FLiT

Locating Floating-Point Variability Induced By Compiler Optimizations

Ignacio Laguna
Lawrence Livermore National Laboratory

Ganesh Gopalakrishnan
University of Utah

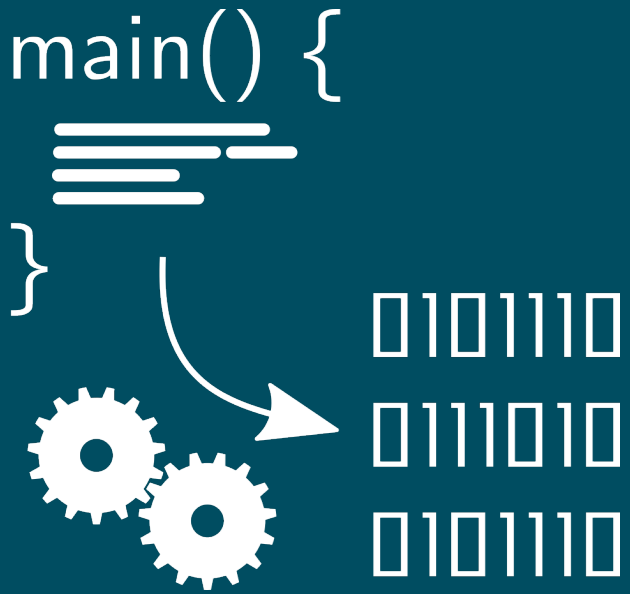
Acknowledgements to
Michael Bentley (author of FLiT)
John Jacobson (bug-fixes, development)
Cayden Lund (beginning GPU-FLiT)

http://fpanalysistools.org/

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 (LLNL-PRES-780623).

Numerical Reproducibility Across Compilers

… desired, but not guaranteed under optimizations



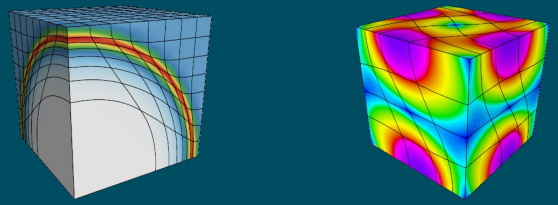
Compiling using aggressive optimizations (e.g., -O3 and Fast-Math) can give vastly different program results

- Not because the compiler has a bug
- But because of floating-point rounding effects

This can seriously undermine one's quest for higher speed … by giving the wrong answer!

