Introduction to Floating-Point Analysis and Reproducibility

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Topics in this full-day tutorial

- Floating-point analysis
  - For improving the performance of the code
- Non-Reproducibility
  - Caused by program execution
  - Caused by floating-point result nondeterminism
- Why combine FP analysis and Non-Reproducibility in one tutorial?
    - Because, separating them through external symptoms alone is difficult in practice!

Reproducibility

The hope/expectation that a subsequent run of the program under “identical conditions” will produce the same answer

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Life works around reproducibility

Even babies expect it

Lecun’s Turing lecture

Reasons for Lack of Reproducibility in Numeric Programs, and Tools We Present

- Nondeterministic MPI message matching
  - Send messages that race to match a wildcard receive
    - TOOL: **ReMPI**
- Data races that change the space of executions
  - “Pink-elephant values” [Sutter]
    - TOOL: **Archer**
- Compiler optimizations that change the binaries that get linked
  - Makes code non-portable across platforms
    - TOOL: **FLiT**
- FP Exceptions that are thrown
  - Makes the execution unexpectedly terminate
    - TOOL: **FPChecker**

Floating-point Analysis Topics and Tools

- Understanding and Benchmarking Floating-Point Codes
  - So that we have an objective truth to tool behavior, comparisons
    - FRAMEWORK: FPBench
- Precision Tuning
  - Determine precision changes that improve performance
    - TOOLS: Precimonious, HiFPTuner
- Framework for source-to-source precision tuning & analysis
  - Enables community to conduct precision tuning research
    - TOOLS: ADAPT, FloatSmith

A quick introduction to today's major topic

Some basics of Floating-Point Arithmetic

The Floating-Point number system is not new

Then

Zuse Z1 (~1938)

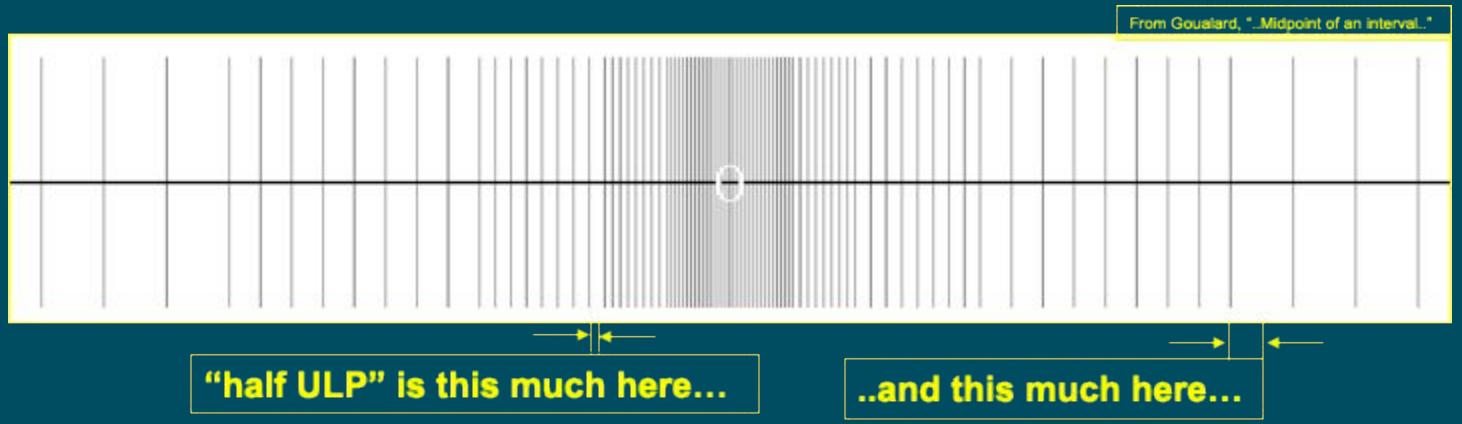
Now

IEEE Standard for Floating-Point Arithmetic

Floating-Point approximates Reals

- Because of rounding, (x+y)+z != x+(y+z)
  - And many more such identities are violated
- Compilers can change your math
  - x/y → x * (1/y)
- Rounding errors are non-intuitive
  - Because of the uneven FP number scale

The Floating-Point Rounding is Non-Intuitive



The FP number system tries to span a large range using an “insufficient number of bits”

