Award #: OAC-1931408

CSSI Element: C++ as a service - rapid software development and dynamic interoperability with Python and beyond

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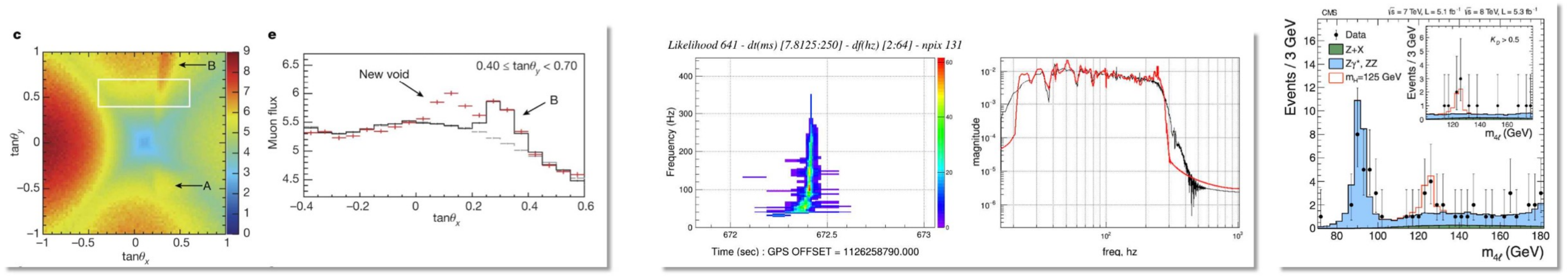
PRINCETON UNIVERSITY

Project Goals

CaaS aims to provide programmers and data scientists a simple and general solution to language interoperability:

- Advance interpretative technology to provide scientists a state-of-the-art C++ execution environment
- Enable functionality to provide dynamic, native-like, runtime interoperability between C++ and Python
- Allow seamless utilization of heterogeneous hardware (e.g., hardware accelerators)
- To enable rapid application development even with a complex codebase

Our approach is to generalize a high-energy physics analysis code (“Cling”) to a generally accessible and fully functional tool that is part of LLVM/Clang.



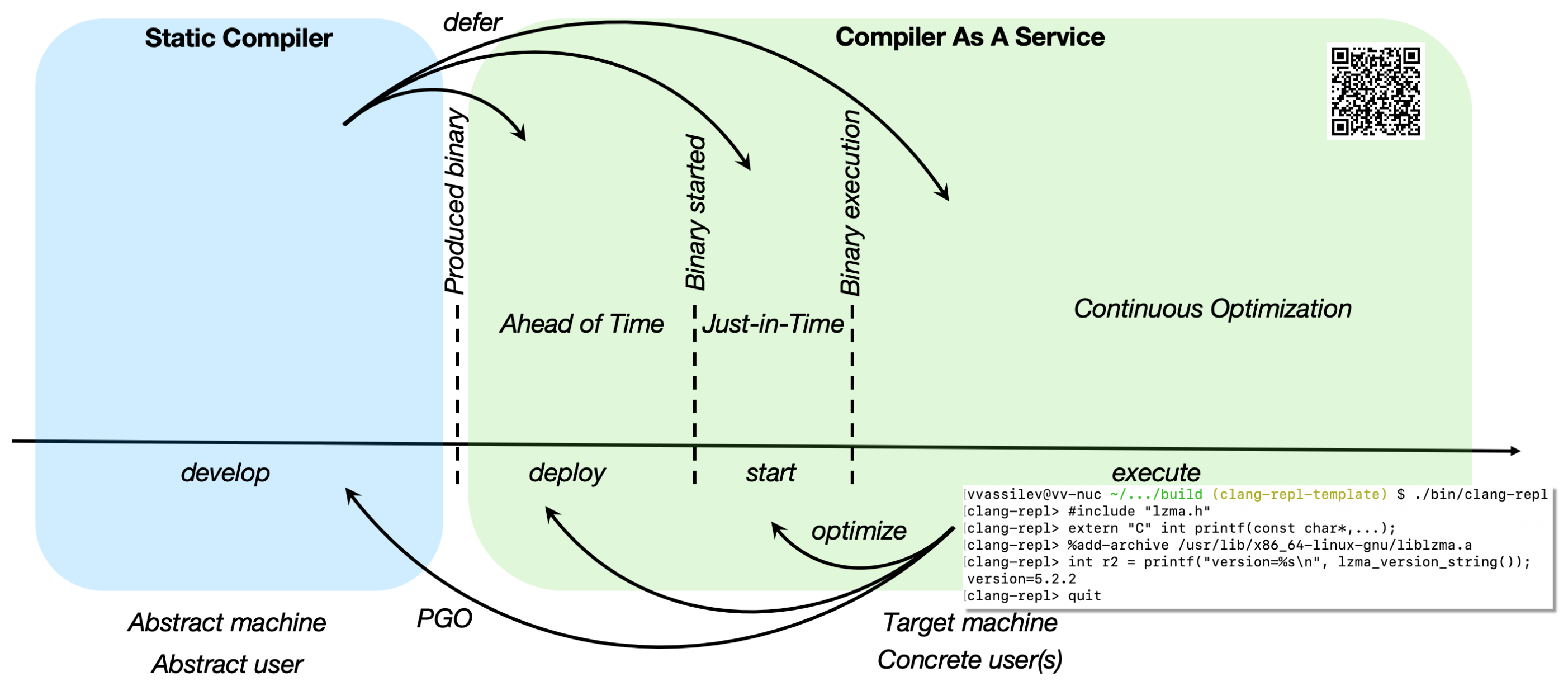
[1] [2] [3]