Example of Compiler-Induced Variability

Laghos: A high-order Lagrangian hydrodynamics mini-application



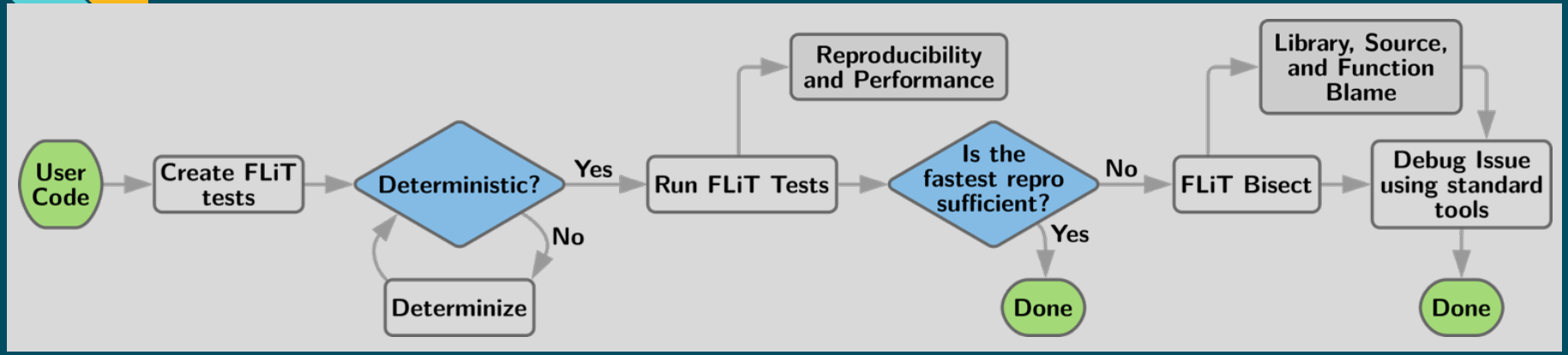
xlc - O2 ⟶ xlc - O3

In one iteration: **11.2% relative error, negative gas density!**

And speedup by a factor of 2.42

What happened? How can I investigate it?

FLiT Workflow



Multiple Levels:

1. Determine variability-inducing compilations
2. Analyze the tradeoff of reproducibility and performance
3. Locate variability by identifying files and functions causing variability

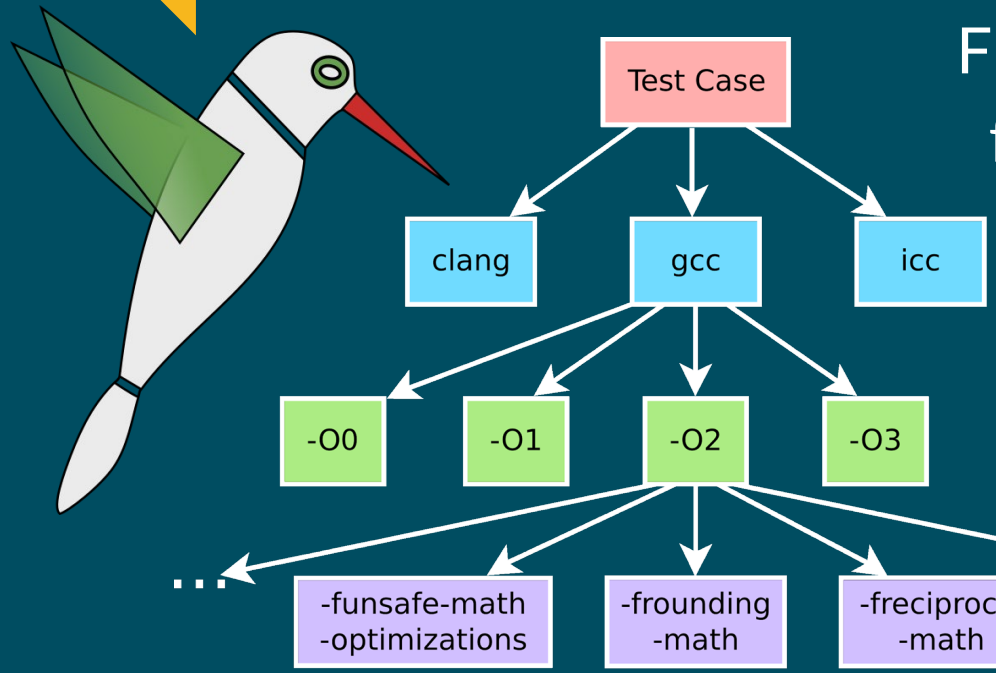
FLiT Installation

FLiT is easy to install

- Very few dependencies
- Use from repository or install on the system

```
 git $      git clone https://github.com/PRUNERS/FLiT.git
Cloning into 'FLiT'...
[...]
 git $      cd FLiT
 FLiT $     make
   src/timeFunction.cpp          - > src/timeFunction.o
   src/flitHelpers.cpp           - > src/flitHelpers.o
   src/TestBase.cpp        - > src/TestBase.o
   src/flit.cpp          - > src/flit.o
   src/FlitCsv.cpp         - > src/FlitCsv.o
   src/InfoStream.cpp          - > src/InfoStream.o
   src/subprocess.cpp          - > src/subprocess.o
   src/Variant.cpp         - > src/Variant.o
   src/fsutil.cpp          - > src/fsutil.o
   mkdir    lib
Building lib/libflit.so
 FLiT $     sudo make install
Installing...
   Generating /usr/share/flit/scripts/flitconfig.py
 FLiT $     sudo apt install python3          - toml python3     - pyelftools
[...]
```

Multi-Compilation Search



FLiT is a reproducibility test framework in the PRUNERS toolset (pruners.github.io).

