Enabling Interactive C++ in Clang

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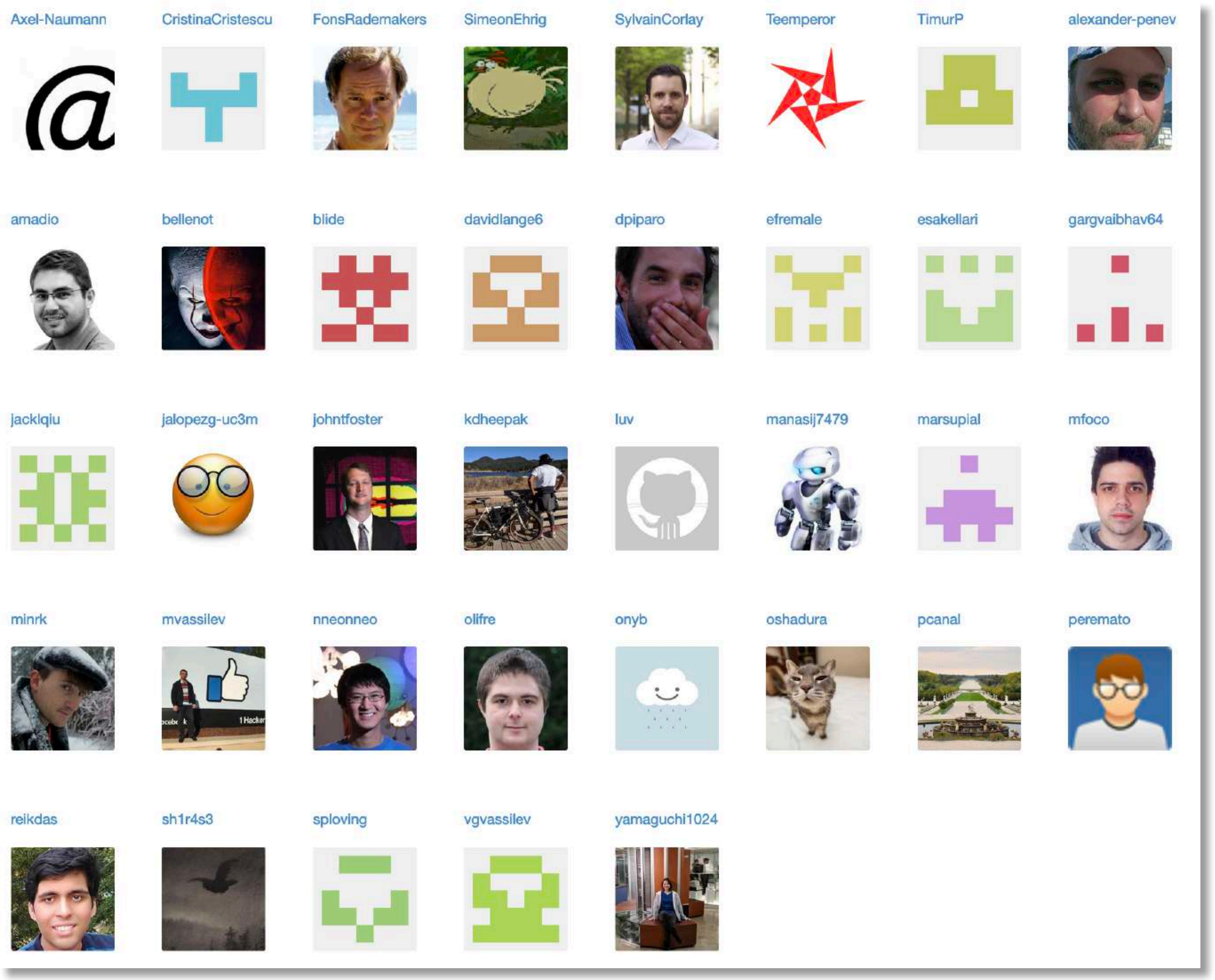
Outline

- Introduction
  - Key insights of Interactive C++
  - Interpreting C++. Tools and technology
- Applications of interactive C++
  - C++ in Jupyter notebooks; Interactive CUDA C++; Automatic language bindings; Eval-style programming
- Compiler As A Service
  - Crossing compile-time/runtime boundaries; Extensions; Automatic differentiation
- Evolving the technology towards Clang mainline via Clang-Repl
  - Showcase incremental compilation in Clang; Demonstrate template instantiation in C and Python
- Summary

Acknowledgement & Disclaimer

- This talk includes technologies developed by various individuals and organizations in the area of interpretative C++ since 1998
- This talk is about work conducted by me but also the work of dozens colleagues and contributors from science and industry. In the slides I have tried to mention individuals and organizations where possible.
- Any characterizations, mischaracterizations, emphasis or errors are solely mine and do not necessarily represent the views of other individuals or organizations.



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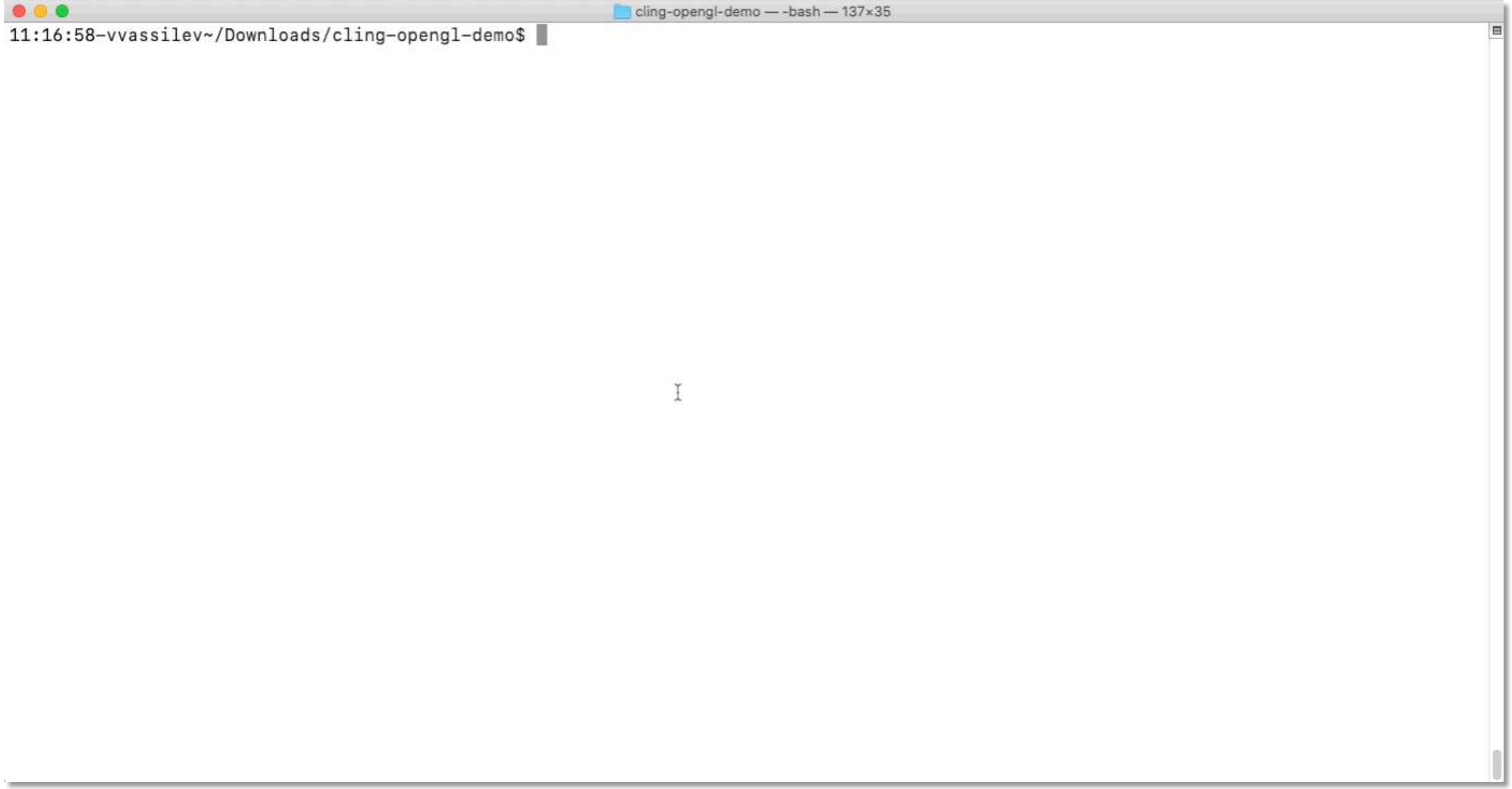
Interactive C++