Scientific breakthroughs such as the discovery of the large void in the Khufu’s Pyramid, 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*

Project Accomplishments

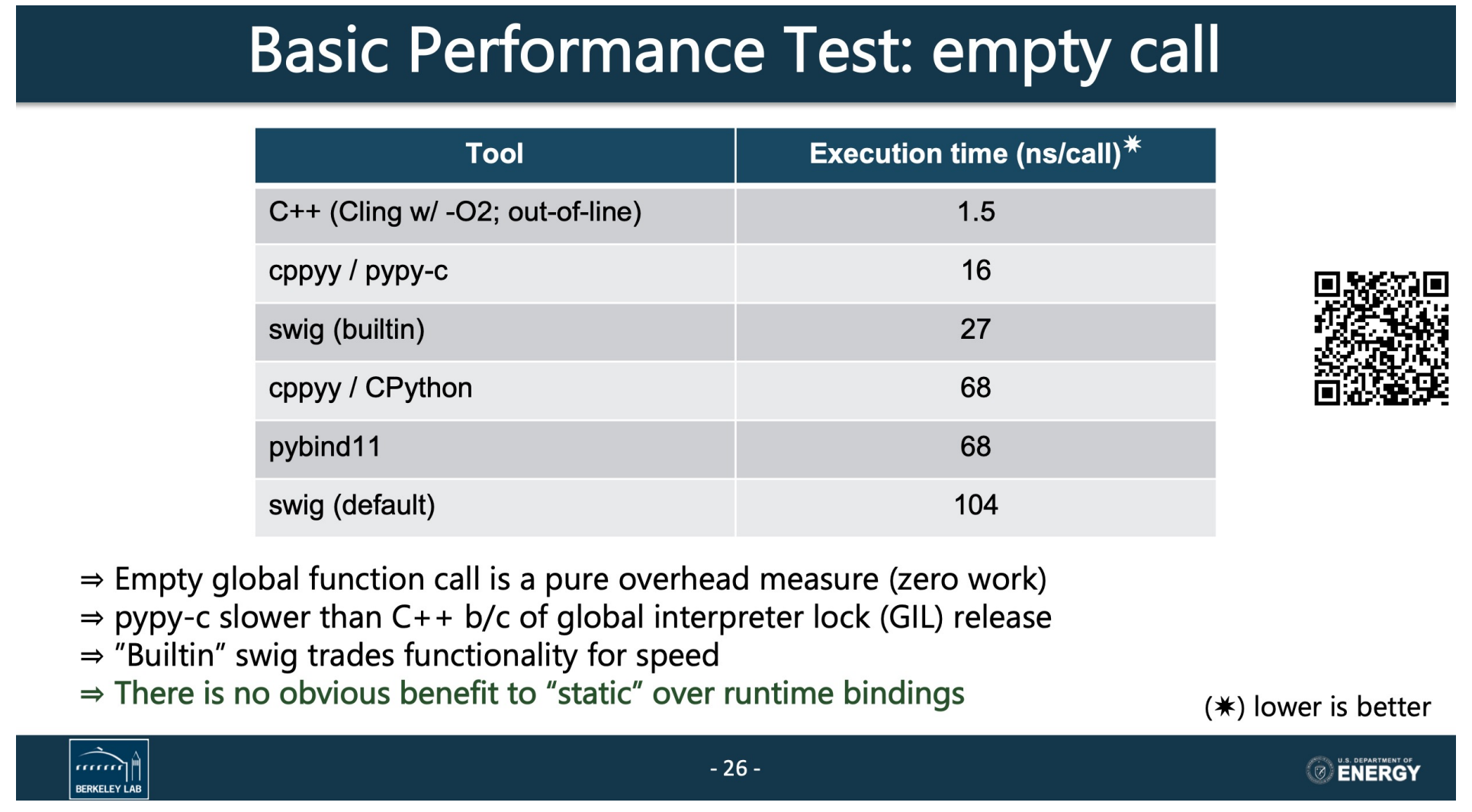
- LLVM community engagement / acceptance of CaaS concept and approach
- Initial release of Clang-Repl achieved in LLVM13
- Clang-Repl based plugin (Clad) implemented and demonstrated including offload of calculations to GPU
- LibInterop design completed after extensive community discussion. Now co-developing with application developers including
  - CPPYY package enabling run-time python <-> C++ bindings
  - Xeus based Jupyter plugin supporting interoperability and data exchange between C++ and python
- Science applications include automatic differentiation, uncertainty quantification, and embedded device control



```
vvassilev@vv-nuc ~/.../build (clang-repl-template) $ ./bin/clang-repl
clang-repl> #include "lzma.h"
clang-repl> extern "C" int printf(const char*,...);
clang-repl> %add-archive /usr/lib/x86_64-linux-gnu/liblzma.a
clang-repl> int r2 = printf("version=%s\n", lzma_version_string());
version=5.2.2
clang-repl> quit
```

