

Enabling Interactive C++ in Clang

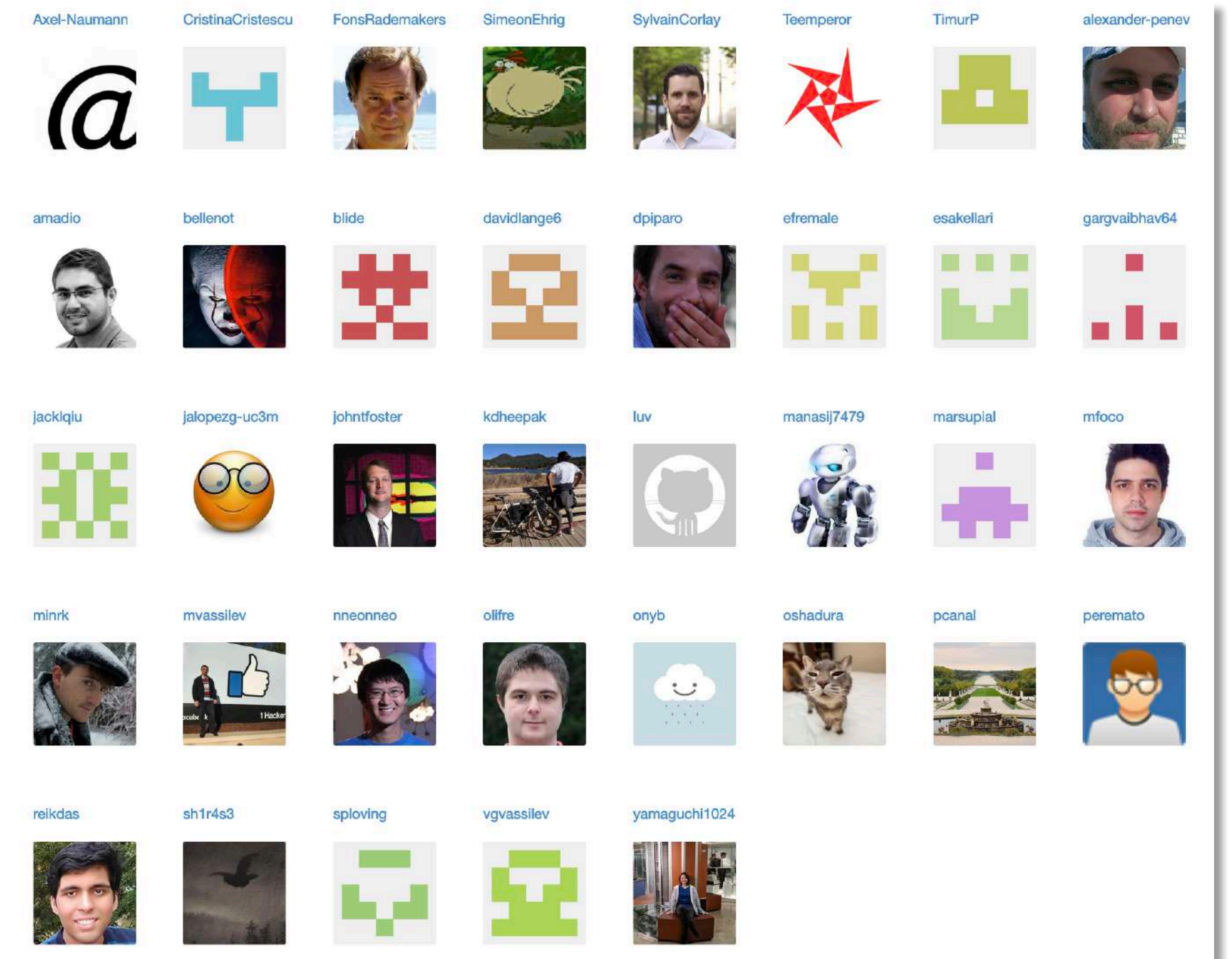
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compiler-research.org

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

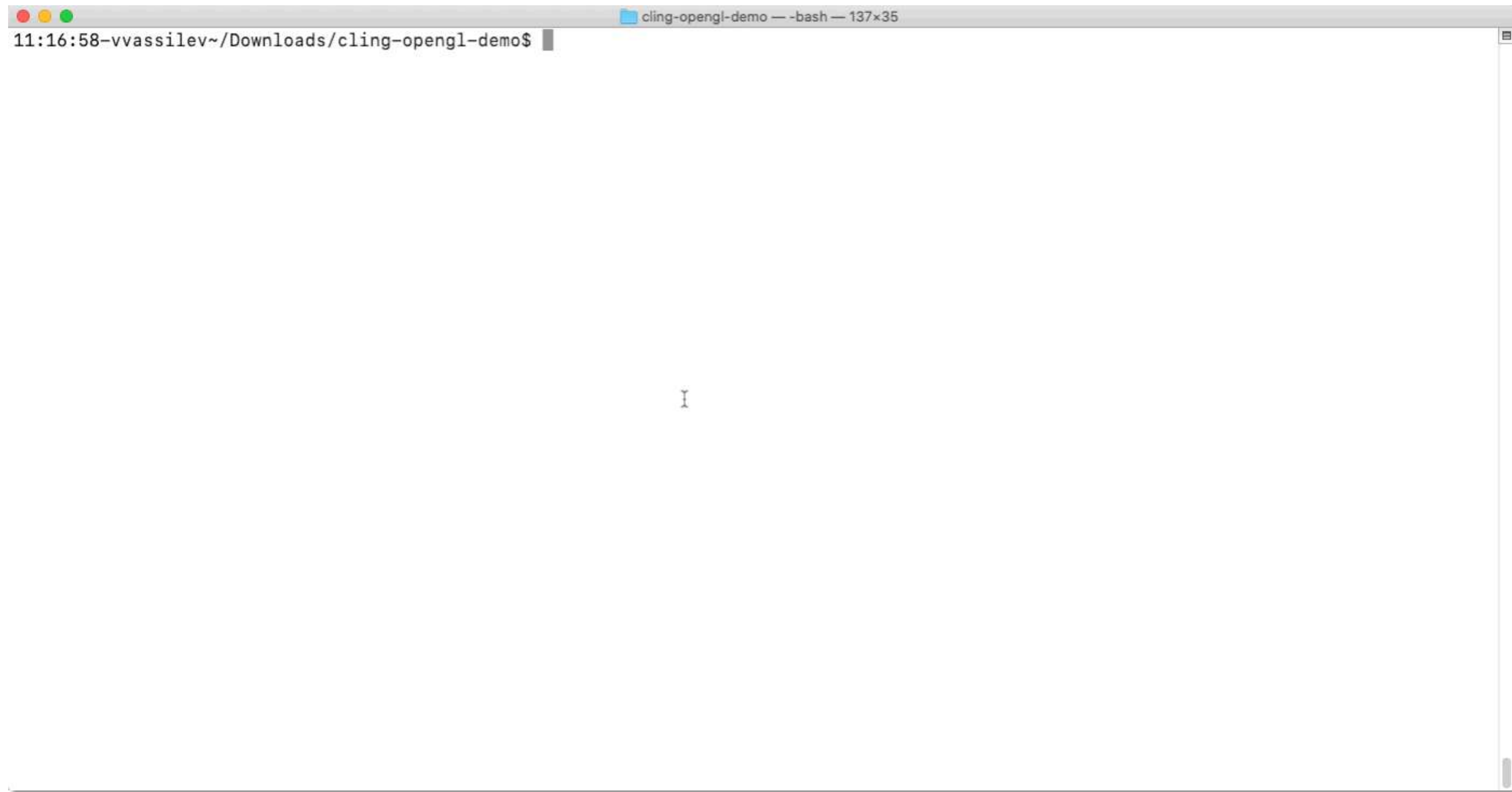
Acknowledgement & Disclaimer

- 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.



