EP-SFT
Software Frameworks and Tools

Hands-on Using Clang as a library: Incremental Compilation and Language Interoperability

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EuroLLVM 2026, Dublin

Overview

- Learn how to use Clang as a library
- Build a simple C++ REPL with clang::Interpreter
- See how we can bridge compiled and interpreted code
- Develop building blocks for a basic Compiler-as-a-Service
- Use the CaaS layer to bridge Python and C++

Setup

Requirements:

LLVM21 installation, CMake ≥ 3.13 and a C++17 compiler

Python3 for exercises 4 and 5.

Build:

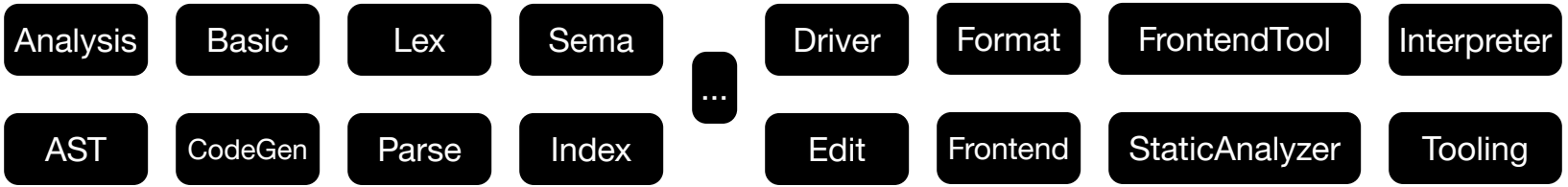
```
git clone https://github.com/compiler-research/eurollvm26-tutorial.git
cd eurollvm26-tutorial && mkdir build && cd build
cmake -DLLVM_DIR=/usr/lib/llvm-21/lib/cmake/llvm \
      -DClang_DIR=/usr/lib/llvm-21/lib/cmake/clang ..
make
```

Substitute whichever /usr/lib/llvm-21 with your install:

- mac: `$(brew --prefix llvm@21)/lib/cmake/...`
- Source build: `path/to/build/lib/cmake/...`

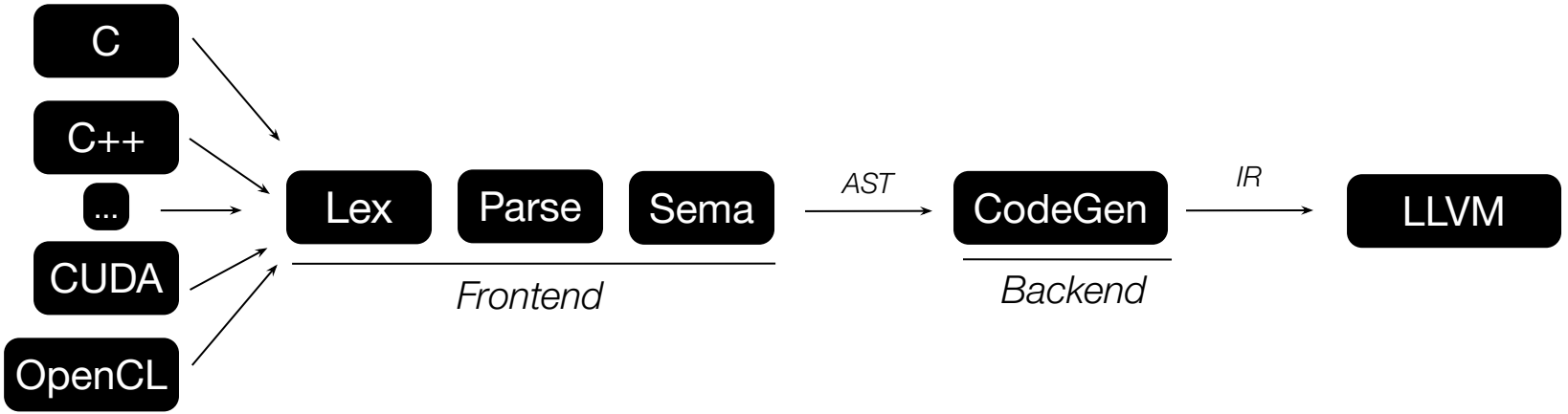
The Clang Project

- Clang is a compiler which supports C, C++, Objective-C, and Objective-C++ programming languages, as well as the OpenMP, OpenCL, RenderScript, CUDA, SYCL, and HIP frameworks.
- Just like LLVM, Clang is built by a set of reusable components and can be used as a library.