Project Results and Applications

CPPYY run-time bindings are first libInterop use case



Basic Performance Test: empty call

Tool	Execution time (ns/call)*
C++ (Cling w/ -O2; out-of-line)	1.5
cppyy / pypy-c	16
swig (builtin)	27
cppyy / CPython	68
pybind11	68
swig (default)	104

⇒ Empty global function call is a pure overhead measure (zero work)
⇒ pypy-c slower than C++ b/c of global interpreter lock (GIL) release
⇒ ”Builtin” swig trades functionality for speed
⇒ There is no obvious benefit to “static” over runtime bindings

(*) lower is better

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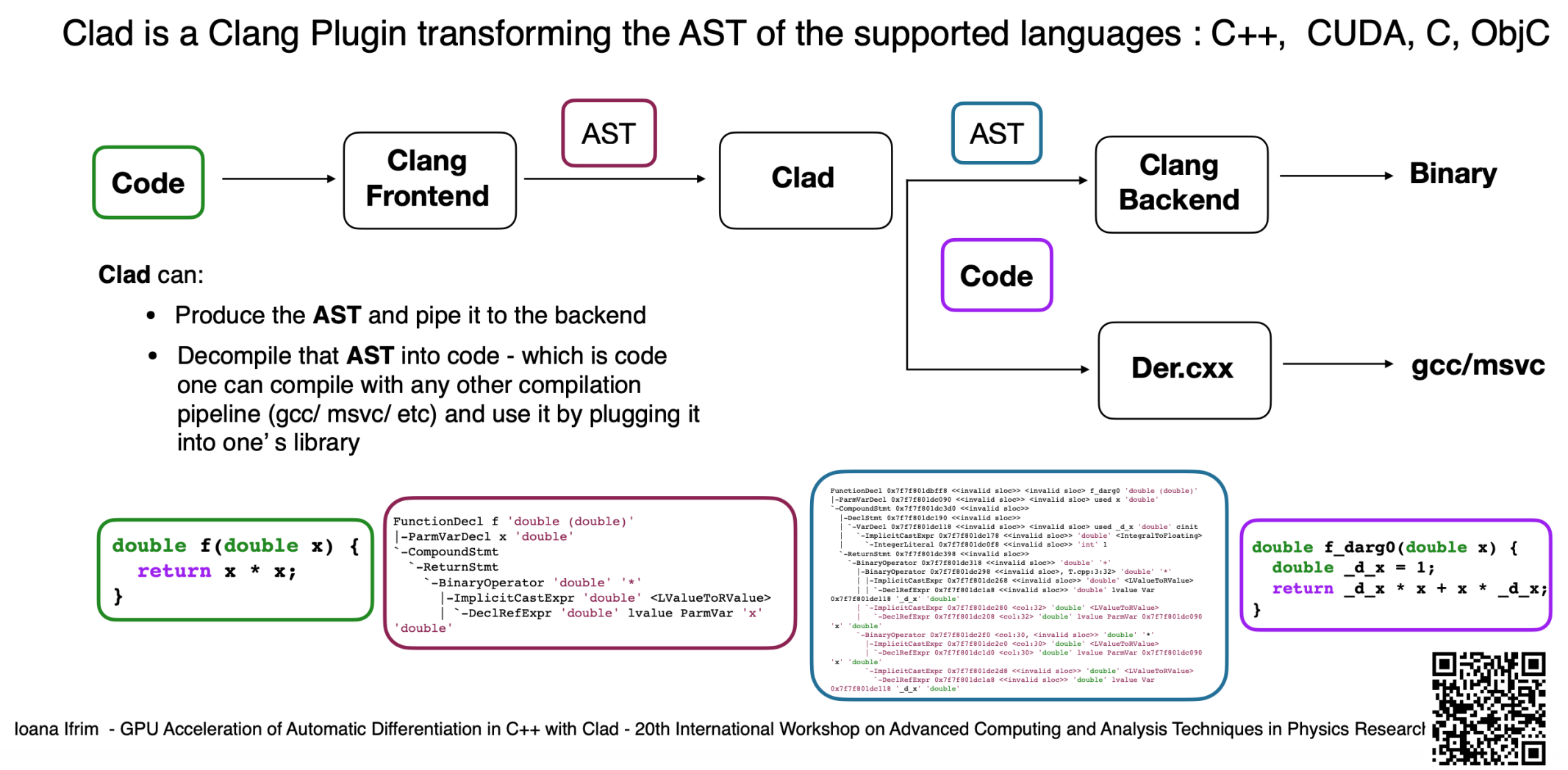
CLAD: Source transformation Automatic Differentiation