The current work is partially supported by National Science Foundation under Grant OAC-1931408. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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

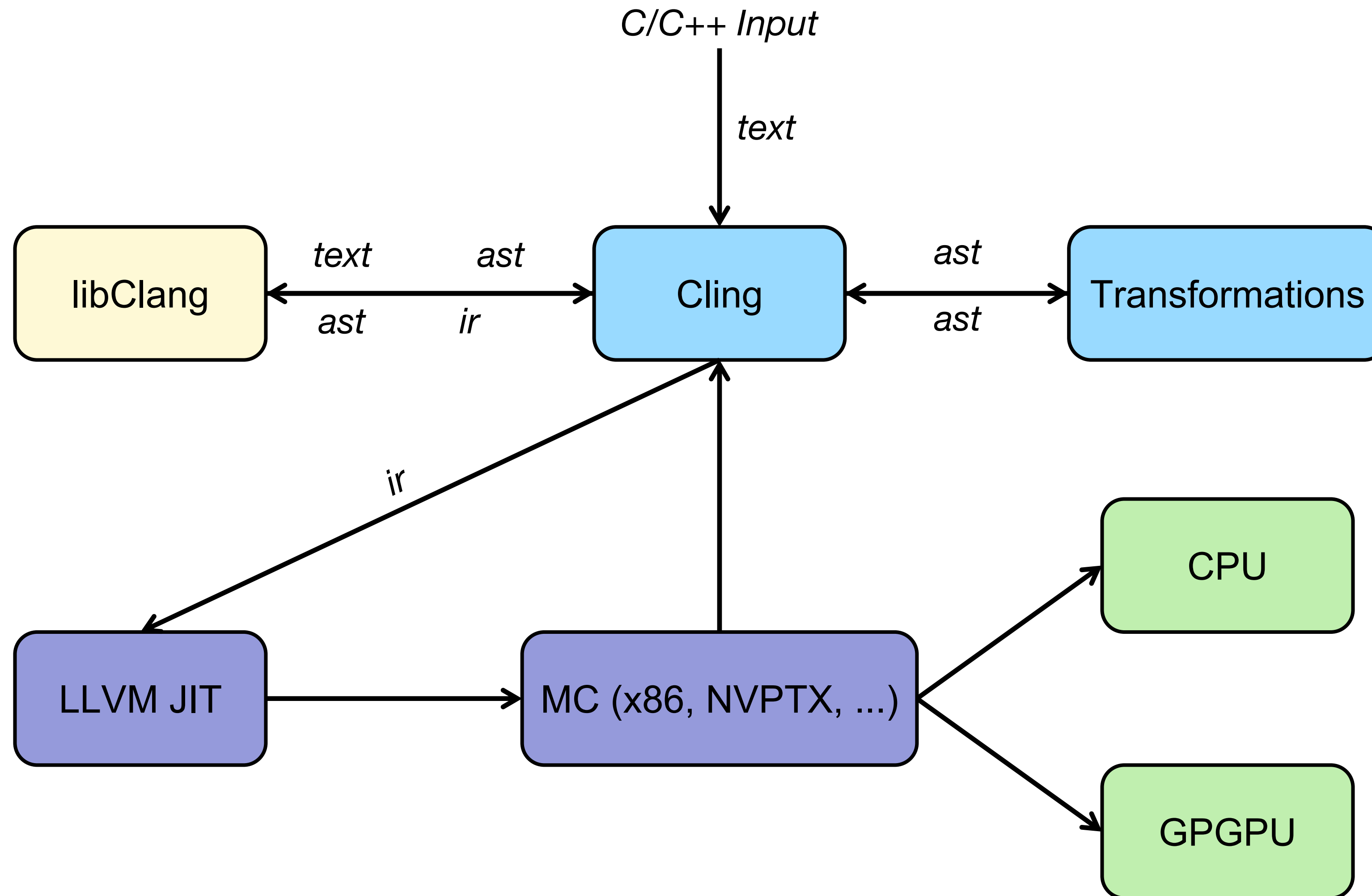
```
[cling] #include <vector>
[cling] std::vector<int> v = {1,2,3,4,5};
```

```
[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 }
```

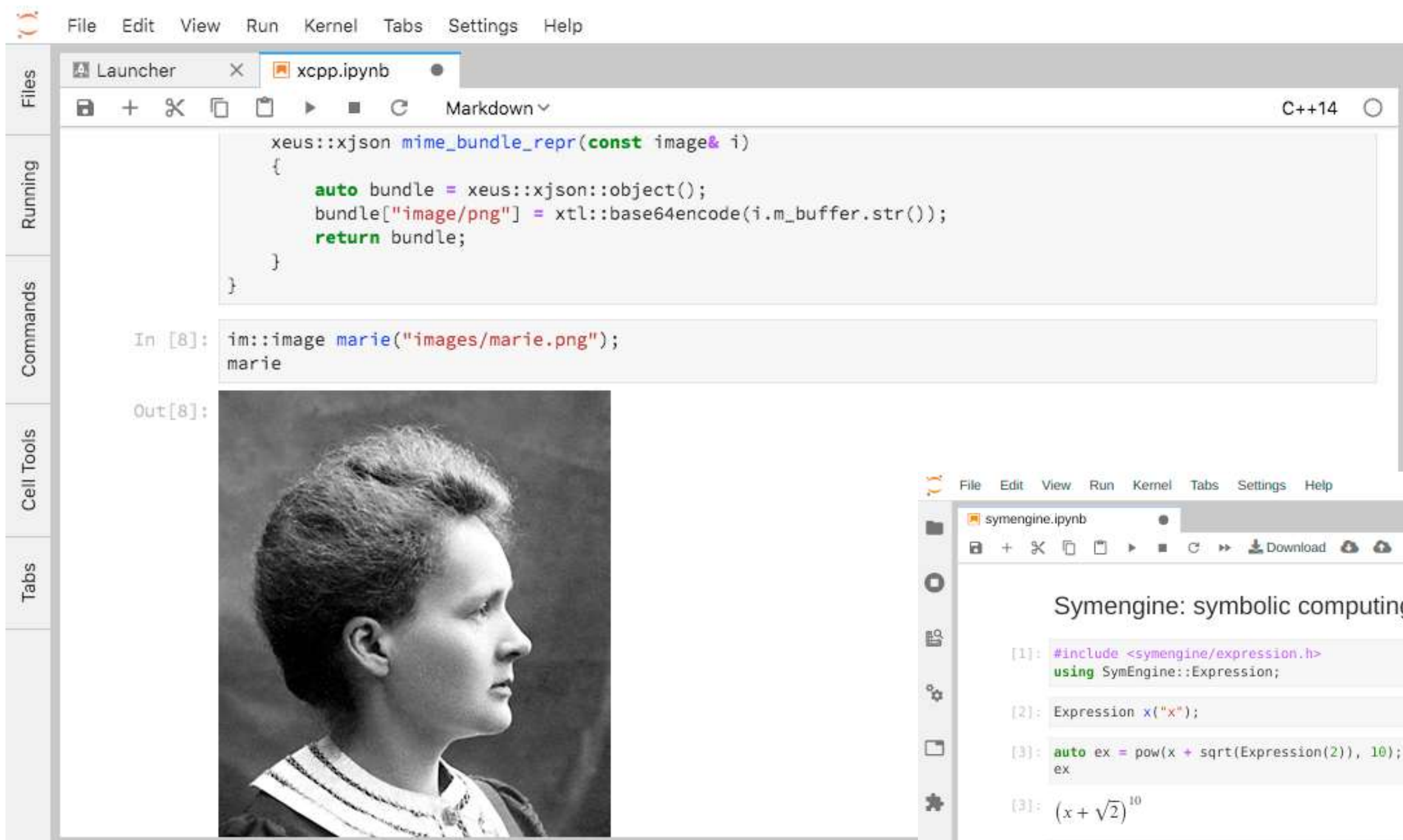
```
[cling] std::string v = "Hello World"
(std::string &) "Hello World"
```

