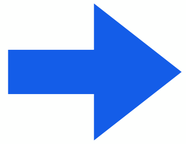
- PCMs are **separated**



✓ Compile-time scalability

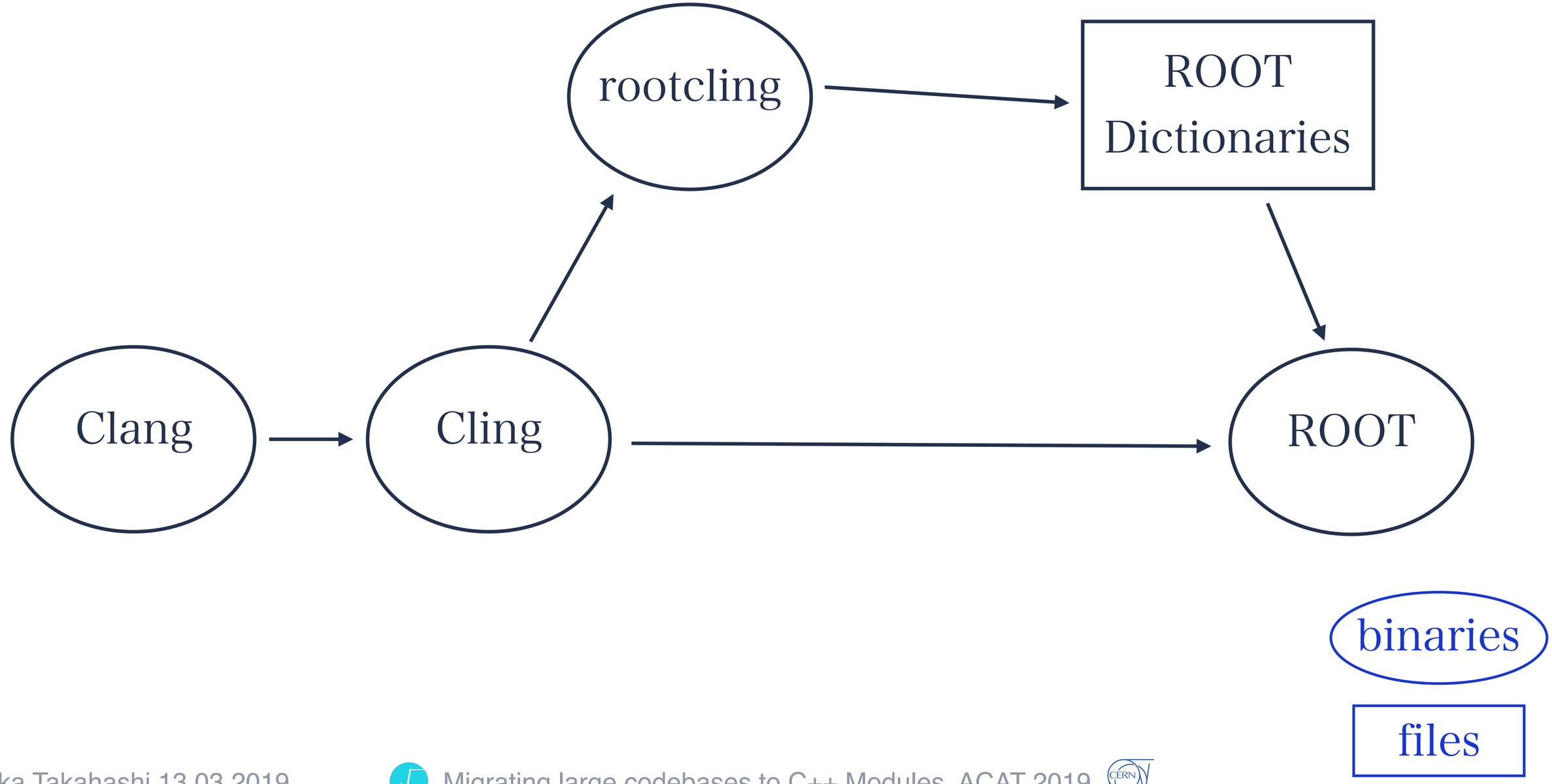
✓ Fragility

✓ Separable

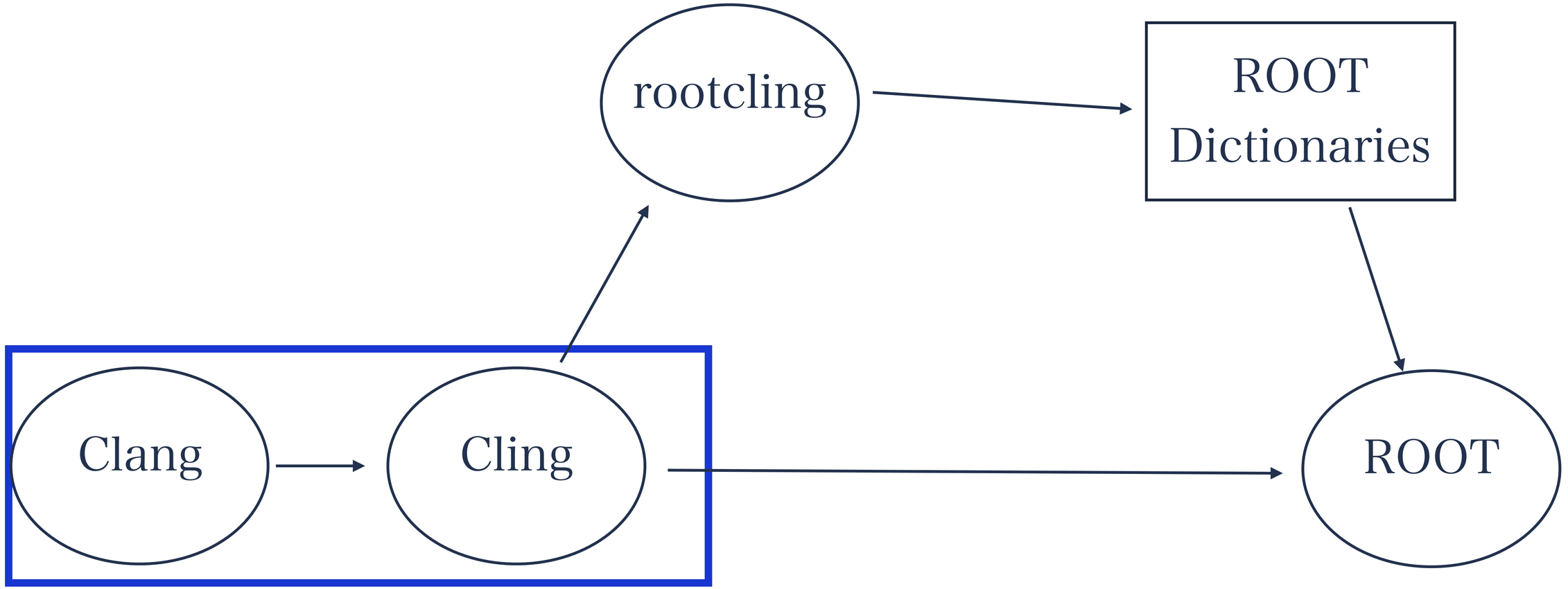
C++ Modules in ROOT

Technology Preview released in ROOT 6.16

Overview - Dependency Graph



Overview - Dependency Graph

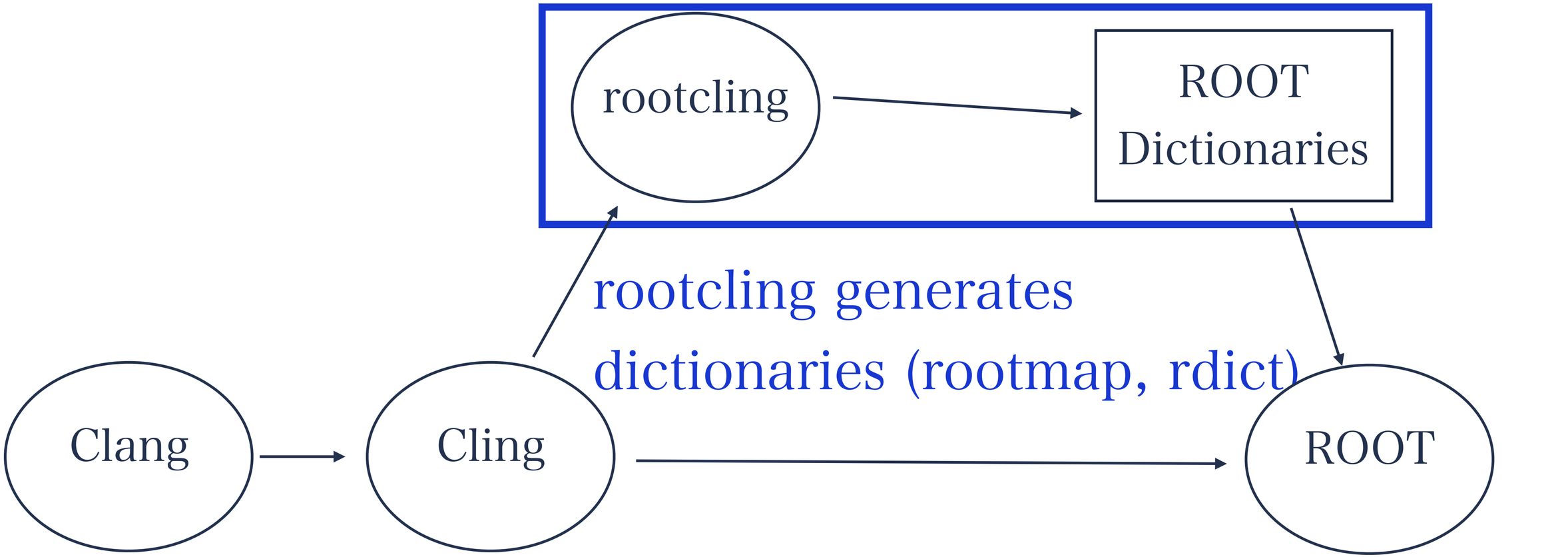


