Optimizing Frameworks’ Performance Using C++ Modules Aware ROOT

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Abstract. ROOT is a core HEP framework which is used broadly in and outside HEP. As HEP software frameworks always strive for performance, ROOT was extended with experimental support for using C++ modules during runtime. C++ modules are designed in part to improve the performance of parsing C++. As ROOT is parsing and interpreting C++ during runtime, C++ modules offer a promising way to improve ROOT’s runtime performance. This paper presents the results and challenges of integrating C++ modules into ROOT and its early adoption to CMSSW.

1 Introduction

A central part of ROOT is the C++ interpreter cling, which is based on the C++ compiler Clang. The interpreter allows users to have interactive ROOT sessions. It also serves as a back end for some of ROOT’s language bindings such as PyROOT.

To offer these features, cling has to parse source code during runtime. This does not only include code manually entered by the user on the command line, but also a multitude of header files coming from libraries and frameworks. The parsing of these header files can negatively affect ROOT’s performance as it consumes notable amounts of memory and CPU time.

Because the inefficient header parsing in C++ is a well-known issue, the C++ standard introduced C++ modules: a compact, efficient representation of header files. As modules are a promising technology, the adoption of C++ modules into ROOT was proposed [1] and we implemented them in ROOT and it’s interpreter cling. This allowed us to avoid the expensive parsing of headers and improve ROOT’s runtime performance.

2 Background

Even before C++ modules, ROOT has been heavily optimized and employs several mechanisms to improve the performance of the interpreter. In this section we will discuss three 

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of the existing mechanisms in the context of C++ modules: The ROOT precompiled header (PCH); rootmap files (ROOTMAP) and RDICT files.

2.1 Optimizing ROOT using a PCH

ROOT ships with a precompiled header containing a subset of ROOT’s components. This precompiled header reduces the CPU and memory cost for ROOT’s heavily used libraries. The precompiled header technology is well-understood since decades. It is an efficient on-disk representation of the state of the compiler after parsing a set of headers. It can be loaded before starting the next instance to avoid doing redundant work. However, this approach limits compiler to use only a single PCH, as it’s usually too complicated to merge multiple compilers states loaded from different PCH files. ROOT’s dictionary generator, rootcling, generates one PCH file at build time. This PCH file is attached on startup and ROOT proceeds to lazily load code from the file when needed.

The PCH is by design a monolithic and not extensible. This is a problem for third party libraries who want to improve the performance of their code with a PCH. They can’t provide a second PCH file with their code as this is not possible by design. For ROOT developers the PCH brings the problem that changing a single header requires the regeneration of the whole PCH file.

A less restrictive alternative to PCH files are C++ modules (PCM files). Unlike a PCH, PCM files are designed so that multiple can be attached to the same interpreter or compiler at once. This means it is possible to split up the content of a single PCH into multiple PCMs as shown in Figure 1. Also, rebuilding only a part of all attached PCMs is possible. In ROOT, a single PCM file usually corresponds to a single library.

ROOT’s C++ modules implementation is based on Clang’s implementation. Clang uses configuration files called module maps for defining the contents of a C++ module. To stay consistent with Clang, ROOT also uses module map files to configure module contents.

![Diagram](Figure 1. Comparison of PCH and C++ Modules in ROOT)