Hundreds of compilations are compared against a baseline compilation.

Exercises

Exercises with FLiT

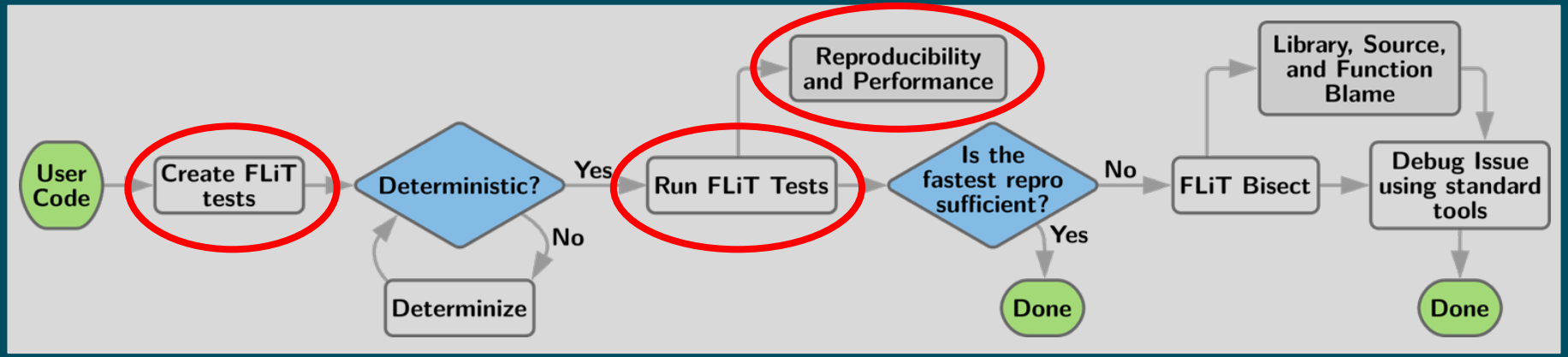
1. MFEM: many compilations and measure variability — this tutorial
2. MFEM: locate site of variability with FLiT Bisect — partly this tutorial
3. LULESH: auto-run many FLiT Bisects and Bisect-Biggest — try on your own later

Directory Structure

```
Module - FLiT/
├── exercise  - 1/
├── exercise  - 2/
├── exercise  - 3/
├── packages/
├── README.md
└── setup.sh
```