Cling calls Clang API

binaries

files

Overview - Dependency Graph



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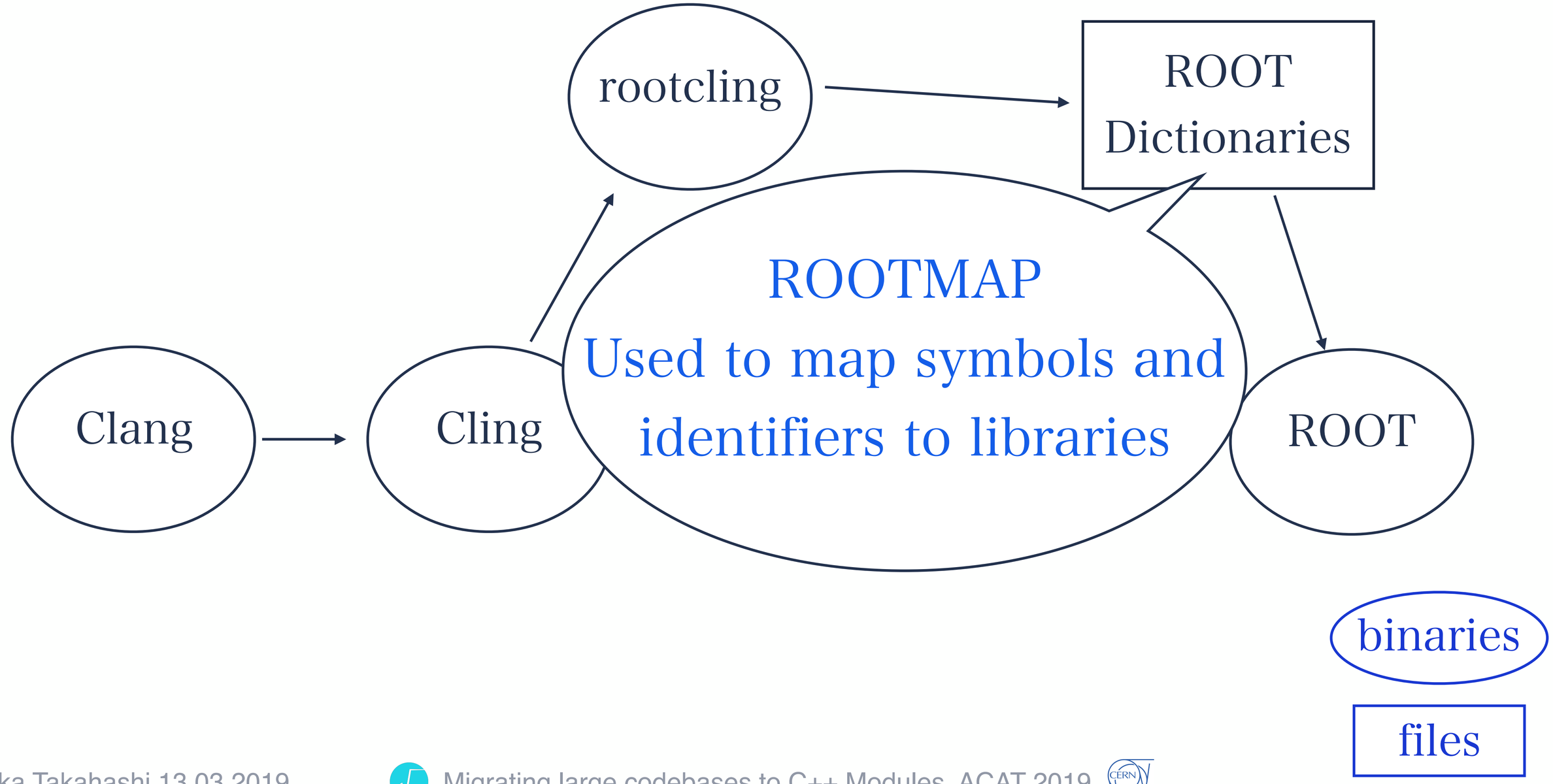

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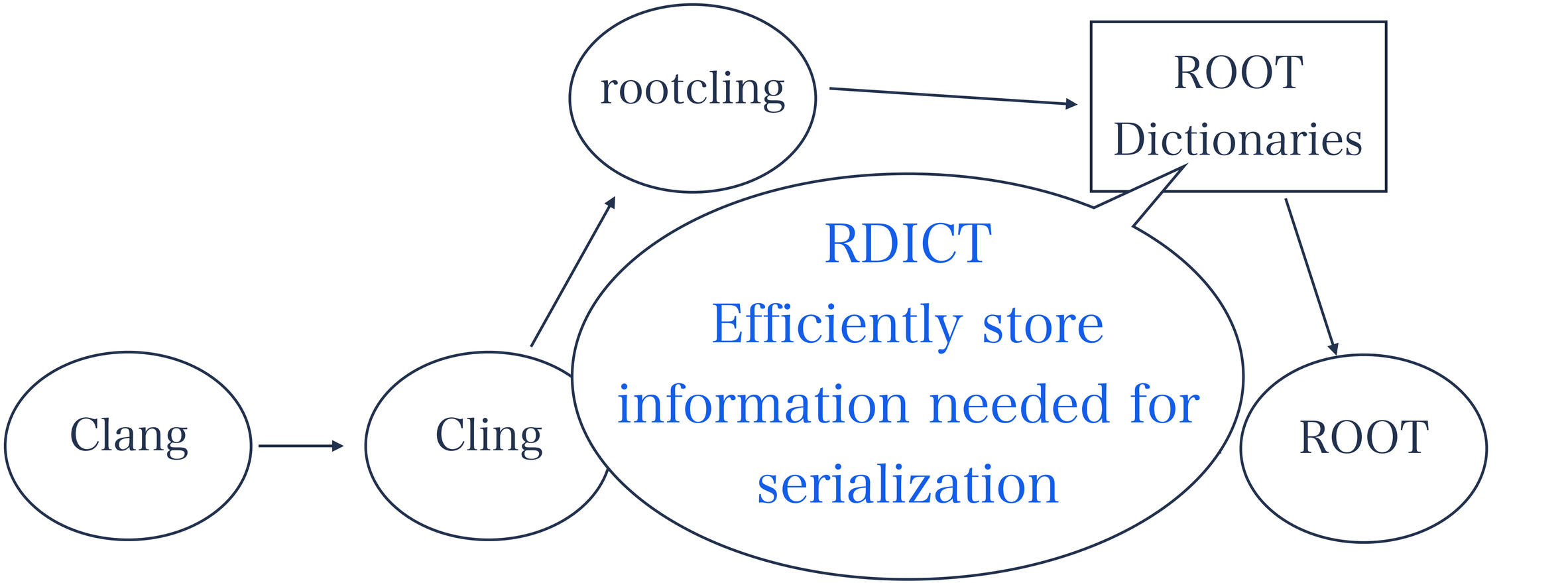

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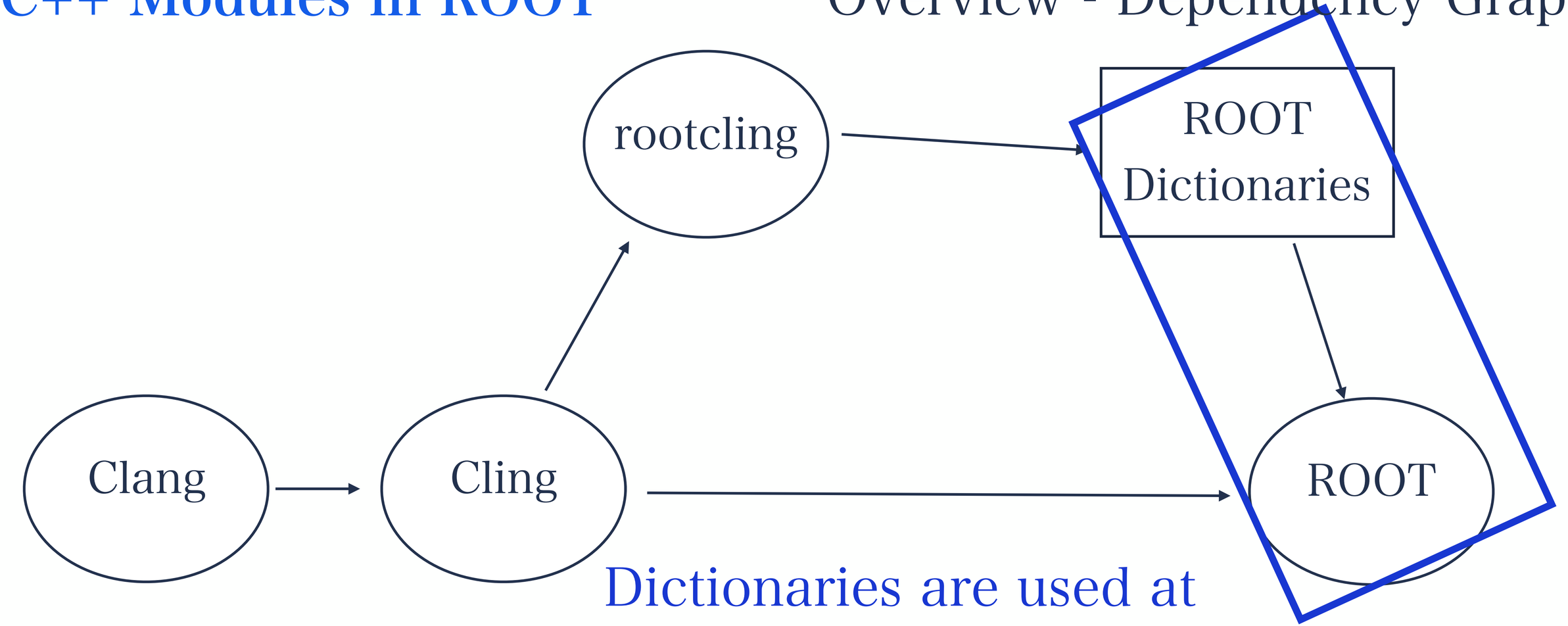