Interpreting C++. Cling

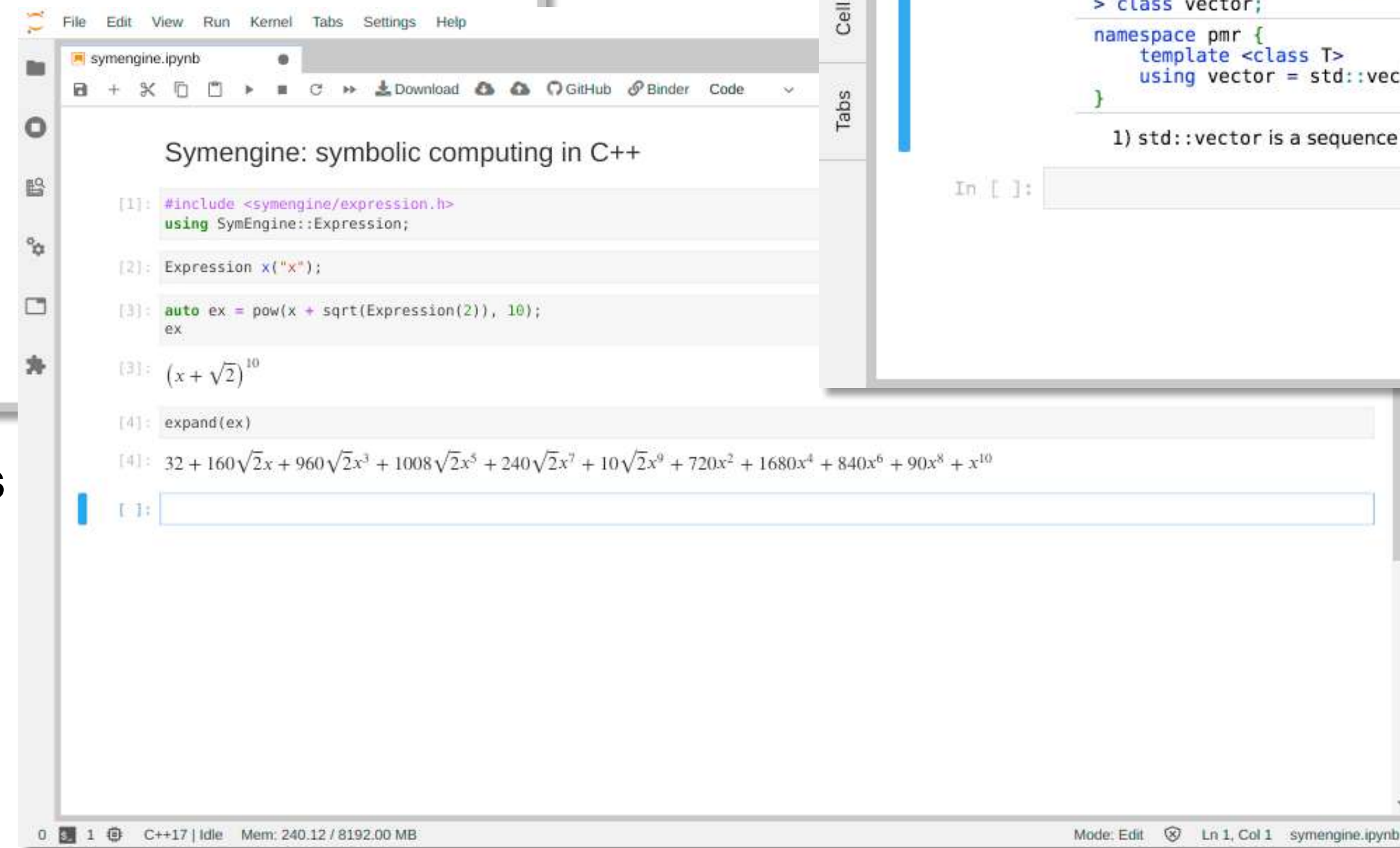


Applications of Interactive C++

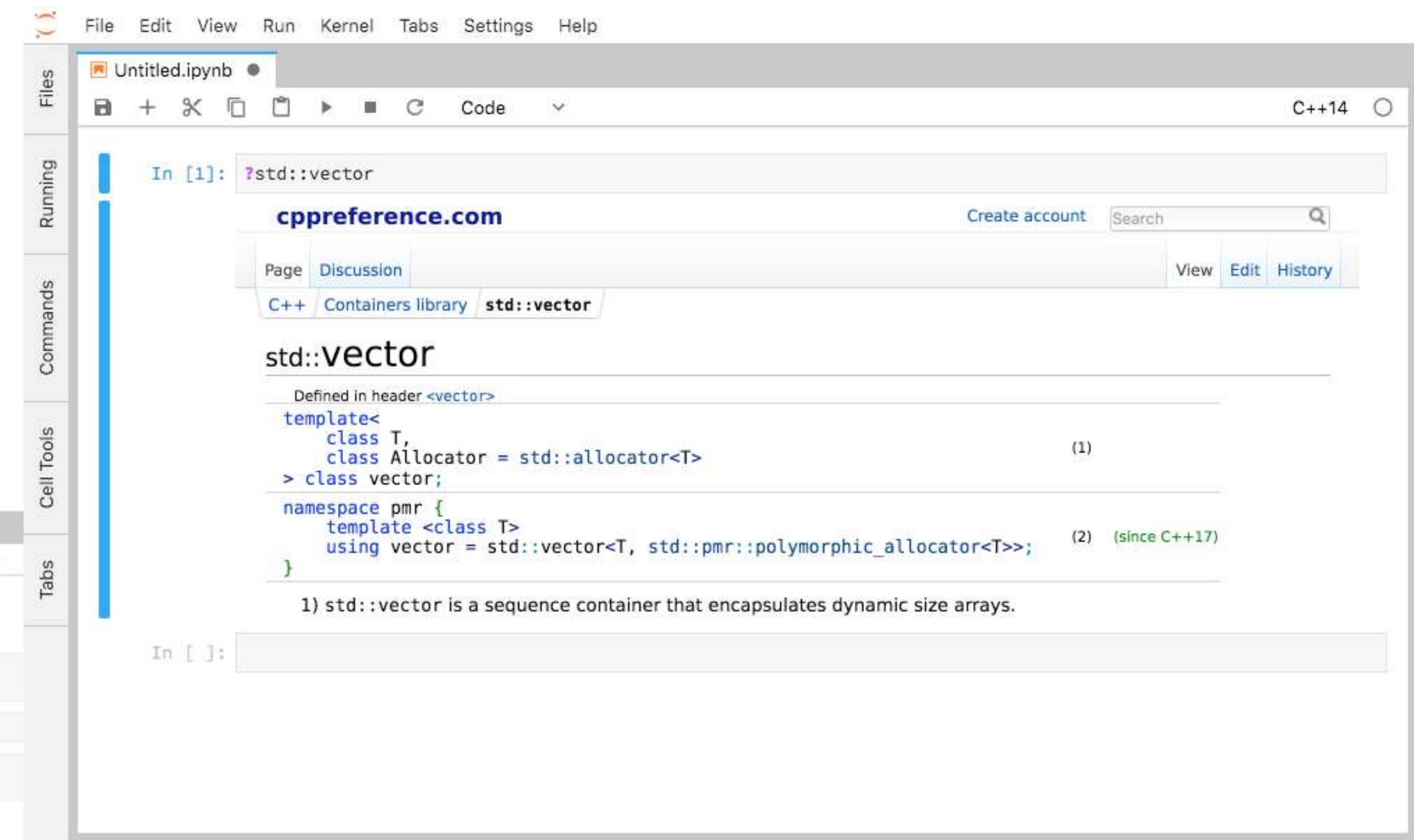
Xeus-Cling. C++ in Notebooks



Visualization of user-defined images

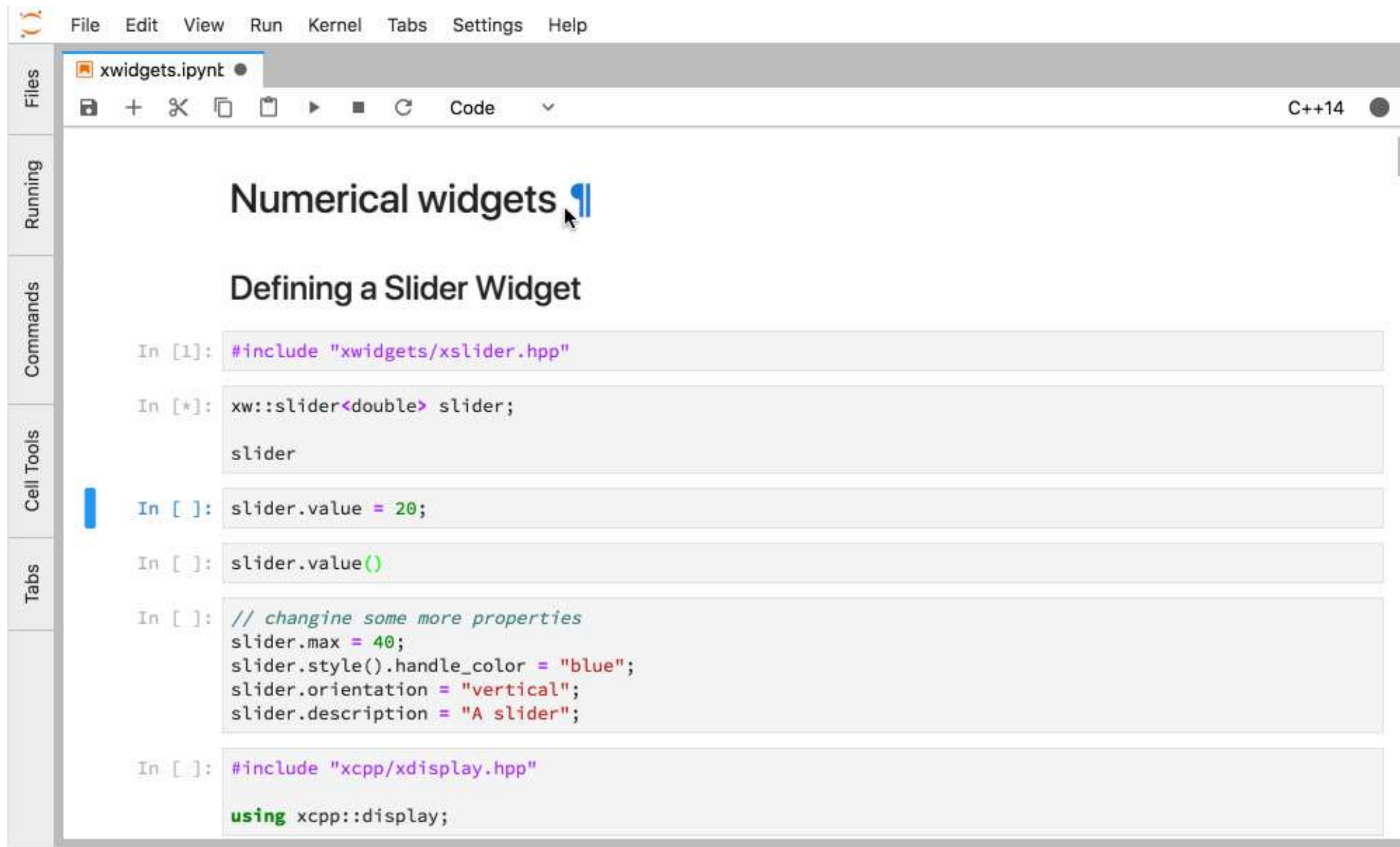


Rich mime type rendering in Jupyter



Direct access to documentation

Xeus-Cling. C++ in Notebooks



The screenshot shows a Jupyter notebook titled 'xwidgets.ipynb' in the Xeus-Cling environment. The notebook contains several code cells for defining and configuring a slider widget. The first cell includes the header file 'xwidgets/xslider.hpp'. The second cell declares a slider widget. The third cell sets the slider's value to 20. The fourth cell calls the slider's value method. The fifth cell configures the slider's maximum value, handle color, orientation, and description. The sixth cell includes the 'xcpp/xdisplay.hpp' header and uses the 'xcpp::display' namespace.