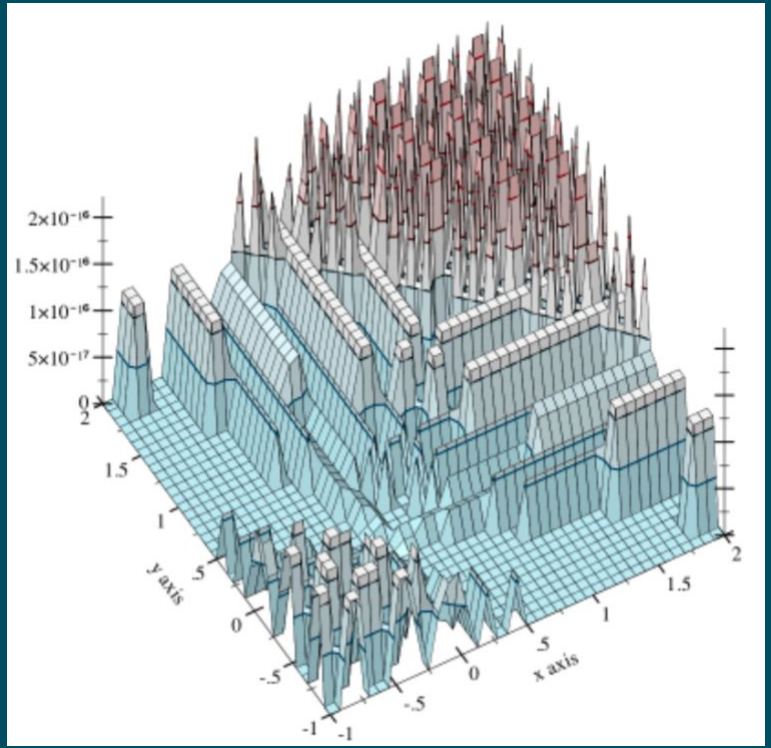
The FP error function is highly non-intuitive

E.g.

Rounding error of (x+y) as a function of x and y

IEEE Model of error:

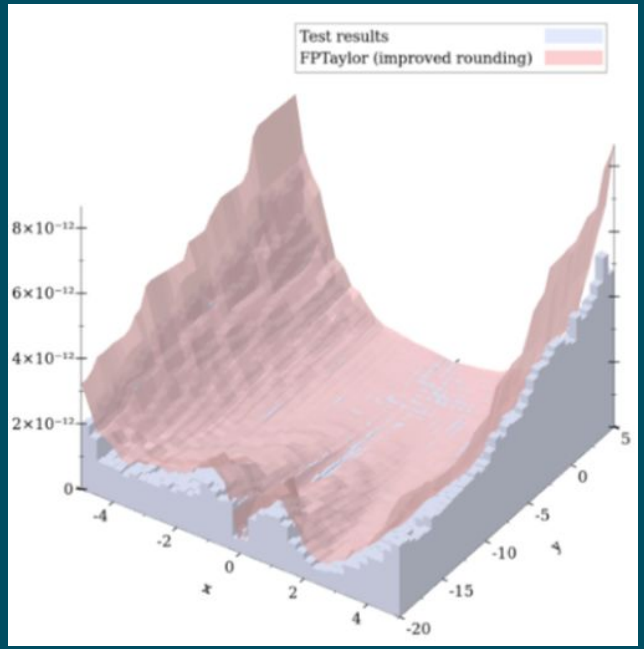
(x+y) . half-ULP



The FP error function is highly non-intuitive even at a more macroscopic level… Heuristic solutions recommended in practice!

E.g. Rounding error of the JetEngine benchmark of Darulova and Kuncak as plotted by Solovyev using his FPTaylor tool, with ground-truth obtained thru shadow-value simulation.

```
double jetEngine(double x1, double x2) {
  double t = 3 * x1 * x1 + 2 * x2 - x1
  double q = x1 * x1 + 1
  double p = t / q
  double s1 = 2 * x1 * p * (p - 3)
  double s2 = x1 * x1 * (4 * p - 6)
  double s3 = 3 * x1 * x1 * p
  double s4 = x1 * x1 * x1
  double s5 = 3 * p
  return x1 + ((s1 + s2) * q + s3 + s4 + x1 + s5)
}
```



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Kahan’s observation

> Numerical errors are rare, rare enough
> not to care about them all the time,
> but yet not rare enough to ignore them.
> — William M. Kahan

Floating-Point Analysis is Suddenly “Front and Center” in HPC + many other areas

- Allocating needlessly high precision increases data movement
  - Multiple precision types are on the rise
    - Often driven by ML
- The variety of hardware is increasing
  - GPUs and other accelerators
    - Their normal behaviors as well as EXCEPTIONS are on the rise
- Compilers exploit floating-point in an increasing number of ways
  - Compiler flags mean different things
    - Compilers may heed your flags selectively

Frenetic pace of FP research now

- Multiple conferences
- Many sessions per conference
- Many different issues

Very little that is tangible for a practitioner to try some of these out

PURPOSE OF THIS TUTORIAL: Change this!