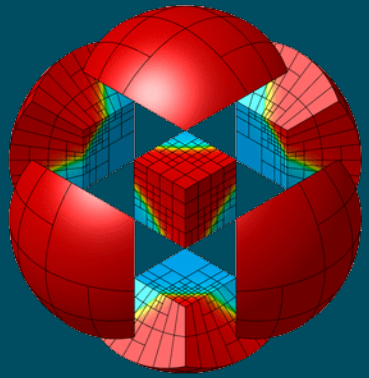
Exercise 1

Exercise 1 - Goal



1. Generate a FLiT test
2. Run the test with many compilations
3. Look at the results

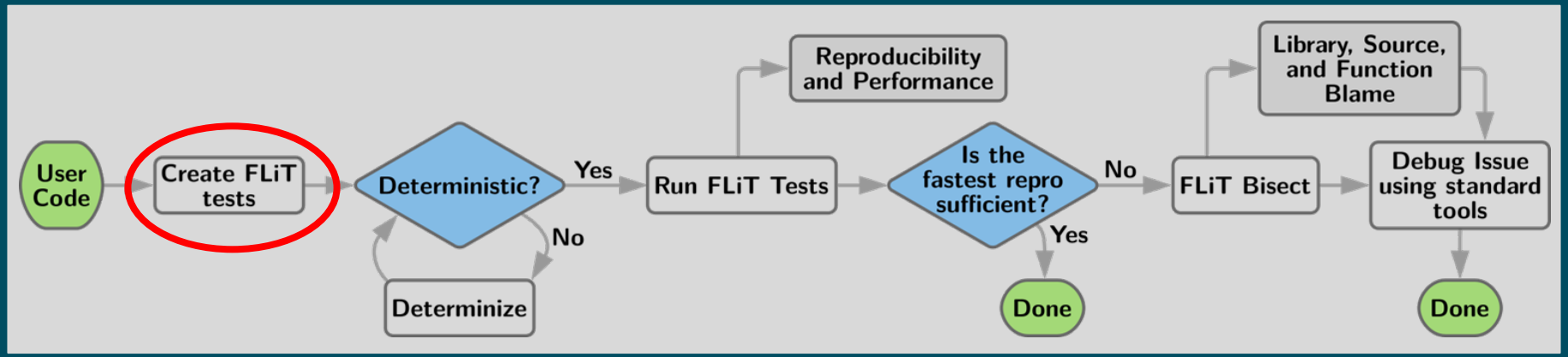
Application: MFEM



source files	97
average functions per file	31
total functions	2,998
source lines of code	103,205

- Open-source finite element library
  - Developed at LLNL
  - https://github.com/mfem/mfem.git
- Provides many example use cases
- Represents real-world code

Exercise 1 - Create MFEM Test



What does it take to create a FLiT test from an MFEM example?

Let's find out!

Exercise 1 - Create MFEM Test

```
Module - FLiT $ cd exercise - 1
```

Let's look at the test for MFEM example #13
tests/Mfem13.cpp

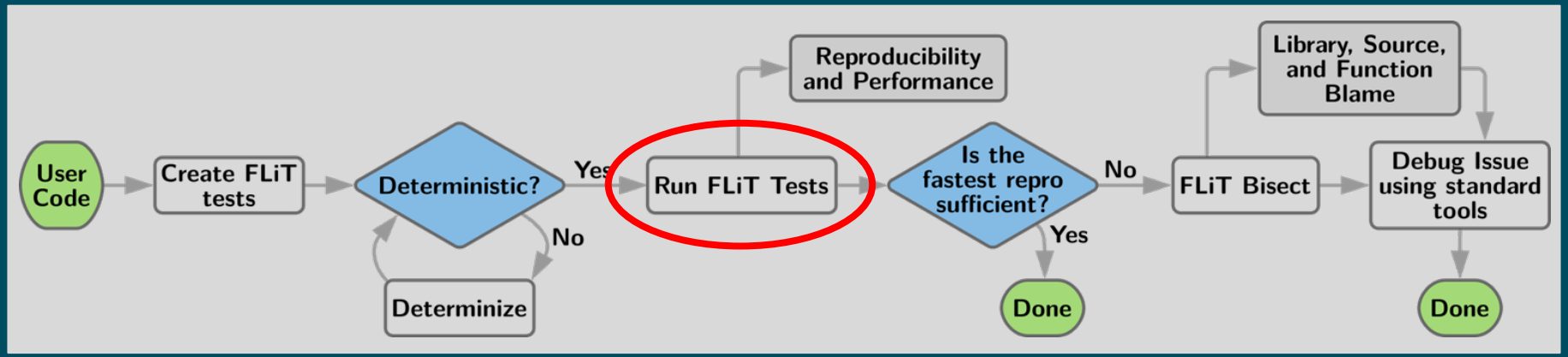
```
exercise - 1 $ vim tests/MFEM13.cpp
```

or

```
exercise - 1 $ pygmentize tests/Mfem13.cpp | cat - n
```

Further details skipped; provided at the end of this slide deck

Exercise 1 - Run the MFEM Test



Each command has a script.

