

Tutorial



FPChecker:

Floating-Point Profiling Through Compiler-Instrumentation

<https://fpchecker.org>

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Agenda

Intro & Motivation	10 min
Tool's Overview	10 min
Installation & Exercises (hands-on)	35 min
Q&A	5 min

Floating-Point is Nonintuitive & Tricky to Understand

- Representation error:

Mathematically: $0.1 + 0.2 = 0.3$

In floating-point: 0.30000000000000004

- Comparing two numbers for equality is unreliable

Say we calculate $a = 0.1 + 0.2$ and $b = 0.3$

We would expect $a == b$ to be true. But it's not!

Floating-Point is Nonintuitive & Tricky to Understand (2)

- Loss of precision:

This could evaluate to 0.0: $(10e8 + 1e-8) - 10e8$

- Cancellation:

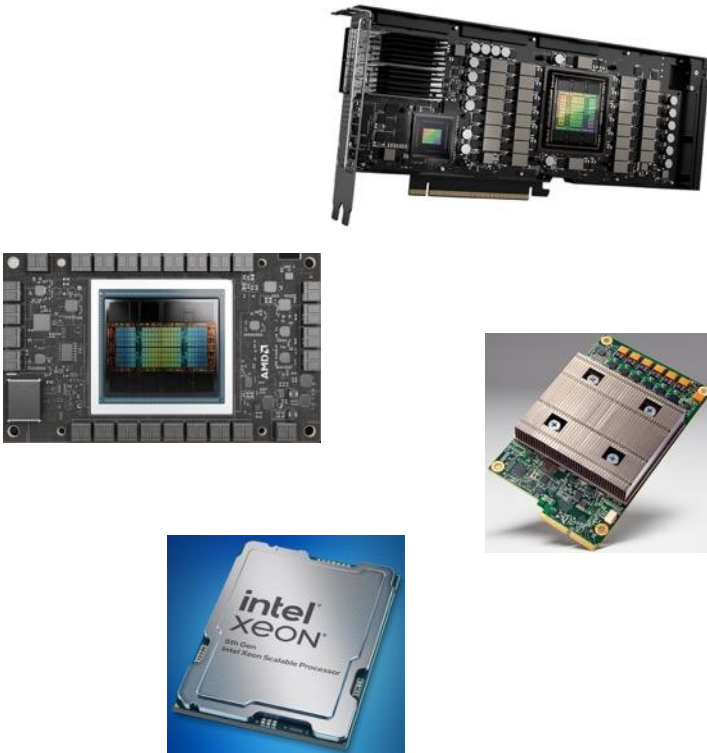
Suppose: $x=1.000000000000000001$, $y=1.000000000000000002$

Mathematically $y-x = 0.000000000000000001$

In floating-point: $y-x = 2.220446049250313e-16$

Large relative error!

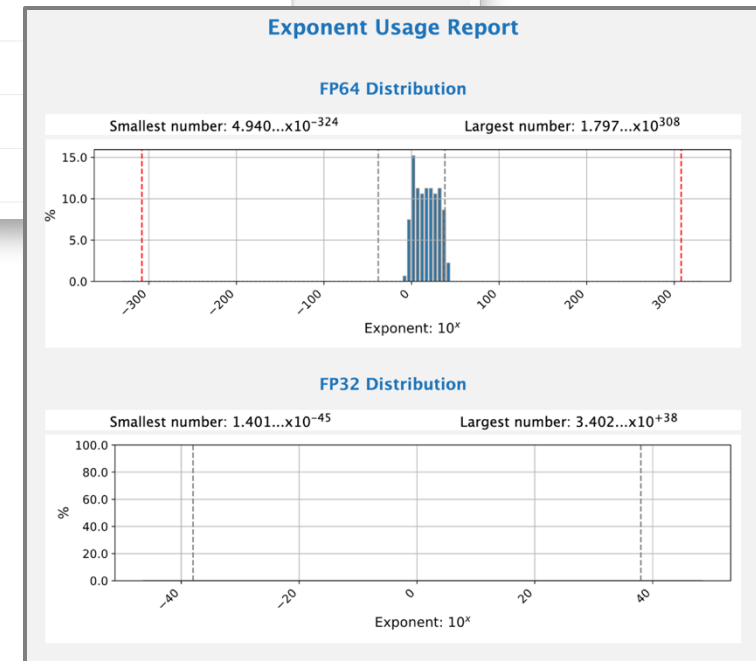
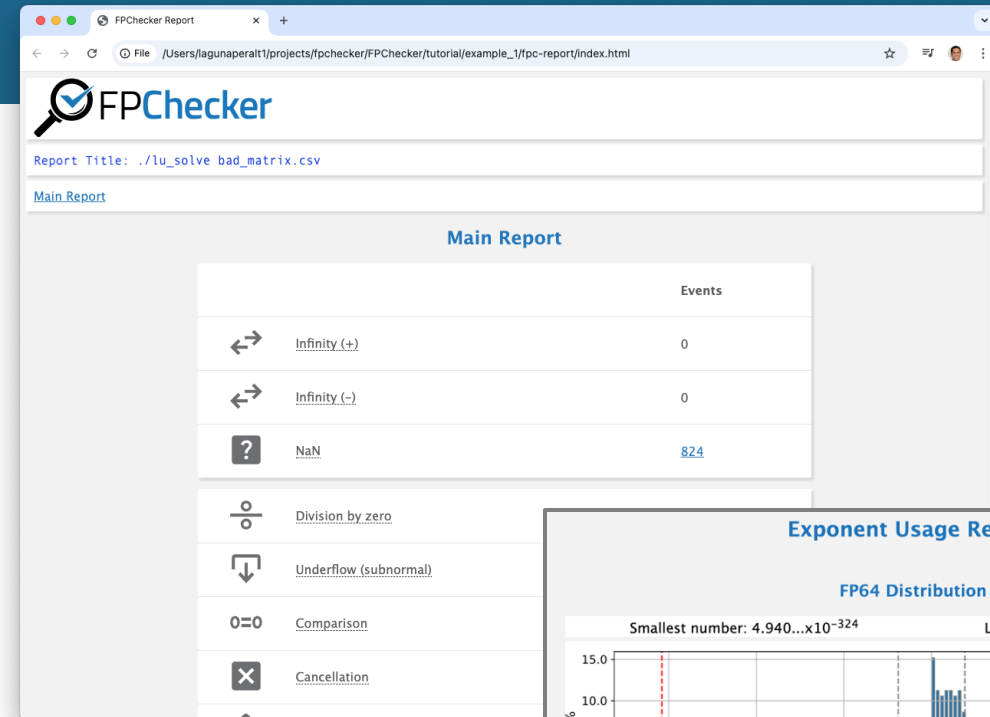
The World is Going Low-Precision