```
In [1]: #include "xwidgets/xslider.hpp"

In [*]: xw::slider<double> slider;

slider

In [ ]: slider.value = 20;

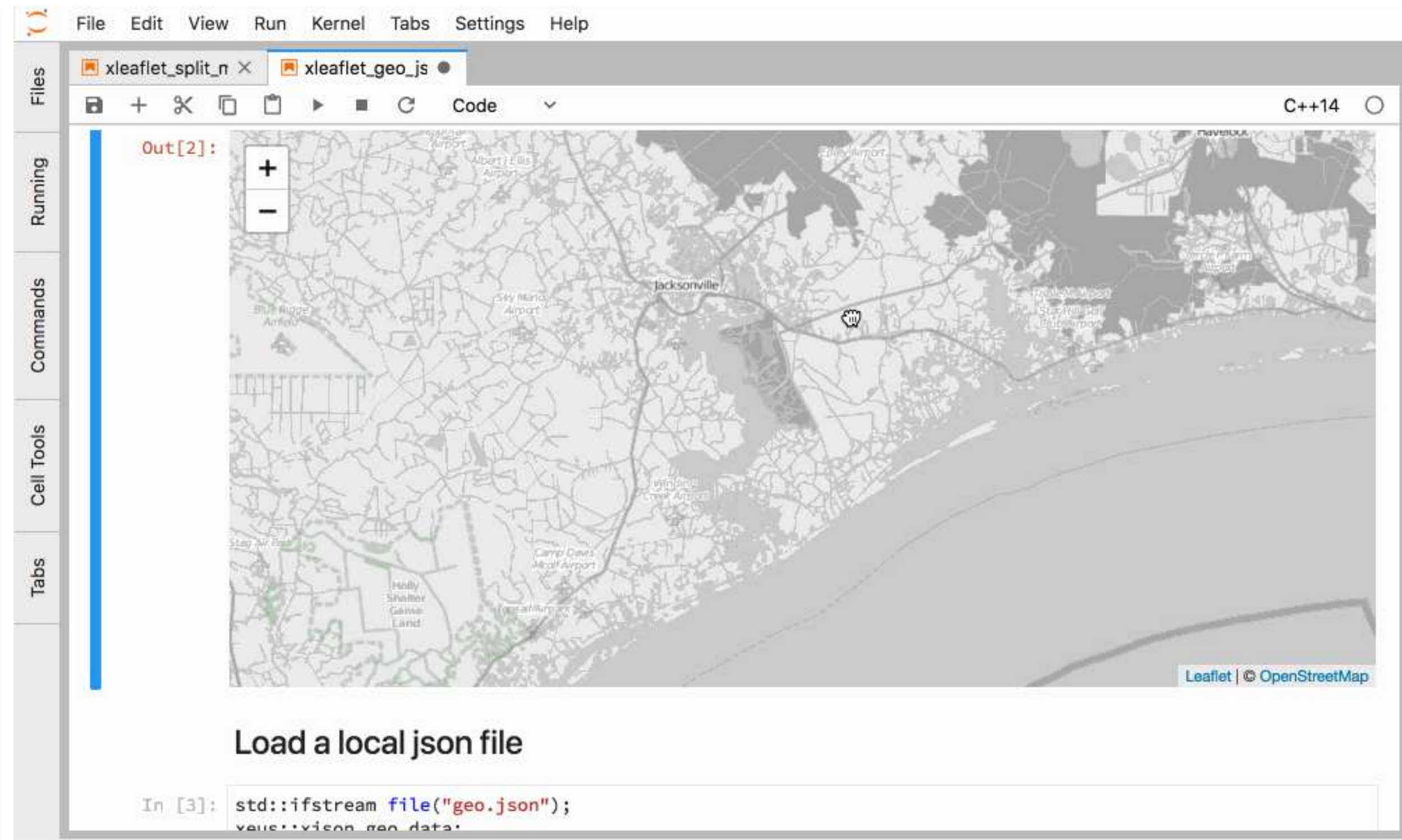
In [ ]: slider.value()

In [ ]: // changine some more properties
slider.max = 40;
slider.style().handle_color = "blue";
slider.orientation = "vertical";
slider.description = "A slider";

In [ ]: #include "xcpp/xdisplay.hpp"

using xcpp::display;
```

Xwidgets – User-defined controls



The screenshot shows a Jupyter notebook titled 'xleaflet_geo.js' in the Xeus-Cling environment. The notebook displays an interactive map of Jacksonville, Florida, using the Leaflet library. The map includes a zoom control in the top-left corner. Below the map, there is a code cell for loading a local JSON file.

```
Out[2]:
```

