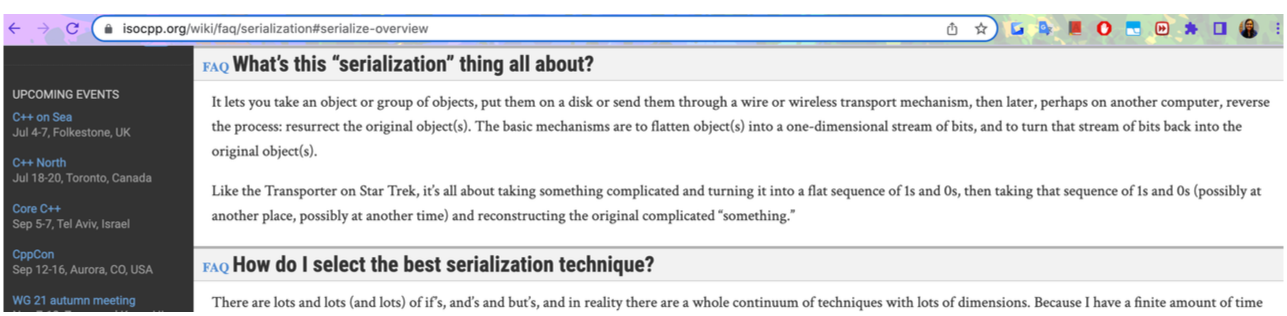
Improving performance of C++ modules in Clang

Problem Statement

The C++ modules technology aims to provide a scalable compilation model for the C++ language. The C++ Modules technology in Clang provides an io-efficient, on-disk representation capable to reduce build times and peak memory usage. The internal compiler state such as the **abstract syntax tree (AST) is stored on disk and lazily loaded on demand.** C++ Modules improve the memory footprint for interpreted C++ through the Cling C++ interpreter developed by CERN and the compiler research group at Princeton. The current implementation is pretty good at making most operations on demand.
However in a few cases, **we eagerly load pieces of the AST**, for example **at module import time** and upon **selecting a suitable template specialization.** When selecting the template specialization **we load all template specializations from the module files just to find out they are not suitable.** There is a patch that partially solves this issue by introducing a template argument hash and use it to look up the candidates without deserializing them. However, **the data structure it uses to store the hashes leads to quadratic search which is inefficient when the number of modules becomes sufficiently large**.

Serialization

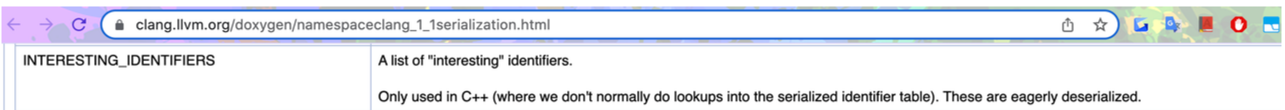
Serialization is the process of writing or reading an object to or from a persistent storage medium such as a disk file.



Deserialization

The byte stream, once created, also can be streamed across a communication link to a remote receiving end. The reverse of serialization is called deserialization, where the data in the byte stream is used to reconstruct it to its original object form.

Eager Deserialization


clang.llvm.org/doxygen/namespaceclang_1_1serialization.html

INTERESTING_IDENTIFIERS	A list of "interesting" identifiers. Only used in C++ (where we don't normally do lookups into the serialized identifier table). These are eagerly deserialized.

Example when eager deserialization cannot be avoided: until c++20 we could lazily deserialize the vtable information but due to `constexpr virtual` in c++20 we cannot anymore.