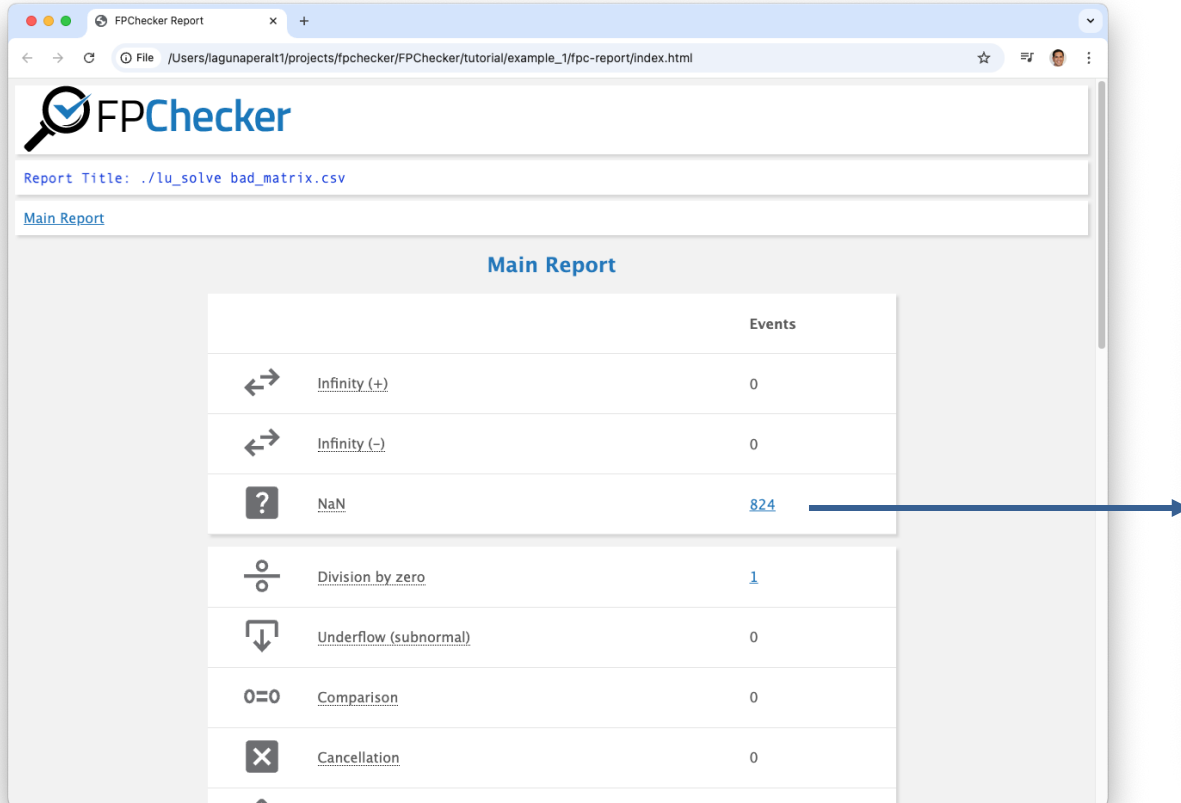
- Architectures promote lower precision formats:
 - FP16, FP8
 - Bfloat16
 - TensorFloat-32
- We need tools to understand **mixed-precision** codes
- Important metrics to understand:
 - Dynamic range of FP32, FP16
 - Rounding error accumulation

FPChecker Overview

- Detects floating-point **exceptions**
 - NaN, Infinity
- Shows impacted *lines of code*
- Shows other “**code smells**”
 - Cancellations, underflows
- Analyzes **dynamic range**
 - Is FP32 or FP64 enough?
- Works by **compiler instrumentation**
 - Relies on Clang/LLVM
- Documentation: <https://fpchecker.org/>



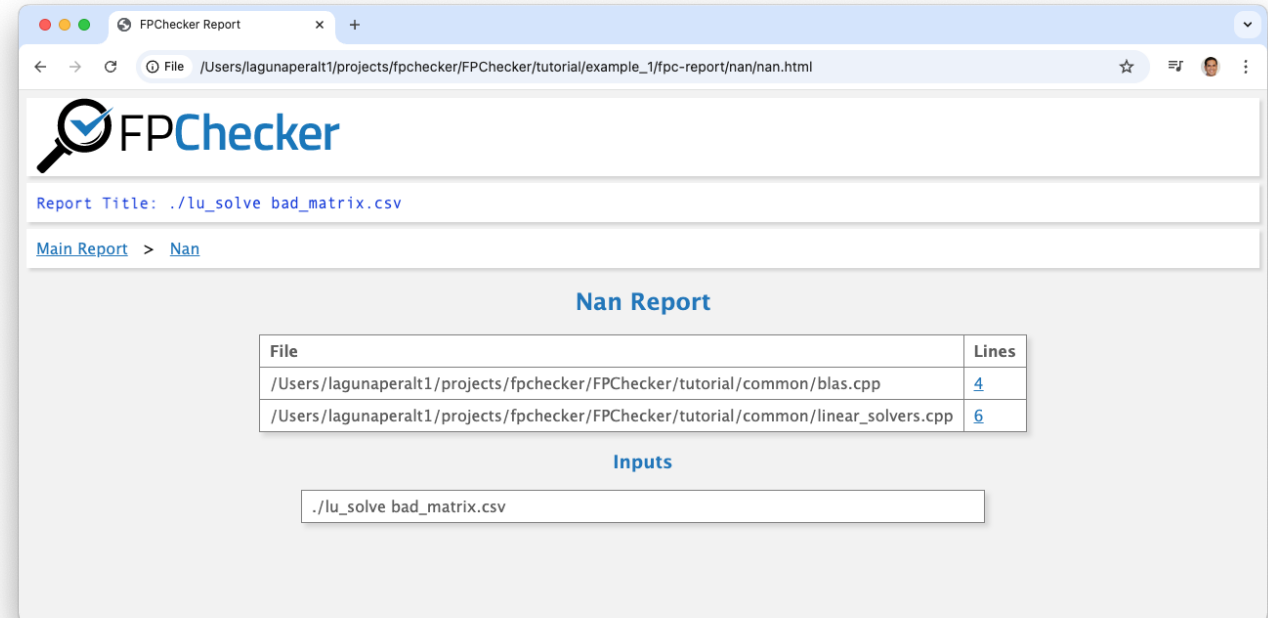
Report Example



The screenshot shows the FPChecker Main Report interface. The browser address bar displays the file path: `/Users/lagunaperalt1/projects/fpchecker/FPChecker/tutorial/example_1/fpc-report/index.html`. The report title is `./lu_solve bad_matrix.csv`. A link for [Main Report](#) is visible. The main content area is titled "Main Report" and contains a table with floating-point error events.

	Events
Infinity (+)	0
Infinity (-)	0
NaN	824
Division by zero	1
Underflow (subnormal)	0
Comparison	0
Cancellation	0

A blue arrow points from the [824](#) value in the NaN row to the right-hand screenshot.



The screenshot shows the FPChecker Nan Report interface. The browser address bar displays the file path: `/Users/lagunaperalt1/projects/fpchecker/FPChecker/tutorial/example_1/fpc-report/nan/nan.html`. The report title is `./lu_solve bad_matrix.csv`. A link for [Main Report](#) is visible, followed by [Nan](#). The main content area is titled "Nan Report" and contains a table listing files with NaN events.

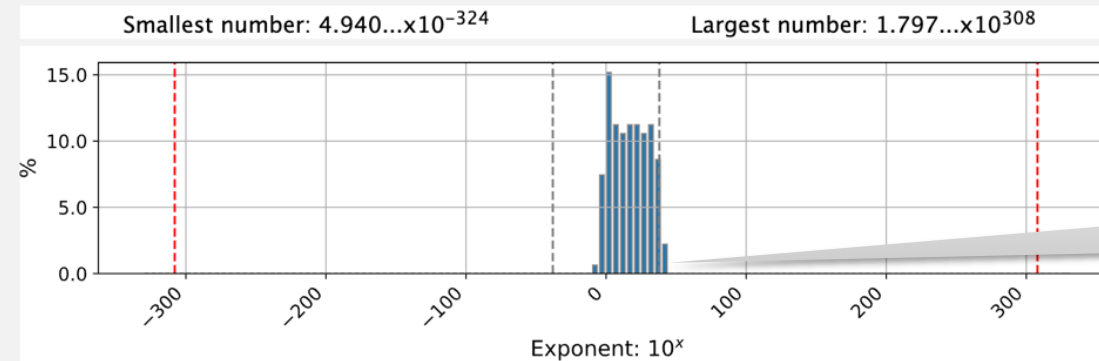
File	Lines
<code>/Users/lagunaperalt1/projects/fpchecker/FPChecker/tutorial/common/blas.cpp</code>	4
<code>/Users/lagunaperalt1/projects/fpchecker/FPChecker/tutorial/common/linear_solvers.cpp</code>	6

Below the table, the section is titled "Inputs" and contains a text box with the input file name: `./lu_solve bad_matrix.csv`.