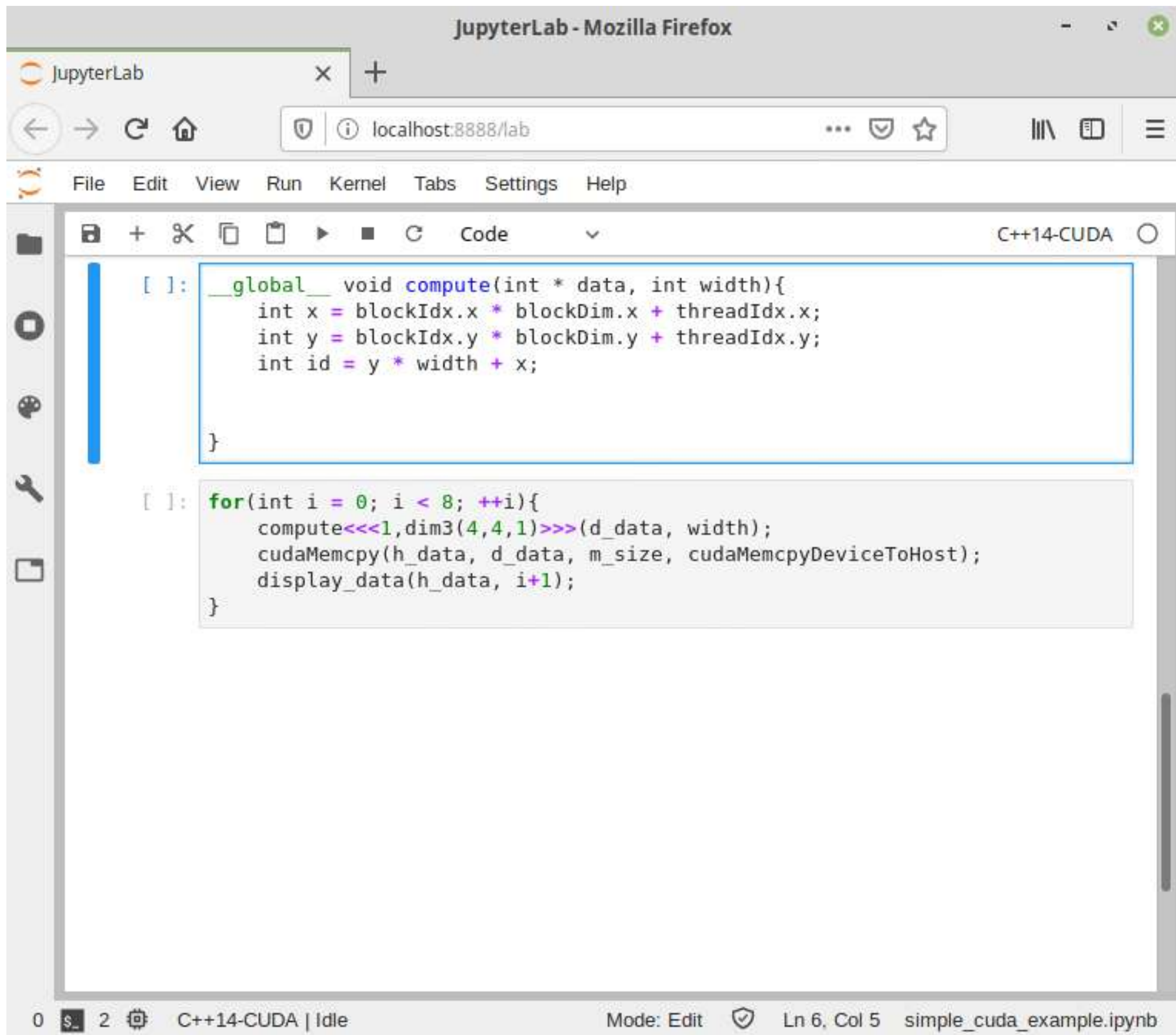
Load a local json file

```
In [3]: std::ifstream file("geo.json");
         yeus::xjson geo_data;
```

Xleaflet – Interactive Geo Information System

S. Corlay, Quantstack, [Deep dive into the Xeus-based Cling kernel for Jupyter](https://compiler-research.org/deep-dive-into-the-xeus-based-cling-kernel-for-jupyter/), May 2021, compiler-research.org

Interactive CUDA C++

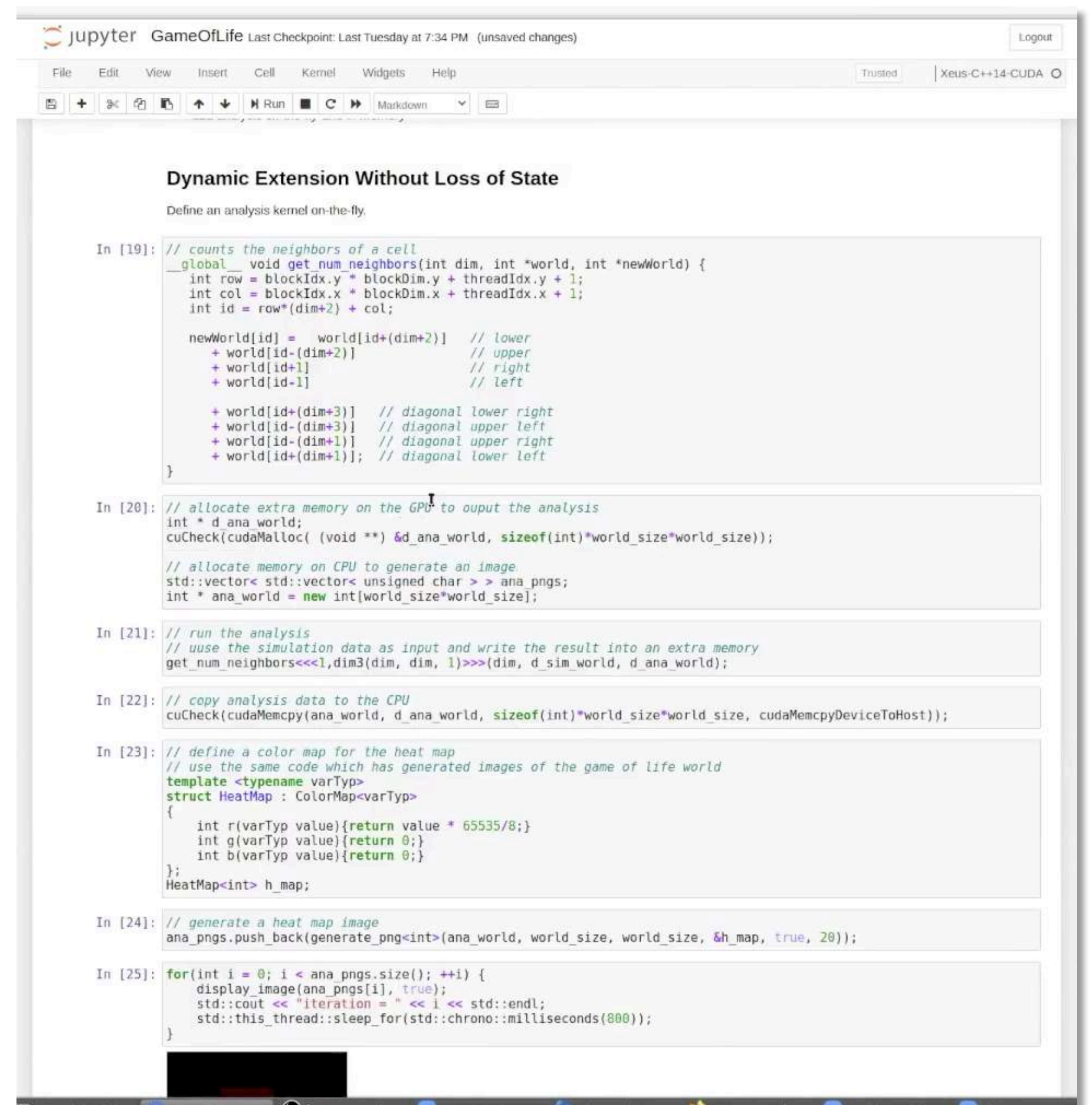


The screenshot shows the JupyterLab interface in Mozilla Firefox. The browser address bar displays 'localhost:8888/lab'. The JupyterLab toolbar includes icons for file operations, code execution, and settings. The main editor area shows a C++14-CUDA code file named 'simple_cuda_example.ipynb'. The code is written in C++ and includes CUDA-specific functions like 'compute' and 'display_data'. The status bar at the bottom indicates 'Mode: Edit' and 'Ln 6, Col 5'.

```
[ ]: global void compute(int * data, int width){
    int x = blockIdx.x * blockDim.x + threadIdx.x;
    int y = blockIdx.y * blockDim.y + threadIdx.y;
    int id = y * width + x;

}

[ ]: for(int i = 0; i < 8; ++i){
    compute<<<1,dim3(4,4,1)>>>(d_data, width);
    cudaMemcpy(h_data, d_data, m_size, cudaMemcpyDeviceToHost);
    display_data(h_data, i+1);
}
```