In Clang

Serialization and Deserialization

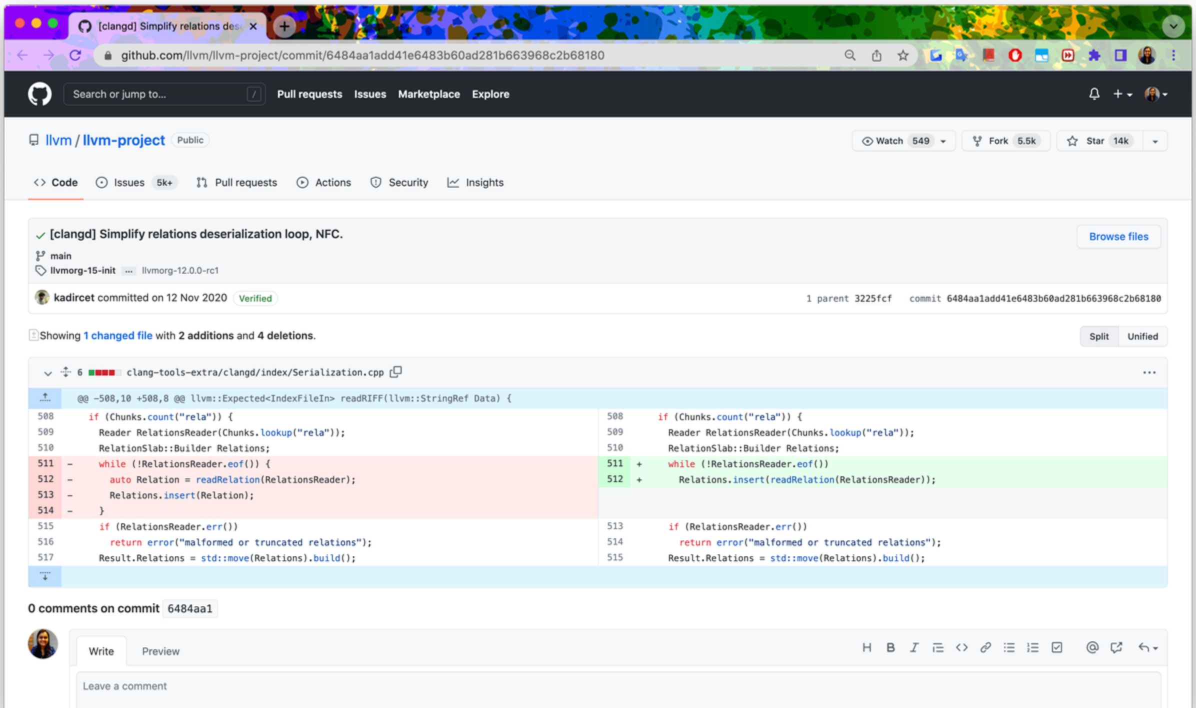
`clang/include/clang/Serialization/ASTDeserializationListener.h`

```cpp
#include "clang/Basic/IdentifierTable.h"
#include "clang/Serialization/ASTBitCodes.h"

namespace clang {

class Decl;
class ASTReader;
class QualType;
class MacroDefinitionRecord;
class MacroInfo;
class Module;
class SourceLocation;

class ASTDeserializationListener {
public:
  virtual ~ASTDeserializationListener();

  /// The ASTReader was initialized.
  virtual void ReaderInitialized(ASTReader *Reader) { }

  /// An identifier was deserialized from the AST file.
  virtual void IdentifierRead(serialization::IdentID ID,
                              IdentifierInfo *II) { }
  /// A macro was read from the AST file.
  virtual void MacroRead(serialization::MacroID ID, MacroInfo *MI) { }
  /// A type was deserialized from the AST file. The ID here has the
  ///        qualifier bits already removed, and T is guaranteed to be locally
  ///        unqualified.
  virtual void TypeRead(serialization::TypeIdx Idx, QualType T) { }
  /// A decl was deserialized from the AST file.
  virtual void DeclRead(serialization::DeclID ID, const Decl *D) { }
  /// A selector was read from the AST file.
  virtual void SelectorRead(serialization::SelectorID iD, Selector Sel) {}
  /// A macro definition was read from the AST file.
  virtual void MacroDefinitionRead(serialization::PreprocessedEntityID,
                                   MacroDefinitionRecord *MD) {}
  /// A module definition was read from the AST file.
  virtual void ModuleRead(serialization::SubmoduleID ID, Module *Mod) {}
  /// A module import was read from the AST file.
  virtual void ModuleImportRead(serialization::SubmoduleID ID,
                                SourceLocation ImportLoc) {}
};
```

```cpp
void ASTWriter::ModuleRead(serialization::SubmoduleID ID, Module *Mod) {
  assert(SubmoduleIDs.find(Mod) == SubmoduleIDs.end());
  SubmoduleIDs[Mod] = ID;
```

```
}
```