Exponent Usage (Dynamic Range)

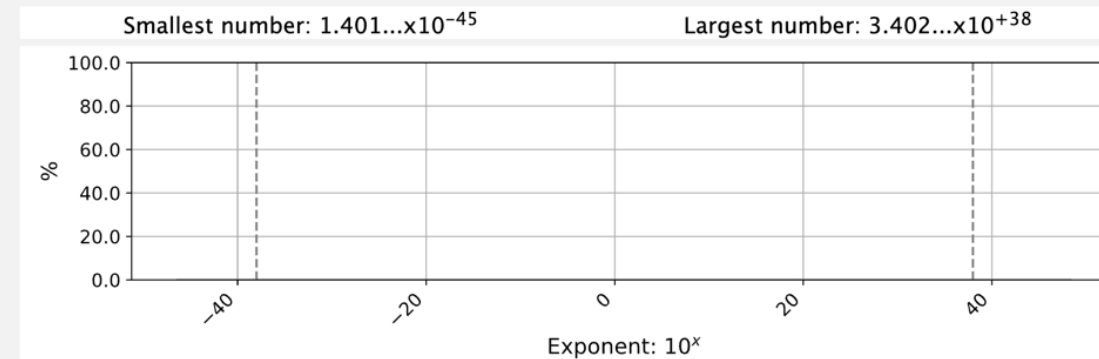
Exponent Usage Report

FP64 Distribution

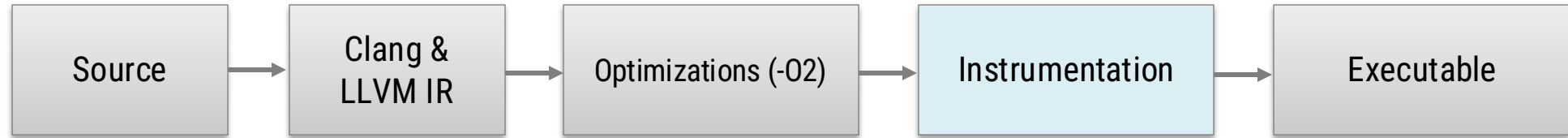


Out of range for
FP32

FP32 Distribution



LLVM Instrumentation Process



1. Use `clang++-fpchecker` wrapper in your Makefile
 - Or add instrumentation pass to your CFLAGS and/or CXXFLAGS
2. Enable `FPC_INSTRUMENT` environment variable when compiling
 - \$ `FPC_INSTRUMENT=1 make`
3. Run executable
4. Create report

Two Classes of Env Variables: *Compile-time & Run-time*

✓ Covered in the Tutorial

Compile-time Variables



Variable	Type	Description
FPC_INTRUMENT	Compile-time	Instruments the application
FPC_ANNOTATED	Compile-time	Indicates that the program is annotated

Run-time Variables



Variable	Type	Description
FPC_EXPONENT_USAGE	Run-time	Profiles exponent usage for FP32/FP64
FPC_TRAP_INFINITY_POS	Run-time	Program exits when Infinity positive is found
FPC_TRAP_INFINITY_NEG	Run-time	Program exits when Infinity negative is found
FPC_TRAP_NAN	Run-time	Program exits when NaN is found
FPC_TRAP_DIVISION_ZERO	Run-time	Program exits when division-by-zero is found
FPC_TRAP_CANCELLATION	Run-time	Program exits when cancellation is found
FPC_TRAP_COMPARISON	Run-time	Program exits when Comparison is found
FPC_TRAP_UNDERFLOW	Run-time	Program exits when underflow is found
FPC_TRAP_LATENT_INF_POS	Run-time	Program exits when Latent Infinity positive is found
FPC_TRAP_LATENT_INF_NEG	Run-time	Program exits when Latent Infinity negative is found
FPC_TRAP_LATENT_UNDERFLOW	Run-time	Program exits when Latent Underflow is found

Software Requirements

- Linux or Mac OS
 - Windows not supported
- LLVM/Clang 19
- Cmake
- Python 3.12
- Matplotlib
- Optional for parallel code:
 - MPI
 - OpenMP

Installation Process

1. Install **Conda** (this allow us to install LLVM easily)
2. Install FPChecker

How to install Anaconda on Mac or Linux

For Mac, watch this YouTube video:

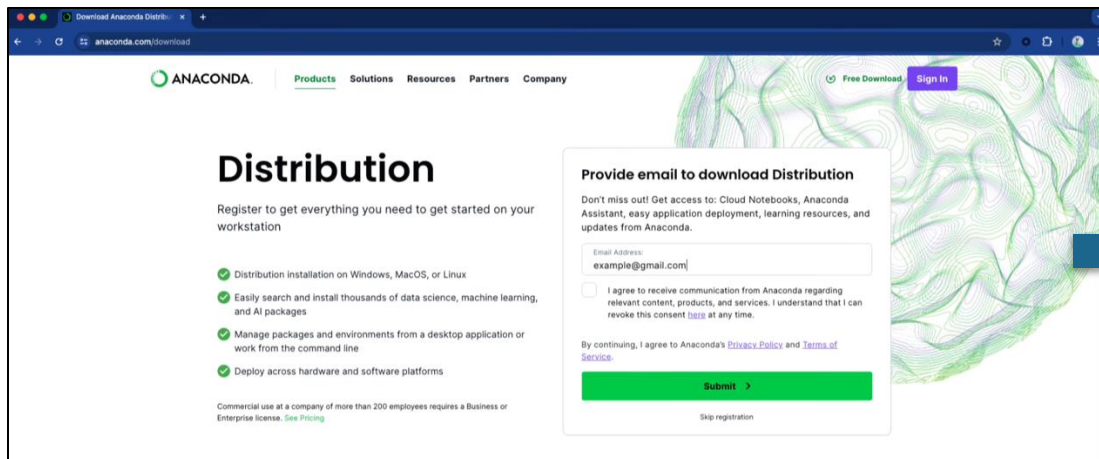
<https://youtu.be/DNu8pQOYRGg>

For Linux:

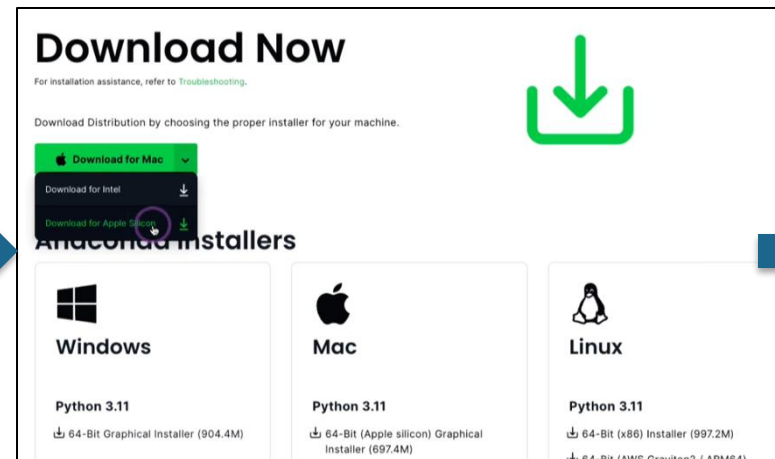
<https://docs.conda.io/projects/conda/en/stable/user-guide/install/linux.html>

Steps to Install Conda in Mac

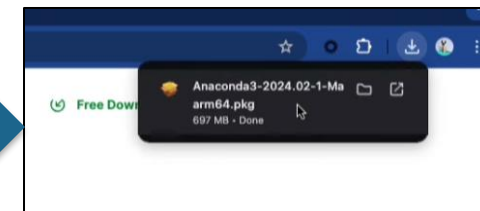
Got <https://www.anaconda.com/> -> Download