Clad is a Clang Plugin transforming the AST of the supported languages : C++, CUDA, C, ObjC

Clad can:

- Produce the **AST** and pipe it to the backend
- Decompile that **AST** into code - which is code one can compile with any other compilation pipeline (gcc/ msvc/ etc) and use it by plugging it into one’ s library

```
double f(double x) {
  return x * x;
}
```

```
FunctionDecl f 'double (double)'
|-ParmVarDecl x 'double'
`-CompoundStmt
  `-ReturnStmt
    `-BinaryOperator 'double' '*'
      |-ImplicitCastExpr 'double' <LValueToRValue>
      | `-DeclRefExpr 'double' lvalue ParmVar 'x'
'double'
```

```
double f_darg0(double x) {
  double _d_x = 1;
  return _d_x * x + x * _d_x;
}
```

Ioana Ifrim - GPU Acceleration of Automatic Differentiation in C++ with Clad - 20th International Workshop on Advanced Computing and Analysis Techniques in Physics Researcl

Clad AD applied to statistical analysis problems

ROOT is a data analysis software package used to process data in the field of high-energy physics.

Clad has replaced numerical gradient calculations for formula based functions.

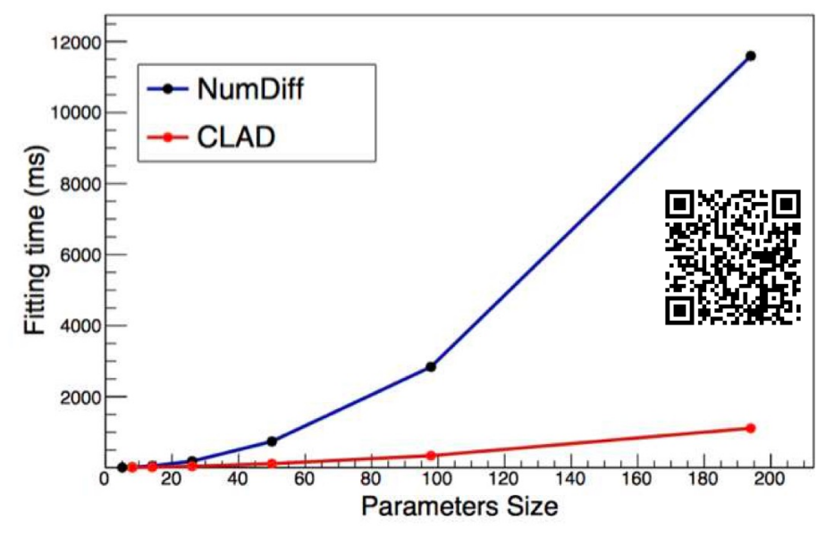
The Clad gradient is then used to compute the gradient of the objective function (χ^2 or negative log-likelihood function) when fitting

$$\chi^2 = \sum_{i=1}^{N} \frac{\left(Y_i - f(x_i, \mathbf{p})\right)^2}{\sigma_i^2}$$

Thus, ROOT fitting class computes $\nabla_{\mathbf{p}}(\chi^2)$ from $\nabla_{\mathbf{p}}(f(x, \mathbf{p}))$ obtained using Clad

Clad Hessian Mode in ROOT
(GSoC 2021- Baidyanath Kundu)