Simple code to understand deserialization



Eager Deserialization

Module import time

https://github.com/llvm/llvm-project/commit/c52efa7d4011a48ea91b353f2cbc40a359d19571

[modules] Don't eagerly deserialize so many ImportDecls. CodeGen basi…

…cally ignores ImportDecls imported from modules, so only eagerly deserialize the ones from a PCH / preamble.

llvm-svn: 245406

main
llvmorg-15-init … 2020.06-alpha

zygoloid committed on 19 Aug 2015 — 1 parent 72be1c1 — commit c52efa7d4011a48ea91b353f2cbc40a359d19571

Browse files

Showing **2 changed files** with **13 additions** and **11 deletions**. Split | Unified

7 clang/lib/CodeGen/CodeGenModule.cpp

```diff
@@ -3363,11 +3363,8 @@ void CodeGenModule::EmitTopLevelDecl(Decl *D) {
     auto *Import = cast<ImportDecl>(D);
 
     // Ignore import declarations that come from imported modules.
-    if (clang::Module *Owner = Import->getImportedOwningModule()) {
-      if (getLangOpts().CurrentModule.empty() ||
-          Owner->getTopLevelModule()->Name == getLangOpts().CurrentModule)
-        break;
-    }
+    if (Import->getImportedOwningModule())
+      break;
     if (CGDebugInfo *DI = getModuleDebugInfo())
       DI->EmitImportDecl(*Import);
```

17 clang/lib/Serialization/ASTWriterDecl.cpp

```diff
@@ -1994,14 +1994,19 @@ void ASTWriter::WriteDeclAbbrevs() {
 /// clients to use a separate API call to "realize" the decl. This should be
```

Upon selecting a suitable template specialization

When selecting the template specialization we load all template specializations from the module files just to find out they are not suitable.

Don't eagerly deserialize every templated function (and every static …

…data

member inside a class template) when loading a PCH file or module.

llvm-svn: 178496

main
studio-1.4 … 2020.06-alpha

zygoloid committed on 2 Apr 2013 — 1 parent 3435327 — commit 5205a8cfd815e4e71ccd3f067080c11c8980c399

Browse files

Showing **3 changed files** with **20 additions** and **2 deletions**. Split | Unified

10 clang/lib/AST/ASTContext.cpp

```diff
@@ -7673,7 +7673,15 @@ bool ASTContext::DeclMustBeEmitted(const Decl *D) {
   if (const VarDecl *VD = dyn_cast<VarDecl>(D)) {
     if (!VD->isFileVarDecl())
       return false;
-  } else if (!isa<FunctionDecl>(D))
+  } else if (const FunctionDecl *FD = dyn_cast<FunctionDecl>(D)) {
+    // We never need to emit an uninstantiated function template.
+    if (FD->getTemplatedKind() == FunctionDecl::TK_FunctionTemplate)
+      return false;
+  } else
+    return false;
+
+  // If this is a member of a class template, we do not need to emit it.
+  if (D->getDeclContext()->isDependentContext())
     return false;
 
   // Weak references don't produce any output by themselves.
```

2 clang/test/PCH/cxx-templates.cpp

With lazy deserialization, builtins are loaded on-demand, and unused builtins are never loaded into the Isolate. Lazy deserialization comes with memory savings.

Existing (using print statements)

https://github.com/llvm/llvm-project/blob/main/clang/include/clang/Serialization/ASTBitCodes.h#L484-L492
`EAGERLY_DESERIALIZED_DECLS`

github.com/llvm/llvm-project/blob/main/clang/include/clang/Serialization/ASTBitCodes.h#L484-L492

```
484    /// Record code for the array of eagerly deserialized decls.
485    ///
486    /// The AST file contains a list of all of the declarations that should be
487    /// eagerly deserialized present within the parsed headers, stored as an
488    /// array of declaration IDs. These declarations will be
489    /// reported to the AST consumer after the AST file has been
490    /// read, since their presence can affect the semantics of the
491    /// program (e.g., for code generation).
492    EAGERLY_DESERIALIZED_DECLS = 6,
493
```