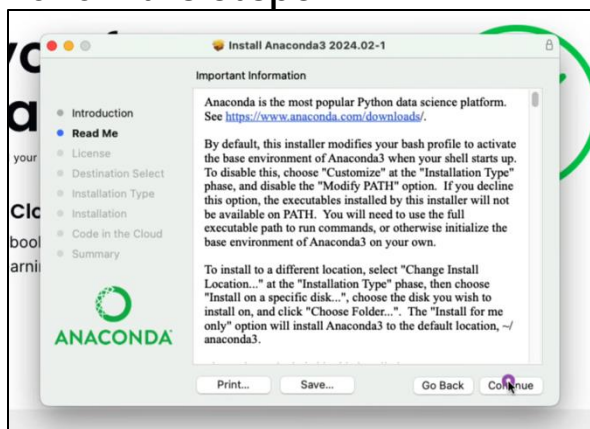
Download



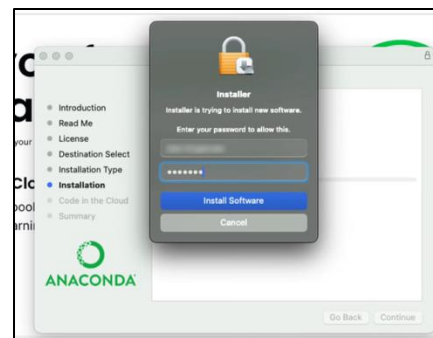
Open Installer



Follow the steps



Provide password if asked



In the terminal, you should see the word **base**:

```
(base) [user@system] $
```

Get FPChecker

This tutorial is based on release **v0.5**

```
# We will install all in /tmp
$ cd /tmp
$ mkdir tutorial
$ cd tutorial

# Clone FPChecker
$ git clone https://github.com/LLNL/FPChecker.git
$ cd FPChecker
```


Install FPChecker Dependencies with Conda (Option 1)

Manual Installation

```
# Create a conda env
$ conda create --name tutorial_env
$ conda activate tutorial_env

# Install dependencies: cmake, LLVM, clang++, python
$ conda install cmake
$ conda install llvmdev=19.1.7 -c conda-forge
$ conda install clangxx=19.1.7 -c conda-forge
$ conda install python=3.12.9

# Install matplotlib. Not required to build FPChecker, but needed for reports
$ pip3 install matplotlib

# MPI for some examples, but not required to build for FPChecker
$ conda install openmpi=5.0.7 -c conda-forge
```

Install FPChecker Dependencies with Conda (Option 2)

With environment file for Mac (ARM)

```
# Create a conda env and dependencies
$ cd tutorial
$ conda create --name tutorial_env --file conda_environment.txt -c conda-forge
$ conda activate tutorial_env
```

- The `conda_environment.txt` file provides the packages for Mac (ARM 64-bit)
- This installs all the dependencies:
 - LLVM 19
 - Clang++ 19
 - Cmake

Install FPChecker

```
$ cd ..  
$ mkdir build  
$ cd build/  
$ cmake -DCMAKE_INSTALL_PREFIX=../../install ..  
$ make && make install  
  
# Export installation path  
$ export PATH=/tmp/tutorial/install/bin:$PATH
```

```
# If the right python3 is not found, set the DPython3_ROOT_DIR  
$ cmake -DCMAKE_INSTALL_PREFIX=../../install -DPython3_ROOT_DIR=/opt/anaconda3 ..
```

Tutorial Exercises

Tutorial Examples

Topics

Example Program

- | | | |
|---|---|--|
| 1 | NaN and Infinity exceptions | Linear system ($Ax=b$) solver with LU decomposition + partial pivoting |
| 2 | Exponent usage – from FP64 and FP32 precision | Finite differences + 1D Reaction-Diffusion PDE |
| 3 | Controlling slowdown with code annotations | Finite Elements + 2D Heat Conduction PDE solver |
| 4 | Analyzing parallel code: MPI/OpenMP | MPI-based Parallel Heat PDE solver |

First, build the *common* library

It will be used in all examples

- Common library:
 - BLAS operations
 - Linear solvers (LU, CG)
 - Matrix & vector printing
 - Other functionalities

```
# Compile library
$ cd /tmp/tutorial/FPChecker/tutorial/common/
$ FPC_INSTRUMENT=1 make
```

Example 1:

NaN & Infinity exception in linear solver

- Location:
tutorial/example_1/lu_solve.cpp
- Program description
 - Linear solver $Ax = b$
 - Solves $Ax = 1$
 - LU decomposition: $PA = LU$
 - Partial pivoting
 - Solve by forward/backward substitution

FPChecker Use Case

- Use an ill-condition problem (matrix)
- Produces NaN and Infinity
 - U factor ends up with zero diagonal
 - Division by zero
- FPChecker locates the exceptions

Example 1: Script (Good Matrix)

```
# Compile and run problem
$ FPC_INSTRUMENT=1 make
$ ./lu_solve matrix.csv

# List trace files (there is one)
$ ls -l .fpc_logs/

# Create report
$ fpc-create-report -t "./lu_solve matrix.csv"
$ open fpc-report/index.html

# Clear logs and remove report
$ fpc-create-report -rc
```

Nothing interesting in the report

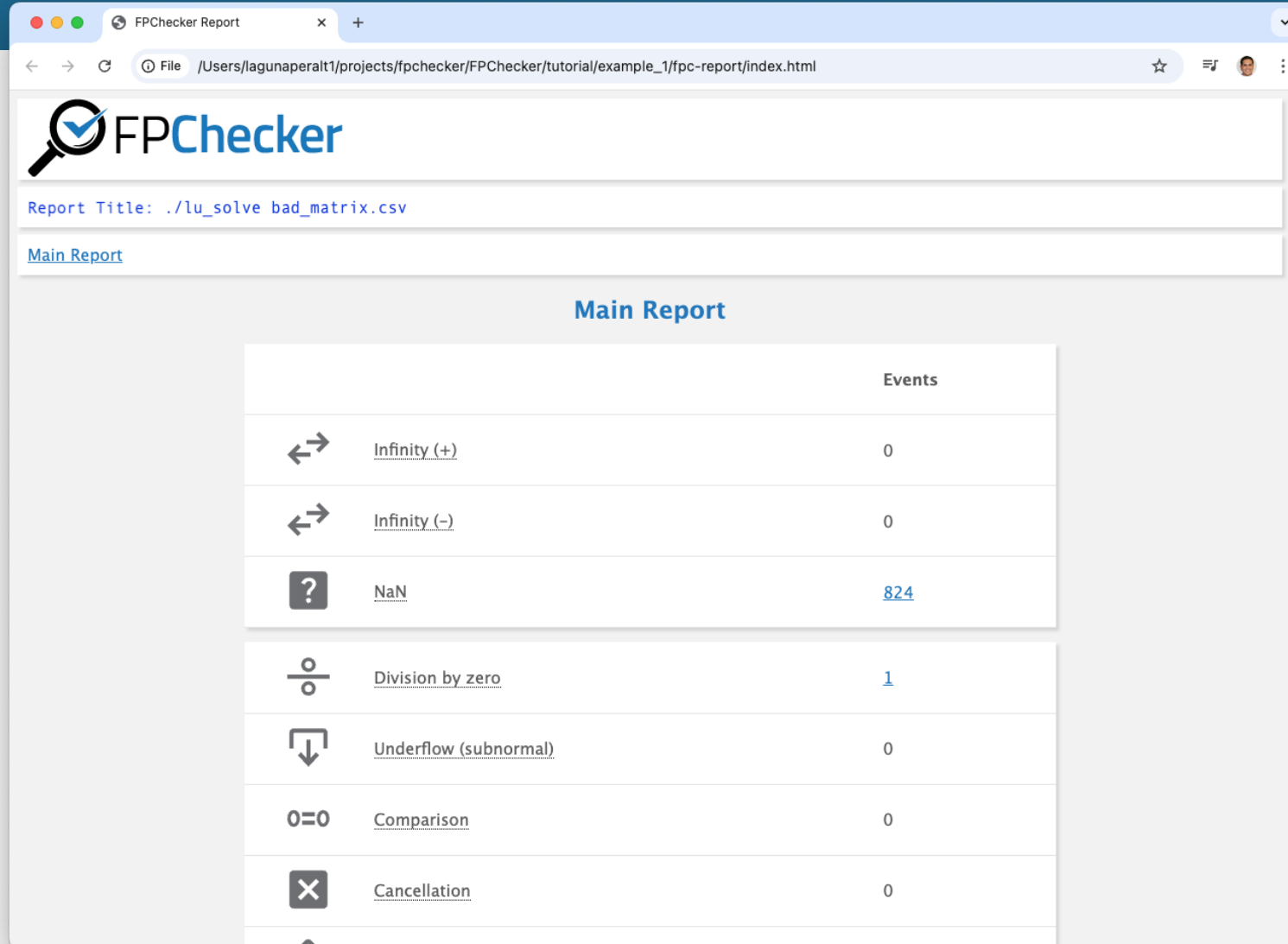
Example 1: Script (Bad Matrix)

```
# Run problem
$ ./lu_solve bad_matrix.csv








# Create report
$ fpc-create-report -t "./lu_solve bad_matrix.csv"
$ open fpc-report/index.html
```