Goals of this Tutorial

- Introduce FOUR mileposts in your repertoire of knowledge
  - Four tools you can practice during the tutorials
  - You can apply them in your own projects!
- We are a resource you can count on during your future work
  - We are invested in multiple research projects in this area
  - We know many more researchers and practitioners whose work we can refer

We hope to build a community of researchers and practitioners

Access to AWS Instances (changeme)

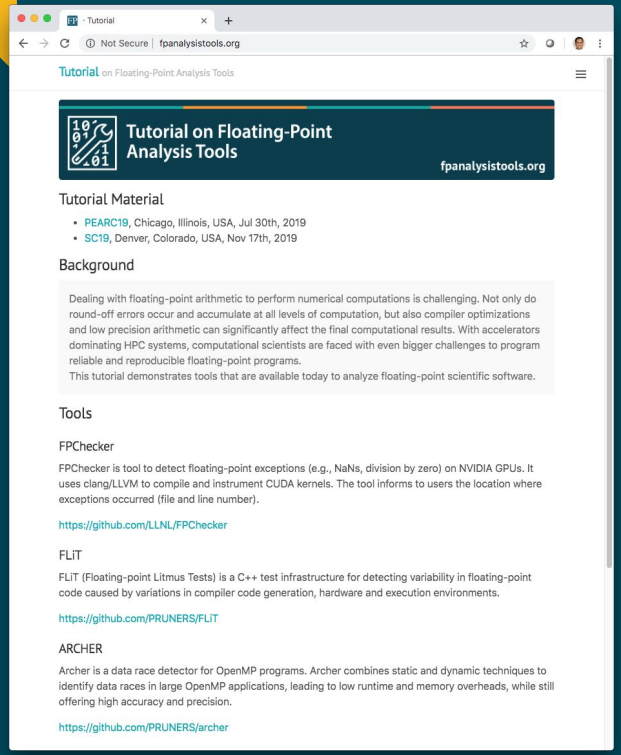
- You will be given access to AWS instances
  - User, password, and IP address will be provided
- How to access your instance:

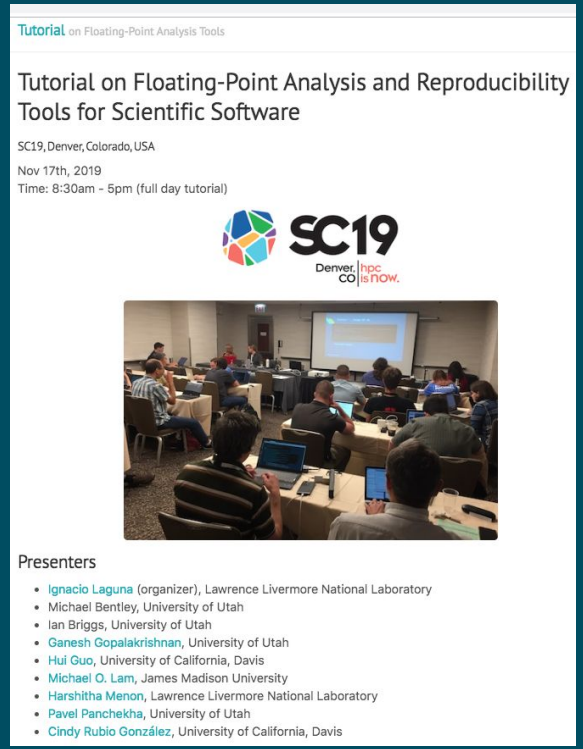
```
ssh user@1.2.3.4
```

- Exercises for each module located in user's /home directory

```
/home/user1/
   |---Module-TOOL1
      |---exercise-1
      |---exercise-2
      |---exercise-3
   |---Module-TOOL2
      |---exercise-1
      |---exercise-2
      |---exercise-3
   ...
```

Website & Schedule: fpanalysistools.org





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