1. https://github.com/llvm/llvm-project/blob/main/clang/lib/Serialization/ASTReader.cpp#L3259-L3264

github.com/llvm/llvm-project/blob/main/clang/lib/Serialization/ASTReader.cpp#L3259-L3264

```
3258
3259      case EAGERLY_DESERIALIZED_DECLS:
3260        // FIXME: Skip reading this record if our ASTConsumer doesn't care
3261        // about "interesting" decls (for instance, if we're building a module).
3262        for (unsigned I = 0, N = Record.size(); I != N; ++I)
3263          EagerlyDeserializedDecls.push_back(getGlobalDeclID(F, Record[I]));
3264        break;
3265
3266      case MODULAR_CODEGEN_DECLS:
3267        // FIXME: Skip reading this record if our ASTConsumer doesn't care about
3268        // them (ie: if we're not codegenerating this module).
3269        if (F.Kind == MK_MainFile ||
```

2. https://github.com/llvm/llvm-project/blob/main/clang/lib/Serialization/ASTReader.cpp#L7486

github.com/llvm/llvm-project/blob/main/clang/lib/Serialization/ASTReader.cpp#L7486

```
  if (!DeclsLoaded[Index]) {
    ReadDeclRecord(ID);
    if (DeserializationListener)
      DeserializationListener->DeclRead(ID, DeclsLoaded[Index]);
  }

  return DeclsLoaded[Index];
}

```

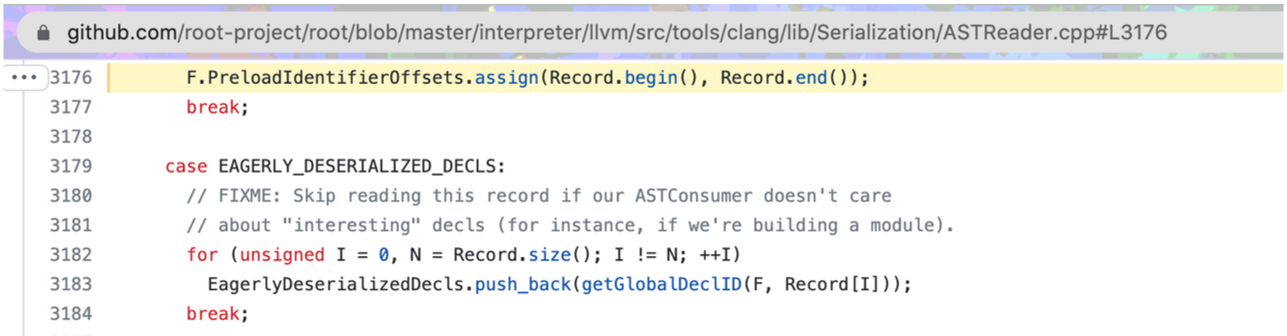
3. https://github.com/llvm/llvm-project/blob/main/clang/lib/Serialization/ASTReader.cpp#L1573-L1604

Preallocated source locations for modules which are not loaded. There was some plan to reduce this but didn't go anywhere.

github.com/llvm/llvm-project/blob/main/clang/lib/Serialization/ASTReader.cpp#L1573-L1604