The Clang Project

Clang takes input pipes it through a frontend and a backend and produces machine code



ex1: Using Clang as a Library

AST

Tooling

ex1:

```
#include "clang/AST/Comment.h"
#include "clang/AST/DeclTemplate.h"
#include "clang/Tooling/Tooling.h"
...
auto ASTU = tooling::buildASTFromCodeWithArgs(Code,
{"-std=c++20"});
auto &C = ASTU->getASTContext();
auto *TU = C.getTranslationUnitDecl();
TU->dump();
```

Run the compiler on given code.

```
|-ClassTemplateDecl 0x7f83db895f48 <input.cc:4:1, line:5:40> col:8
ComplexNumber
| |-TemplateTypeParmDecl 0x7f83db895dd0 <line:4:10, col:19> col:19
| |-CXXRecordDecl 0x7f83db895e98 <line:5:1, col:40> col:8 struct ComplexNumber
| | ...
| | |-FullComment 0x7f83dc00c200 <line:2:4, col:52>
| | | `-ParagraphComment 0x7f83dc00c1d0 <col:4, col:52>
| | |   `-TextComment 0x7f83dc00c1a0 <col:4, col:52>
        Text=" This is the documentation for the ComplexNumber."
```

ex2: A Simple C++ REPL

Frontend

Interpreter

ex2: Incremental Compilation in Clang

```
// Initialize our builder class
clang::IncrementalCompilerBuilder CB;

CB.SetCompilerArgs({"-std=c++20"}); // pass `-xc` for C.

// Create the incremental compiler instance
auto CI = ExitOnErr(CB.CreateCpp());

// Create the interpreter instance
auto Interp = ExitOnErr(Interpreter::create(std::move(CI)));
```

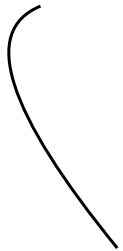
-fplugin=my_plugin.so

Standard compiler flags

Creates an incremental compiler instance

ex2: Incremental Compilation in Clang

```
llvm::LineEditor LE("eurollvm26-repl");
while (std::optional<std::string> Line = LE.readLine()) {
  if (*Line == "%quit")
    break;
  if (auto Err = Interp->ParseAndExecute(*Line)) {
    ...
  }
}
```



Adds a partial translation unit

ex3: Bridging Compiled and Interpreted C++

Frontend

Interpreter

ex3: Bridging Compiled and Interpreted C++

- Transporting results from compiled to interpreted code and back
- Frontend support for taking control of object lifetime
- Frontend support handling C++ semantics such as non-assignable types

ex3.cpp: Bridging Compiled and Interpreted C++

An efficient, ref-counted, small-buffer optimized facility to transport results
Supports pretty printing and type conversion operations

```
// Create a value to store the transport the result from JIT.
clang::Value V;

Interp->ParseAndExecute(R"(extern "C" int sq(int x){return x*x;}
                           sq(12))", &V);
printf("From JIT: square(12)=%d\n", V.getInt());

// Or just get a function pointer and call it in compiled code:
auto SymAddr = ExitOnErr(Interp->getSymbolAddress("sq"));
auto sqPtr = SymAddr.toPtr<int(*)(int)>();
printf("From compiled code: square(13)=%d\n", sqPtr(13));
```

ex4: Building a Compiler-as-a-Service

Frontend

Interpreter

Programmatically Instantiating C++ Templates

Frontend Interpreter

- Create a library containing CaaS building blocks and create an interface for it
- Build a C binary to programmatically instantiate and call a C++ template function
- Teach Python to express C++: `cpp.myclass.myfunc["int"]`

Programmatically Instantiating C++ Templates

Frontend Interpreter

```
#include <typeinfo>

class A {};
struct B {
    template <typename T>
    static void callme(T) {
        printf(" Instantiated with [%s] \n", typeid(T).name());
    }
};
```

ex4-lib: A Library Capable of Instantiating a Template

```
void Clang_Parse(const char* Code);

void* Clang_LookupName(...);

unsigned Clang_GetFunctionAddress(...);

void* Clang_CreateObject(...);

void* Clang_InstantiateTemplate(...);
```