2.2 Optimizing third-party code with ROOTMAP and RDICT

ROOTMAP files are used by ROOT to map unknown symbols and identifiers to libraries. When encountering an unknown symbol or identifier, ROOT uses this map to load the corresponding library. Another advantage of this approach is that ROOTMAP files allow ROOT to only parse headers of libraries that are actually used. Before a library is actually used by the user, the only overhead is the ROOTMAP file. The expensive header parsing only happens once it is actually needed.
RDICT files efficiently store information needed for serialization and deserialization of data types. They allow ROOT to perform IO operations on these data types without loading the respective code from the PCH or parsing the respective library headers.

```
1  Foo.h
2  namespace foo { struct bar(); }
3  struct S{};
4
5  libFoo.rootmap
6  { decls }
7  namespace foo { }
8  struct S;
9
10 [ libFoo.so ]
11 # List of selected classes
12 class bar
13 struct S;
14
g__Foo.cxx (aka libFoo dictionary)
15 namespace {
16 void TriggerDictionaryInitialization_libFoo_Impl() {
17 static const char* headers[] = {"Foo.h"}
18 // More scaffolding
19 extern int __Cling_Autoloading_Map;
20 namespace foo{struct __attribute__((annotate("$clingAutoload$Foo.h"))) bar;}
21 struct __attribute__((annotate("$clingAutoload$Foo.h"))) S;
22 // More initialization scaffolding.
23 }
```

Listing 1: Example of ROOT dictionary for libFoo.

When starting, ROOT will locate all files with extensions *.rootmap. It parses the code in Line 6 {decls} section and creates an internal map for the entities defined in Line 10 [libFoo.so] section. Upon seeing an unknown identifier, the implementation searches in the database if this is a known entity.

```
1  root [] S *s; // Does not require a definition.
2  root [] foo::bar *baz1; // Does not require a definition.
3  root [] foo::bar baz2; // Requires a definition.
```

Listing 2: Illustrative example for usage of the ROOT dictionary contents.

Listing 2 shows the efforts which ROOT does to avoid parsing redundant code. S is defined in Line 3 in Listing 1 and foo::bar is defined in Line 2 in Listing 1. Line 1 does not require a definition and the forward declaration consumed at the initialization time is sufficient, so the parsing of Foo.h is not required. The behavior of Line 1 in Listing 2 is equivalent to Line 1 and 2 in Listing 3.

```
1  root [] namespace foo { }; struct S;
2  root [] S *s; // Implicitly at ROOT startup
3  root [] foo::bar /*store parsing state*/
4  gSystem->Load("Foo");
5  // More scaffolding.
6  extern int __Cling_Autoloading_Map;
7  namespace foo{struct __attribute__((annotate("$clingAutoload$Foo.h"))) bar;}
8  struct __attribute__((annotate("$clingAutoload$Foo.h"))) S;
9  // More initialization scaffolding.
10  /*restore parsing state*/ *baz1;
11
12 #include <Foo.h>/*restore parsing state*/;
```

Listing 3: Information flow from libFoo dictionary.
Line 2 in Listing 2 also does not require a definition. The second identifier lookup fails, but ROOT knows that `foo::bar` is in `libFoo` by the information from rootmap files (Line 10). It dlopen `libFoo` which in turn, during its static initialization, inserts annotated forward declaration as shown in `G__Foo.cxx`. This resolves `foo::bar` which avoids the parsing of `Foo.h` at relatively small overhead. The loading of the annotated forward declarations can happen at any time during parsing. This is so-called "recursive parsing" and is a code path that exists only in ROOT, and is not exercised by clang itself. The behavior of Line 2 is equivalent to Listing 3 Line 1 to 10.

Line 3 in Listing 2 requires a definition and the implementation behaves exactly as in Line 2. When a definition is required, it reads the information in the annotation and also parses `Foo.h` as is shown in Line 12 in Listing 3. The Line 3 in Listing 2 behavior is equivalent to Line 1 to 12 in Listing 3.

ROOTMAP files and RDICT files are important for ROOT's performance. However, they require various mechanisms to work together and can fail in corner cases. Also, due to the complicated way they are implemented on top of the Clang API, they have a high probability to become unusable if certain parts of Clang's internal behavior changes. C++ modules can partly replace their performance benefits while also offer a more stable implementation.