- NaN
- Division by zero

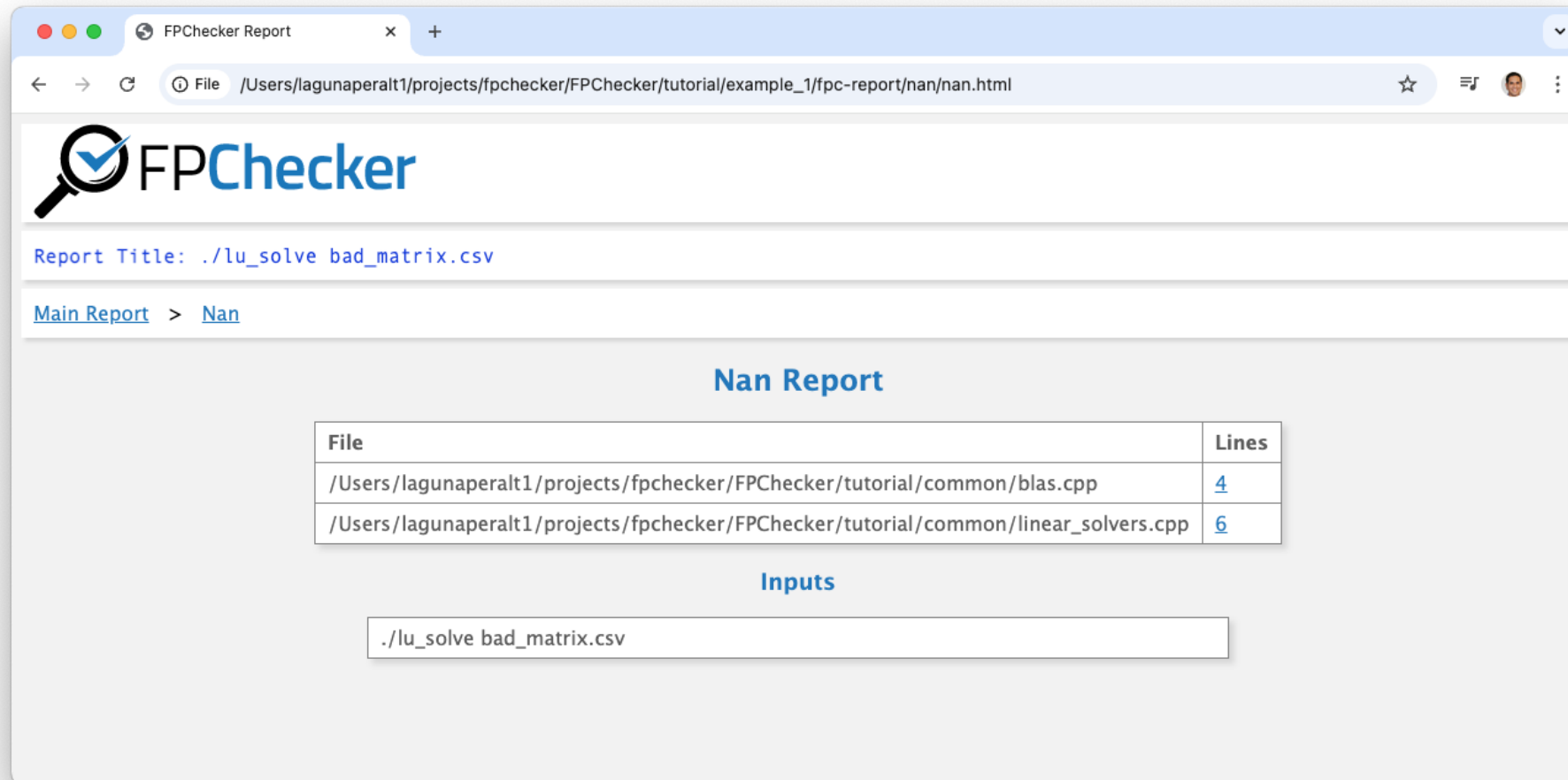
Report of Example 1



The screenshot shows a web browser window with the title 'FPChecker Report'. The address bar shows the file path: `/Users/lagunaperalt1/projects/fpchecker/FPChecker/tutorial/example_1/fpc-report/index.html`. The page features the FPChecker logo (a magnifying glass over a checkmark) and the text 'FPChecker'. Below the logo, the report title is displayed: 'Report Title: ./lu_solve_bad_matrix.csv'. A link labeled 'Main Report' is provided. The main content area is titled 'Main Report' and contains a table with floating-point error events.

	Events
 <u>Infinity (+)</u>	0
 <u>Infinity (-)</u>	0
 <u>NaN</u>	824
 <u>Division by zero</u>	1
 <u>Underflow (subnormal)</u>	0
 <u>Comparison</u>	0
 <u>Cancellation</u>	0

Report of Example 1



The screenshot shows a web browser window with the title 'FPChecker Report'. The address bar shows the file path: `/Users/lagunaperalt1/projects/fpchecker/FPChecker/tutorial/example_1/fpc-report/nan/nan.html`. The page features the FPChecker logo, which includes a magnifying glass over a checkmark. Below the logo, the report title is displayed as `./lu_solve_bad_matrix.csv`. A breadcrumb trail shows [Main Report](#) > [Nan](#). The main section is titled 'Nan Report' and contains a table with two columns: 'File' and 'Lines'. The table lists two files: `/Users/lagunaperalt1/projects/fpchecker/FPChecker/tutorial/common/blas.cpp` at line 4, and `/Users/lagunaperalt1/projects/fpchecker/FPChecker/tutorial/common/linear_solvers.cpp` at line 6. Below the table, the 'Inputs' section shows the command `./lu_solve_bad_matrix.csv`.