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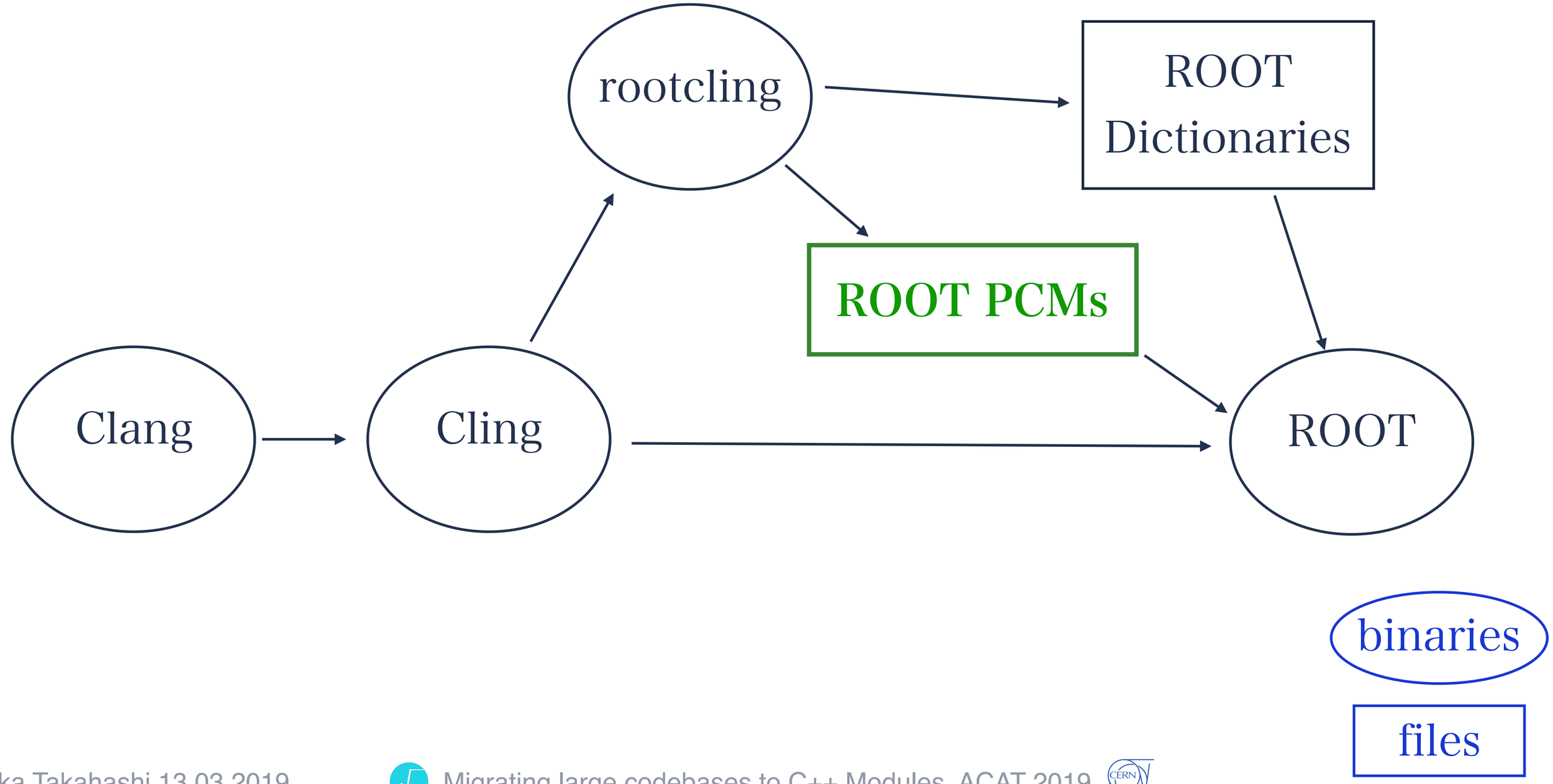
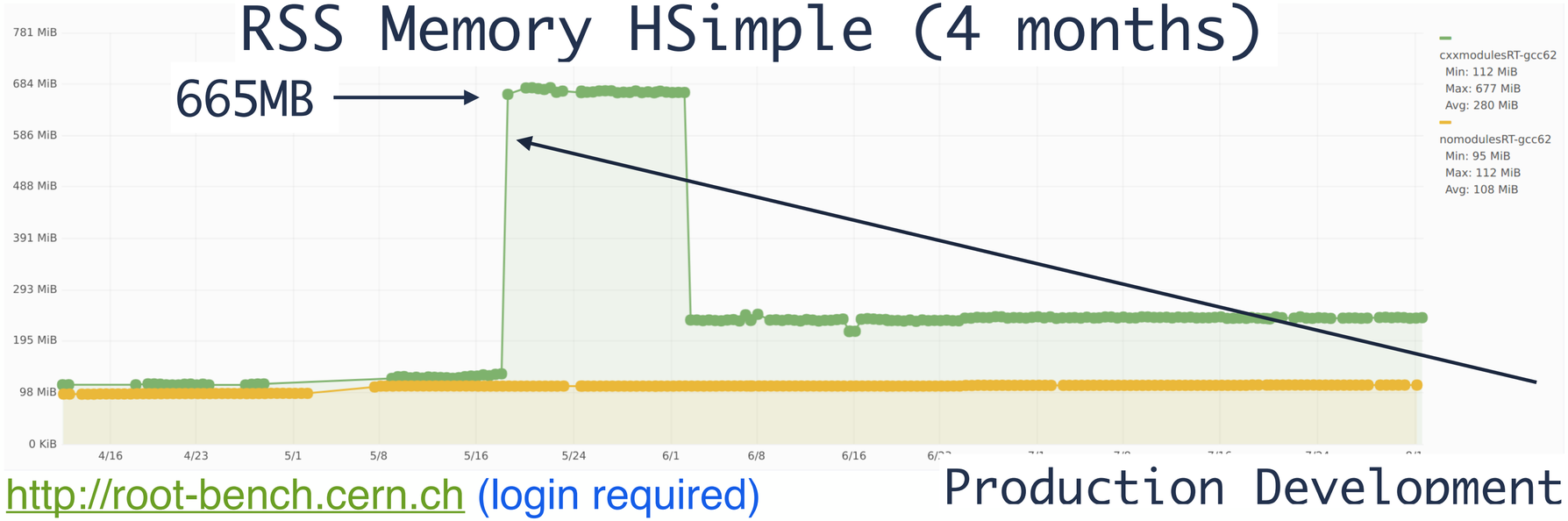


Preloading of modules

- Replace some functionality of RDICT and ROOTMAP with a more stable implementation
- Load all ROOT modules at the startup time



Preloading of all modules

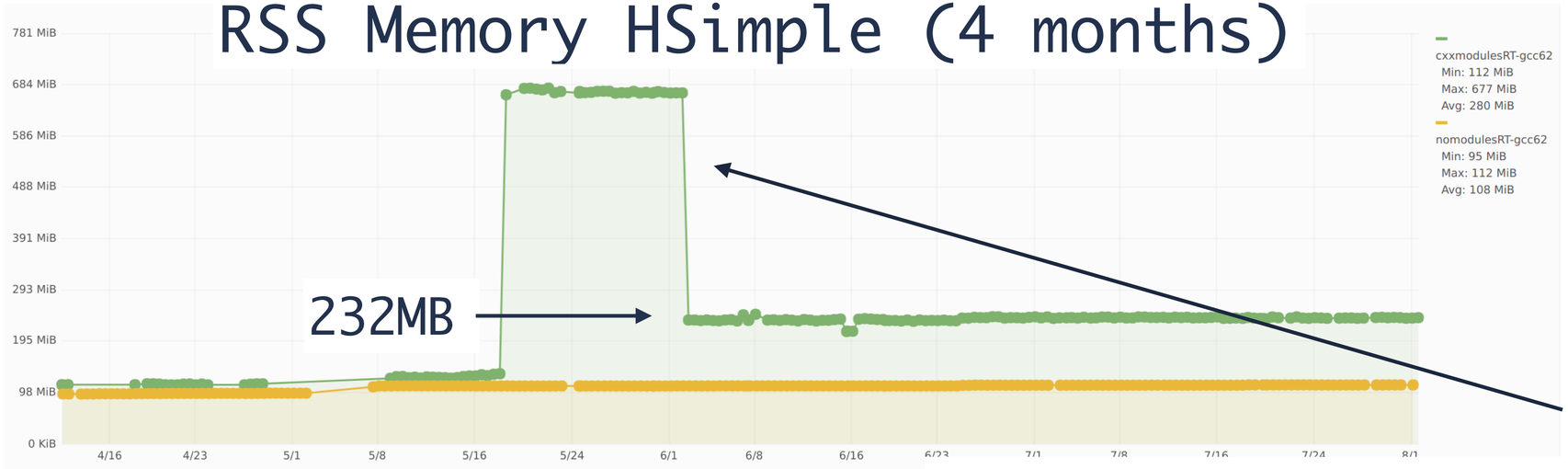
http://root-bench.cern.ch (login required)

Global Modules Index

- Remove further overhead in ROOT
- Mechanism to create the table of symbols and PCM names
  - ROOT will be able to load corresponding library when a symbol lookup failed
  - The prototype shows promising results

Bloom filter

- False positive hash section in shared object file (further read)
- Preloading of Modules triggered a overhead coming from the excessive library loading



Bloom filter

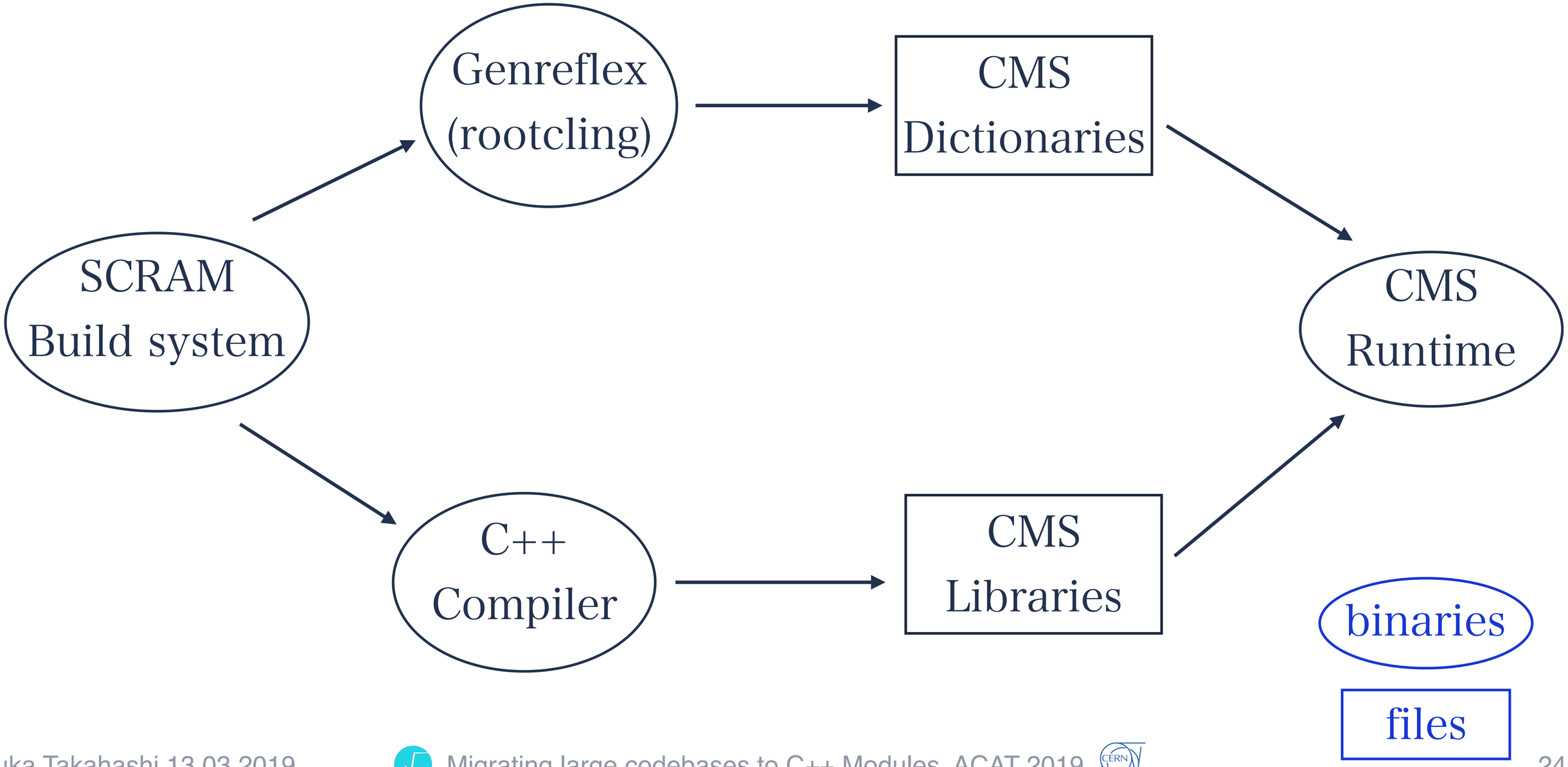
http://root-bench.cern.ch (login required) Production Development