Video Credits: A. Penev

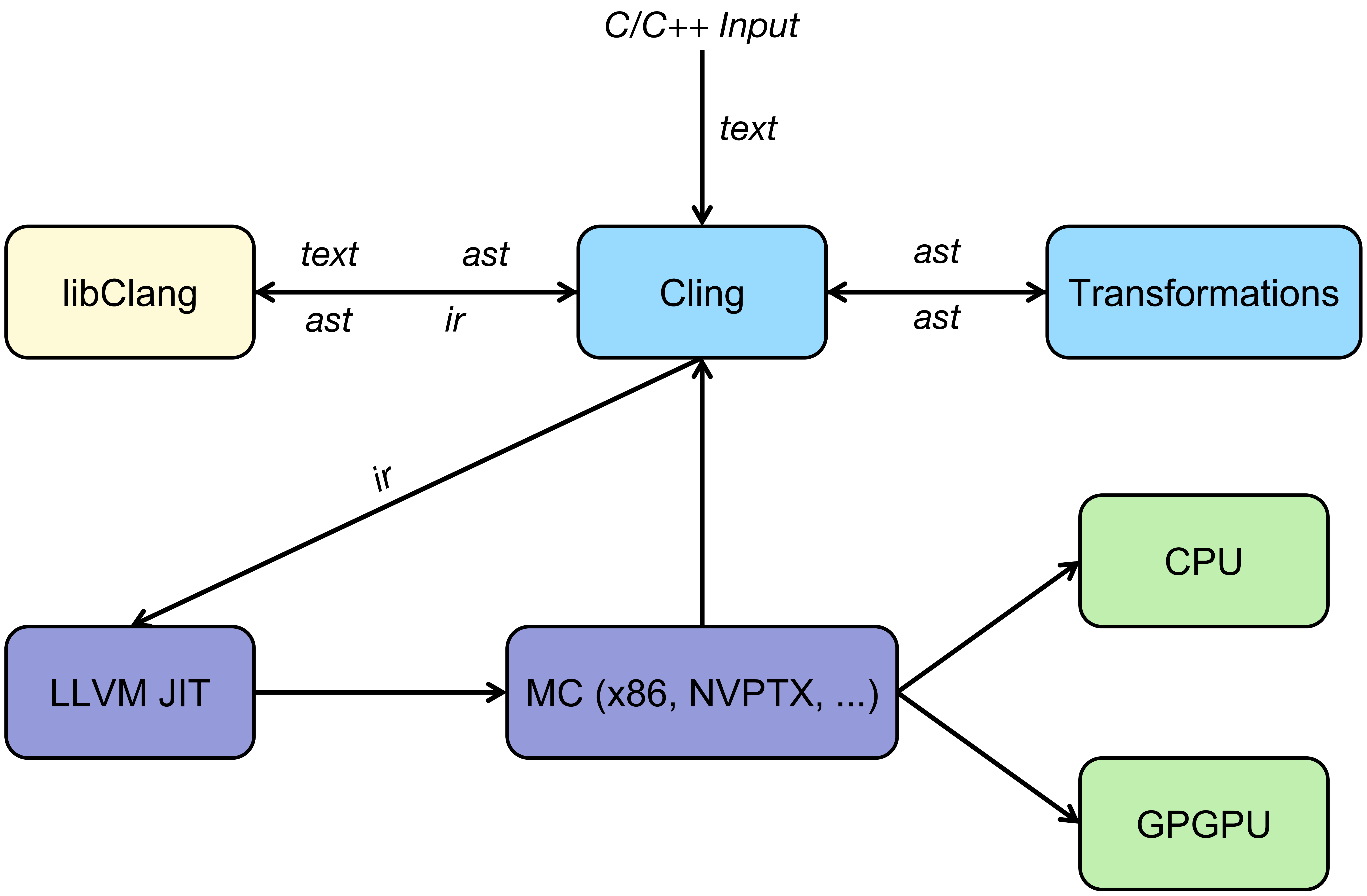
The invisible compile-run cycle aids interactive use and offers a different programming experience while enhancing productivity. It becomes trivial to orient a shape, choose size and color or compare to previous settings

Interactive C++. Key Insights

- Incremental Compilation
- Handling errors
  - Syntactic
  - Semantic
- Execution of statements
- Displaying execution results
- Entity redefinition

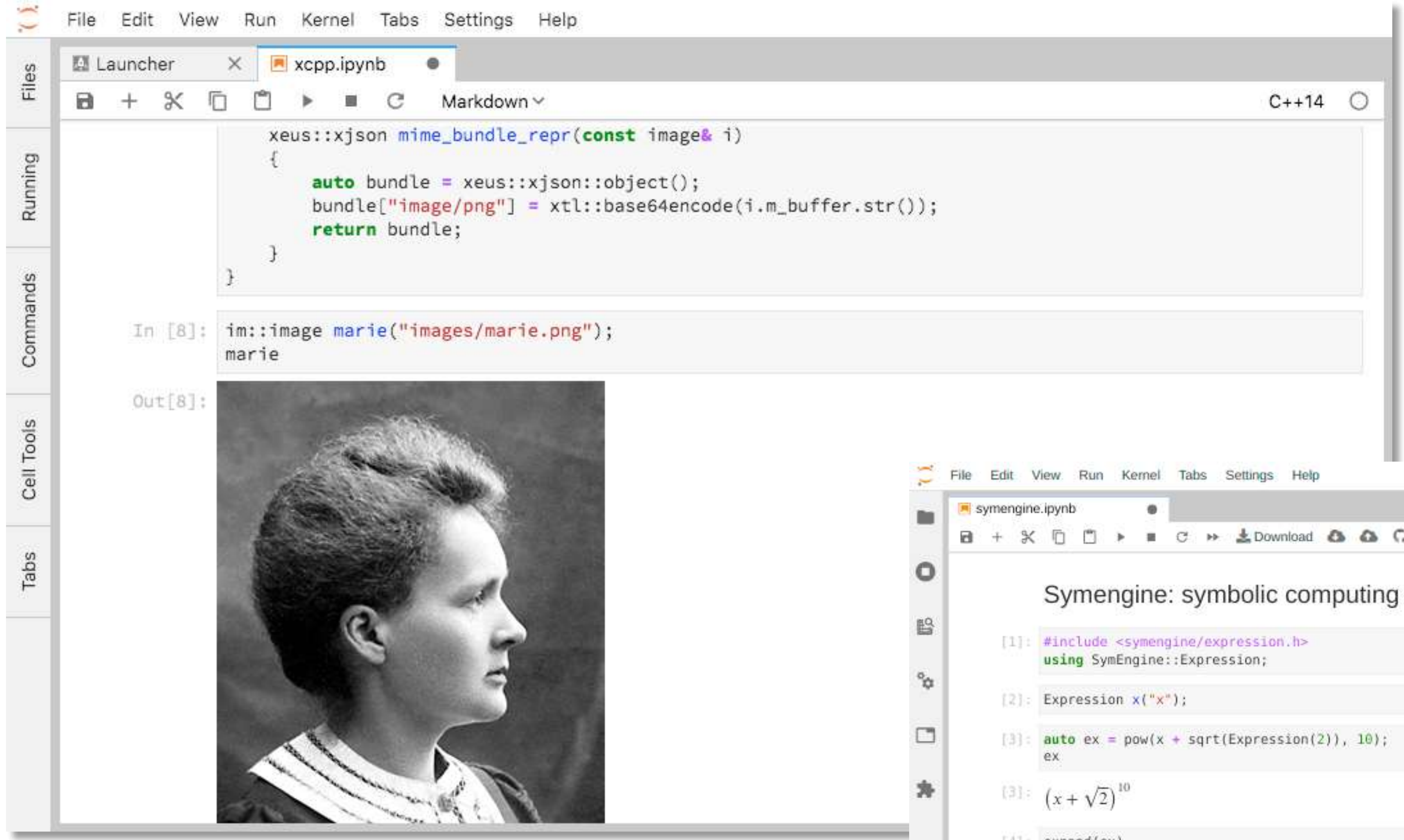
```
[cling] #include <vector>
[cling] std::vector<int> v = {1,2,3,4,5};

[cling] std.sort(v.begin(), v.end());
input_line_1:1:1: error: unexpected namespace
name 'std': expected expression
std.sort(v.begin(), v.end());
^

[cling] std::sort(v.begin(), v.end());
[cling] v // No semicolon
(std::vector<int> &) { 1, 2, 3, 4, 5 }

[cling] std::string v = "Hello World"
(std::string &) "Hello World"
```