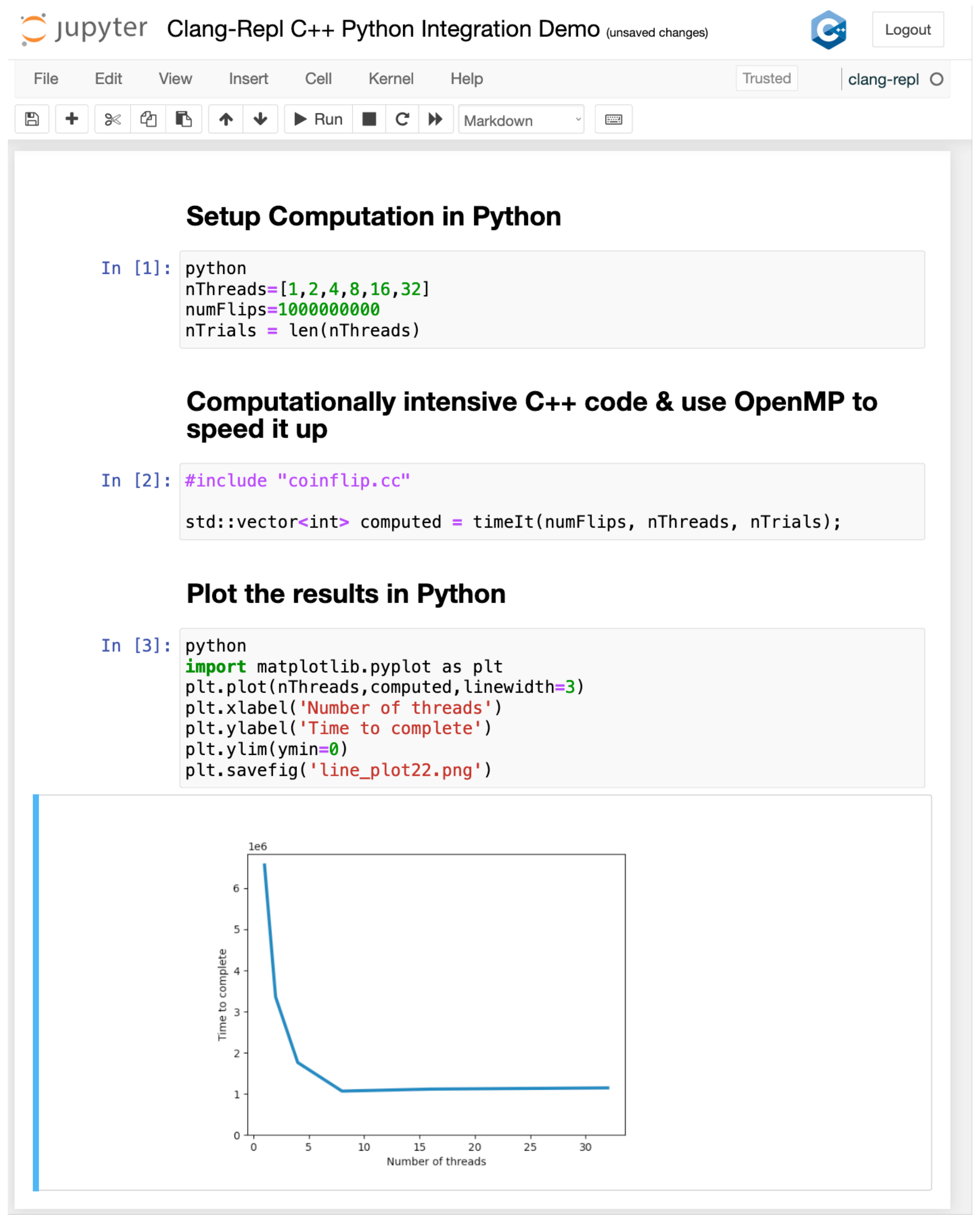
Comparison of fitting time using Clad VS Numerical Diff of objective function - fitting sum of gaussians



Lorenzo Moneta 94th ROOT PPP Meeting

* current implementation still requires one numerical gradient call for second derivatives (when seeding) - higher speedups will be possible when introducing second derivatives computation using Clad

Proposed CaaS programing model now realized in prototype



Setup Computation in Python

```
In [1]: python
        nThreads=[1,2,4,8,16,32]
        numFlips=1000000000
        nTrials = len(nThreads)
```