C++ Modules in CMSSW

Available in CMS CXXMODULE IB

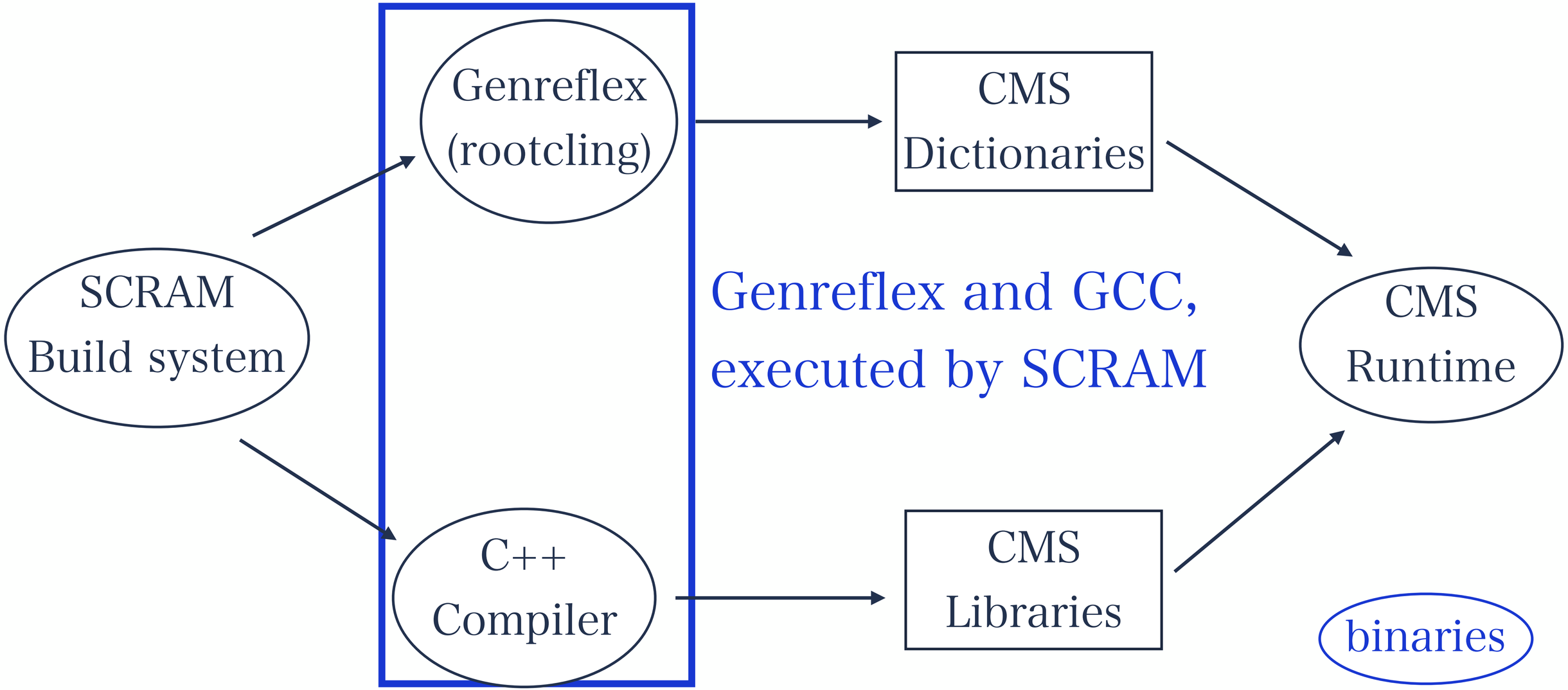
C++ Modules in CMSSW

Overview - Dependency Graph



C++ Modules in CMSSW

Overview - Dependency Graph



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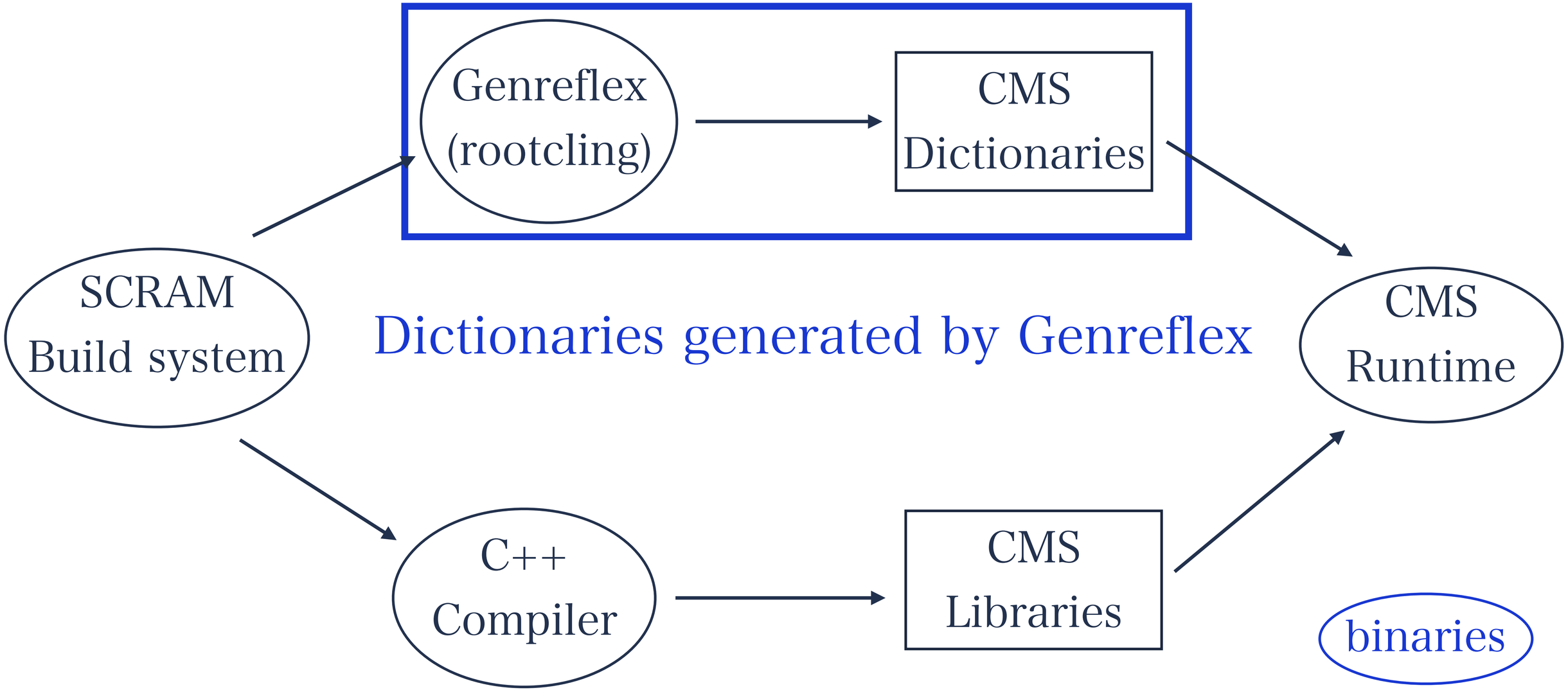
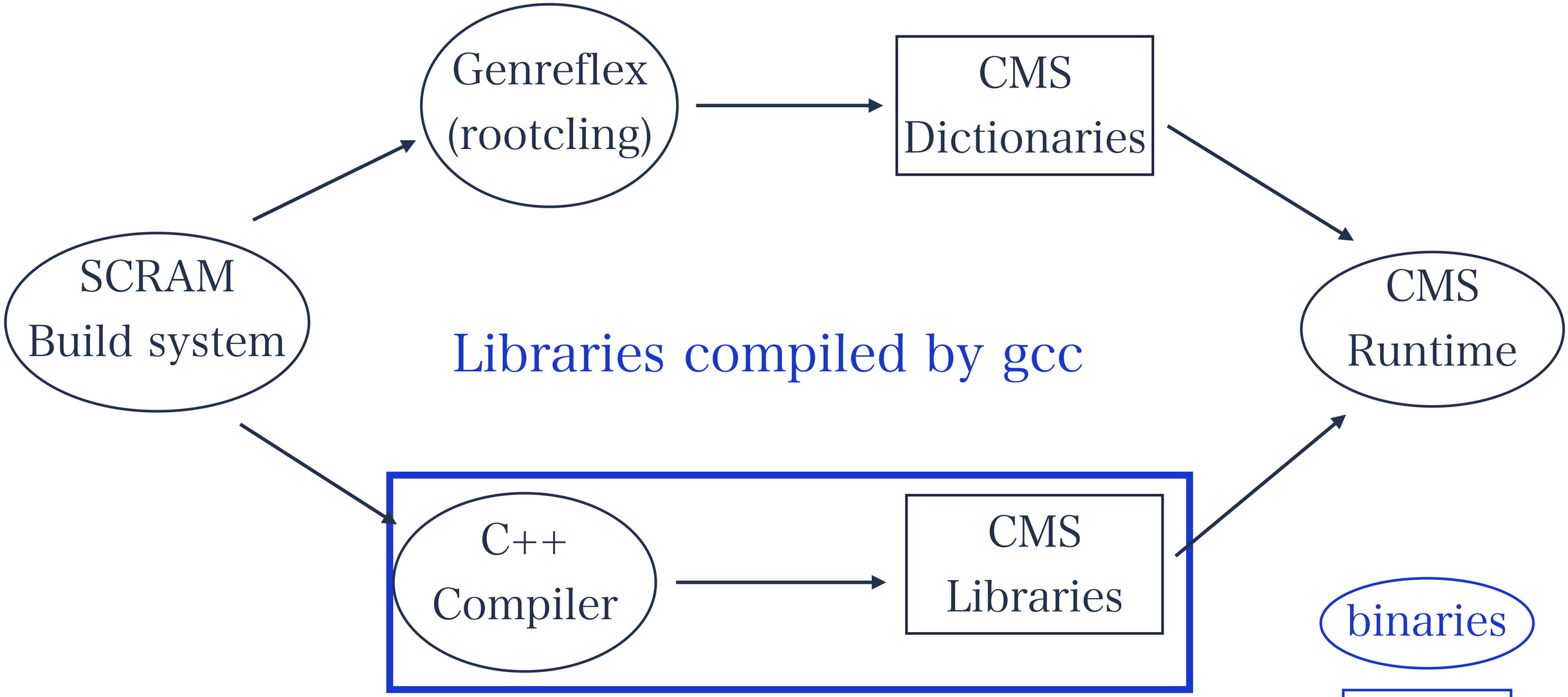


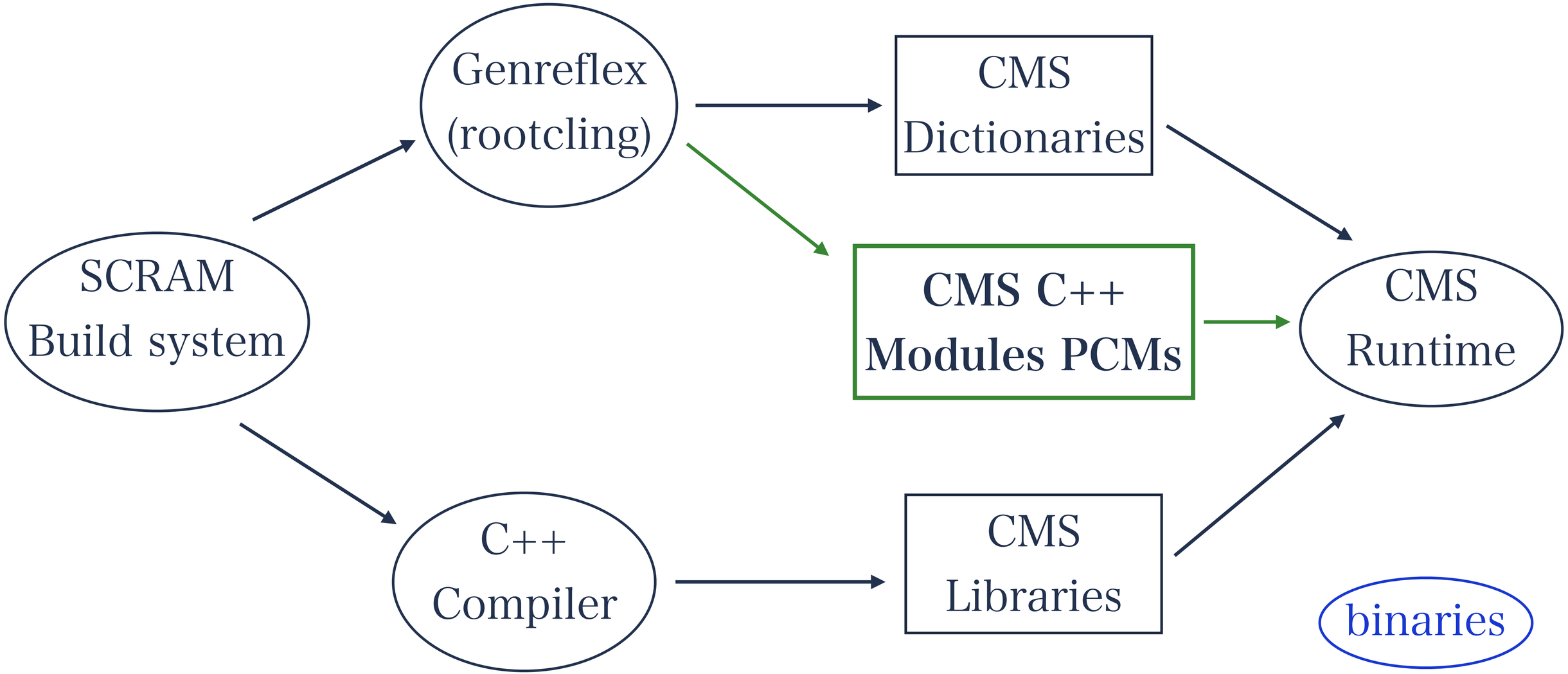
C++ Modules in CMSSW

Overview - Dependency Graph



C++ Modules in CMSSW

Overview - Dependency Graph



Implicit PCMs in CMSSW

Implicit pcms

Implicitly generated **without** modulemaps

- Add all possible header files needed for the generation of the dictionary
  - **Huge header duplication**