Interpreting C++. Cling

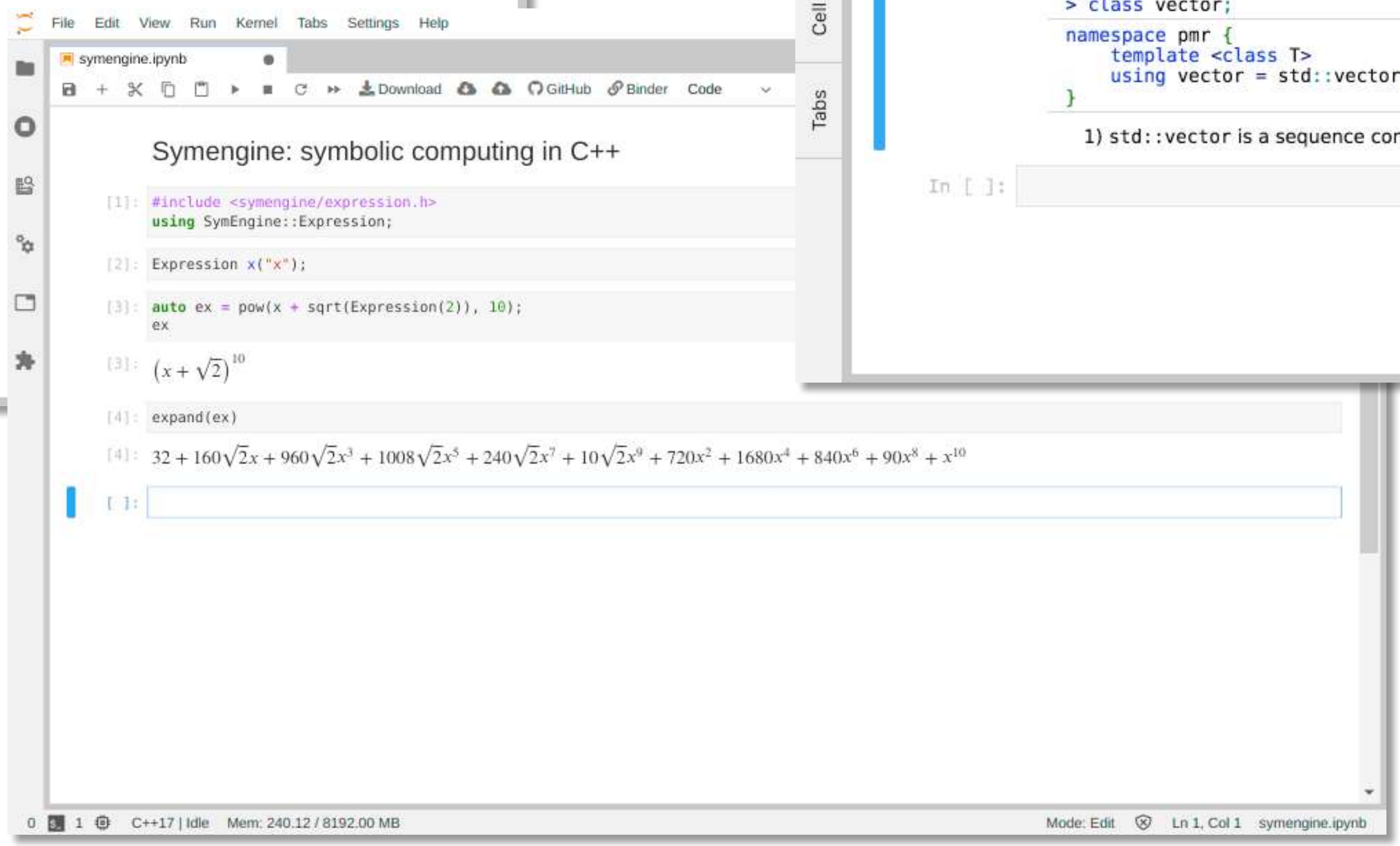


Applications of Interactive C++

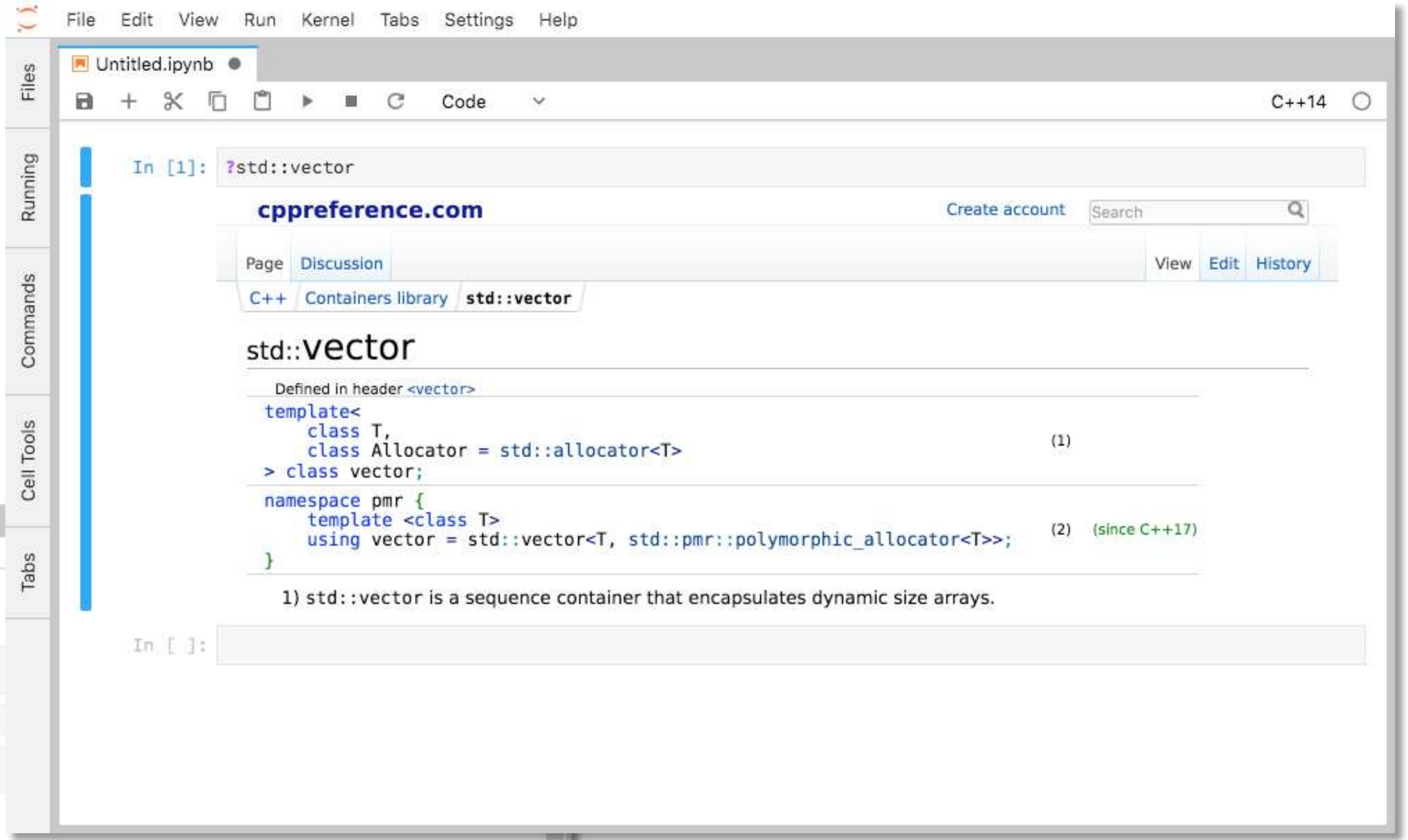
Xeus-Cling. C++ in Notebooks



Visualization of user-defined images

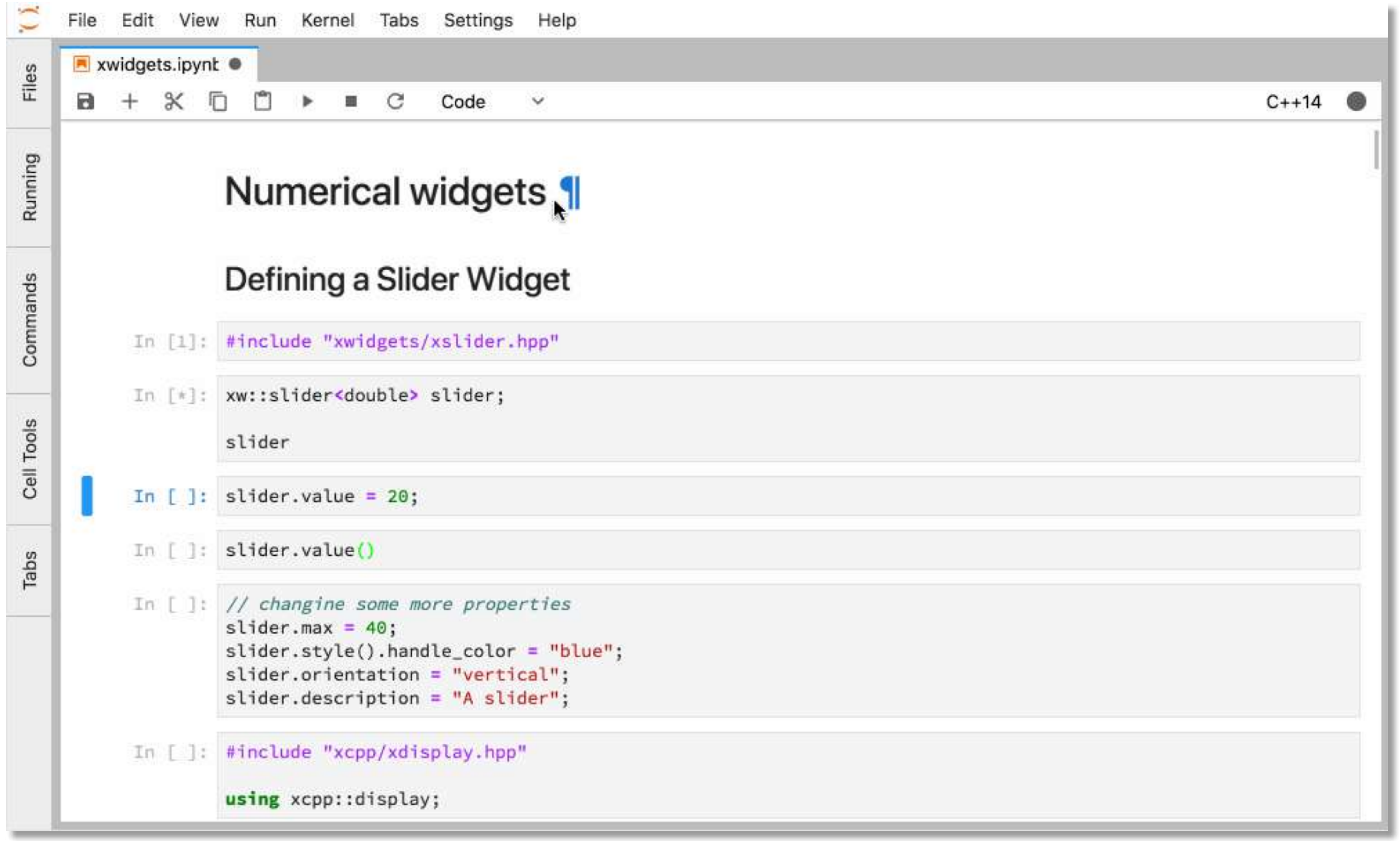


Rich mime type rendering in Jupyter

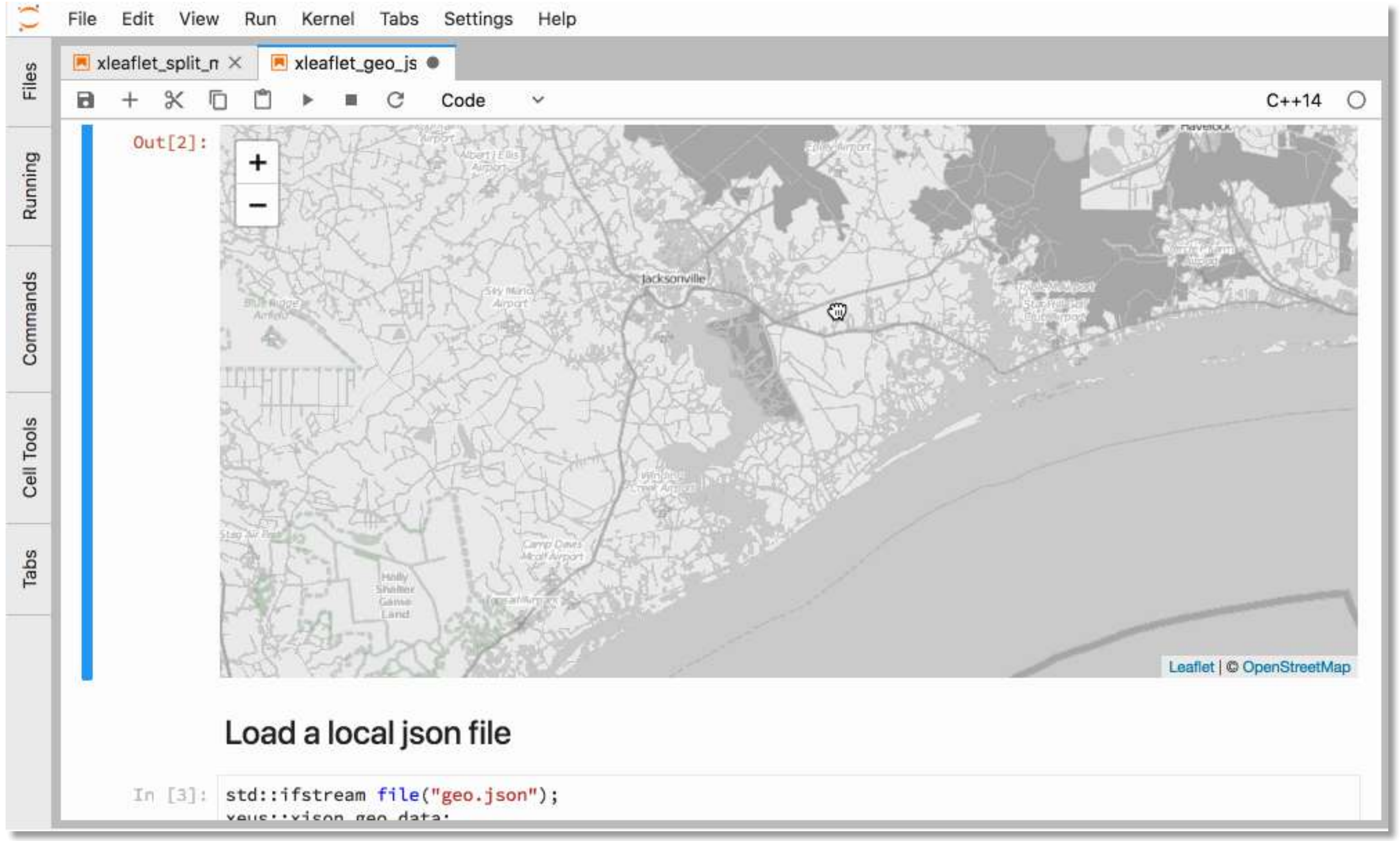


Direct access to documentation

Xeus-Cling. C++ in Notebooks



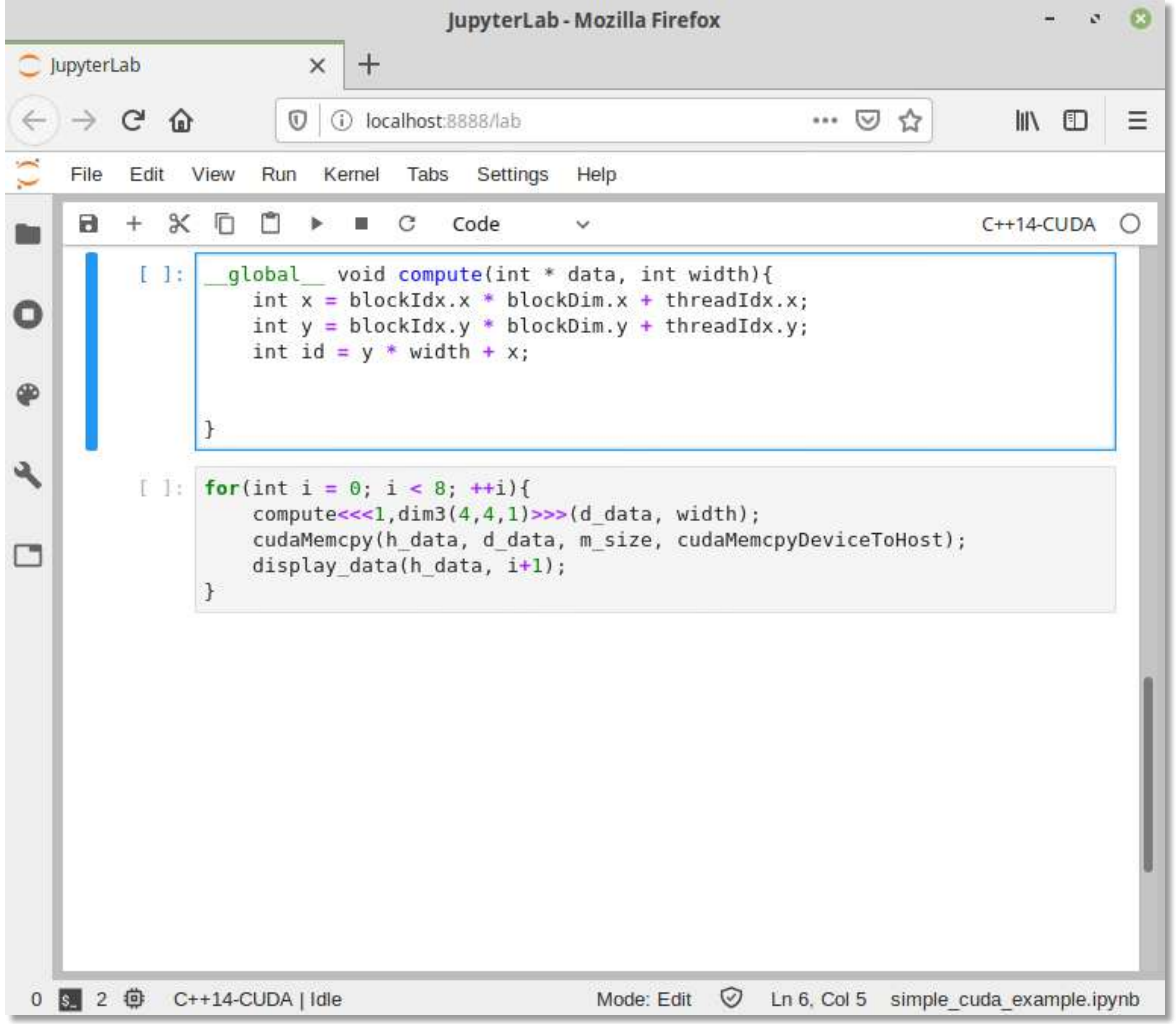
Xwidgets – User-defined controls

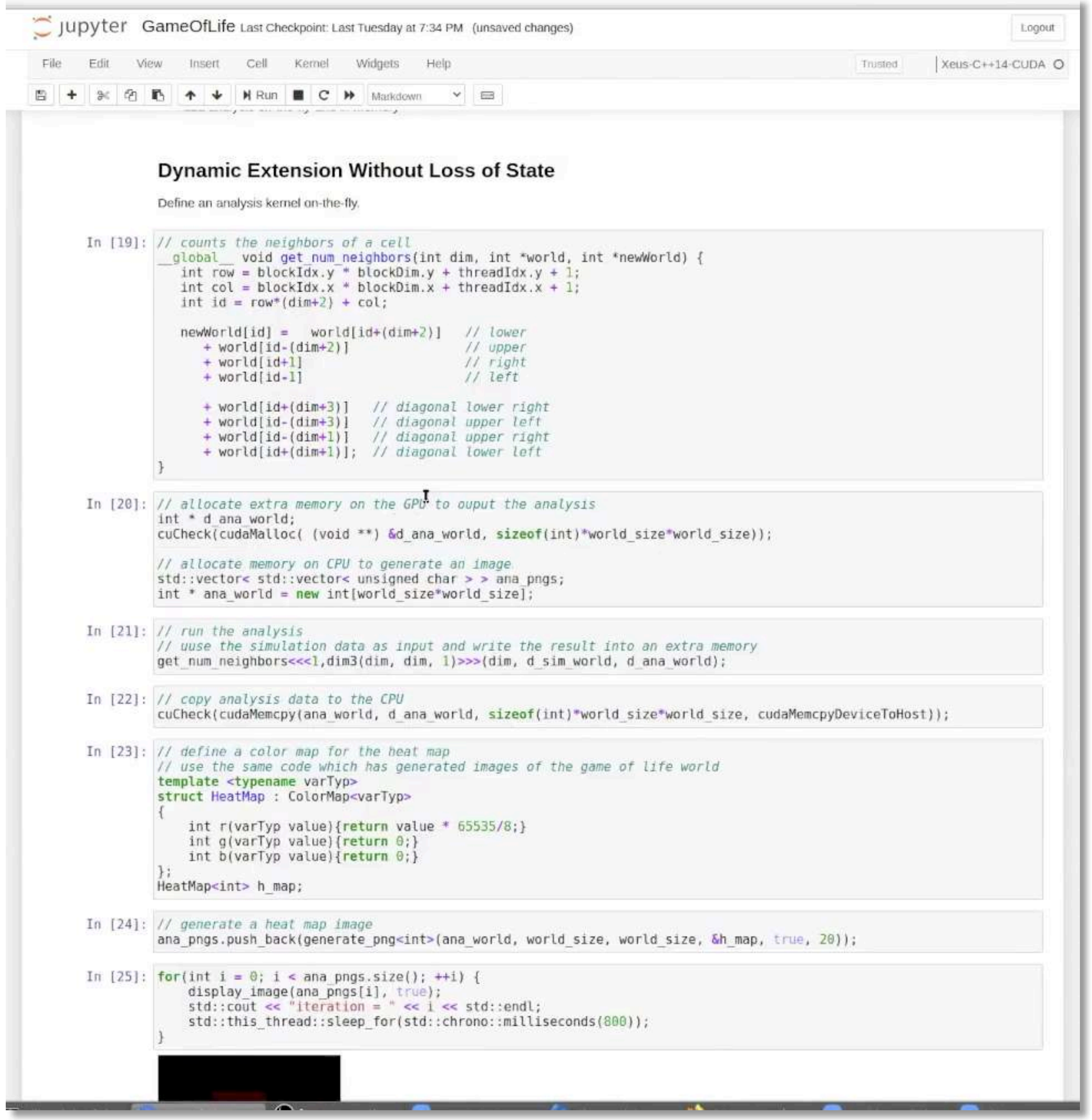


Xleaflet – Interactive Geo Information System