The screenshot shows the JupyterLab interface in Mozilla Firefox. The browser address bar displays 'localhost:8888/lab'. The JupyterLab toolbar includes icons for file operations, code execution, and settings. The main editor area shows a C++14-CUDA code file named 'GameOfLife'. The code is written in C++ and includes CUDA-specific functions like 'compute' and 'display_data'. The status bar at the bottom indicates 'Mode: Edit' and 'Ln 6, Col 5'.

```
In [19]: // counts the neighbors of a cell
global void get_num_neighbors(int dim, int *world, int *newWorld) {
    int row = blockIdx.y * blockDim.y + threadIdx.y + 1;
    int col = blockIdx.x * blockDim.x + threadIdx.x + 1;
    int id = row*(dim+2) + col;

    newWorld[id] = world[id+(dim+2)] // lower
    + world[id-(dim+2)] // upper
    + world[id+1] // right
    + world[id-1] // left

    + world[id+(dim+3)] // diagonal lower right
    + world[id-(dim+3)] // diagonal upper left
    + world[id+(dim+1)] // diagonal upper right
    + world[id+(dim+1)]; // diagonal lower left
}

In [20]: // allocate extra memory on the GPU to output the analysis
int * d_ana_world;
cuCheck(cudaMalloc( (void **) &d_ana_world, sizeof(int)*world_size*world_size));

// allocate memory on CPU to generate an image
std::vector< std::vector< unsigned char > > ana_pngs;
int * ana_world = new int[world_size*world_size];

In [21]: // run the analysis
// use the simulation data as input and write the result into an extra memory
get_num_neighbors<<<1,dim3(dim, dim, 1)>>>(dim, d_sim_world, d_ana_world);

In [22]: // copy analysis data to the CPU
cuCheck(cudaMemcpy(ana_world, d_ana_world, sizeof(int)*world_size*world_size, cudaMemcpyDeviceToHost));

In [23]: // define a color map for the heat map
// use the same code which has generated images of the game of life world
template <typename varTyp>
struct HeatMap : ColorMap<varTyp>
{
    int r(varTyp value){return value * 65535/8;}
    int g(varTyp value){return 0;}
    int b(varTyp value){return 0;}
};
HeatMap<int> h_map;

In [24]: // generate a heat map image
ana_pngs.push_back(generate_png<int>(ana_world, world_size, world_size, &h_map, true, 20));

In [25]: for(int i = 0; i < ana_pngs.size(); ++i) {
    display_image(ana_pngs[i], true);
    std::cout << "iteration = " << i << std::endl;
    std::this_thread::sleep_for(std::chrono::milliseconds(800));
}
```

S. Ehrig, HZDR, [Cling's CUDA Backend: Interactive GPU development with CUDA C++](https://compiler-research.org/), Mar 2021, compiler-research.org

Automatic Language Bindings

cppyy: Yet another Python – C++ binder?!

- Yes, but it has its niche: *bindings are runtime*
 - Python is all runtime, so runtime is more natural
 - C++-side runtime-ness is provided by Cling
- Very complete feature-set (not just “C with classes”)
- Good performance on CPython; great with PyPy*

pip: <https://pypi.org/project/cppyy/>
conda: <https://anaconda.org/conda-forge/cppyy>
git: <https://github.com/wlav/cppyy>
docs: <https://cppyy.readthedocs.io/en/latest/>

For HEP users: *cppyy* in *ROOT* is an old fork. It won't run all the examples here, doesn't work with PyPy, and has worse performance.

(*) PyPy support lags CPython

[1]

sil-cling: Interface with cppyy

- binds with cppyy through the direct inclusion of the latter's C header using dpp

```
1 //cling.dpp
2
3 #include "capi.h" // cppyy's C header
4
5 // D code ↓
6 import std.string : fromStringz, toStringz;
7
8 string resolveName(string cppItemName)
9 {
10     import core.stdc.stdlib : free;
11     // Calling cppyy_resolve_name ↓
12     char* chars = cppyy_resolve_name(cppItemName.toStringz);
13     string result = chars.fromStringz.idup;
14     free (chars);
15     return result;
16 }
```

```
→ ~ dub run dpp -- cling.dpp --keep-d-files -c
```

[2]

How does it work? - Runtime

```
julia> cxx"""
struct nontrivial { ~nontrivial() { $(println("I got deleted")); }; }
true

julia> a = icxx"nontrivial{};"
(struct nontrivial) {
}

julia> a = nothing;

julia> # Some time later

julia> GC.gc()
I got deleted
```

Nesting works also at global scope

Last reference dropped here

Julia GC deletes object => C++ destructor called

[3]

[1] W. Lavrijsen, LBL, [cppyy](https://compiler-research.org), Sep 2021, compiler-research.org

[2] A. Militaru, Symmetry Investments, [Calling C++ libraries from a D-written DSL: A cling/cppyy-based approach](https://compiler-research.org), Feb 2021, compiler-research.org

[3] K. Fischer, Julia Computing, [A brief history of Cxx.jl](https://compiler-research.org), 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

```
/// 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';
}
```