Computationally intensive C++ code & use OpenMP to speed it up

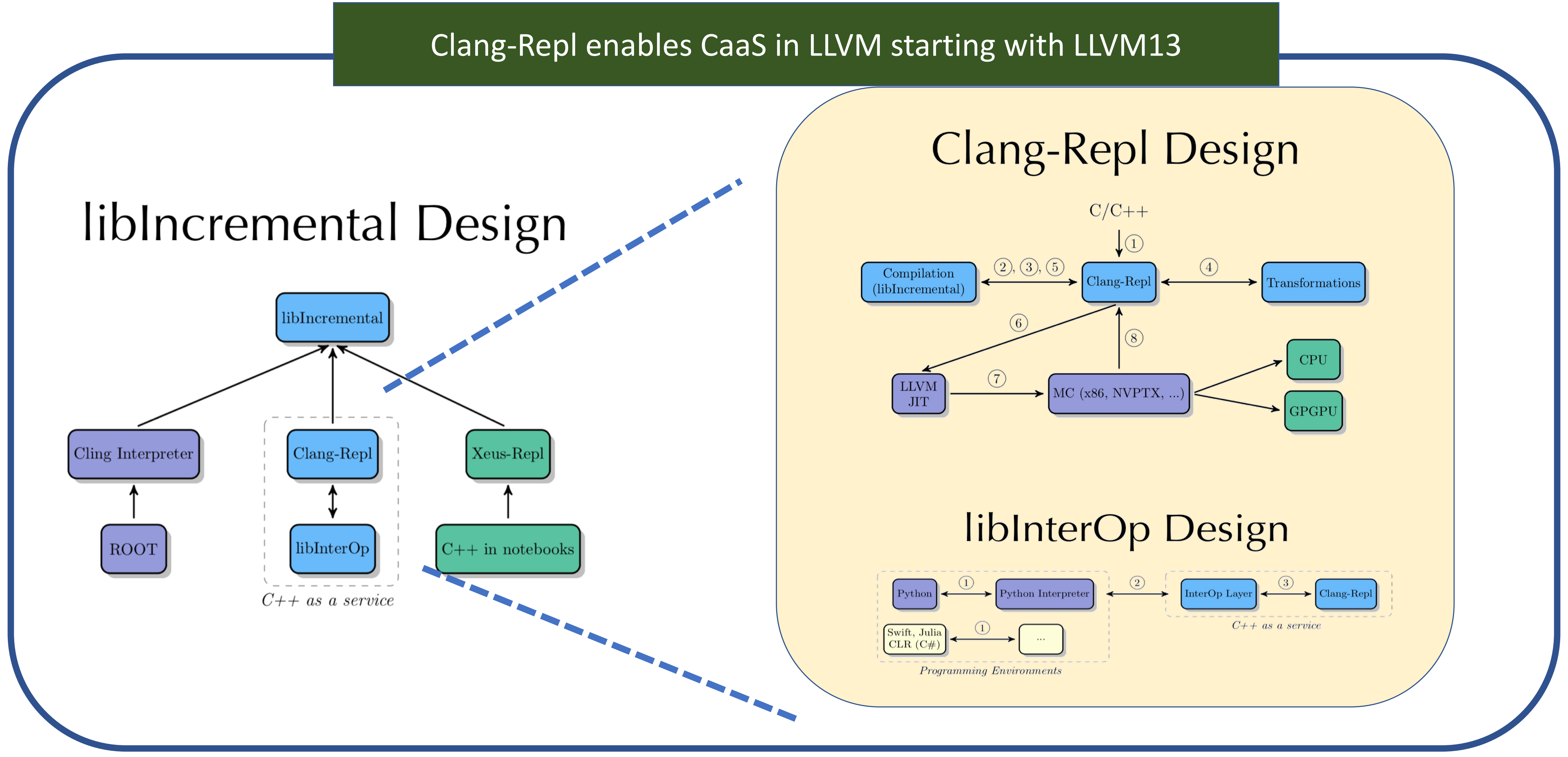
```
In [2]: #include "coinflip.cc"

        std::vector<int> computed = timeIt(numFlips, nThreads, nTrials);
```