S. Corlay, Quantstack, *[Deep dive into the Xeus-based Cling kernel for Jupyter]()*, May 2021, compiler-research.org

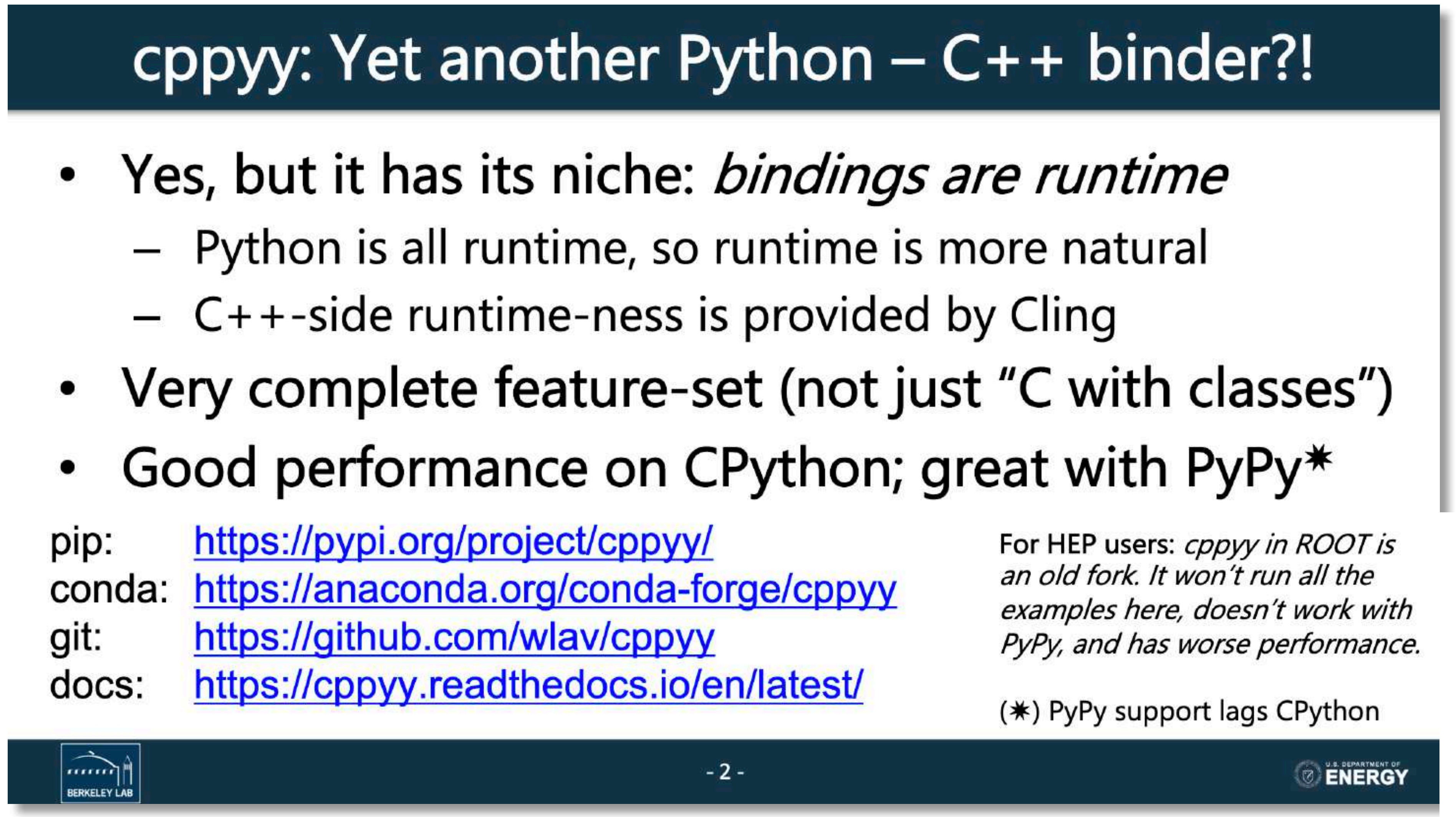
Interactive CUDA C++





S. Ehrig, HZDR, *Cling's CUDA Backend: Interactive GPU development with CUDA C++*, Mar 2021, compiler-research.org

Automatic Language Bindings



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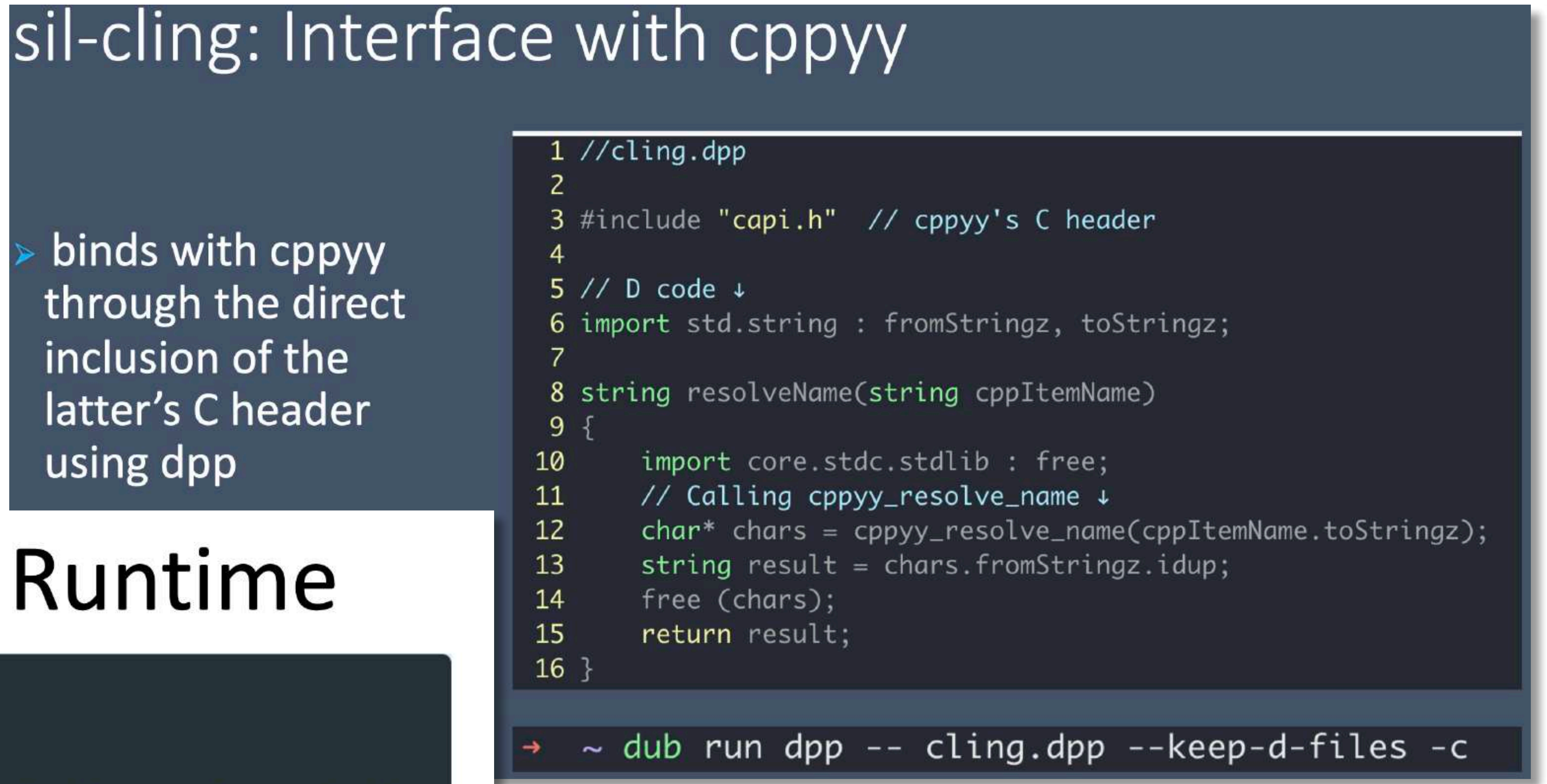

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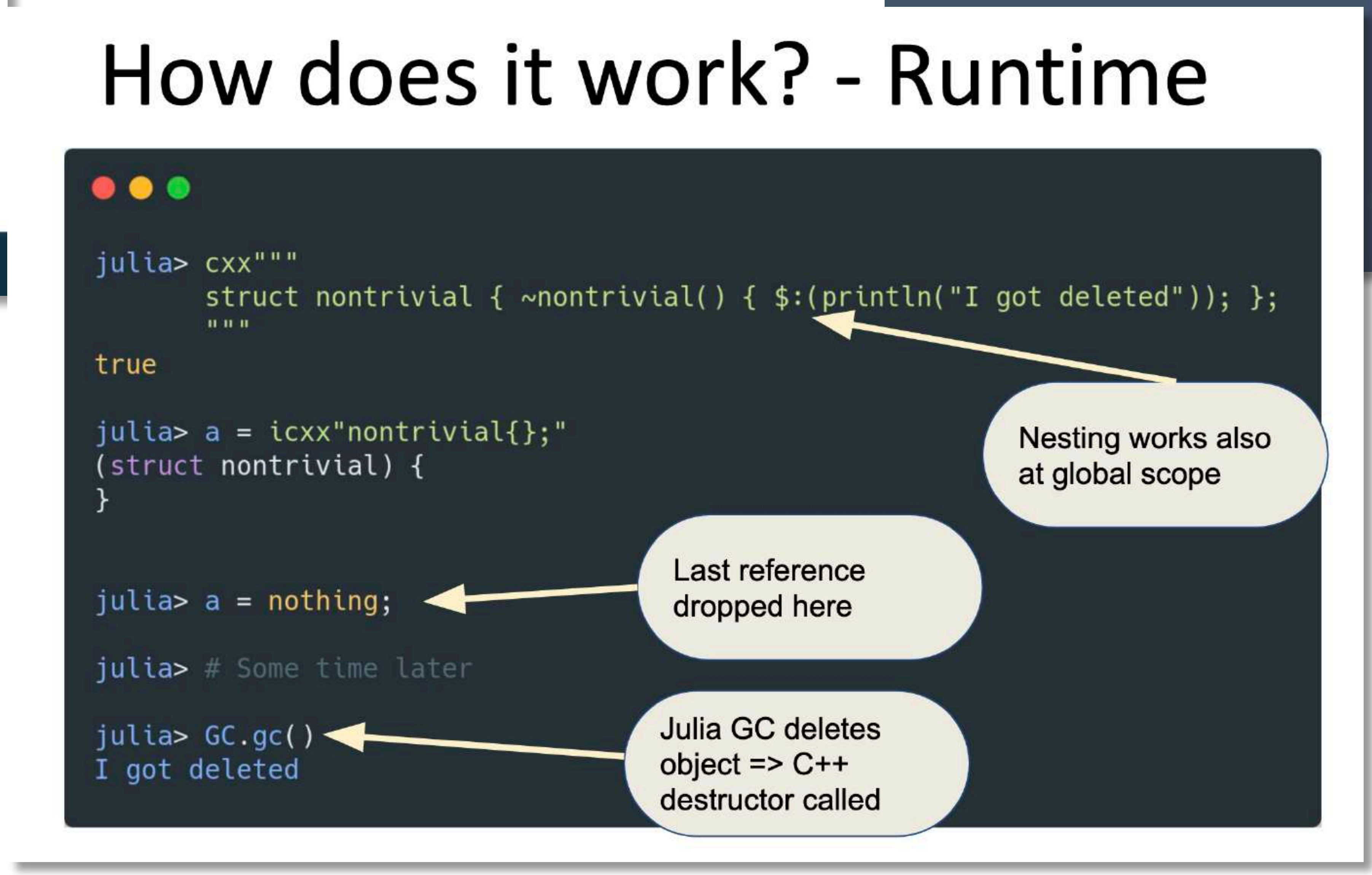


[3]

[1] W. Lavrijsen, LBL, cppyy, Sep 2021, compiler-research.org
[2] A. Militaru, Symmetry Investments, *Calling C++ libraries from a D-written DSL: A cling/cppyy-based approach*, Feb 2021, compiler-research.org
[3] K. Fischer, Julia Computing, *A brief history of Cxx.jl*, Aug 2021, compiler-research.org

Eval-Style Programming

```
[cling]$ #include <cling/Interpreter/Value.h>
[cling]$ #include <cling/Interpreter/Interpreter.h>
[cling]$ int i = 1;
[cling]$ cling::Value V;
[cling]$ gCling->evaluate("++i", V);
[cling]$ i
(int) 2
[cling]$ V
(cling::Value &) boxes [(int) 2]
[cling]$ ++i
(int) 3
[cling]$ V
(cling::Value &) boxes [(int) 2]
```

Eval-style programming enables Cling to be embedded in frameworks.