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

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

```
[vassilev@vv-nuc ~/.../builddir $ ./caas-demo
7 * 7 * 7 = 343
vassilev@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/clang/plugins/lib/clad.so");  
    clang::Interpreter interp(argvExt.size(), &argvExt[0], LLVM_DIR);  
    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("dfdxdx.getFunctionPtr();", &res);

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

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

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

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

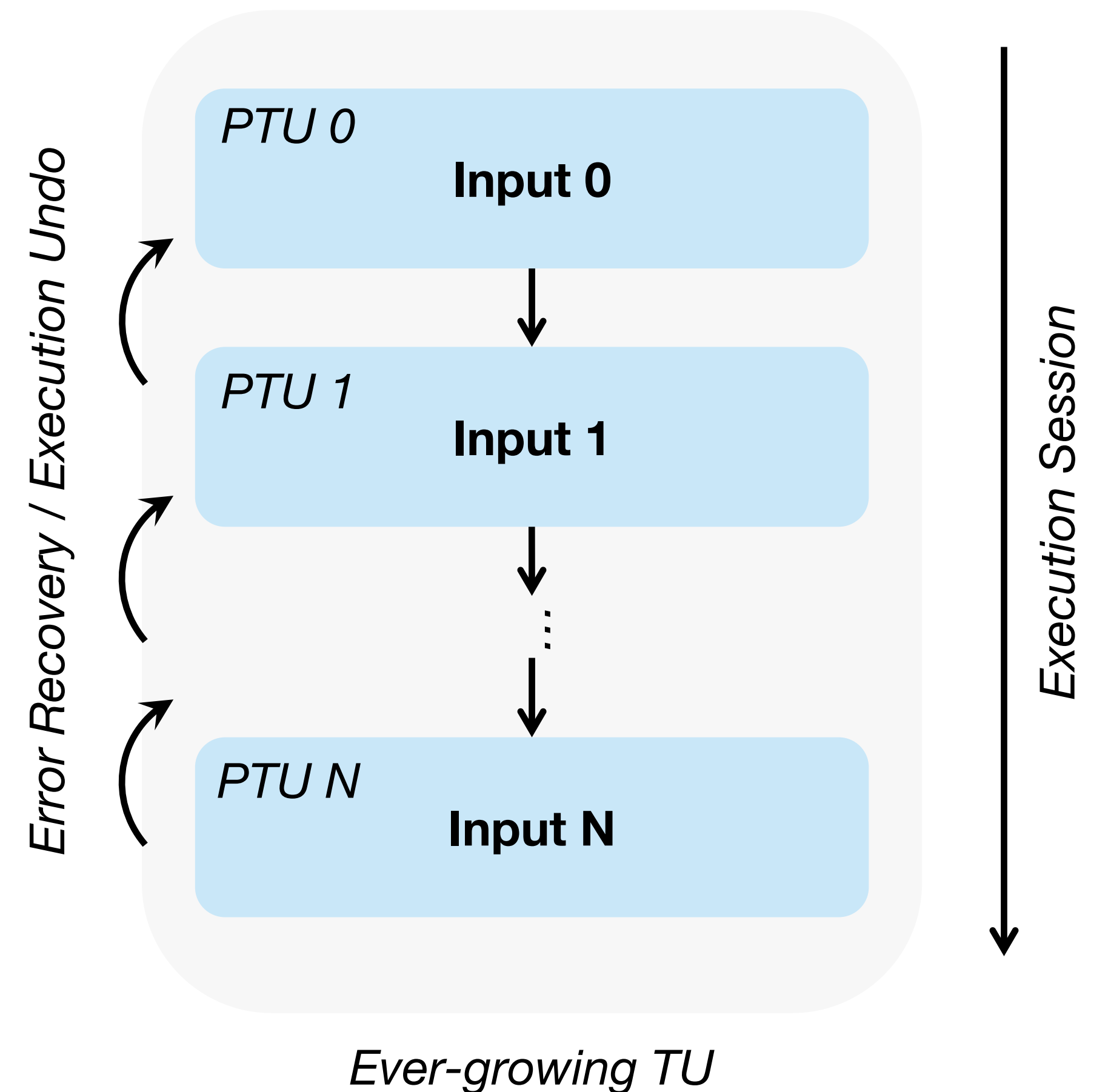

Evolving Cling Into CaaS and Clang-Repl in LLVM Mainline

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
Decl_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')
    })

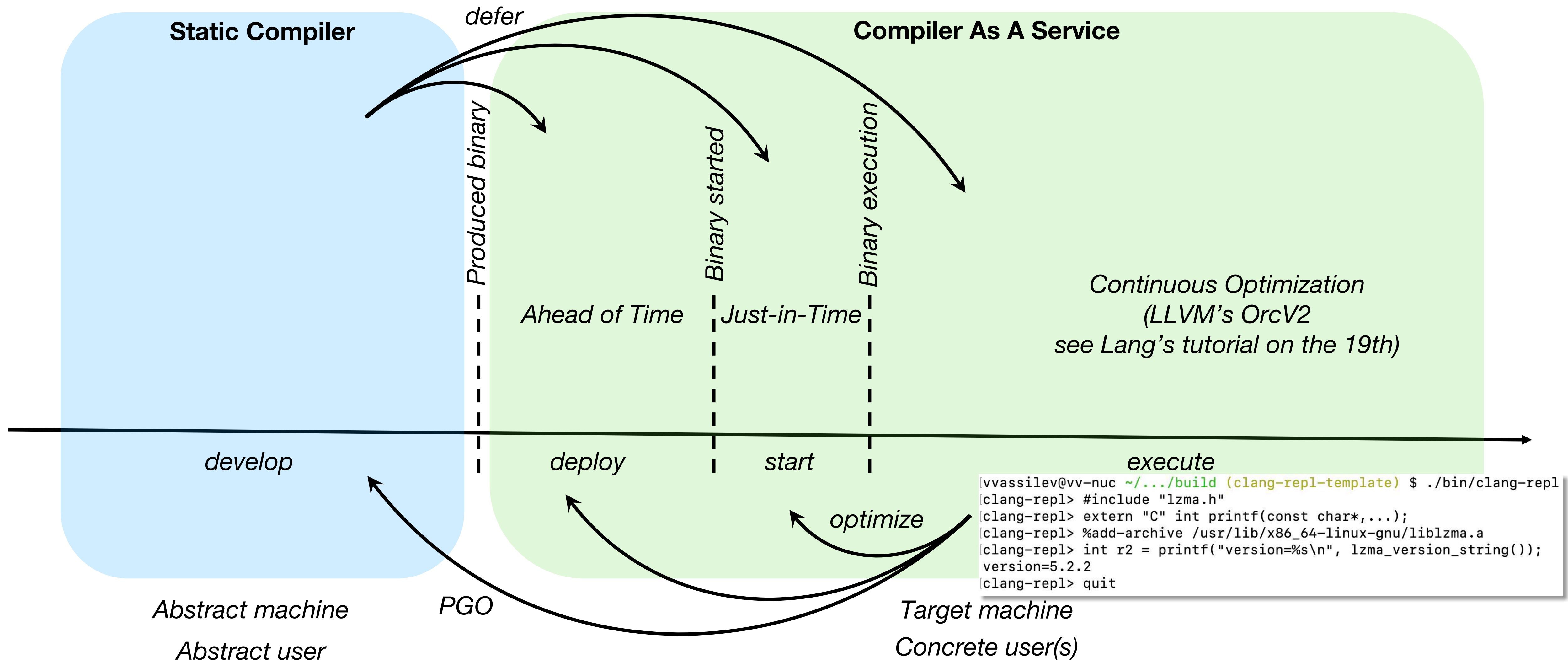
    # call templates
    a = A()
    b = B()

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

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

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

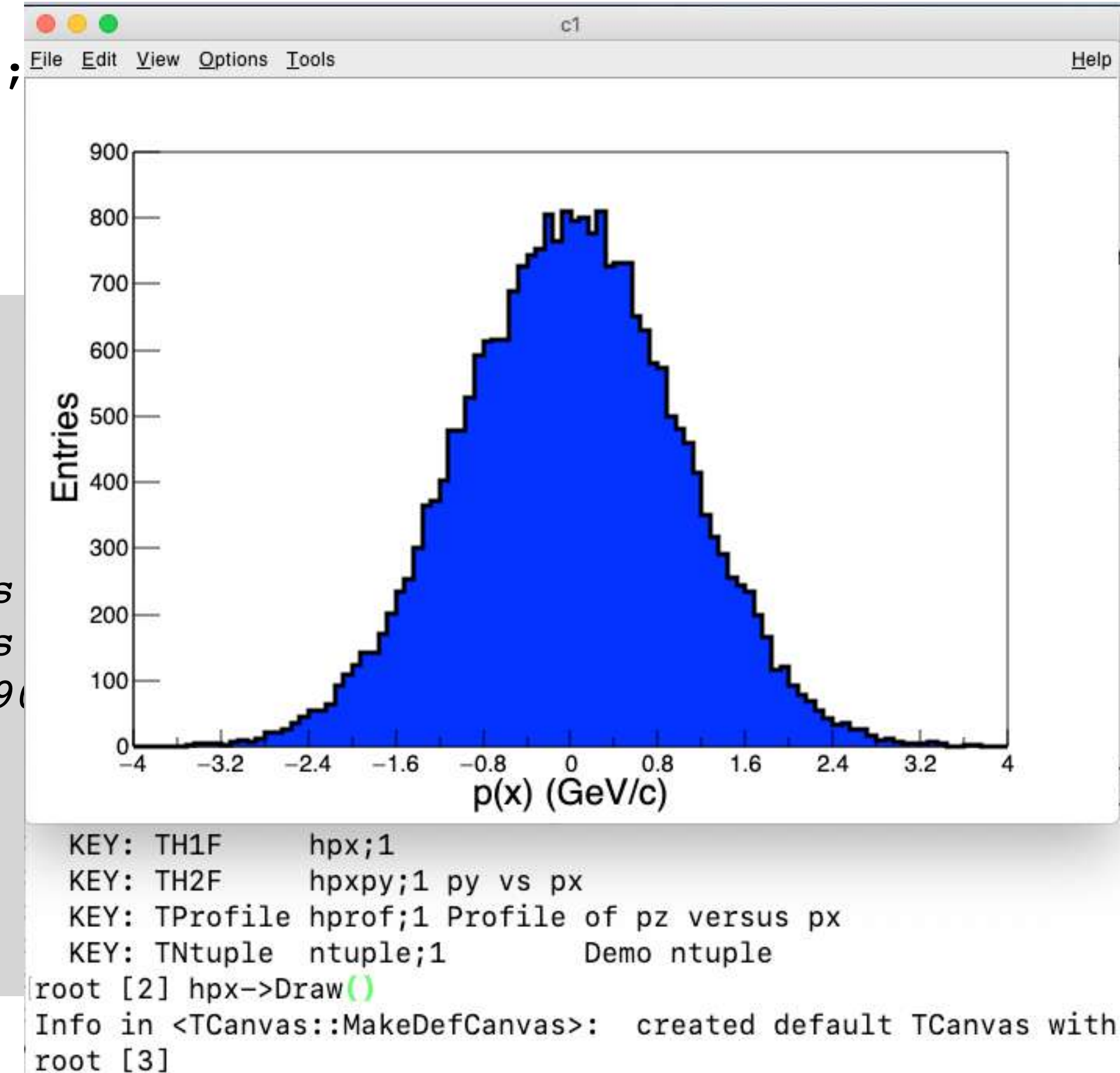


- The ROOT data analysis package embeds Cling to enable interactive C++ but also to use it as a reflection information service for data serialization
- The ROOT and Cling technology are used to store around 1EB physics data facilitating more than 1000 scientific publications last 7 years
- The ROOT package 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

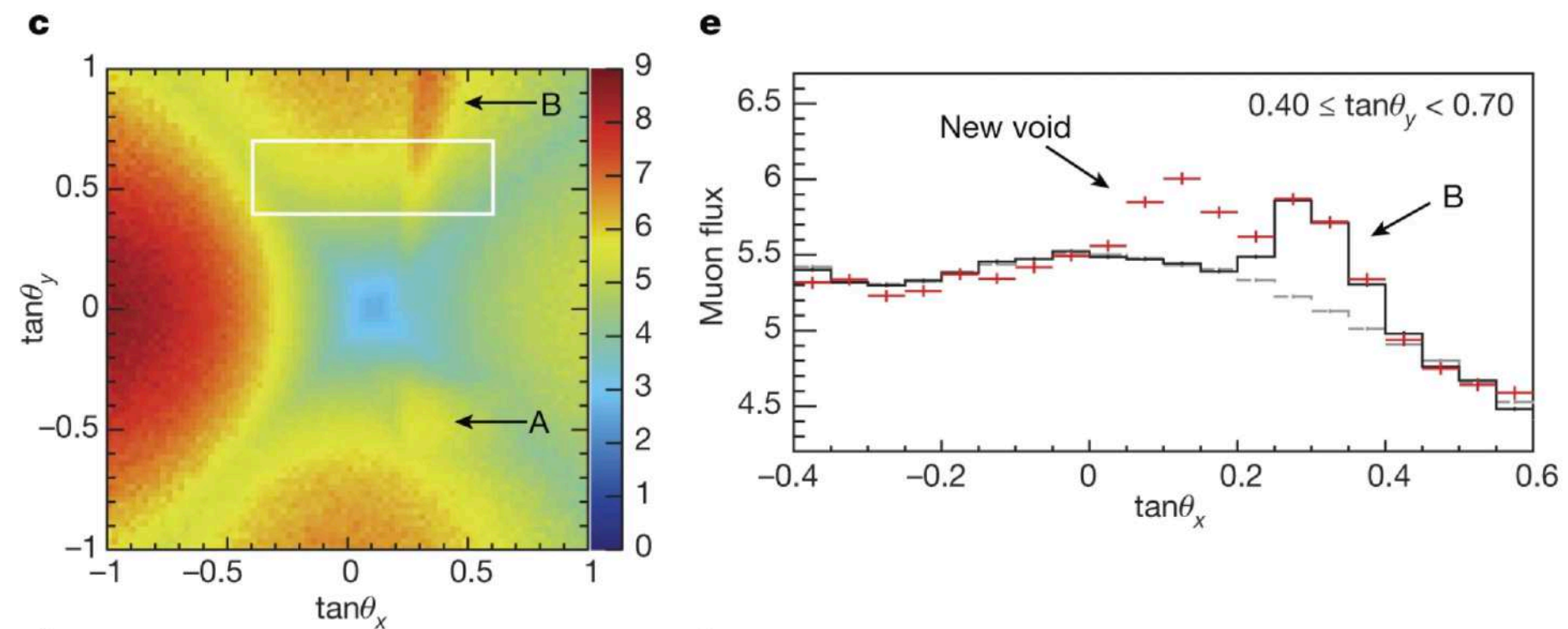
```
gCling->EvaluateT</*ret type*/void>("ntuple->GetTitle()", /*context*/);
```