Plot the results in Python

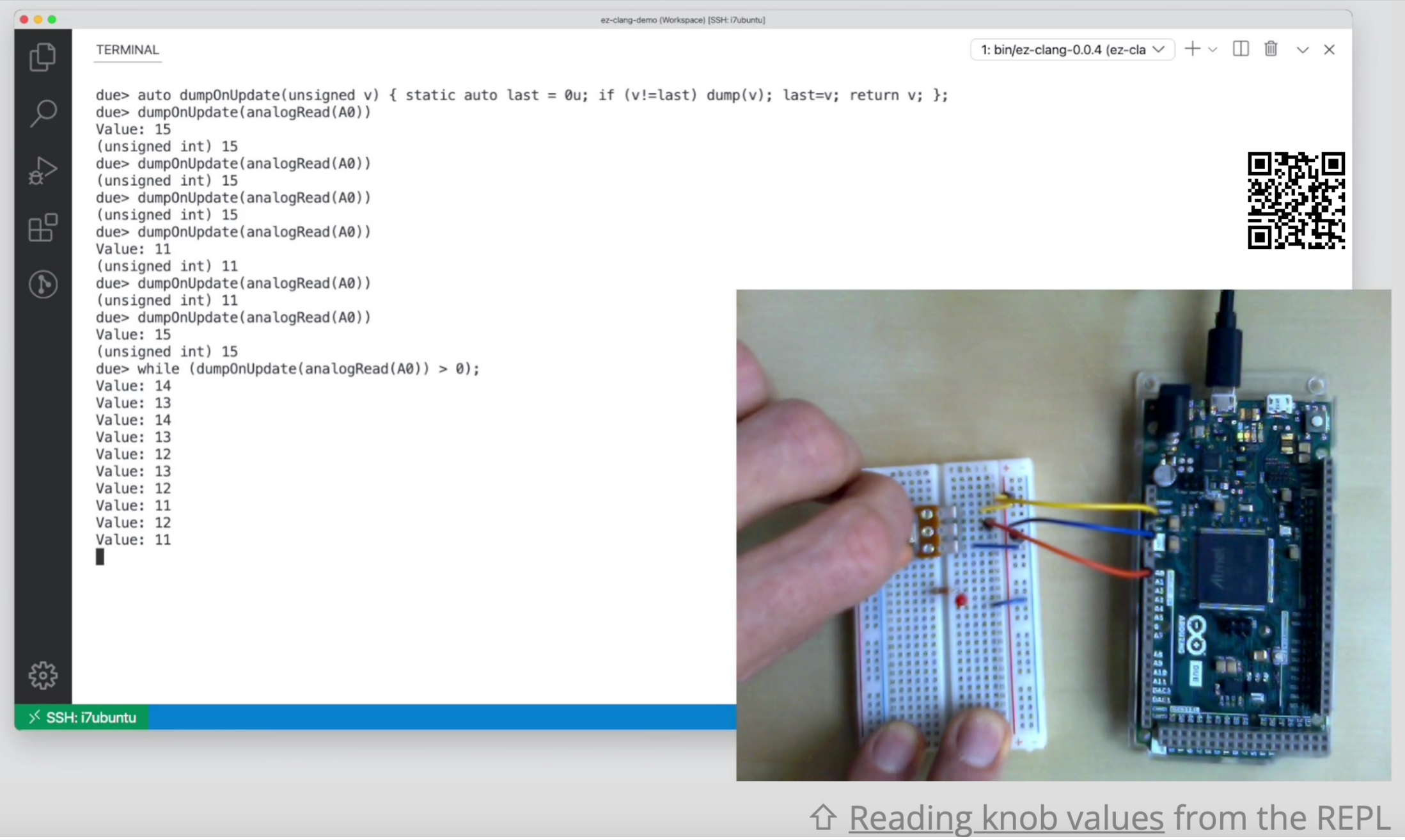
```
In [3]: python
        import matplotlib.pyplot as plt
        plt.plot(nThreads,computed,linewidth=3)
        plt.xlabel('Number of threads')
        plt.ylabel('Time to complete')
        plt.ylim(ymin=0)
        plt.savefig('line_plot22.png')
```

Clang-Repl enables CaaS in LLVM starting with LLVM13



Thanks to this project, we have grown a diverse user community around our technology including contributors from data science and industry. We established a monthly community meeting series to discuss results and applications. Visit us at https://compiler-research.org

EZ-Clang: Extremely small JIT for embedded devices


ez-clang-demo (Workspace) [SSH: i7ubuntu]
TERMINAL
1: bin/ez-clang-0.0.4 (ez-cla
SSH: i7ubuntu

```
due> auto dumpOnUpdate(unsigned v) { static auto last = 0u; if (v!=last) dump(v); last=v; return v; };
due> dumpOnUpdate(analogRead(A0))
Value: 15
(unsigned int) 15
due> dumpOnUpdate(analogRead(A0))
(unsigned int) 15
due> dumpOnUpdate(analogRead(A0))
(unsigned int) 15
due> dumpOnUpdate(analogRead(A0))
Value: 11
(unsigned int) 11
due> dumpOnUpdate(analogRead(A0))
(unsigned int) 11
due> dumpOnUpdate(analogRead(A0))
Value: 15
(unsigned int) 15
due> while (dumpOnUpdate(analogRead(A0)) > 0);
Value: 14
Value: 13
Value: 14
Value: 13
Value: 12
Value: 13
Value: 12
Value: 11
Value: 12
Value: 11
```