Run the script or the command from the slide - your choice

Exercise 1 - ./step - 01.sh

```
exercise - 1 $ flit update
Creating ./Makefile
```

- Auto-generate Makefile
- Since it is auto-generated, it is usually not committed in a repo

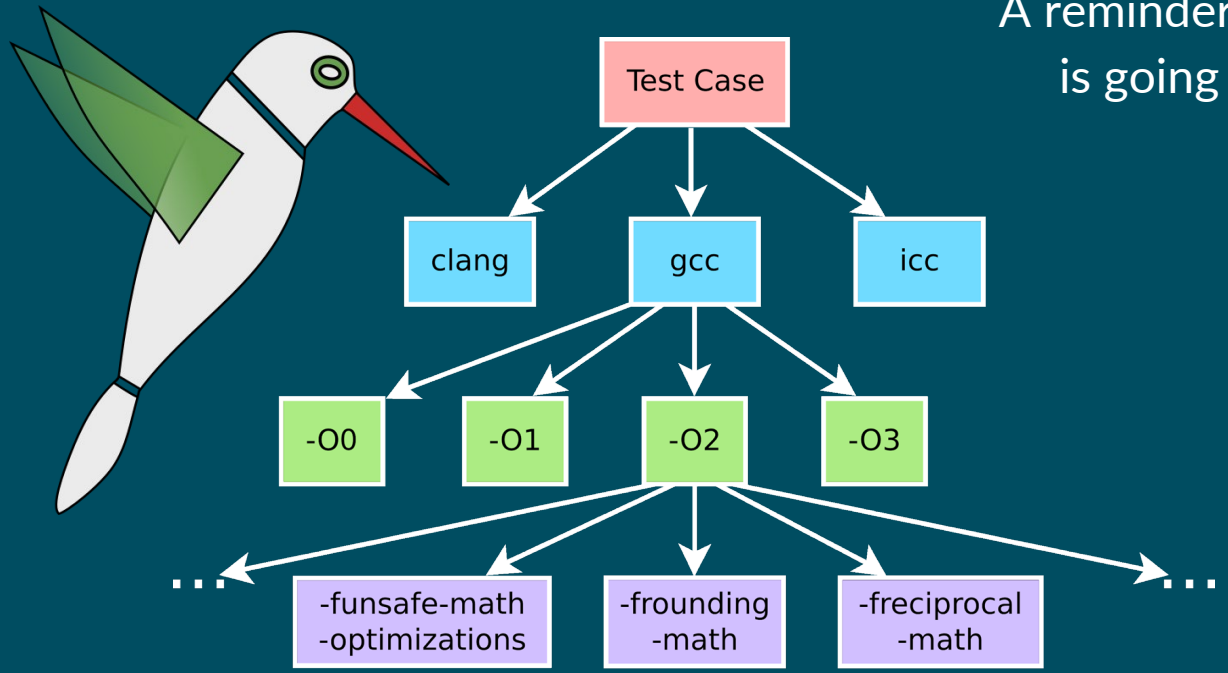
Exercise 1 - ./step - 02.sh

```
exercise - 1 $ make runbuild -j 1
  mkdir obj/gt
  /home/user1/Module - FLiT/packages/mfem/linalg/densemat.cpp -> obj/gt/densemat.cpp.o
  main.cpp -> obj/gt/main.cpp.o
  tests/Mfem13.cpp -> obj/gt/Mfem13.cpp.o
Building gtrun
  mkdir bin
  mkdir obj/GCC_ip-172-31-8-101_FFAST_MATH_O3
  /home/user1/Module - FLiT/packages/mfem/linalg/densemat.cpp -> obj/GCC_ip - 172-31-8[...]
[...]
```

(takes about 1 minute)

- For verbose output use make VERBOSE=1 . . .
- **Will make all compilations from search space into bin/**
- Can do more parallelism (but not for this tutorial)

Exercise 1 - ./step - 02.sh



A reminder about what is going on here...