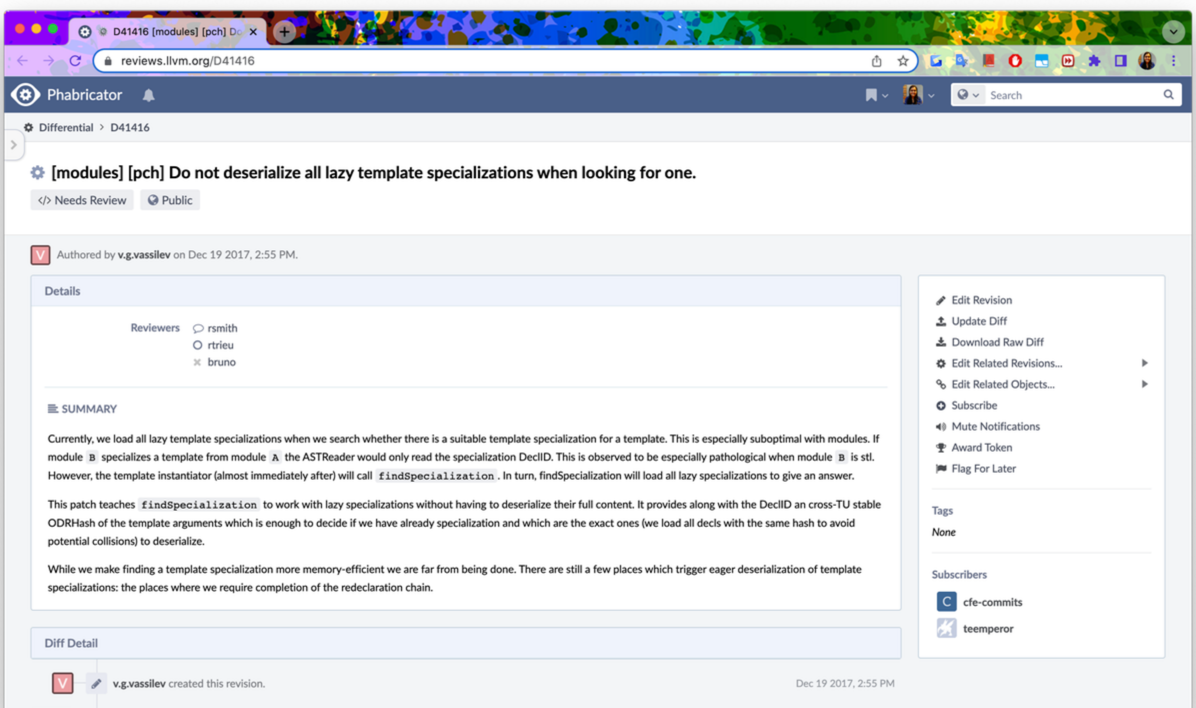
```
  case SM_SLOC_BUFFER_ENTRY: {
    const char *Name = Blob.data();
    unsigned Offset = Record[0];
    SrcMgr::CharacteristicKind
      FileCharacter = (SrcMgr::CharacteristicKind)Record[2];
    SourceLocation IncludeLoc = ReadSourceLocation(*F, Record[1]);
    if (IncludeLoc.isInvalid() && F->isModule()) {
      IncludeLoc = getImportLocation(F);
    }

    auto Buffer = ReadBuffer(SLocEntryCursor, Name);
    if (!Buffer)
      return true;
    SourceMgr.createFileID(std::move(Buffer), FileCharacter, ID,
                           BaseOffset + Offset, IncludeLoc);
    break;
  }

  case SM_SLOC_EXPANSION_ENTRY: {
    LocSeq::State Seq;
    SourceLocation SpellingLoc = ReadSourceLocation(*F, Record[1], Seq);
    SourceLocation ExpansionBegin = ReadSourceLocation(*F, Record[2], Seq);
    SourceLocation ExpansionEnd = ReadSourceLocation(*F, Record[3], Seq);
    SourceMgr.createExpansionLoc(SpellingLoc, ExpansionBegin, ExpansionEnd,
                                 Record[5], Record[4], ID,
                                 BaseOffset + Record[0]);
    break;
  }
  }

  return false;
}
```

4. Another preloading: https://github.com/root-project/root/blob/master/interpreter/llvm/src/tools/clang/lib/Serialization/ASTReader.cpp#L3176



Previous work

https://reviews.llvm.org/D41416



Partially solves this issue by introducing a template argument hash and use it to look up the candidates without deserializing them.

> *This way we managed to catch a few collisions in the ODRHash logic.*

Check if we have already specialization and which are the exact ones (we load all decls with the same hash to avoid potential collisions) to deserialize.

Improvement/Optimization: the data structure it uses to store the hashes leads to quadratic search which is inefficient when the number of modules becomes sufficiently large.

Roadmap

Investigate and resolve eager deserialization where possible

1. Use the internal clang AST counters to file what is eagerly deserialize.
2. Add `printf` in `ASTReader::ReadDecl` and load a bunch of modules without using them. This ideally should be a nop. If that's not the case it has to be debugged and investigated further.