⇧ Reading knob values from the REPL

Compiler driven Uncertainty Quantification

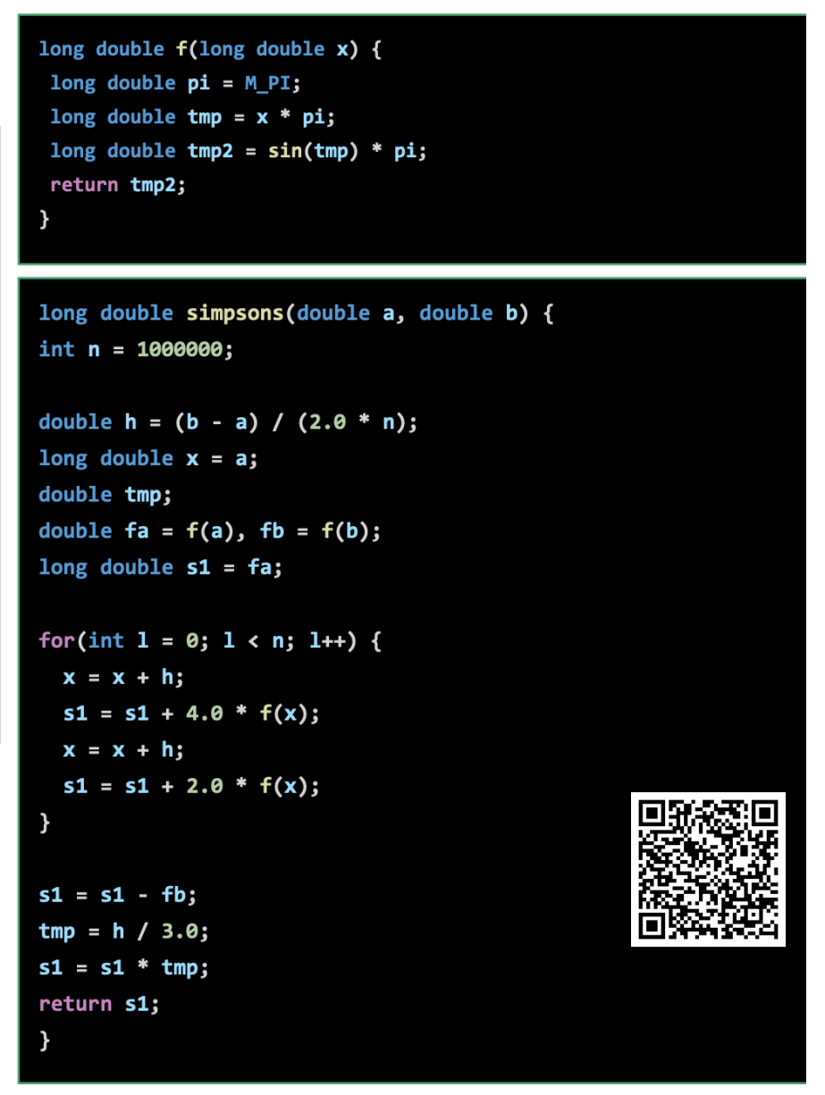
Case Study: Simpson’s Rule

Results

Precision configurations	Absolute Error	Clad’s Estimated Upperbound	Variables in lower precision (out of 11)
10-byte extended precision (*long double*)	4.07e-14	3.1e-12	0
Clad’s mixed precision	4.08e-14	3.0e-12	6
IEEE double-precision (*double*)	6.8e-11	6.2e-9	-
IEEE single-precision (*float*)	0.038	3.31	-

“Demoting” low-sensitivity variables to lower precision improves performance by ~10% in this example.

Clad’s estimate also agrees that there is no significant change in the final error. This can be useful in the cases where an accurate ground-truth comparison is not available.



```
long double f(long double x) {
 long double pi = M_PI;
 long double tmp = x * pi;
 long double tmp2 = sin(tmp) * pi;
 return tmp2;
}
```

```
long double simpsons(double a, double b) {
int n = 1000000;

double h = (b - a) / (2.0 * n);
long double x = a;
double tmp;
double fa = f(a), fb = f(b);
long double s1 = fa;

for(int l = 0; l < n; l++) {
  x = x + h;
  s1 = s1 + 4.0 * f(x);
  x = x + h;
  s1 = s1 + 2.0 * f(x);
}

s1 = s1 - fb;
tmp = h / 3.0;
s1 = s1 * tmp;
return s1;
}
```

V. Vassilev, G. Singh, *Floating-Point Error Estimation Using AD*, SIAM UQ22