Key Insights

- Cling is not just a Repl, it is an embeddable and extensible execution system for efficient incremental execution of C++
- Cling is used in several high-performance systems to provide reflection and introspection information
- Cling can produce efficient code for performance-critical tasks where hot-spot regions can be annotated with specific optimization levels
- Cling allows us to decide how much we want to compile statically and how much to defer for the target platform

Compiler As A Service

Compiler As A Service (CaaS)

Cling can be used on-demand, as a service, to compile, modify, describe or extend C++.

CaaS. Crossing Boundaries

```cpp
/// Call an interpreted function using its symbol address.
void callInterpretedFn(cling::Interpreter& interp) {
  // Declare a function to the interpreter. Make it extern "C”
  // to remove mangling from the game.
  interp.declare(”#pragma cling optimize(1)”
      extern \"C\" int cube(int x) { return x * x * x; }");
  void* addr = interp.getAddressOfGlobal("cube");
  using func_t = int(int);
  func_t* pFunc = cling::utils::VoidToFunctionPtr<func_t*>(addr);
  std::cout << "7 * 7 * 7 = " << pFunc(7) << '\n';
}
```

```cpp
// caas-demo.cpp
// g++ ... caas-demo.cpp; ./caas-demo
int main(int argc, const char* const* argv) {
  cling::Interpreter interp(argc, argv, LLVMDIR);

  callInterpretedFn(interp);
  return 0;
}
```

```
vvassilev@vv-nuc ~/.../builddir $ ./caas-demo
7 * 7 * 7 = 343
vvassilev@vv-nuc ~/.../builddir $
```

CaaS. Extensions

```
int main(int argc, const char* const* argv) {
  std::vector<const char*> argvExt(argv, argv+argc);
  argvExt.push_back("-fplugin=etc/cling/plugins/lib/clad.so");
  cling::Interpreter interp(argvExt.size(), &argvExt[0], LLVMDIR);
  gimme_pow2dx(interp);
  return 0;
}
```

CaaS. Clad Extension for AutoDiff

```
#include <...>
// Derivatives as a service.
void gimme_pow2dx(cling::Interpreter &interp) {
  // Definitions of declarations injected also into cling.
  interp.declare("double pow2(double x) { return x*x; }");
  interp.declare("#include <clad/Differentiator/Differentiator.h>");
  interp.declare("#pragma cling optimize(2)");
  interp.declare("auto dfdx = clad::differentiate(pow2, 0);");

  cling::Value res; // Will hold the evaluation result.
  interp.process("dfdx.getFunctionPtr();", &res);

  using func_t = double(double);
  func_t* pFunc = res.getAs<func_t*>();
  printf("dfdx at 1 = %f\n", pFunc(1));

  interp.process("dfdx.getCode();", &res);
  printf("dfdx code: %s\n %s\n", res.getAs<const char*>());
}
```

```
vvassilev@vv-nuc ~/.../builddir $ ./caas-demo
dfdx at 1 = 2.000000
dfdx code: double pow2_darg0(double x) {
    double _d_x = 1;
    return _d_x * x + x * _d_x;
}

vvassilev@vv-nuc ~/.../builddir $
```

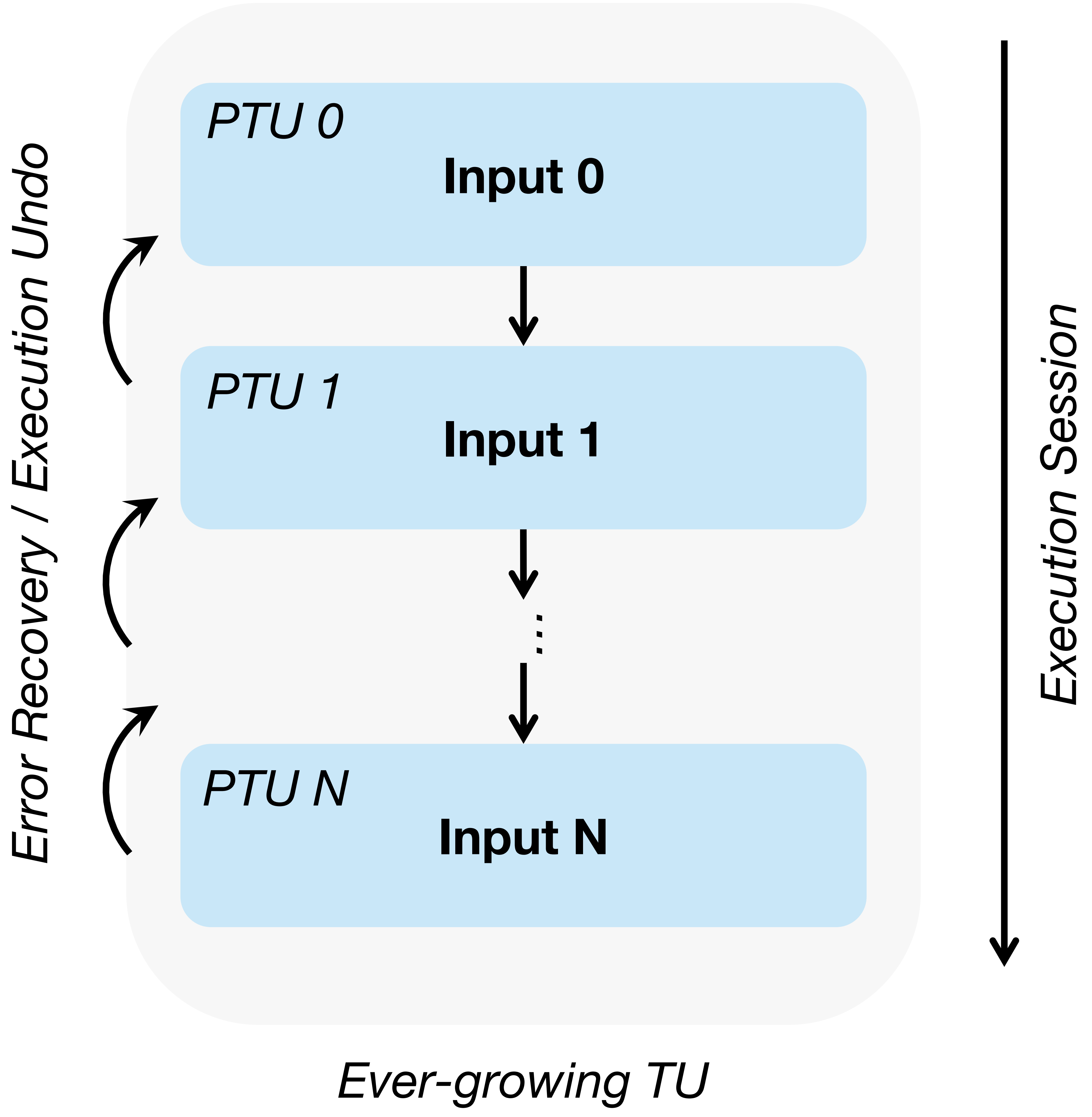
Evolving Cling Into CaaS and Clang-Repl in LLVM Mainline

Evolving Cling Into CaaS and Clang-Repl

- Generalize Cling in a tool available in LLVM mainline (clang/tools/clang-repl)
- Consolidate various incremental compilation APIs in Clang (clang/lib/Interpreter)
- Advance the incremental compilation support in Clang
- libclangInterpreter and clang-repl are available in LLVM13

Ever-growing TU in Clang

- We can split the translation unit into a sequence of partial translation units (PTU)
- Processing a PTU might extend an earlier PTU (template instantiation)
- Each PTU can have its own allocator



Incremental Compilation in Clang

```
#include "clang/Interpreter/Interpreter.h"
// ...
int main() {
  std::vector<const char*> Args;
  auto CI = clang::IncrementalCompilerBuilder::create(Args);
  auto Interp = clang::Interpreter::create(std::move(CI));
  auto PTU = Interp->Parse("extern \"C\" int printf(const char*,...);");
  Interp->ParseAndExecute("auto r = printf(\"Hello interpreted world\");");
  // prints ‘Hello interpreted world’
}
```

Instantiating a C++ template in C

```
// gcc ... template_instantiate_demo.C
#include "InterpreterUtils.h" // libInterOp.so

int main(int argc, char **argv) {
  Clang_Parse("void* operator new(__SIZE_TYPE__,
void* __p);"
      "extern \"C\" int printf(const char*,...);"
      "class A {};"
      "\n #include <typeinfo> \n"
      "struct B {"
      "  template<typename T>"
      "  void callme(T) {"
      "    printf(\" Instantiated with [%s] \\n \",
typeid(T).name());"
      "  }"
      "};");
  const char * InstArgs = "A*";
  Decl_t T = Clang_LookupName("A");
  Decl_t TemplatedClass = Clang_LookupName("B");
```

```
  // ...
  // Instantiate B::callme with the given types
  Delc_t Inst
     = Clang_InstantiateTemplate(TemplatedClass,
"callme", InstArgs);


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

  // Create object of type T
  void* NewT = Clang_CreateObject(T);

  callme_fn_ptr(NewT);

  return 0;
}
```

```
vvassilev@vv-nuc ~/.../cpptemplate $ LD_LIBRARY_PATH="." ./template_instantiate_demo.out
Instantiated with [P1A]
vvassilev@vv-nuc ~/.../cpptemplate $ LD_LIBRARY_PATH="." ./template_instantiate_demo.out "class MyClass1{};" "MyClass1" "MyClass1*"
Instantiated with [P8MyClass1]
vvassilev@vv-nuc ~/.../cpptemplate $
```