Rework the patch to use on-disk hash tables to avoid the quadratic search complexity

1. Move to using an on-disk hash table for template specialization lookup, at least for templates with large numbers of specializations
2. Currently when we hash a tag type the visitor calls ODRHash::AddDecl which mostly relies on the decl name give distinct hash value. The types coming from template specializations have very similar properties (including decl names). For those we need to provide more information in order to disambiguate them. This patch adds the template arguments for the template specialization decl corresponding to its type. We manage to reduce further the amount of deserializations from 1117 down to 451.

V

v.g.vassilev updated this revision to **Diff 128802**. Jan 5 2018, 2:32 PM

Reduce further the deserializations from 451 to 449 by providing a more complete implementation of `ODRHash::AddTemplateArgument`.

Kudos @rtrieu !

3. Stats:
   - `types read` is down from 30% to 17%
   - `declarations read` is down from 34% to 23%
   - number of `ClassTemplateSpecializations` read has decreased by 30%,
   - number of `CXXRecordDecls` read is down 25%
   - total `ASTContext` memory usage is down by 12%
4. calculate hash

```
unsigned TemplateArgumentList::ComputeODRHash(ArrayRef<TemplateArgument> Args) {
  ODRHash Hasher;
  for (TemplateArgument TA : Args)
    Hasher.AddTemplateArgument(TA);

  return Hasher.CalculateHash();
}

FunctionTemplateSpecializationInfo *
```

5. Add template argument

```
// If this was a specialization we should take into account its template
// arguments. This helps to reduce collisions coming when visiting template
// specialization types (eg. when processing type template arguments).
ArrayRef<TemplateArgument> Args;
if (auto *CTSD = dyn_cast<ClassTemplateSpecializationDecl>(D))
  Args = CTSD->getTemplateArgs().asArray();
else if (auto *VTSD = dyn_cast<VarTemplateSpecializationDecl>(D))
  Args = VTSD->getTemplateArgs().asArray();
else if (auto *FD = dyn_cast<FunctionDecl>(D))
  if (FD->getTemplateSpecializationArgs())
    Args = FD->getTemplateSpecializationArgs()->asArray();

for (auto &TA : Args)
  AddTemplateArgument(TA);
```

6. ASTWriter.cpp

7. Added template specialistion info.

8. https://github.com/root-project/root/blob/master/interpreter/llvm/src/tools/clang/lib/Serialization/ASTReader.cpp#L3134-L3145

github.com/root-project/root/blob/master/interpreter/llvm/src/tools/clang/lib/Serialization/ASTReader.cpp#L3134-L3145

```
    case IDENTIFIER_TABLE:
      F.IdentifierTableData = Blob.data();
      if (Record[0]) {
        F.IdentifierLookupTable = ASTIdentifierLookupTable::Create(
            (const unsigned char *)F.IdentifierTableData + Record[0],
            (const unsigned char *)F.IdentifierTableData + sizeof(uint32_t),
            (const unsigned char *)F.IdentifierTableData,
            ASTIdentifierLookupTrait(*this, F));

        PP.getIdentifierTable().setExternalIdentifierLookup(this);
      }
      break;