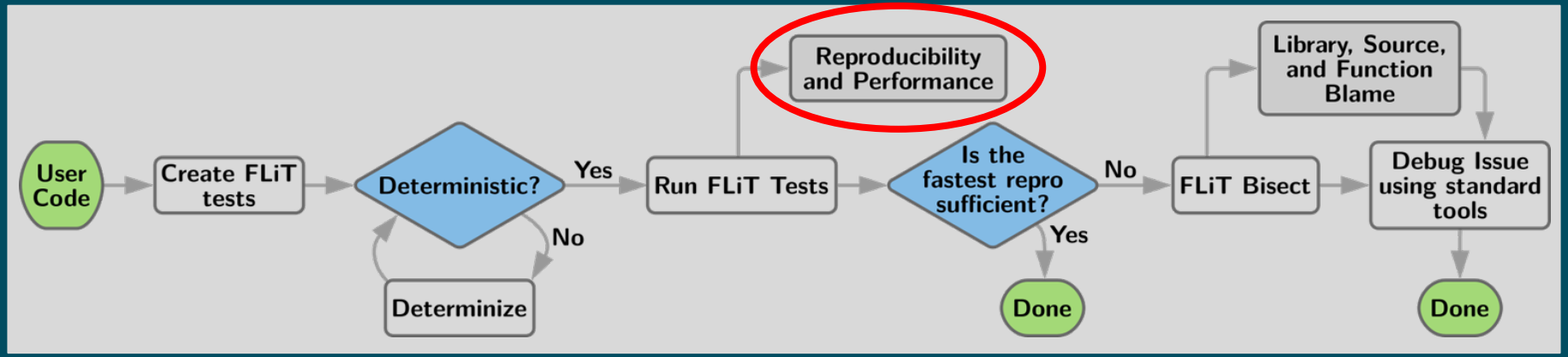
Exercise 1 - ./step - 03.sh

```
exercise - 1 $ make run -j 1
mkdir results
gtrun - > ground - truth.csv
results/GCC_ip - 172 - 31 - 8 - 101_FFAST_MATH_O3 out - > results/GCC_ip - 172 - 31 - 8 - 101_FFA[...]
results/GCC_ip - 172 - 31 - 8 - 101_FUNSAFE_MATH_OPTIMIZATIONS_O3 out - > results/GCC_ip - [...]
results/GCC_ip - 172 - 31 - 8 - 101_MFMA_O3 out - > results/GCC_ip - 172 - 31 - 8 - 101_MFMA_O3 o[...]
results/CLANG_ip - 172 - 31 - 8 - 101_FFAST_MATH_O3 out - > results/CLANG_ip - 172 - 31 - 8 - 101[...]
results/CLANG_ip - 172 - 31 - 8 - 101_FUNSAFE_MATH_OPTIMIZATIONS_O3 out - > results/CLANG[...]
results/CLANG_ip - 172 - 31 - 8 - 101_MFMA_O3 out - > results/CLANG_ip - 172 - 31 - 8 - 101_MFMA_[...]
[...]
```

(takes about 1 minute)

- Runs the test and the compare() function

Exercise 1 - Analyze Results



Let us look at the generated results

They are in the results/ directory

Exercise 1 - ./step - 04.sh

```
exercise - 1 $ flit import results/*.csv
Creating results.sqlite
Importing results/CLANG_yoga - manjaro_FFAST_MATH_O3- out - comparison.csv
Importing results/CLANG_yoga - manjaro_FUNSAFE_MATH_OPTIMIZATIONS_O3- out - comparison.csv
Importing results/CLANG_yoga - manjaro_MFMA_O3- out - comparison.csv
Importing results/GCC_yoga - manjaro_FFAST_MATH_O3- out - comparison.csv
Importing results/GCC_yoga - manjaro_FUNSAFE_MATH_OPTIMIZATIONS_O3- out - comparison.csv
Importing results/GCC_yoga - manjaro_MFMA_O3- out - comparison.csv
```