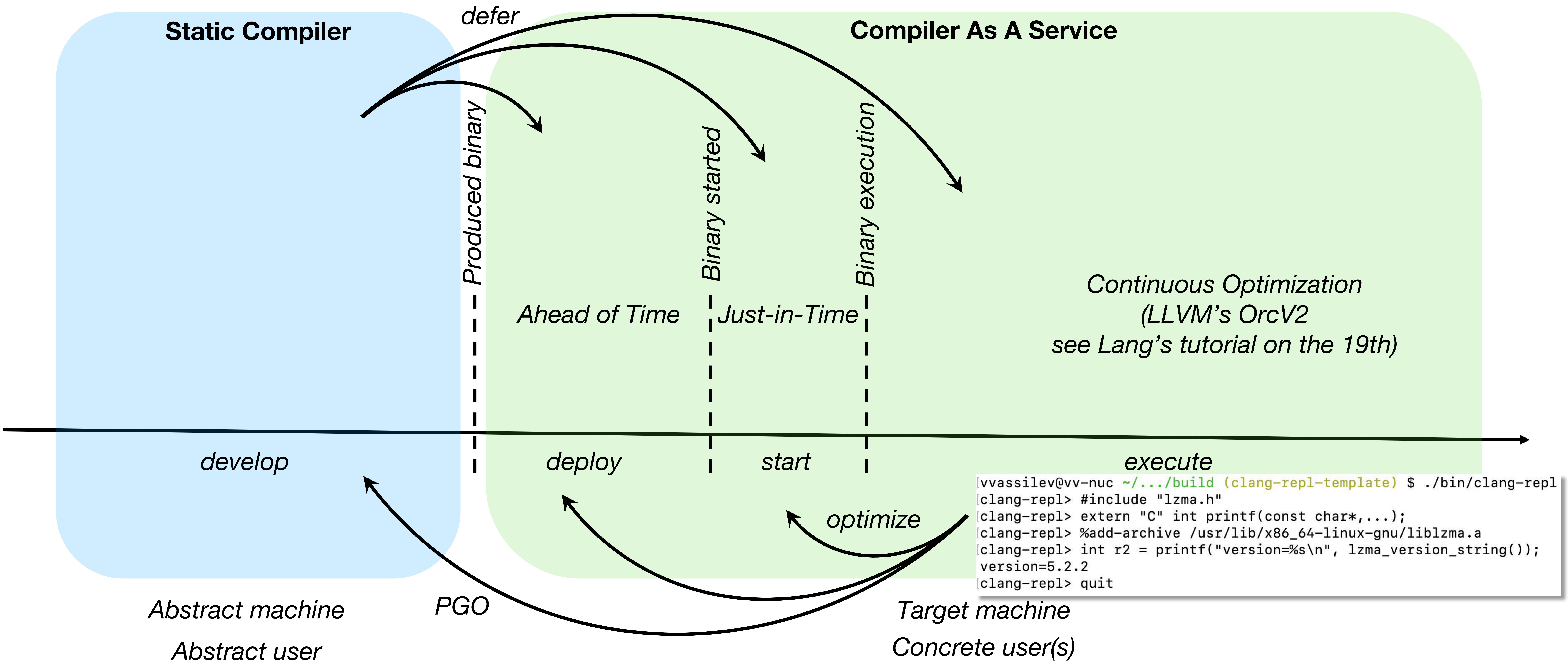
Instantiating a C++ template in Python

```
# template_instantiate_demo.py
import ctypes

libInterop = ctypes.CDLL("./libInterOp.so")
# tell ctypes which function to call and what are the
expected in/out 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"""\
void* operator new(__SIZE_TYPE__, void* __p);
extern "C" int printf(const char*,...);
class A {};
class B {
public:
    template<typename T, typename S>
    void callme(T, S) { printf(" callme in B! \n"); }
};
""")
...
```

```
# initialize our C++ interoperability layer wrapper
gIL = InterOpLayerWrapper()

if __name__ == '__main__':
 # create a couple of types to play with
  A = type('A', (), {
    'handle'  : gIL.get_scope('A'),
    '__new__' : cpp_allocate
  })
  h = gIL.get_scope('B')
  B = type('B', (A,), {
    'handle'  : h,
    '__new__' : cpp_allocate,
    'callme'  : TemplateWrapper(h, 'callme')
  })
  # call templates
  a = A()
  b = B()

  # explicit template instantiation
  b.callme['A, int'](a, 42)

  # implicit template instantiation
  b.callme(a, 42)
```

```
vvassilev@vv-nuc ~/.../cpptemplate $ python3 template_instantiate_demo.py
 callme in B!
 callme in B!
vvassilev@vv-nuc ~/.../cpptemplate $
```

Lifelong Optimization



Summary

- Interactive C++ is more than just a REPL
- CaaS allows to defer computations until runtime, possibly improving performance and reducing binary sizes (template instantiations)
- CaaS offers ways to extend the language for a particular use or domain

Thank You!

Selected References

- https://blog.llvm.org/posts/2020-11-30-interactive-cpp-with-cling/
- https://blog.llvm.org/posts/2020-12-21-interactive-cpp-for-data-science/
- https://blog.llvm.org/posts/2021-03-25-cling-beyond-just-interpreting-cpp/
- https://Compiler-Research.org
- https://root.cern

Q&A

Backup

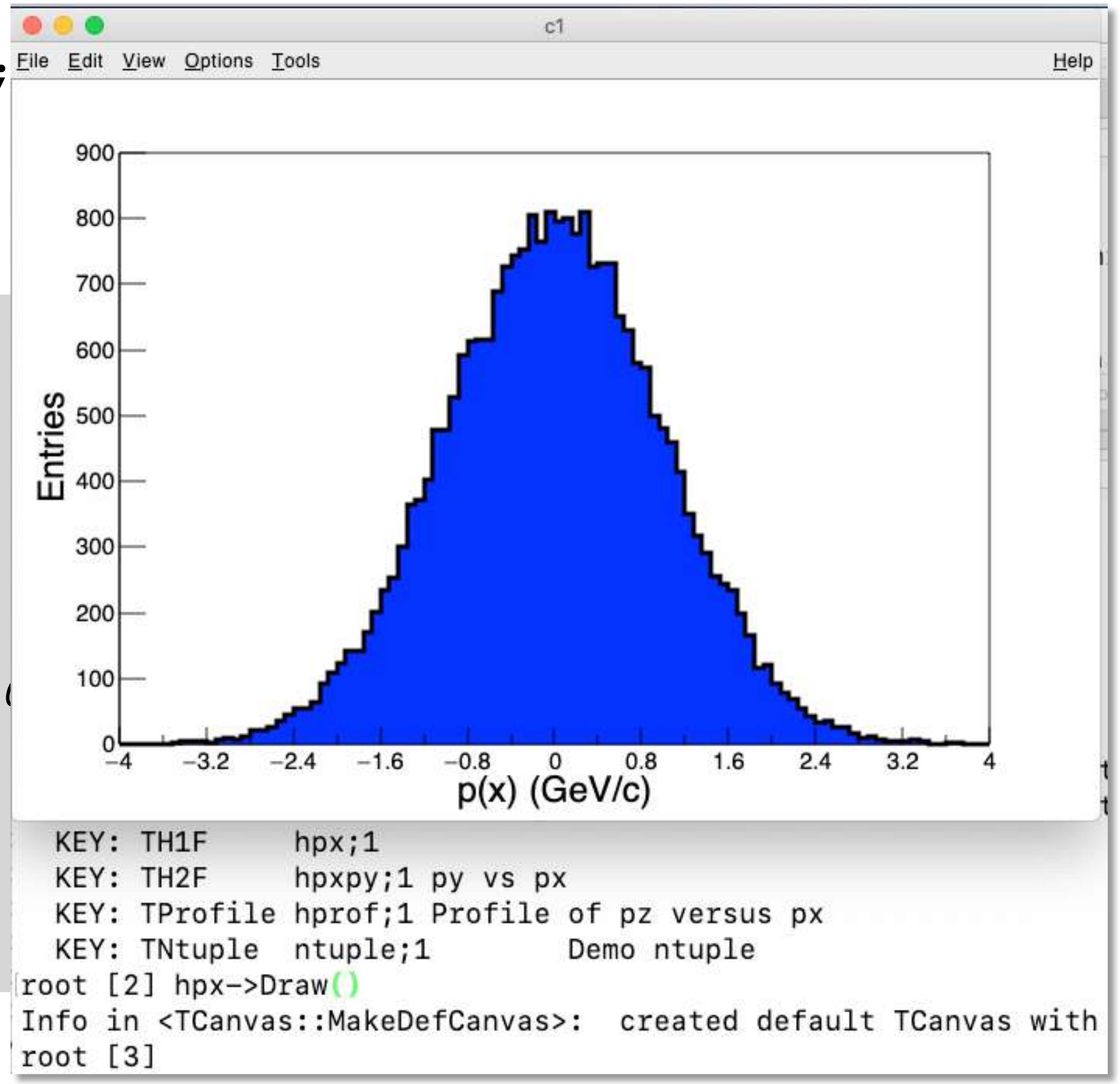
ROOT – Scientific Data Analysis

- The ROOT data analysis package embeds Cling to enable interactive C++ but also to use it as a reflection information service for data serialization
- The ROOT and Cling technology are used to store around 1EB physics data facilitating more than 1000 scientific publications last 7 years
- The ROOT package is developed and maintained by the field of high-energy physics and organizations such as CERN, FNAL, GSI, University of Nebraska, UC San Diego, Princeton