```
[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: 0x7fadbb84e390  
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()
```

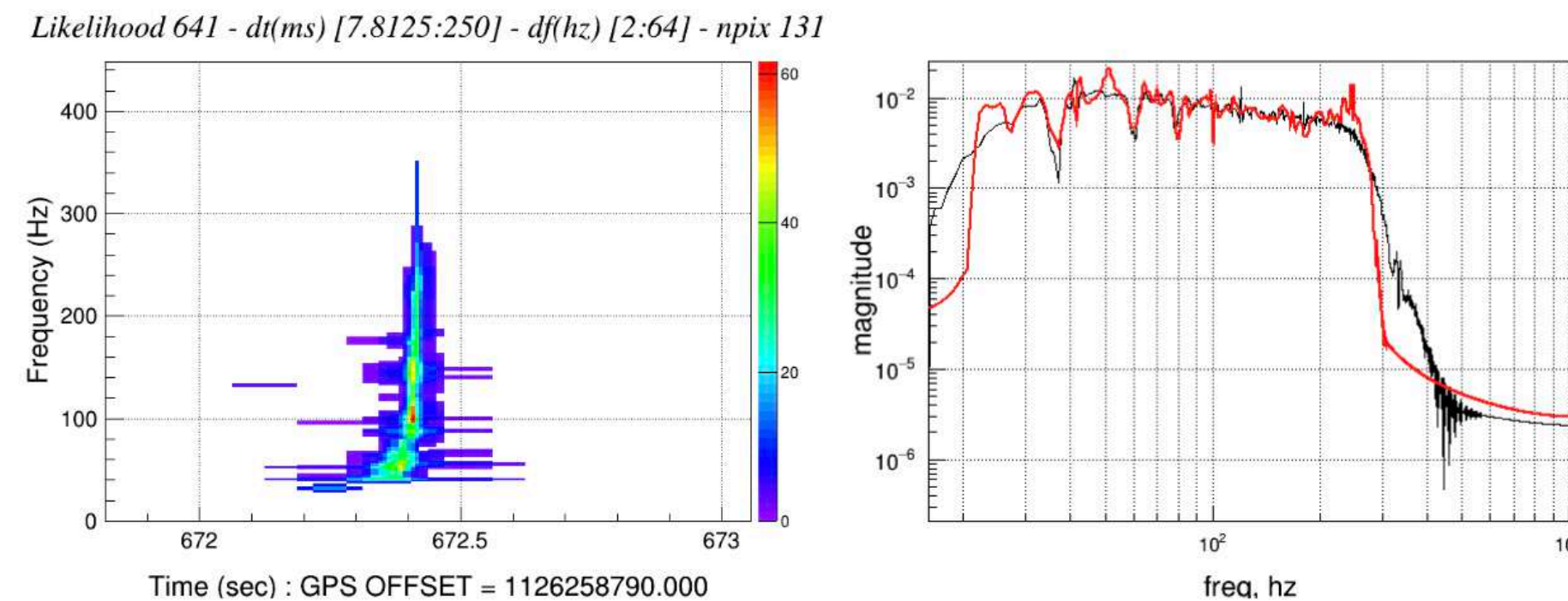


Eval-style programming enables Cling to be embedded in frameworks.

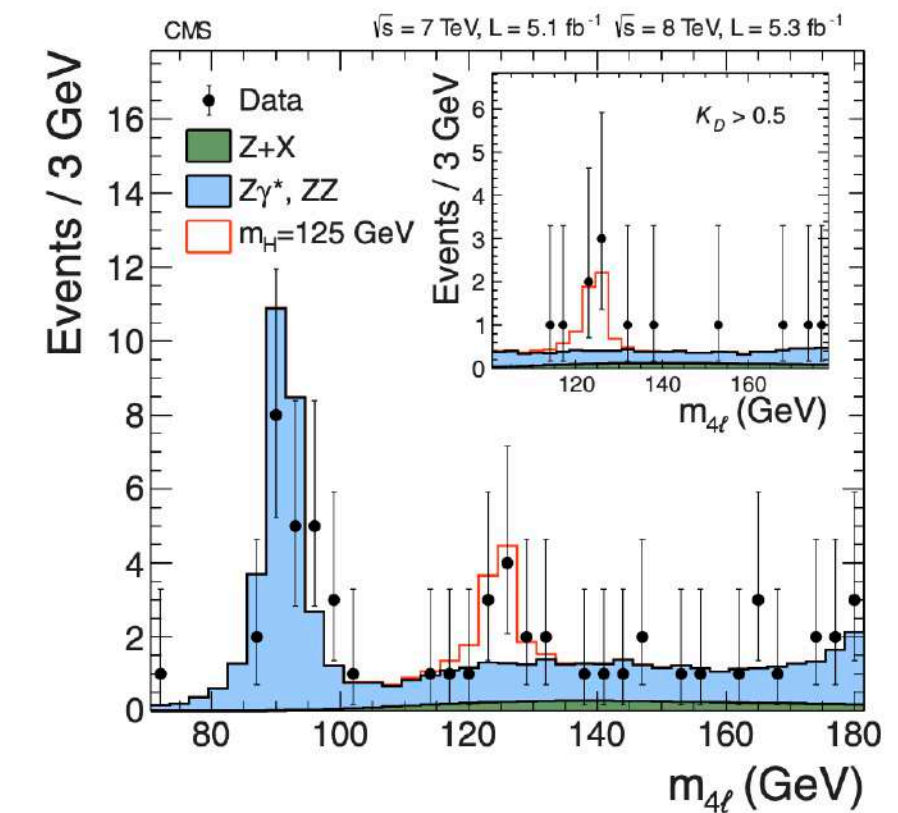
Impact of Interactive C++ in Physics



[1]



[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++.