Explicit pcms

Explicitly generated **with** modulemaps

- Only add defined headers to the PCM
  - **Reduce header duplication**

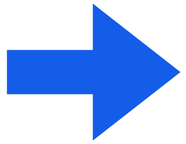
Explicit PCMs in CMSSW

module.modulemap

- Definition file of headers to build a PCM in Clang
- Contain all “interface” headers, which are used by libraries

```
module "MathCore" {
  module “TComplex name” { header "TComplex.h" export * }
  module <name of the file> {
    header <relative path to the header file location> }
}
```

modulemap will contain all interface header files



Autogeneration of modulemap

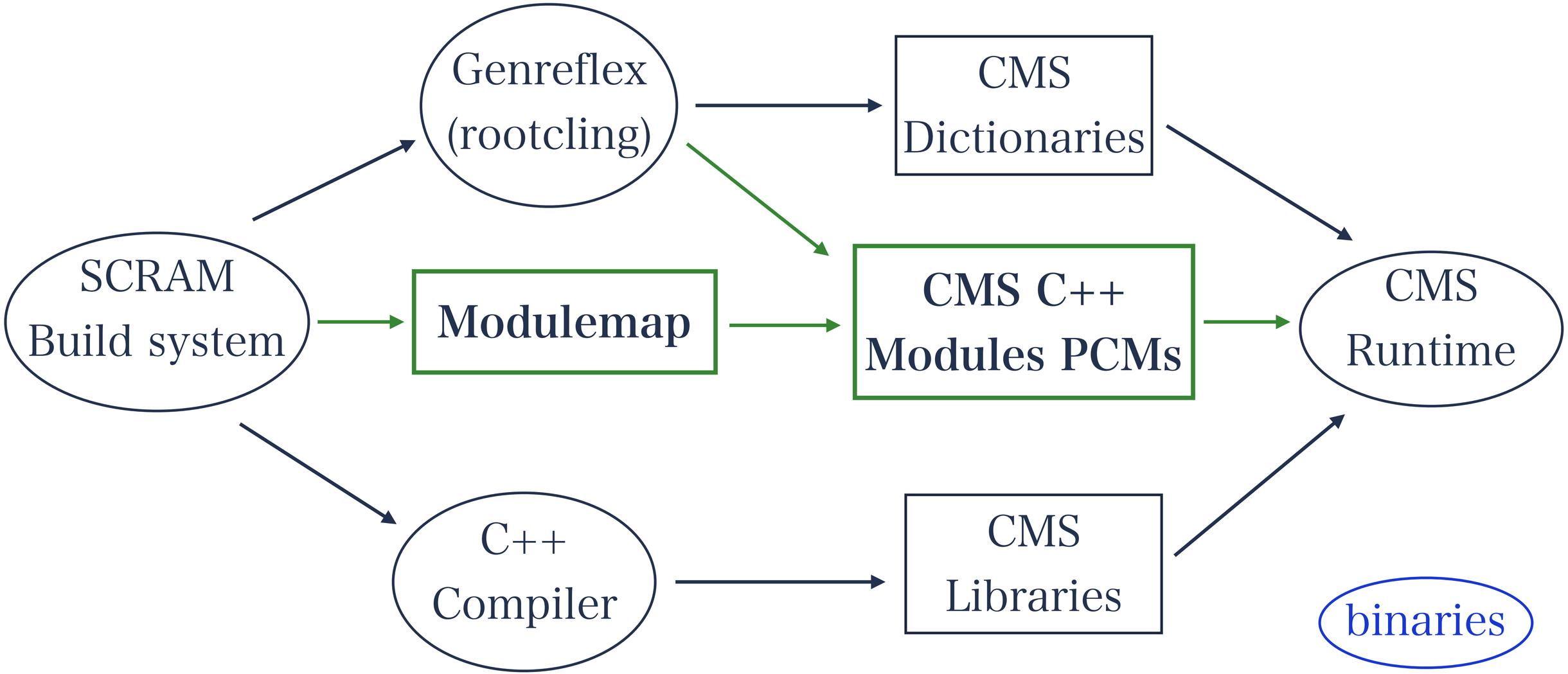
Explicit PCMs in CMSSW

Autogeneration of modulemap

- CMSSW has “**interface**” headers
  - Exposed to libraries outside
- **Automatically generate the modulemap** by adding interface headers
  - Modulemap needs to be generated before the execution of **genreflex**

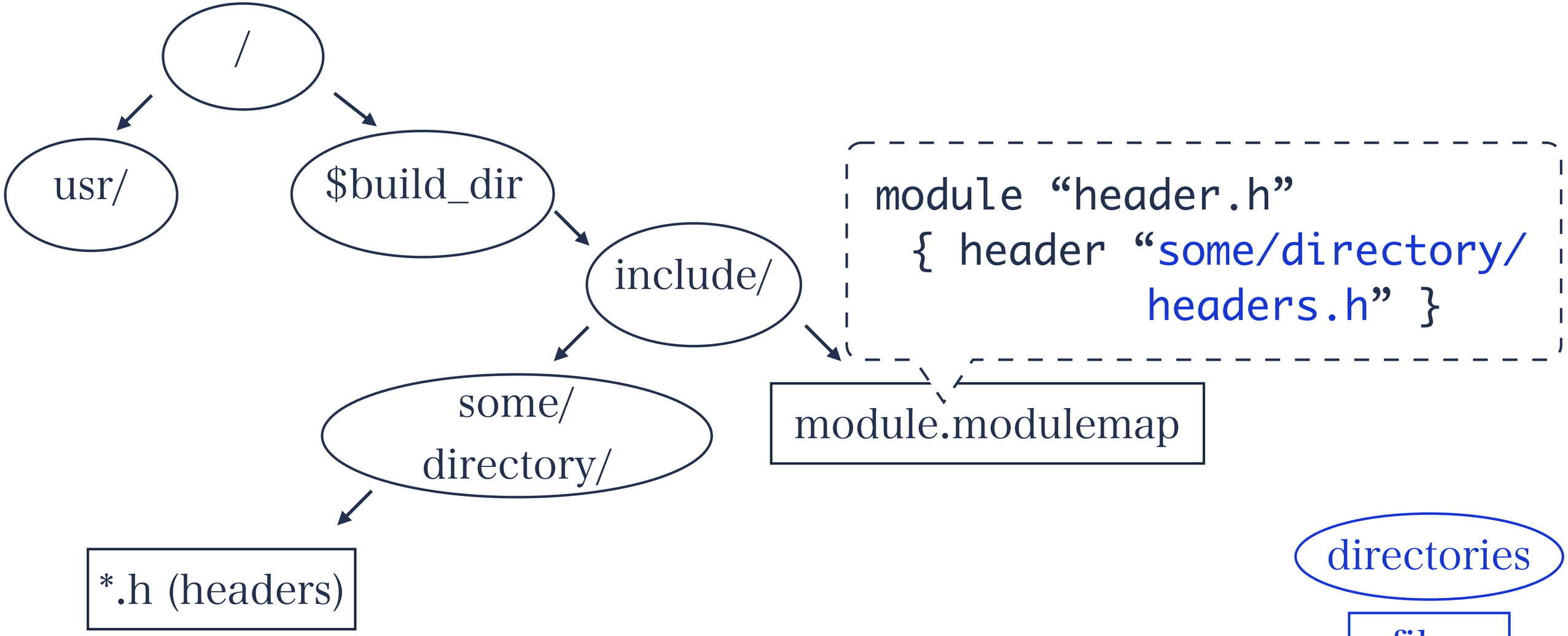
C++ Modules in CMSSW

Explicit PCMs in CMSSW



Mechanism of the modulemap

modulemap, modulemap overlay file, virtual modulemap overlay



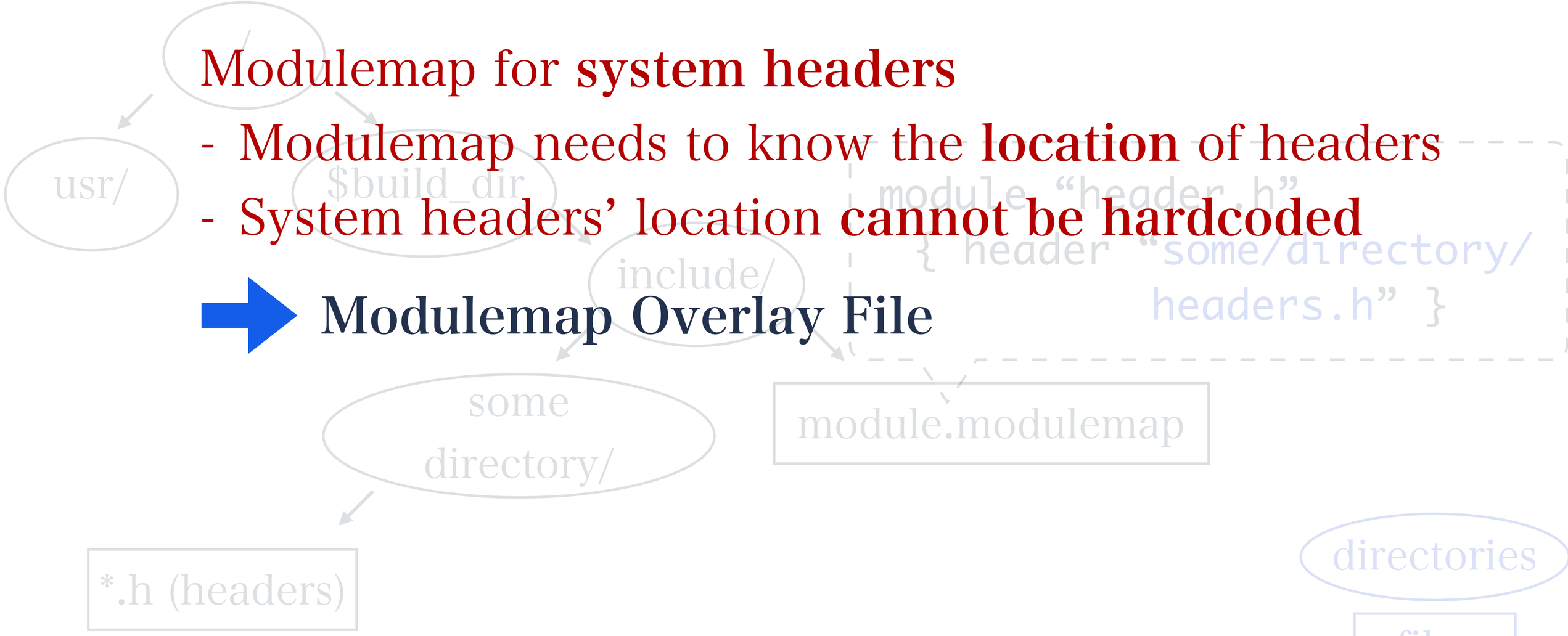
Mechanism of the modulemap

modulemap, modulemap overlay file, virtual modulemap overlay

Modulemap for **system headers**

- Modulemap needs to know the **location** of headers
- System headers' location **cannot be hardcoded**