FPChecker

Report Title: `./lu_solve_bad_matrix.csv`

[Main Report](#) > [Nan](#)

Nan Report

File	Lines
<code>/Users/lagunaperalt1/projects/fpchecker/FPChecker/tutorial/common/blas.cpp</code>	4
<code>/Users/lagunaperalt1/projects/fpchecker/FPChecker/tutorial/common/linear_solvers.cpp</code>	6

Inputs

`./lu_solve_bad_matrix.csv`

Tutorial Examples

Topics

Example Program

- | | | |
|---|---|--|
| 1 | NaN and Infinity exceptions | Linear system ($Ax=b$) solver with LU decomposition + partial pivoting |
| 2 | Exponent usage – from FP64 and FP32 precision | Finite differences + 1D Reaction-Diffusion PDE |
| 3 | Controlling slowdown with code annotations | Finite Elements + 2D Heat Conduction PDE solver |
| 4 | Analyzing parallel code: MPI/OpenMP | MPI-based Parallel Heat PDE solver |

Example 2:

Exponent Usage on FP64-to-FP32 porting

- Location:

tutorial/example_2/reaction_diffusion.cpp

- Program description

- 1D linear **reaction-diffusion equation**
- *PDE*: $\frac{\partial u}{\partial t} = D \frac{\partial^2 u}{\partial x^2} + \lambda u$
- Explicit finite difference method
 - Forward Euler in time, Central Difference in space
- Large λ provides positive feedback
 - Over time, it leads to **exponential growth**

- Code parameters:

$$D = 0.01$$

$$\lambda = 25$$

FPChecker Use Case

- Run simulation in FP64 and FP32
- Vizualize exponent usage
- In FP32, values are "out-of-range"
 - Produce exceptions

Example 2: Script

FP64 Version

```
# Compile and run problem
$ FPC_INSTRUMENT=1 make
$ FPC_EXPONENT_USAGE=1 ./reaction_diffusion

# List trace files (there are two)
$ ls -l .fpc_logs/

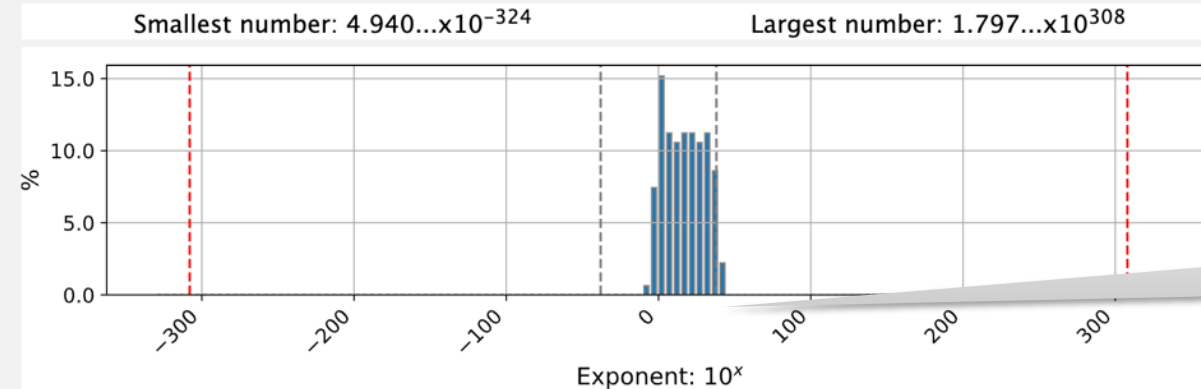
# Create report
$ fpc-create-report
$ open fpc-report/index.html

# Clear logs and remove report
$ fpc-create-report -rc
```


Report (Example 1, FP64)

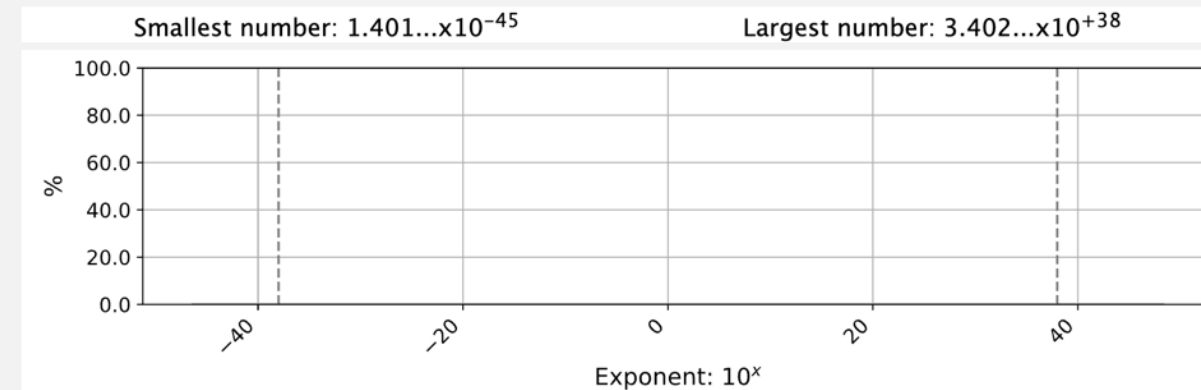
Exponent Usage Report

FP64 Distribution



Out of range for
FP32

FP32 Distribution



Example 2: Script

First Step:

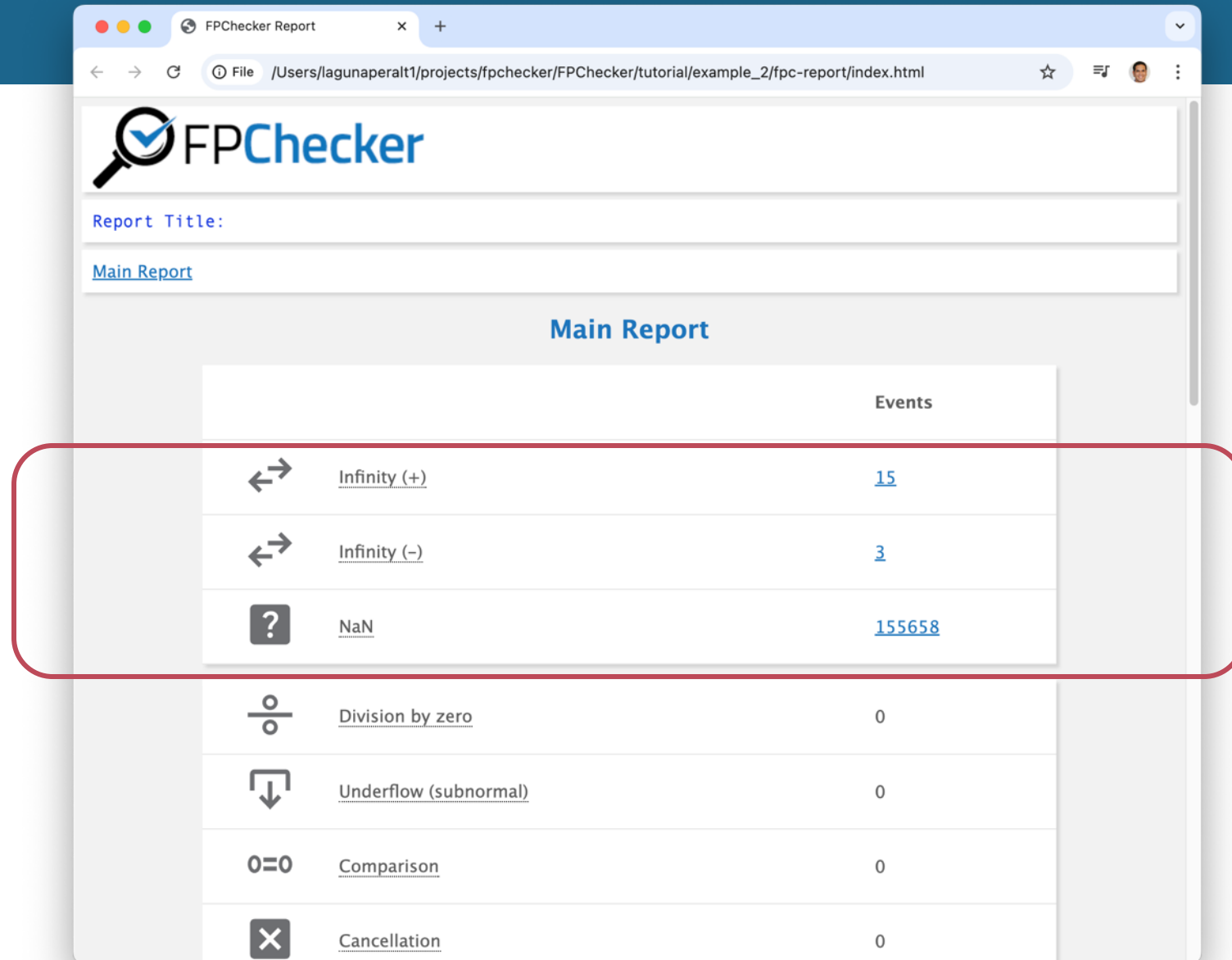
- Open `reaction_diffusion.cpp`
- Modify lines 7-8 to use FP32








```
typedef double Real_t;  
// typedef float Real_t;
```