```

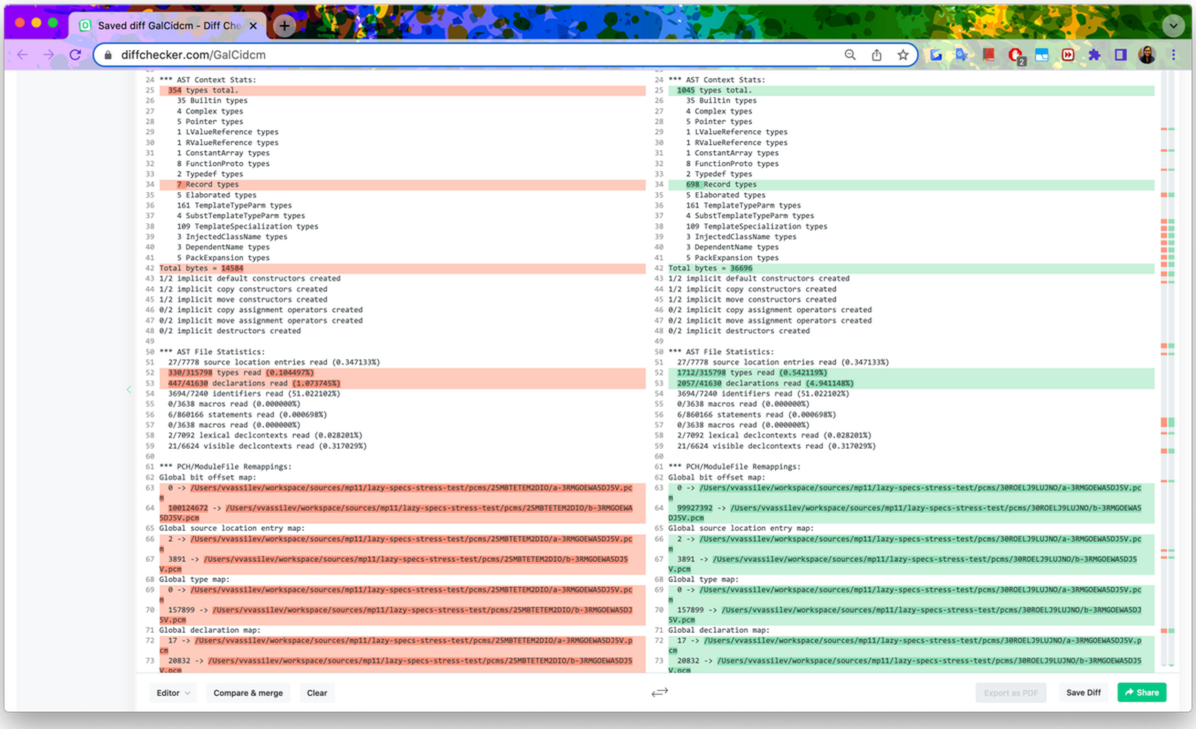
Read a blob of identifiers from a module file and then put that blob into that table which is of type `llvm::OnDiskIterableChainedHashTable`.

Measure performance improvements

Size — du -sh *pcm
sort largest to smallest measure of file space amount recursively stored in directory

Memory Consumption — /usr/bin/time -v root.exe -l -b -q tutorials/hsimple.C
Compared against eager deserialization, reduce heap size.