➡ **Modulemap Overlay File**



C++ Modules in CMSSW

Mechanism of the modulemap

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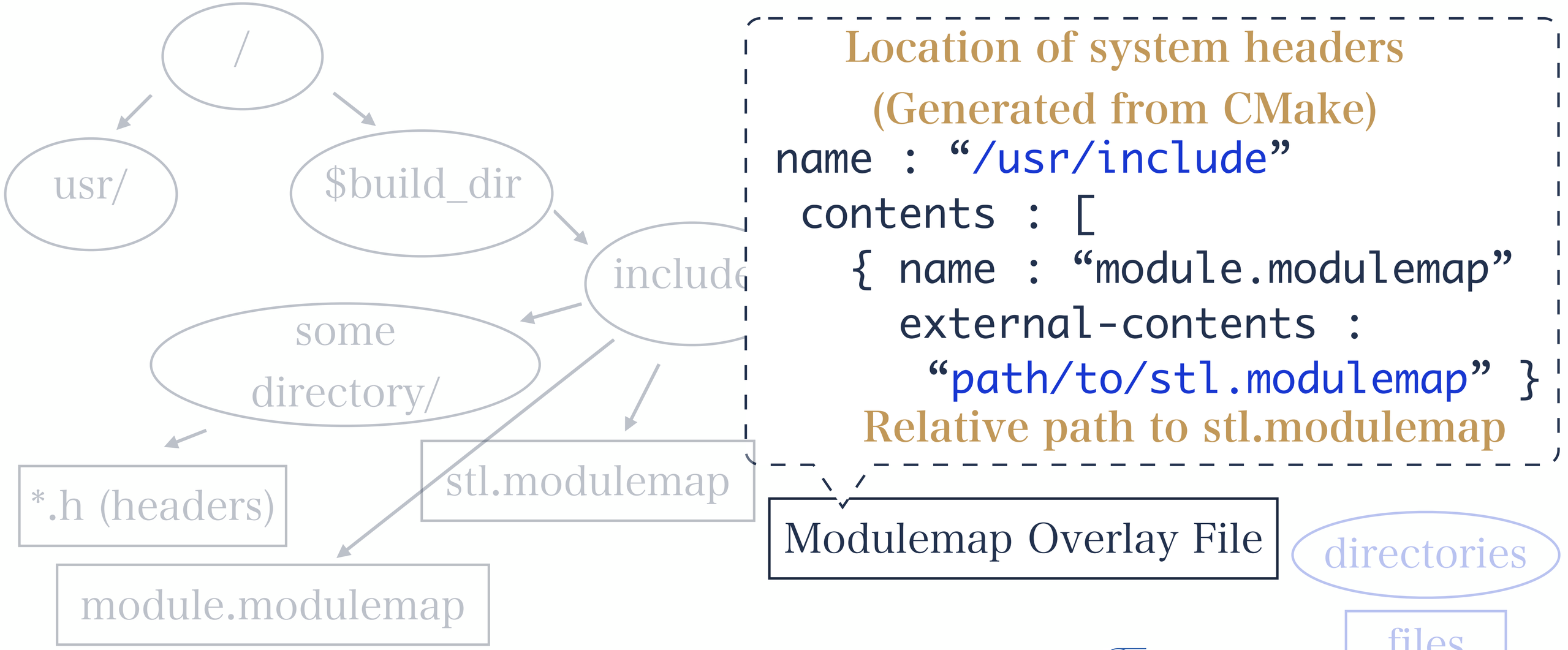

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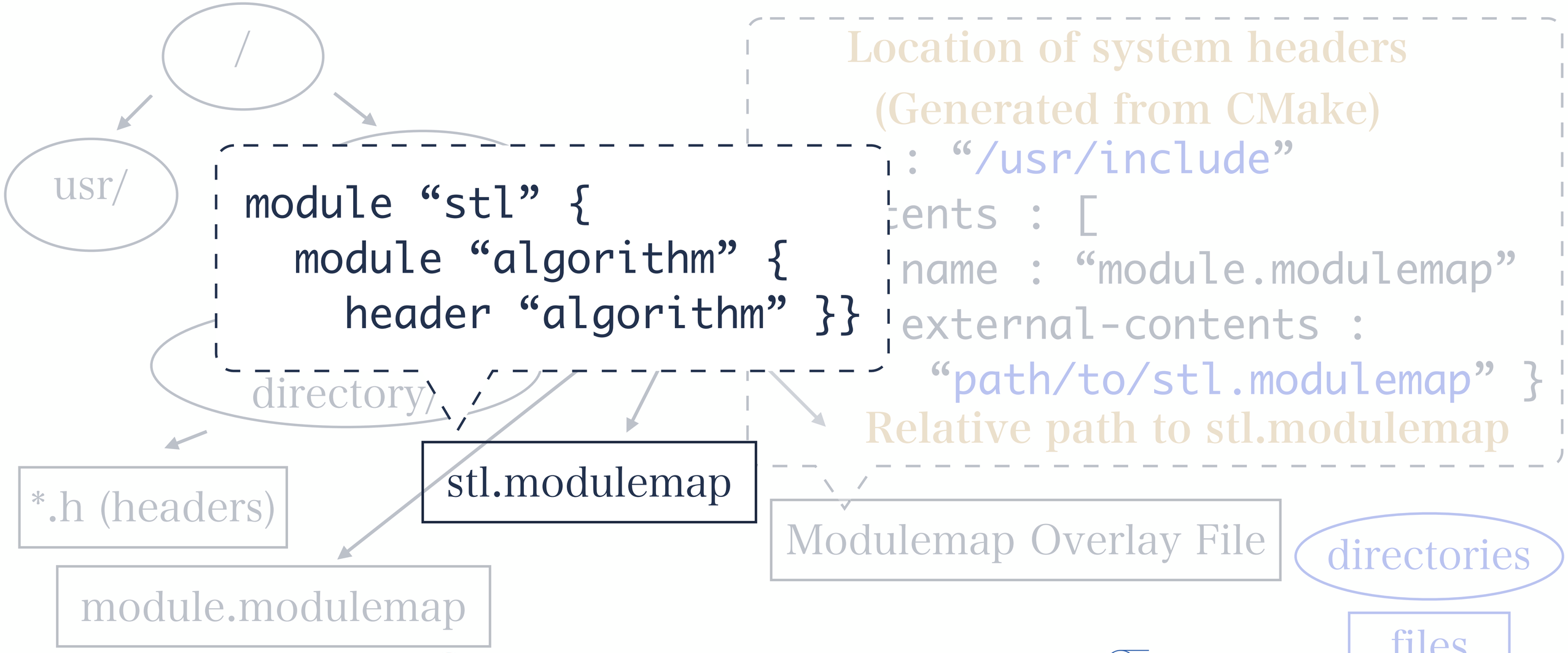


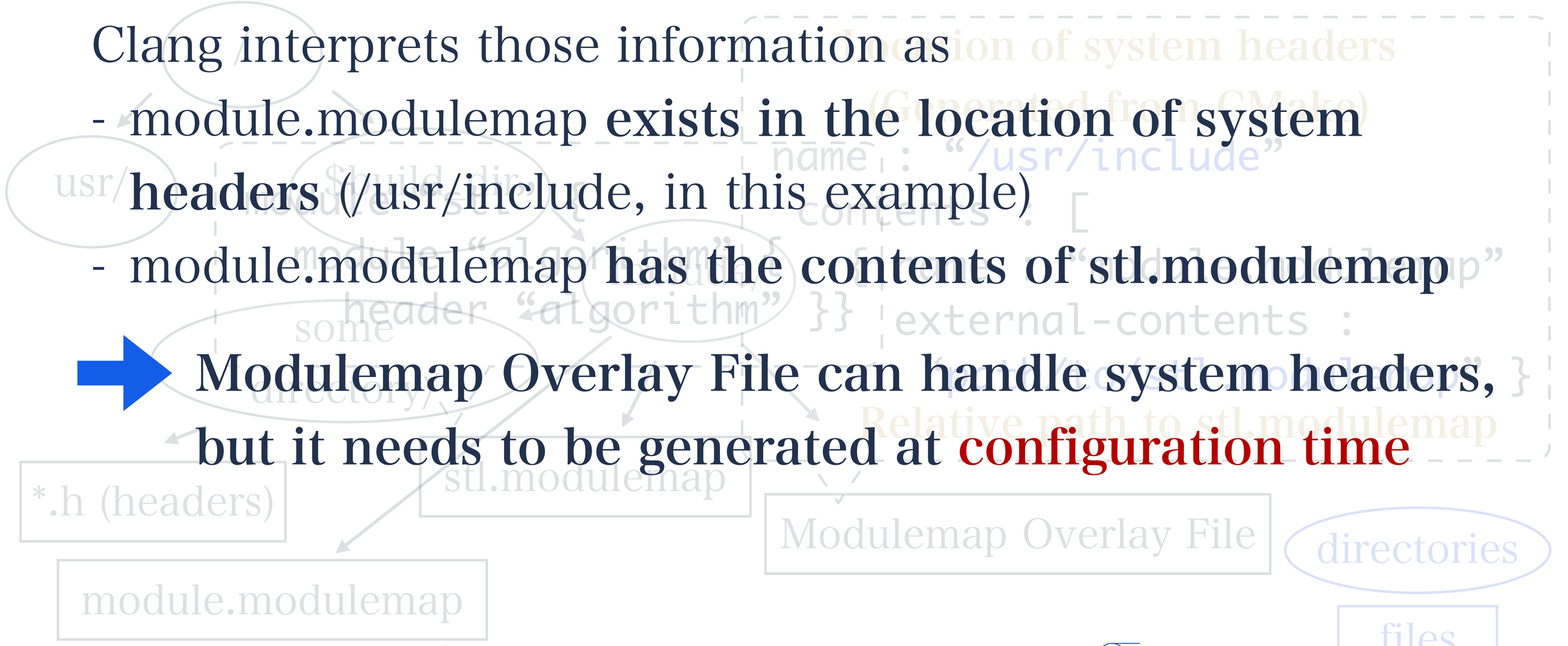
Mechanism of the modulemap

modulemap, modulemap overlay file, virtual modulemap overlay

Clang interprets those information as

- module.modulemap **exists in the location of system headers** (/usr/include, in this example)
- module.modulemap **has the contents of stl.modulemap**

➡ **Modulemap Overlay File can handle system headers, but it needs to be generated at configuration time**