Returns a declaration given a string

Returns the in-memory address of JIT'd function

Allocates storage for a declaration

ex4-lib: A Library Capable of Instantiating a Template

```
int main(int argc, char **argv) {
  Clang_Parse(Code);
  Decl_t TemplatedClass = Clang_LookupName("B", /*Context=*/0);

  // Instantiate B::callme with the given types
  Decl_t Instantiation = Clang_InstantiateTemplate(TemplatedClass, "callme", "A");

  // Get the symbol to call
  typedef void (*fn_def)(void*);
  fn_def callme_fn_ptr = (fn_def) Clang_GetFunctionAddress(Instantiation);

  // Create objects of type A
  Decl_t T = Clang_LookupName("A", /*Context=*/0);
  void* NewA = Clang_CreateObject(T);

  callme_fn_ptr(NewA);
}
```

Instantiating C++ templates on-demand with Python

Let's build a Python wrapper for the the functions in ex4-lib:

- InteropLayerWrapper — Responsible for instantiating a C++ template
- TemplateWrapper — Finds and matches C++ template arguments
- CallCppFunc — Invokes the C++ template function

Instantiating C++ templates on-demand with Python

```python
import ctypes

libInterop = ctypes.CDLL("ex4-lib.so")
# tell ctypes which function to call and the expected param/return types.
_cpp_compile = libInterop.Clang_Parse
_cpp_compile.argtypes = [ctypes.c_char_p]

def cpp_compile(arg):
  return _cpp_compile(arg.encode("ascii"))
# define some classes to play with
cpp_compile(r"""\
class A {};
struct B : public A {
  template<typename T> static void callme(T*) {
   printf("Template: %s\n", typeid(T).name());
 }
};
""")
```

```
void Clang_Parse(const char* Code);
```

Lookup and object creation

```
class InteropLayerWrapper:
  # Provide a Python wrapper over the interop layer
  _get_scope = libInterop.Clang_LookupName
  _get_scope.restype = ctypes.c_size_t
  _get_scope.argtypes = [ctypes.c_char_p]

  _construct = libInterop.Clang_CreateObject
  _construct.restype = ctypes.c_void_p
  _construct.argtypes = [ctypes.c_size_t]

  _get_template_ct = libInterop.Clang_InstantiateTemplate
  _get_template_ct.restype = ctypes.c_size_t
  _get_template_ct.argtypes = [ctypes.c_size_t, ctypes.c_char_p, ctypes.c_char_p]

  def _get_template(self, scope, name, args):
    return self._get_template_ct(scope, name.encode("ascii"), args.encode("ascii"))

  def get_scope(self, name):
    return self._get_scope(name.encode("ascii"))
```

```
void* Clang_LookupName(...);

void* Clang_CreateObject(...);

void* Clang_InstantiateTemplate(...);
```

Python-side template handling

```
class TemplateWrapper:
  # Find, instantiate and invoke a template function given arguments
  def __init__(self, scope, name):
    self._scope = scope
    self._name  = name

  def __getitem__(self, *args, **kwds):
    # Look up the template and return the overload
    return gIL.get_template(
      self._scope, self._name, tmpl_args = args)

  def __call__(self, *args, **kwds):
    # find the appropriate overload
    ol = self.get_template(self._scope, self._name, tpargs = [type(a) for a in args])

    # Call actual method
    ol(*args, **kwds)
```

Overloads index bracket access for array-like entries
`my_list[2]` calls `my_list.__getitem__(2)` to return the element at index 2, but here we replace this functionality with a way to specialize our templates as an analog to <>

Function Invocation

```
class CallCppFunc:
  # Responsible for calling low-level function pointers.
  _get_funcptr = libInterop.Clang_GetFunctionAddress
  _get_funcptr.restype = ctypes.c_void_p
  _get_funcptr.argtypes = [ctypes.c_size_t]

  def __init__(self, func):
    # Ideally this should go through the interop layer to know
    # whether to pass pointer, reference, or value of which type etc.
    proto = ctypes.CFUNCTYPE(None, ctypes.c_void_p)
    self._funcptr = proto(self._get_funcptr(func))

  def __call__(self, *args, **kwds):
    # See the comment above.
    a0 = ctypes.cast(args[0].cppobj, ctypes.POINTER(ctypes.c_void_p))
    return self._funcptr(a0)
```

```
unsigned Clang_GetFunctionAddress(...);
```