3 Implementation

An implementation of the C++ modules concept itself exists in the LLVM frontend Clang [2] which is used as a library by ROOT. Clang supports the Modules TS and hosts modules research and development work. Clang's implementation encourages incremental, bottom-up adoption of the C++ modules [6]. The implementation is designed to work for C, C++, ObjectiveC, ObjectiveC++ and Swift [3]. Users can enable the modules feature without modifications in header files. Clang allows users to specify module interfaces in a dedicated file, called module maps files. A module map file expresses the mapping between a module file and a collection of header files. It can be mounted using the compiler's virtual file system overlay mechanism to non-writable library installation paths. In practice, a non-invasive modularization can be done easily by introducing a module map file. In some cases the module map files can be automatically generated if the build system knows about the list of header files in every package.

Several steps were taken to adopt C++ modules in ROOT. First, we supported compiling ROOT with C++ modules. It halfed ROOT's compilation time. This effort includes generating module map files and resolving cyclic header dependency inside ROOT. Next, we taught rootcling dictionary generator to generate PCM files attached with I/O information. We taught ROOT to preload all PCMS at the startup time in order to make declaration available without #including the appropriate headers. Also, we implemented the autoloading of libraries in ROOT which is not depending on old infrastructure (ROOTMAPS), which gives correctness benefits shown in section 4.2 and is efficient compared to ROOTMAPS.

For the C++ modules adoption in experiments, we have been working closely with CMSSW team [9]. ROOT can already be compiled with runtime C++ in CMS environment, and we will enable PCM generation for their libraries one by one. We can gradually migrate dictionary generation to PCM, as our current implementation falls back to ROOTMAP when a PCM is not generated. It enables us to incrementally migrate from the old to the new infrastructure.

3.1 Registration Mechanism and Automatic discovery of C++ declarations
Listing 4: Pseudo code shows the loading of all modules at the ROOT startup time.

A C++ Modules aware ROOT preloads all modules at its startup time. Listing 2 becomes equivalent to Listing 4. Listing 4 shows the example of implicit #include. `foo::bar` can be used without even including `foo.h`. With modules, this feature is supported by importing all modules at the startup time, as shown in Line 1 and 2. This implementation relies on a well-defined (by the C++ standard) behavior. Currently, importing all modules comes with a constant performance overhead which we explain in detail in section 4.1.

However, there is another way to support this feature: the global modules index, which makes the list of identifiers and PCMs at the initialization time. Upon the identifier lookup failure, the interpreter can refer to the list to decide which PCM to load. The possible drawback of this implementation is that the interpreter has no control over where the lookup failure can happen. It can happen inside a nested scope where importing a PCM may cause an incomprehensible error.

Regarding automatic discovery of C++ declarations, a naive implementation of this feature would require the inclusion of all reachable library descriptors at ROOT startup time, which is not feasible. ROOT inserts a set of optimization from ROOTMAP files to fence itself from the costly full header inclusion. Unfortunately, several of them are home-grown and in a few cases inaccurate causing a notable technical debt.

With runtime C++ modules, ROOT iterates through libraries found in prebuilt modules paths and LD_LIBRARY_PATH until it finds the definition of currently searching mangled name. It searches the library in prebuilt modules path first as it is more likely that the symbols are in ROOT related library. When it fails, the implementation fallbacks to system libraries from LD_LIBRARY_PATH for system library autoloading. The overhead is extremely low as it is only looking into 64 bytes hash in the library to determine whether this library likely has a definition or not, which is called bloom filter. Not only the symbols defined in regular symbol tables but also the dynamic symbols can be autoloaded as we are also checking .dynsym section where the dynamic symbols are defined. This feature is new and is not supported without C++ modules in ROOT. The benefit of this implementation can be seen in section 4.2.

### 4 Results

#### 4.1 Performance Results

Performance measurements in ROOT are often done by running tutorials and tests in ROOT. We measured the performance with Archlinux 4.18.16 GNU/Linux, Intel(R) Core(TM) i7-8550U CPU and Ubuntu 18.04.1 LTS, i7-7500U NVIDIA GeForce 940MX. Figure 2 and Figure 3 are the performance results we receive from modules, compared to PCH and textual headers which is synthetic benchmarks close to the experiment software stacks.