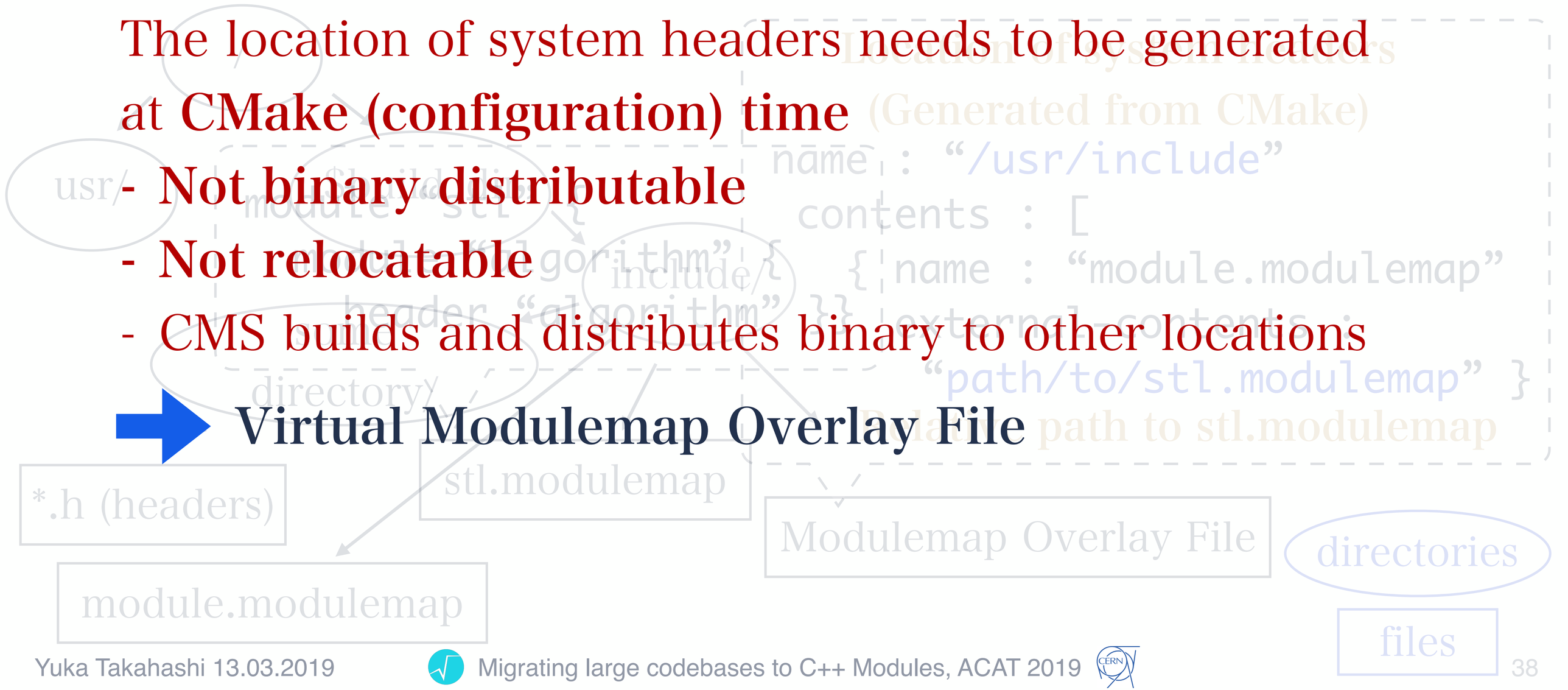
Mechanism of the modulemap

modulemap, modulemap overlay file, virtual modulemap overlay

The location of system headers needs to be generated at **CMake (configuration) time**

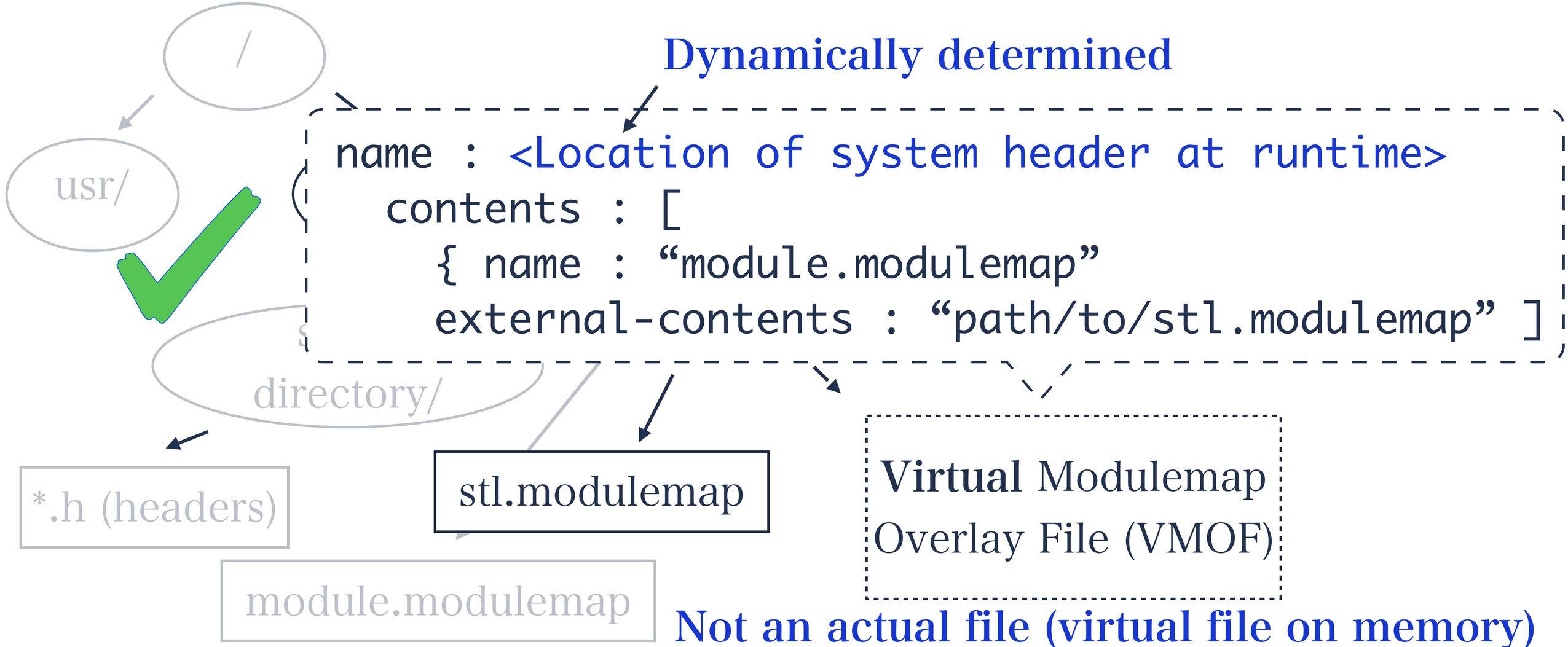
- **Not binary distributable**
- **Not relocatable**
- CMS builds and distributes binary to other locations

➡ **Virtual Modulemap Overlay File**



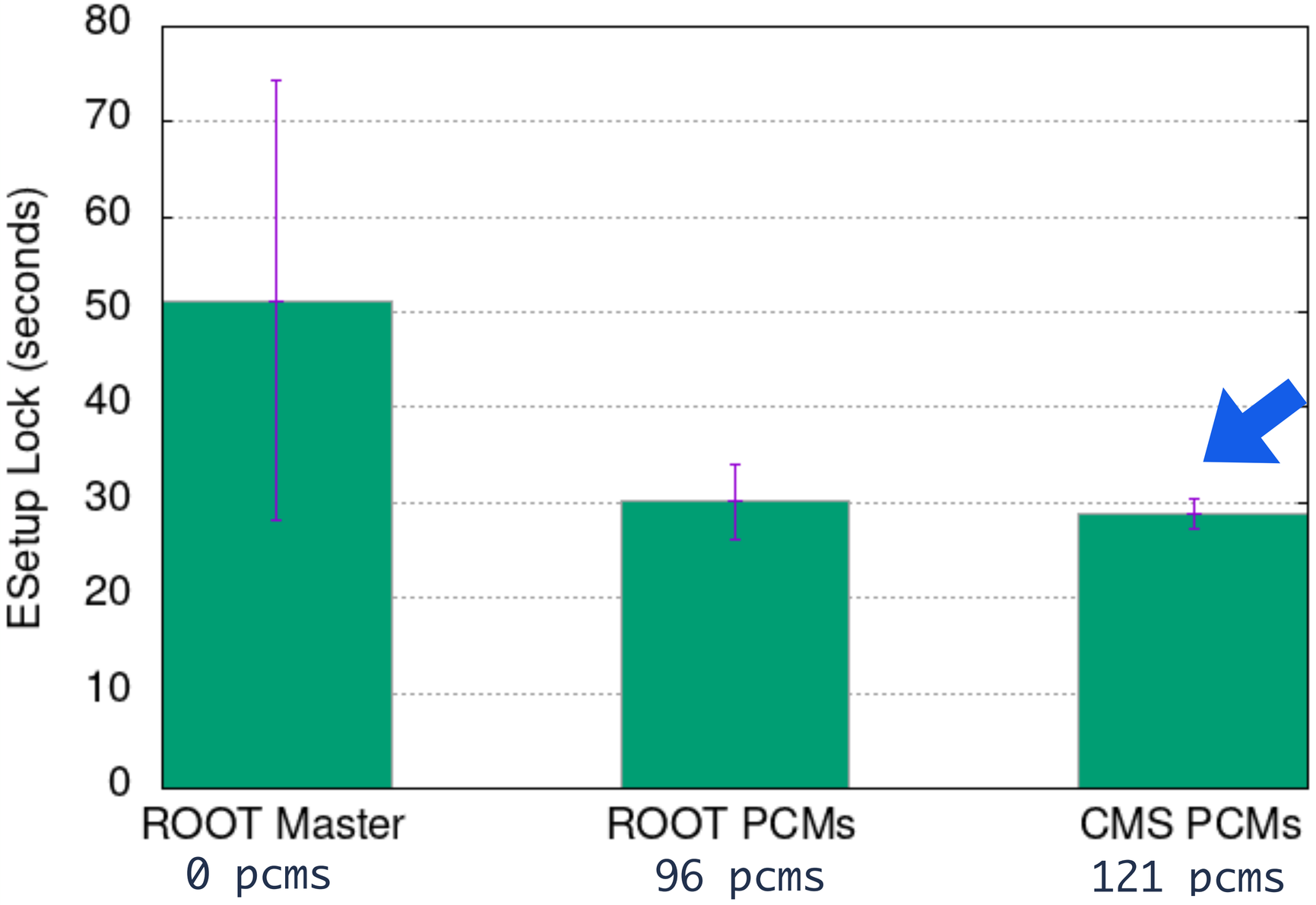
Mechanism of the modulemap

modulemap, modulemap overlay file, virtual modulemap overlay



CMS Performance Results

“Fast simulation test” ESetup Lock (seconds)