Use the internal performance counters in clang - https://godbolt.org/z/s61fxoYPs



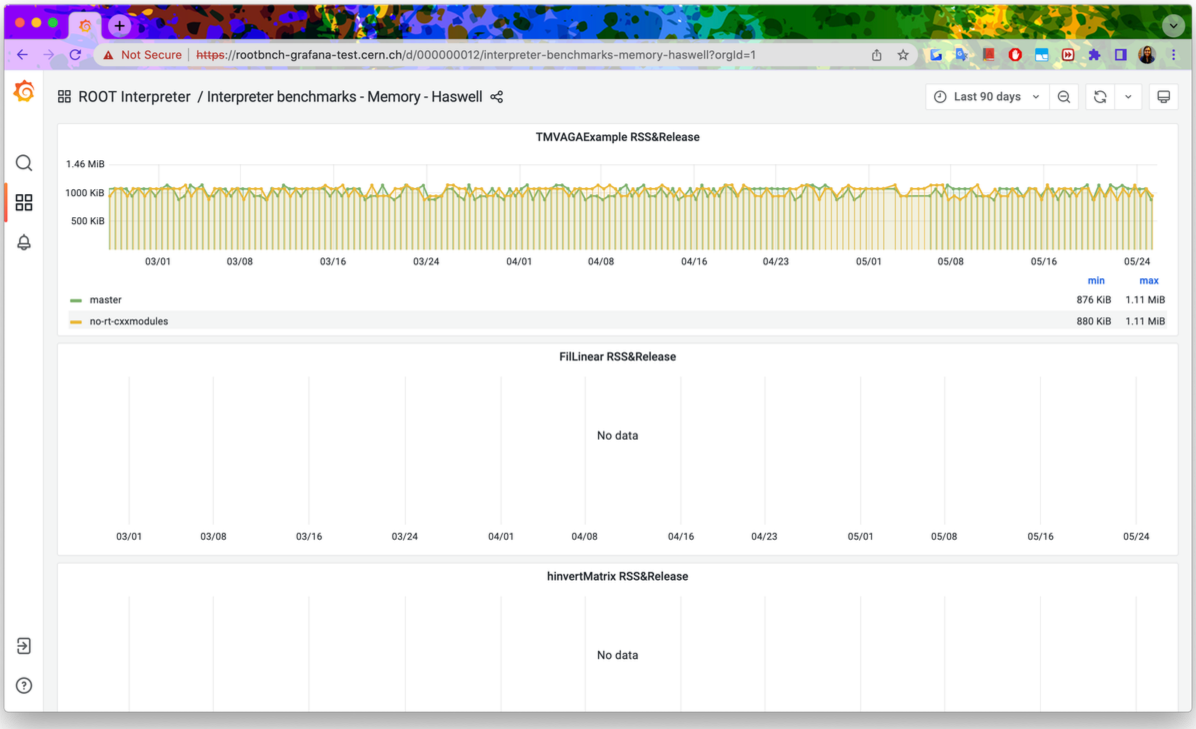
Internal performance counters:

```
*** AST Context Stats:
  25662 types total.
    5 Decayed types, 48 each (240 bytes)
    133 ConstantArray types, 56 each (7448 bytes)
    21 DependentSizedArray types, 64 each (1344 bytes)
    19 IncompleteArray types, 40 each (760 bytes)
    62 Builtin types, 24 each (1488 bytes)
    103 Decltype types, 40 each (4120 bytes)
    18 Auto types, 48 each (864 bytes)
    969 DependentName types, 48 each (46512 bytes)
    43 DependentTemplateSpecialization types, 48 each (2064 by
tes)
    736 Elaborated types, 48 each (35328 bytes)
    6419 FunctionProto types, 40 each (256760 bytes)
    645 InjectedClassName types, 40 each (25800 bytes)
```

```
    76 MemberPointer types, 48 each (3648 bytes)
    148 PackExpansion types, 40 each (5920 bytes)
    98 Paren types, 40 each (3920 bytes)
    1861 Pointer types, 40 each (74440 bytes)
    1505 LValueReference types, 40 each (60200 bytes)
    324 RValueReference types, 40 each (12960 bytes)
    1015 SubstTemplateTypeParm types, 40 each (40600 bytes)
    87 Enum types, 32 each (2784 bytes)
    716 Record types, 32 each (22912 bytes)
    6815 TemplateSpecialization types, 40 each (272600 bytes)
    2935 TemplateTypeParm types, 40 each (117400 bytes)
    32 TypeOfExpr types, 32 each (1024 bytes)
    869 Typedef types, 32 each (27808 bytes)
    1 UnaryTransform types, 48 each (48 bytes)
    7 Using types, 40 each (280 bytes)
Total bytes = 1029272
31/518 implicit default constructors created
98/591 implicit copy constructors created
54/543 implicit move constructors created
34/595 implicit copy assignment operators created
7/543 implicit move assignment operators created
43/544 implicit destructors created

Number of memory regions: 513
Bytes used: 7701107
Bytes allocated: 7929856
Bytes wasted: 228749 (includes alignment, etc)
```

Reduced memory consumption — ask Google to run the reimplemenation of D41416 on their builds

https://rootbnch-grafana-test.cern.ch/dashboards



Build ROOT with -Druntime_cxxmodules=On on Windows

How to model the partial template specializations

Allows customizing class and variable templates for a given category of template arguments.
Examples of partial specializations in the standard library include std::unique_ptr, which has a partial specialization for array types.

example: from https://en.cppreference.com/w/cpp/language/partial_specialization

> *When a class or variable template is instantiated, and there are partial specializations available, the compiler has to decide if the primary template is going to be used or one of its partial specializations.*

> *1) If only one specialization matches the template arguments, that specialization is used*

> *2) If more than one specialization matches, partial order rules are used to determine which specialization is more specialized. The most specialized specialization is used, if it is unique (if it is not unique, the program cannot be compiled)*
> *3) If no specializations match, the primary template is used*

> *- the first function template has the same template parameters as the first partial specialization and has just one function parameter, whose type is a class template specialization with all the template arguments from the first partial specialization*
> *- the second function template has the same template parameters as the second partial specialization and has just one function parameter whose type is a class template specialization with all the template arguments from the second partial specialization.*
>
> *The function templates are then ranked as if for function template overloading.*