FP32 Version

```
# Compile and run problem  
$ FPC_INSTRUMENT=1 make  
$ FPC_EXPONENT_USAGE=1 ./reaction_diffusion  
  
# List traces files (there are two)  
$ ls -l .fpc_logs/  
  
# Create report  
$ fpc-create-report  
$ open fpc-report/index.html  
  
# Clear logs and remove report  
$ fpc-create-report -rc
```

Report (Example 2, FP32)



	Events
 <u>Infinity (+)</u>	15
 <u>Infinity (-)</u>	3
 <u>NaN</u>	155658
 <u>Division by zero</u>	0
 <u>Underflow (subnormal)</u>	0
 <u>Comparison</u>	0
 <u>Cancellation</u>	0

Tutorial Examples

Topics

- 1 NaN and Infinity exceptions
- 2 Exponent usage – from FP64 and FP32 precision
- 3 Controlling slowdown with code annotations
- 4 Analyzing parallel code: MPI/OpenMP

Example Program

Linear system ($Ax=b$) solver with LU decomposition + partial pivoting

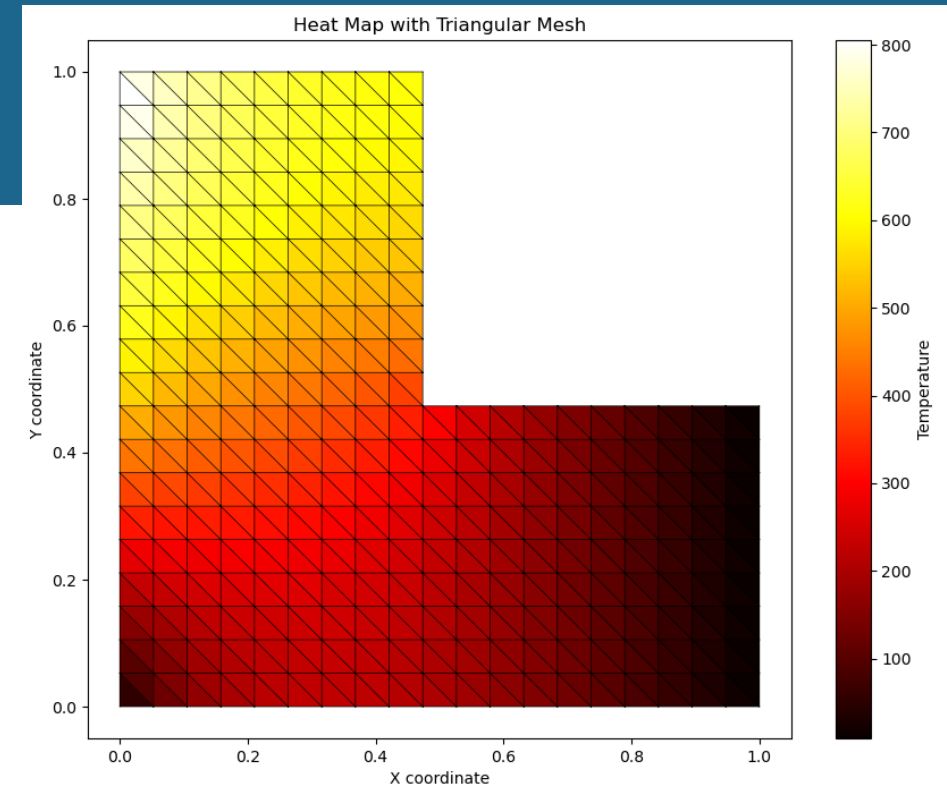
Finite differences + 1D Reaction-Diffusion PDE

Finite Elements + 2D Heat Conduction PDE solver

MPI-based Parallel Heat PDE solver

Example 3: Annotations to Control Slowdown

- Location:
`tutorial/example_3/heat_PDE_finite_elements.cpp`
- Program description
 - **2D Heat conduction equation** with a source term
 - Steady state
 - *PDE*: $\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = s(x, y)$
 - Finite elements method
 - Triangular shapes
 - $T(x, y)$: temperature distribution
 - Domain: L shape
 - Source $s(x, y) = 0$
 - Boundary conditions: temp applied on the sides



FPChecker Use Case

- Slowdown can be high (for a large problem)
- Reduce slowdown by annotating the code

Example 3: Script

- Run small problem (10 nodes)
- Should take less than 1 second

```
# Compile and run problem
$ FPC_INSTRUMENT=1 make
$ time FPC_EXPONENT_USAGE=1
$ ./heat_PDE_finite_elements 10

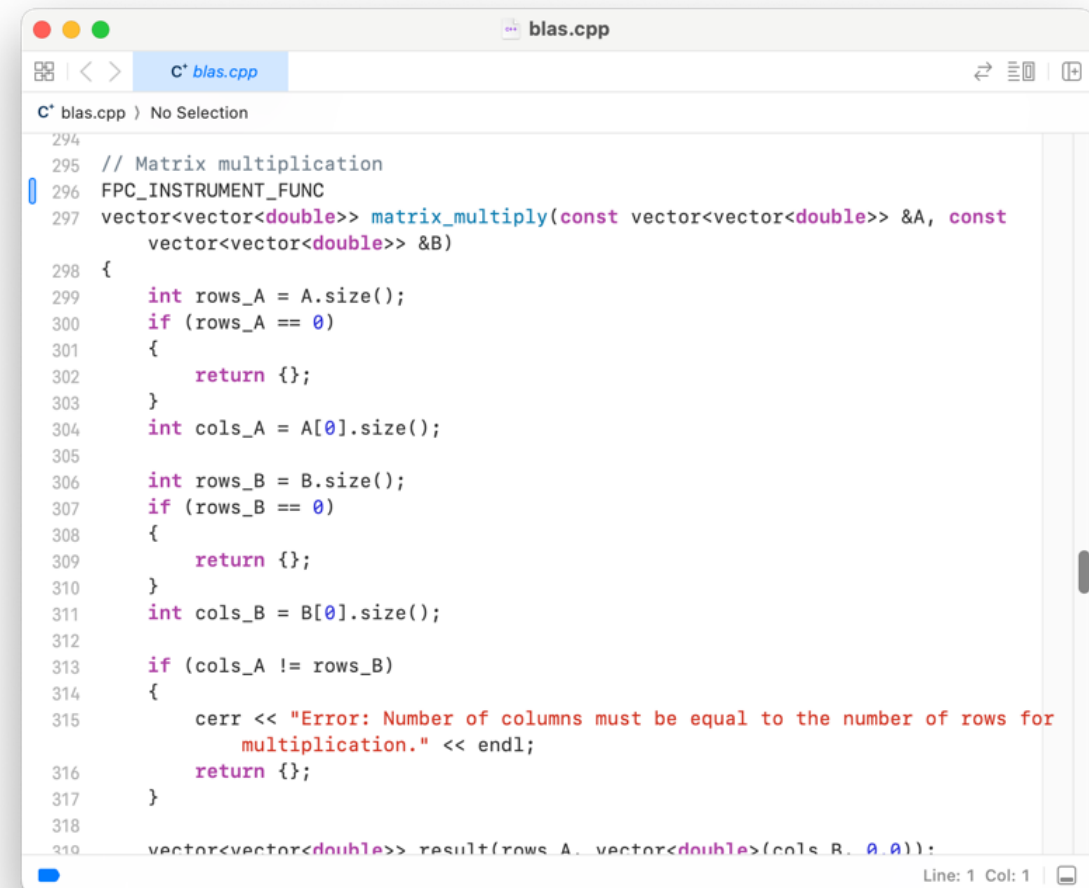
# Optional: Vizualize heat map
$ python3 plot.py
```