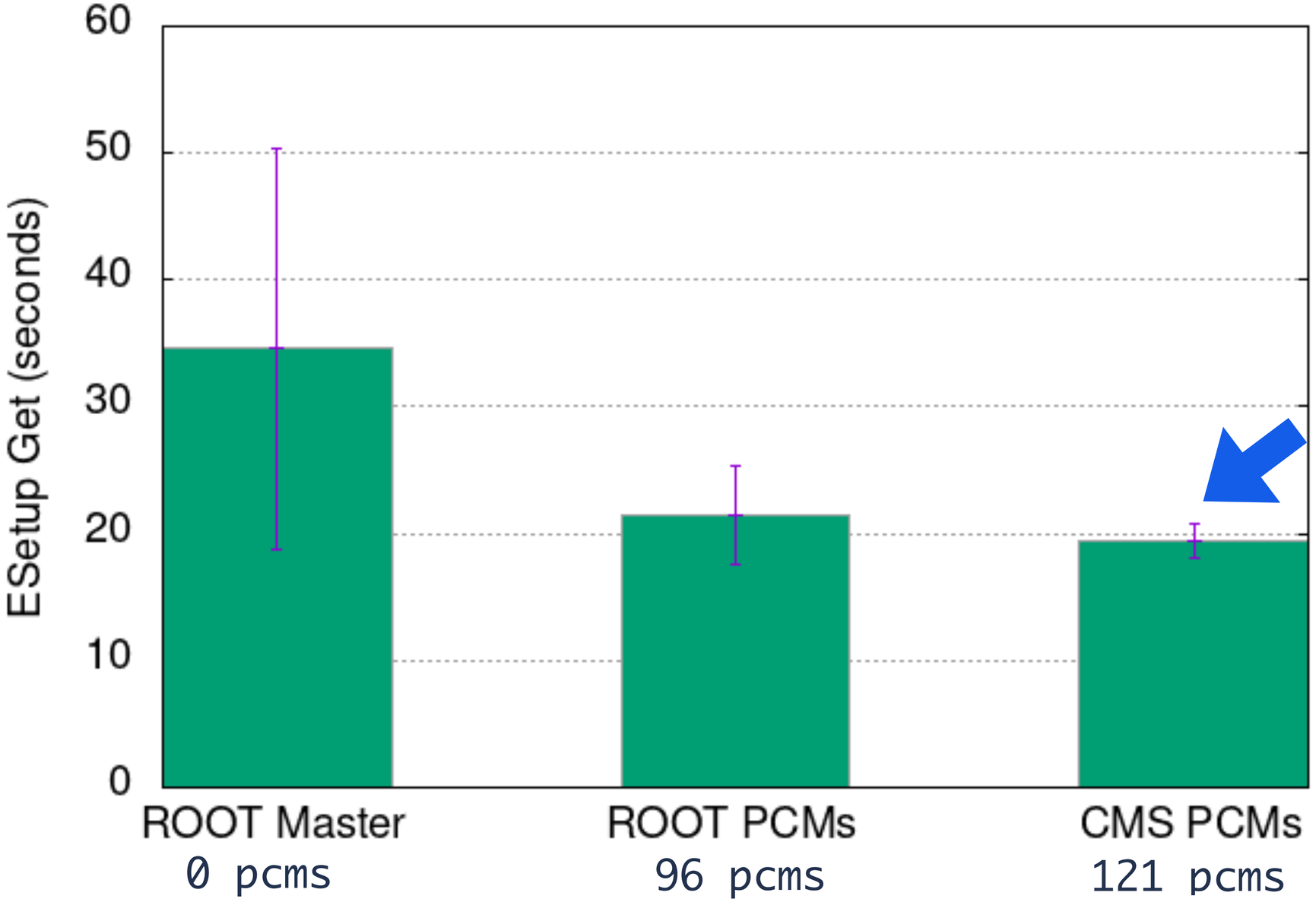


22.5 seconds better than ROOT Master

100 events
15 times execution

Standard deviation

“Fast simulation test” ESetup Get (seconds)

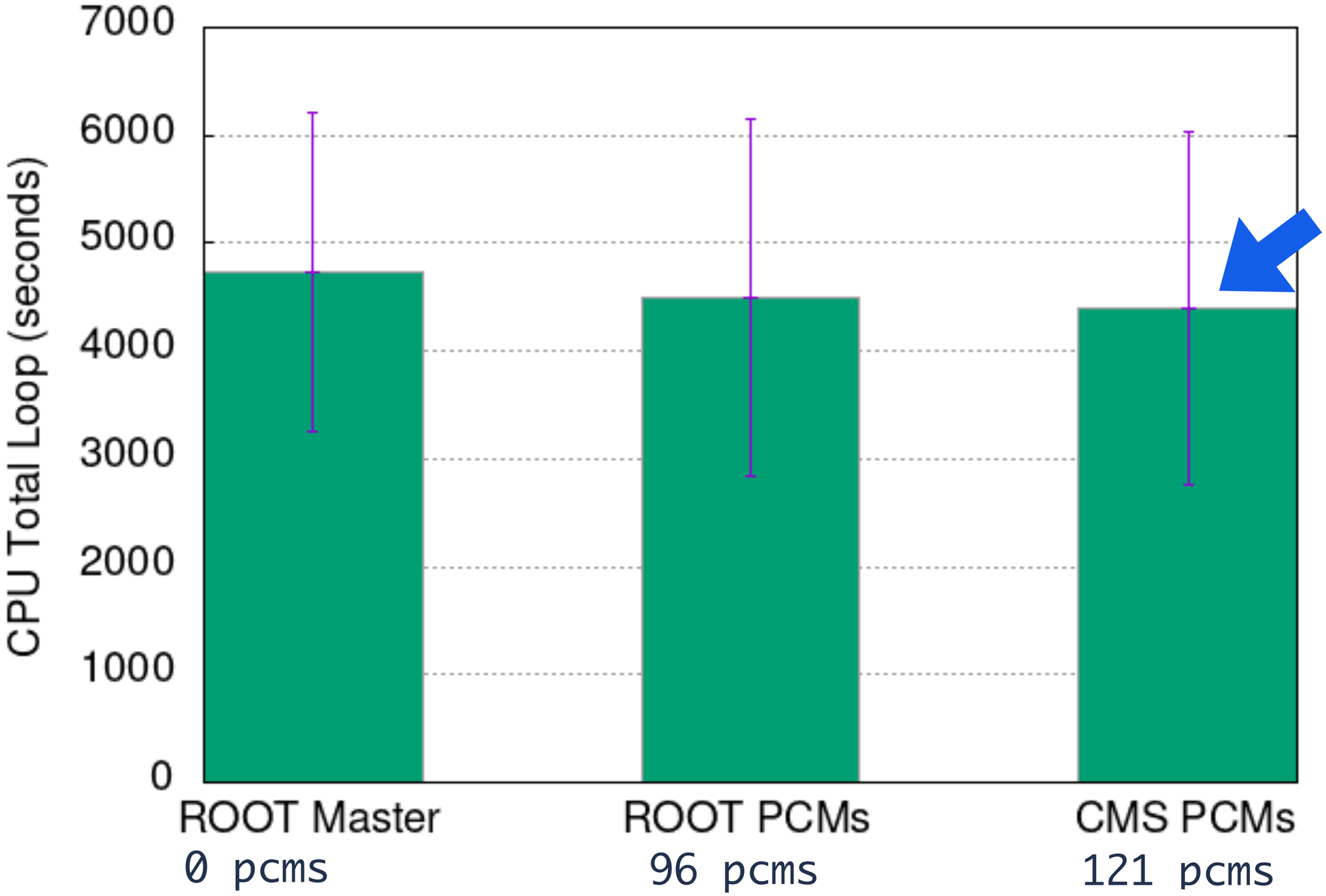


15.2 seconds better than ROOT Master

100 events
15 times execution

Standard deviation

“Digitization test” CPU Total Loop (seconds)

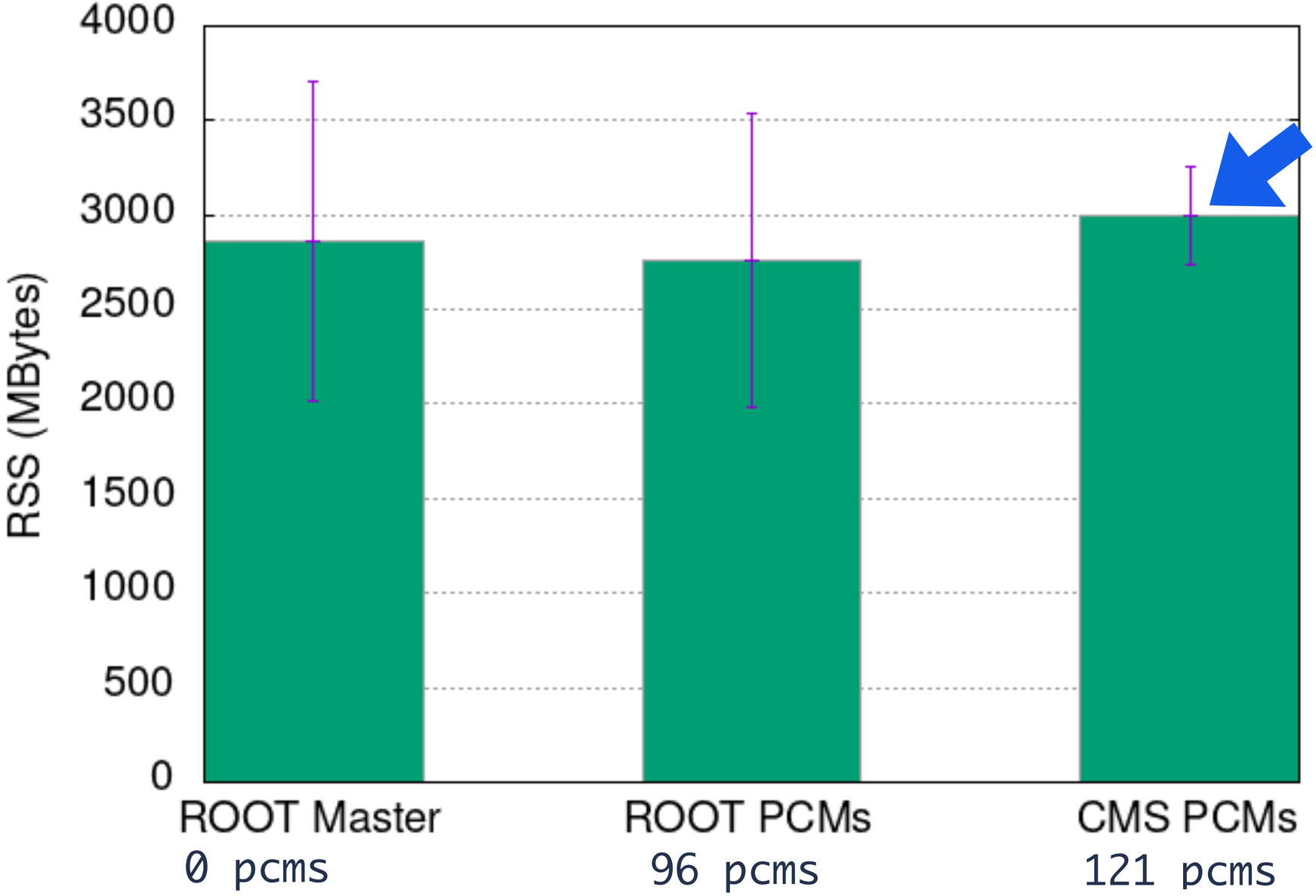


331 seconds better than ROOT Master

100 events
15 times execution

Standard deviation

“Digitization test” RSS Memory (MBytes)



143 Mbytes worse than ROOT Master

100 events
15 times execution

Standard deviation

Conclusion

Conclusion

- C++ Modules implemented in tested in ROOT and CMSSW
- Work on performance improvement is ongoing
- C++ Modules will provide experiments a benefit of
  - Header modularity of libraries
  - Performance improvement

Thank you for your attention!

Backup slides

Performance Results

CMSSW with ROOT master

CMSSW with ROOT pcms (-Druntime_cxxmodules=On)

Core.pcm, RIO.pcm, etc.

CMSSW with ROOT pcms + genreflex CMS pcms (25 pcms)

DataFormatsCommon_xr.pcm, DataFormatsMath_xr.pcm..