The CPU time of ROOT is measured in (a), (c) in Figure 2 and (a) in Figure 3. On the other hand, (b) (d) in Figure 2 and (b) in Figure 3 are measuring the residential memory of ROOT.

ROOT long tests are the tests which take more than 30 seconds, and are measured in (a), (b) in Figure 2, (c), (d) in Figure 3 are testing short tests which are not in PCH, which means that they are still using textual include. Thus from those tests, we can get a rough assumption of the performance result we will get from modularizing experiments. Figure 3 is measuring...
Figure 2. Performance results: (a), (c) are the measurement of CPU time. (b), (d) are the measurement of RSS. (a), (b) are measuring long tests (over 30 seconds) in ROOT with and without runtime C++ modules. (c), (d) are measuring short tests which is not in PCH.

Figure 3. Basic benchmarks: The startup time of ROOT and hSimple tutorial.

The startup of ROOT and hsimple tutorial, to show the actual startup time overhead we have from preloading pcms.

The RSS memory regression which can be seen in Figure 2(d) and in Figure 3(b) are mostly due to importing all C++ Modules at the startup. RSS overhead is seen in correspondence of the number of preloaded modules. The startup time overhead is between 40-60 MB depending on the concrete configuration. However, when the workload increases (Figure 2(b)) we notice that the overall memory performance decreases in the number of cases.
The CPU time regression in Figure 3 (a) and in Figure 2 (c) are also due to importing all pcm's at the startup time. However, in Figure 2 (a) the performance of C++ modules is better than PCH by 1 or 2 seconds. It shows that C++ modules can perform better when the workload of the users’ code increases.

The performance of the technology preview is dependent on many factors such as the configuration of ROOT and a workflow. We also implemented a continuous performance monitoring tool \[8\] where we compare the performance of the technology preview with respect to standard ROOT.

### 4.2 Correctness and extra usability features

Listing 5: Correctness results: Left-hand side is ROOT without runtime C++ modules, which cannot autoload extern global variables such as gMinuit. Right-hand side is ROOT with runtime C++ modules, with which gMinuit can be autoloaded.

Listing 6: Autoloading of system libraries: Left-hand side is ROOT without runtime C++ modules, which cannot autoload a system library. Right-hand side is ROOT with runtime C++ modules, where ROOT can autoload the corresponding system library.

As shown in Listing 5, gMinuit is an extern variable which cannot be autoloaded by ROOT at the moment because it is not declared in ROOTMAP files. However, with modules, we can automatically resolve symbols and cases like those are now correctly handled. Moreover, Listing 6 shows that ROOT can also autoload system libraries with dynamic symbols.

Module’s autoloading implementation iterate through LD_LIBRARY_PATH which also includes system libraries. The implementation details are thoroughly discussed in section 3.

### 5 Limitations and Future work

Even though ROOT now supports C++ modules, there remain some problems that need to be solved before C++ modules are fully usable for developers and users.

One limitation is that Clang does not explicitly support the relocation of implicitly built PCM files. It is possible to patch Clang to work with implicitly-build PCM, but it is better to have an official support. The limitation comes from the fact that modules store paths to some configuration and source files in them. These paths become in part invalid once the build directory has been moved.

One significant issue is that C++ modules are currently not as efficient as ROOT’s PCH when used in a minimal environment without experiment frameworks. In this situation the PCH is a more efficient as it was optimized for this specific setup. ROOT’s C++ modules however are kept back by two issues. One issue is the additional overhead coming from management data structures that make PCMs more extensible than the PCH. The other issue...
is that C++ modules in ROOT are currently not as optimized as the PCH. Especially the preloading of modules on startup needs to be optimized as explained in section 3.

Our ultimate goal is to make this feature a default in ROOT. In order to archive this, we will give support to experiments such as CMSSW and will continue optimizing the performance.

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