Python Metaclasses

```
# Initialize our C++ interoperability layer wrapper
gIL = InteropLayerWrapper()

# Create a couple of types to play with
CppA = type('A', (), {
  'handle'   : gIL.get_scope('A'),
  '__new__' : cpp_allocate})

h = gIL.get_scope('B')
CppB = type('B', (A,), {
   'handle'   : h,
   '__new__' : cpp_allocate,
   'callme'   : TemplateWrapper(h, 'callme')})
# Connect to C++ classes
a = CppA()
b = CppB()
# Explicit template instantiation and execution
b.callme['A'](a)
# Implicit template instantiation and execution
b.callme(b)
```

ex5: Transporting clang::Value to Python

Frontend

Interpreter

Building a Compiler-as-a-Service

- In ex4 we could instantiate and call C++ templates from Python — but we couldn't read typed results back
- What if we parse, execute, and capture the result as a typed primitive via clang::Value?
- Goal: Python wrapper gets typed return values without writing a ctypes prototype per signature

```
class Math {
public:
  template<typename T> T pow2(T x)     { return x * x; }
  template<typename T> T add(T a, T b) { return a + b; }
};
```

ex5-lib: The CaaS layer grows

```
typedef enum {
    Clang_Value_Void = 0, Clang_Value_Bool,
    Clang_Value_Int,      Clang_Value_LongLong,
    Clang_Value_Double,   Clang_Value_Ptr,
    Clang_Value_Other,    Clang_Value_Error
  } Clang_ValueKind;

Clang_ValueKind Clang_Eval(const char* Expr);
```

→ Wraps `Interpreter::ParseAndExecute(Expr, &Value)`
The tag tells the caller which accessor to read

```
int       Clang_Value_GetInt(void);
double    Clang_Value_GetDouble(void);
long long Clang_Value_GetLongLong(void);
void *    Clang_Value_GetPtr(void);
```

→ Expose the `clang::Value` result

kind-tag dispatch from Python

```
class ValueEval:
  _eval = libInterop.Clang_Eval
  _eval.restype = ctypes.c_int
  _eval.argtypes = [ctypes.c_char_p]

  _VOID, _BOOL, _INT, _LONGLONG, _DOUBLE, _PTR, _OTHER, _ERROR = range(8)

  def __init__(self):
    self._readers = {
      self._BOOL:     (libInterop.Clang_Value_GetBool,     ctypes.c_int,      bool),
      self._INT:      (libInterop.Clang_Value_GetInt,      ctypes.c_int,      int),
      self._LONGLONG: (libInterop.Clang_Value_GetLongLong, ctypes.c_longlong, int),
      self._DOUBLE:   (libInterop.Clang_Value_GetDouble,   ctypes.c_double,   float),
    }

  def __call__(self, expr):
    kind = self._eval(expr.encode("ascii"))
    if kind in (self._VOID, self._OTHER):
          return None
    fn, _, cast = self._readers[kind]
    return cast(fn())
```

makes a `ValueEval` instance callable: takes a C++ expression, dispatches on the kind, returns a typed Python primitive

Modifying TemplateWrapper

```
class TemplateWrapper:
    def __init__(self, scope_name, method):
      self._scope_name = scope_name
      self._method = method

    def __getitem__(self, key):
      types = key if isinstance(key, str) else ', '.join(key)
      return _Specialised(self._scope_name, self._method, types)

class _Specialised:
    def __call__(self, *args):
      return gEval('{}{{}}.{}<{}>({})'.format(
          self._scope_name, self._method, self._type_args,
          ', '.join(repr(a) for a in args)))
```

Build the expression and call `ValueEval`
ParseAndExecute instantiates the template

Putting it together

```
CppMath = type('Math', (), {
    'pow2': TemplateWrapper('Math', 'pow2'),
    'add' : TemplateWrapper('Math', 'add'),
  })

m = CppMath()

m.pow2['int'](7)
m.pow2['double'](2.5)
m.add['int'](20, 22)

gEval('2 + 40')
gEval('true && false')
```

Same metaclass shape as ex4, but each call returns a typed Python value

About us

Our compiler-research.org initiatives aim to:

- Make compiler research visible and connected
- Train and mentor the next generation of compiler engineers
- Support impactful open-source R&D
- Build bridges between academia, industry, and scientific domains

Internship Opportunities 2026 @ CR

We are happy to announce our Clang-focused fellowship program sponsored by CppAlliance:

- Remote, GSoC-like, project-based
- Upto 6-month internships on Clang oriented projects
- Application form: https://forms.gle/hTCqC2nkTZwqNabc6

Thank You!

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