Dynamic Scopes. Runtime Lookup

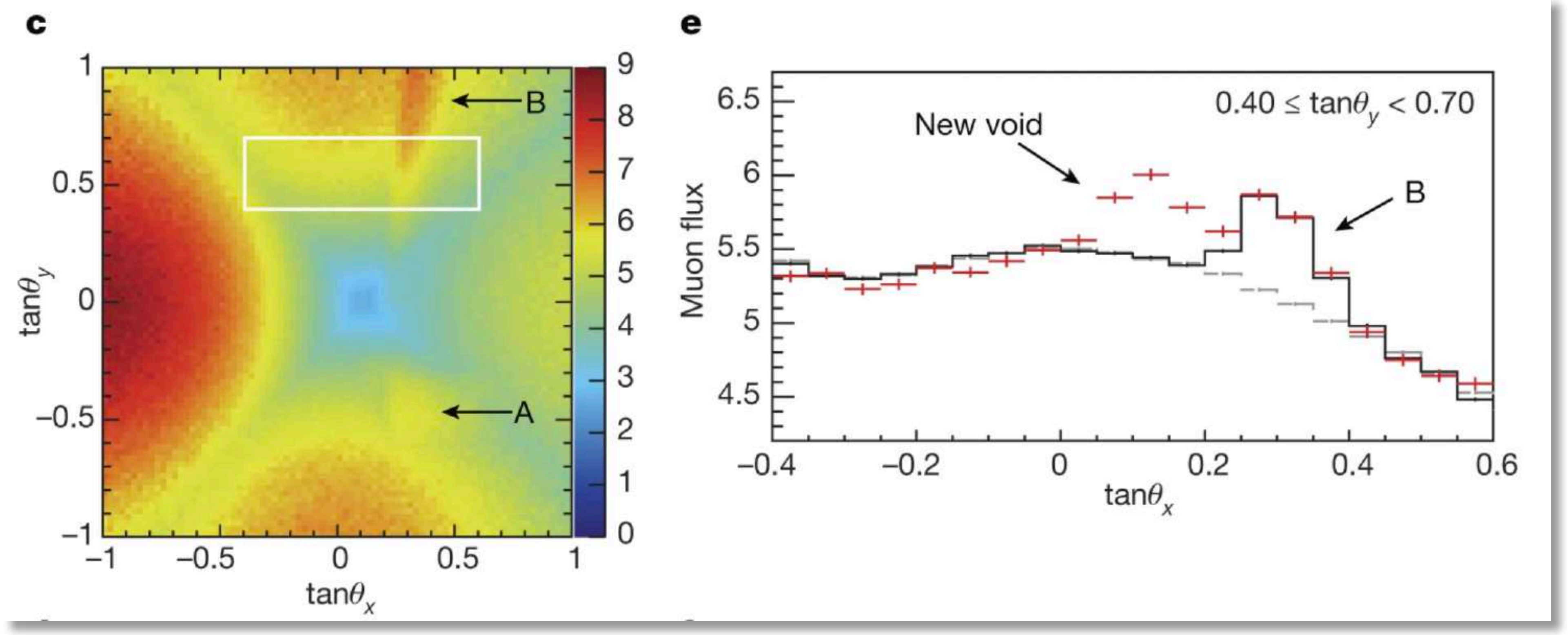
```
gCling->EvaluateT</*ret type*/void>("ntuple->GetTitle()", /*context*/);
```

```
[root] ntuple->GetTitle()
error: use of undeclared identifier 'ntuple'
[root] TFile::Open("tutorials/hsimple.root"); ntuple->GetTitle()
(const char *) "Demo ntuple"
[root] gFile->ls();
TFile**         tutorials/hsimple.root    Demo ROOT file with histograms
 TFile*         tutorials/hsimple.root    Demo ROOT file with histograms
  OBJ: TH1F     hpx      This is the px distribution : 0 at: 0x7fadbb84e39(
  OBJ: TNtuple    ntuple     Demo ntuple : 0 at: 0x7fadbb93a890
  KEY: TH1F     hpx;1     This is the px distribution
  [...]
  KEY: TNtuple    ntuple;1     Demo ntuple
[root] hpx->Draw()
```



Eval-style programming enables Cling to be embedded in frameworks.

Impact of Interactive C++ in Physics



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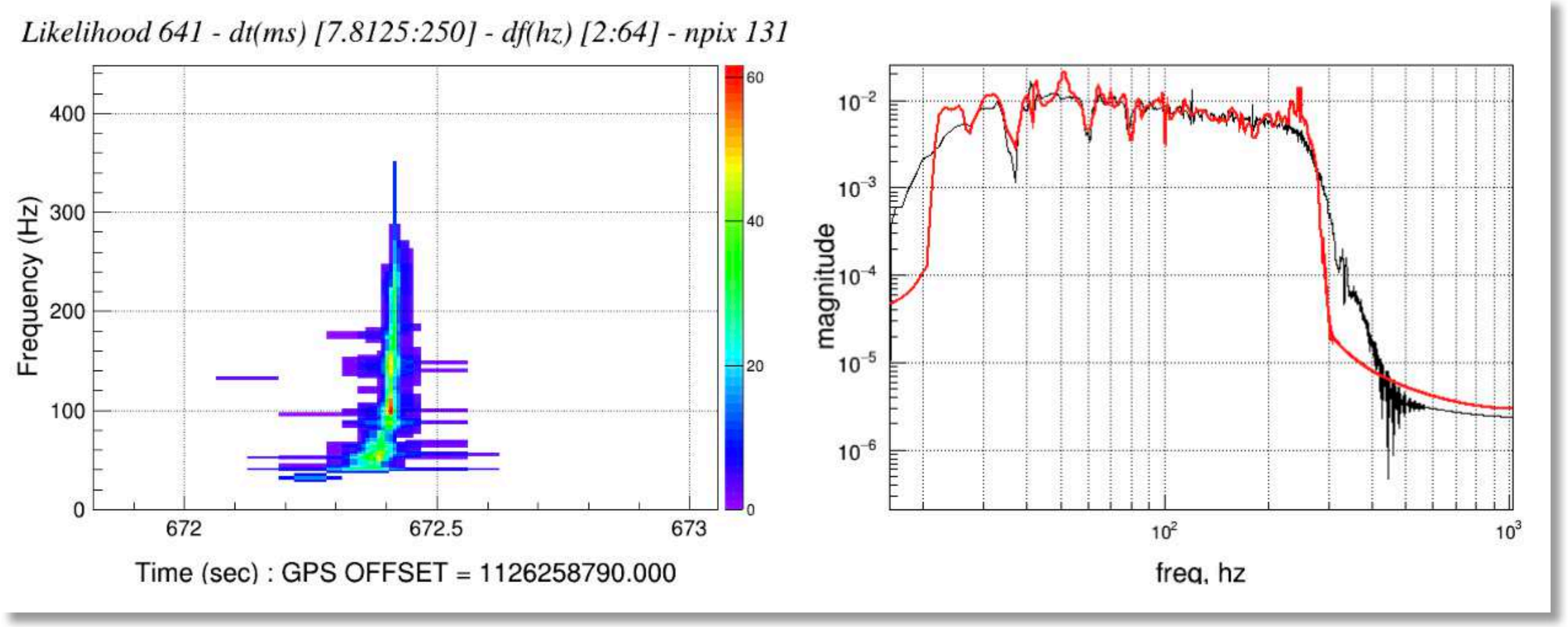
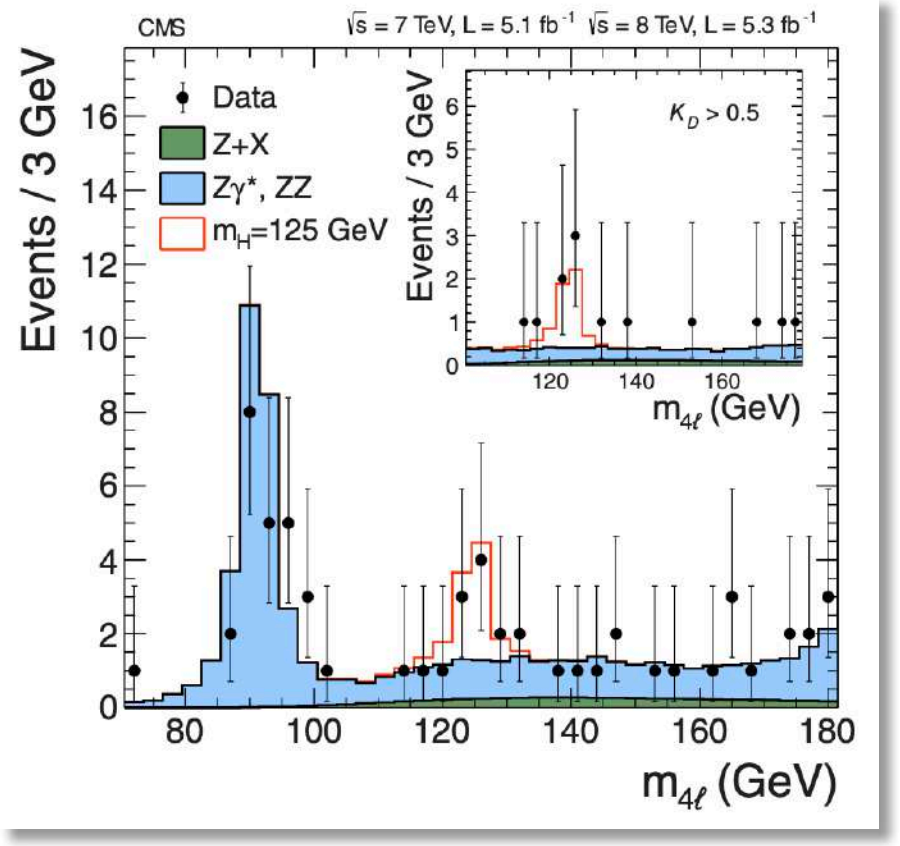


[2]



[3]

Scientific breakthroughs such as the discovery of the big void in the Khufu's Pyramid, the gravitational waves and the Higgs boson heavily rely on the ROOT software package

[1] K. Morishima et al, **Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons**, *Nature*, *2017*
[2] Abbott et al, **Observation of gravitational waves from a binary black hole merger**. *Physical review letters, 2016*
[3] CMS Collab, **Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC**. *Physics Letters B, 2012*

Interpreting C++. Cling

- Cling was originally developed in the field of high energy physics to enable interactivity, dynamic interoperability and rapid prototyping capabilities to C++ developers.
- Cling supports the full C++ feature set including the use of templates, lambdas, and virtual inheritance.
- Cling adds a small set of extensions in C++ to allow interactive exploration and makes the language more welcoming for use.
- Cling compiles C++ code incrementally and relies on JIT compilation.
- Cling enables exploratory programming for C++.