- Run a larger problem (50 nodes)
- It takes about 20 seconds in my laptop

```
# Compile and run problem
$ time FPC_EXPONENT_USAGE=1 ./heat_PDE_finite_elements 50
```

Code Annotations

- Let's annotate the matrix-multiply function
 - That is: **we only instrument and analyze that function**
 - Should reduce overhead significantly
- Location:
tutorial/common/blas.cpp
- Search for:
`vector<vector<double>> matrix_multiply(...`
- Add (or uncomment):
`FPC_INSTRUMENT_FUNC`



```
blas.cpp
C* blas.cpp
294
295 // Matrix multiplication
296 FPC_INSTRUMENT_FUNC
297 vector<vector<double>> matrix_multiply(const vector<vector<double>> &A, const
    vector<vector<double>> &B)
298 {
299     int rows_A = A.size();
300     if (rows_A == 0)
301     {
302         return {};
303     }
304     int cols_A = A[0].size();
305
306     int rows_B = B.size();
307     if (rows_B == 0)
308     {
309         return {};
310     }
311     int cols_B = B[0].size();
312
313     if (cols_A != rows_B)
314     {
315         cerr << "Error: Number of columns must be equal to the number of rows for
            multiplication." << endl;
316         return {};
317     }
318
319     vector<vector<double>> result(rows_A, vector<double>(cols_B, 0.0));
```


Example 3: Script

Recompile the common library

```
$ cd ../common/  
$ make clean  
$ FPC_INSTRUMENT=1 FPC_ANNOTATED=1 make  
  
$ cd ../example_3/  
$ FPC_INSTRUMENT=1 FPC_ANNOTATED=1 make  
$ time FPC_EXPONENT_USAGE=1 ./heat_PDE_finite_elements 50  
...  
...  
real    0m1.049s  
user    0m0.729s  
sys     0m0.071s
```

Lower run time

Tutorial Examples

Topics

- 1 NaN and Infinity exceptions
- 2 Exponent usage – from FP64 and FP32 precision
- 3 Controlling slowdown with code annotations
- 4 Analyzing parallel code: MPI/OpenMP

Example Program

Linear system ($Ax=b$) solver with LU decomposition + partial pivoting

Finite differences + 1D Reaction-Diffusion PDE

Finite Elements + 2D Heat Conduction PDE solver

MPI-based Parallel Heat PDE solver

Example 4: Analyzing MPI code

- Location:
tutorial/example_4/heat_mpi.cpp
- Program description
 - 1D heat equation
 - $PDE: \frac{\partial u}{\partial t} = \alpha \frac{\partial^2 u}{\partial x^2}$
 - Explicit finite difference method
- MPI domain decomposition:
 - 1D spatial grid divided into NPROC contiguous segments
 - NPROC: number of MPI processes
 - Each process computes temperature in its segment

FPChecker Use Case

- Generates traces for MPI programs
- Combine traces into a single report

Example 4: Script

```
# Show Makefile uses CXX = mpic++-fpchecker
# Compile and run problem
# OMPI_CXX indicates to Open MPI which conda compiler to use
$ OMPI_CXX=clang++ FPC_INSTRUMENT=1 make
$ FPC_EXPONENT_USAGE=1 mpiexec -n 4 ./heat_mpi

# List trace files (there are 4)
$ ls .fpc_logs/
fpc_king01_95250.json fpc_king01_95251.json
fpc_king01_95252.json fpc_king01_95253.json

# Create report
$ fpc-create-report
$ open fpc-report/index.html
```



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Showing the Configuration of the Installation

```
$ fpchecker-show
=====
          FPChecker Configuration
=====

Installation path: /tmp/tutorial/install

Add this to CFLAGS and/or CXXFLAGS:
-g -include /tmp/tutorial/install/src/Runtime_cpu.h -fpass-plugin=/tmp/tutorial/install/lib/libfpchecker_cpu.dylib

Wrappers are located here:
/tmp/tutorial/install/bin/clang-fpchecker
/tmp/tutorial/install/bin/clang++-fpchecker
/tmp/tutorial/install/bin/mpicc-fpchecker
/tmp/tutorial/install/bin/mpicxx-fpchecker
```

Conda Commands:

- Removing an environment:
`conda env remove --name <environment_name>`
- Adding an environment:
`conda env --name <environment_name>`

Demo FPChecker in Some Packages

Package		Build Model
SuperLU	Linear solver	C, cmake
Hypre	Linear solver	C, cmake, MPI
LAMMPS	Molecular dynamics	C, C++, cmake
FFTW	Fourier transform	C, autotools

Example: SuperLU

```
$ git clone git@github.com:xiaoyeli/superlu.git
$ git clone https://github.com/xiaoyeli/superlu.git
$ cd superlu
$ git checkout 4ef39075e029927e8c959b22c8e7052dcb40c995
$ mkdir build
$ cd build
$ CC=clang-fpchecker cmake -DCMAKE_INSTALL_PREFIX=./install -Denable_internal_blaslib=ON ..
$ FPC_INSTRUMENT=1 make -j
make install
```

- Configure to build internal BLAS
 - There seems to be an error with fpchecker-clang and Cmake finding BLAS in Mac

Example: FFTW

```
$ wget https://www.fftw.org/fftw-3.3.10.tar.gz
$ tar -zxvf fftw-3.3.10.tar.gz
$ cd fftw-3.3.10
$ CC=clang-fpchecker ./configure --disable-fortran --prefix=/tmp/tutorial/examples/fftw/fftw-3.3.10/fftw-install
$ FPC_INSTRUMENT=1 make -j
$ make install
```

- See example at:
 - FPChecker/tutorial/other_examples/fftw:
 - fftw_test.c

Example: LAMMPS

```
$ wget https://github.com/lammps/lammps/archive/refs/tags/stable_29Aug2024_update2.tar.gz
$ tar -xvf stable_29Aug2024_update2.tar.gz
$ cd lammps-stable_29Aug2024_update2/
$ cd cmake/
$ mkdir build
$ cd build
$ CC=clang CXX=clang++ cmake \
  -DCMAKE_CXX_FLAGS="-include /tmp/tutorial/install/src/Runtime_cpu.h -fpass-
  plugin=/tmp/tutorial/install/lib/libfpchecker_cpu.dylib -g" \
  -DBUILD_MPI=OFF -DBUILD_OMP=OFF -DBUILD_FORTRAN=OFF \
  -DBUILD_SHARED_LIBS=OFF -DENABLE_TESTING=OFF ..
$ FPC_INSTRUMENT=1 make -j
$ ./lmp -in ../../examples/melt/in.melt
```

Example: Hypre

```
$ git clone git@github.com:hypre-space/hypre.git
$ cd hypre
$ git checkout be52325a3ed8923fb93af348b1262ecfe44ab5d2
$ cd src
$ mkdir build
$ cd build
$ CC=clang cmake -DHYPRE_ENABLE_MPI=ON \
  -DHYPRE_WITH_EXTRA_CFLAGS="-include /tmp/tutorial/install/src/Runtime_cpu.h -fpass-
  plugin=/tmp/tutorial/install/lib/libfpchecker_cpu.dylib -g" ..
$ FPC_INSTRUMENT=1 make -j
$ make install
```

- HYPRE is installed in:
 - /tmp/tutorial/examples/hypre/src/hypre
- Test in tutorial/other_examples/hypre:
 - To compile example:
FPC_INSTRUMENT=1 OMPI_CC=clang make
HYPRE_MATRIX=matrix.csv ./hypre_test 0

Color Palette

Contrast red