Creates results.sqlite

Exercise 1 - ./step - 05.sh

```
exercise - 1 $ sqlite3 results.sqlite
SQLite version 3.28.0 2019 - 04- 16 19:49:53
Enter ".help" for usage hints.
sqlite> .tables
runs  tests
sqlite> .headers on
sqlite> .mode column
sqlite> select * from runs;
id          rdate                      label
----------  -------------------------  ----------
1           2019 - 07- 08 23:05:19.358055  First FLiT Results
```

Two tables in the database:

1. runs : has our label and the date and time of importing
2. tests : test results with timing

Exercise 1 - ./step - 06.sh

```
sqlite> select compiler, optl, switches, comparison, nanosec from tests;
compiler      optl        switches     comparison  nanosec
------------  ----------  -----------  ----------  ----------
clang++-6.0   -O3         -ffast-math  0.0         2857386994
clang++-6.0   -O3         -funsafe-ma  0.0         2853588952
clang++-6.0   -O3         -mfma        0.0         2858789982
g++-7         -O3         -ffast-math  0.0         2841191528
g++-7         -O3         -funsafe-ma  0.0         2868636192
g++-7         -O3         -mfma        193.007351  2797305220
sqlite> .q
```

One compilation had 193% relative error!

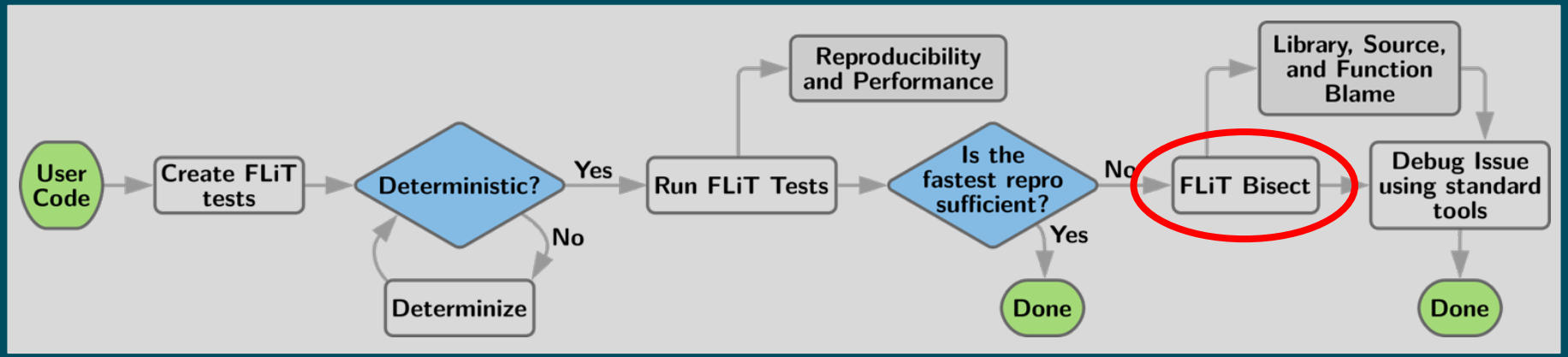
The others had no error.

Now to find the sites in the source code

Exercise 2

```
exercise - 1 $ cd ../exercise - 2
```

Exercise 2 - FLiT Bisect



We want to find the file(s)/function(s) where FMA caused 193% relative error

Compilation: g++- 7 - O3 - mfma

Exercise 2 - ./step - 07.sh

What's Different?

```
exercise - 2 $ diff - u ../exercise - 1/custom.mk ./custom.mk
--- ../exercise - 1/custom.mk 2019 - 07- 01 16:09:39.239923037 - 0600
+++ custom.mk 2019 - 07- 01 16:07:41.090571010 - 0600
@@ 17,9 +17,15 @@
 #SOURCE += $(wildcard ${MFEM_SRC}/linalg/*.cpp)
 #SOURCE += $(wildcard ${MFEM_SRC}/mesh/*.cpp)

- # just the one source file to see there is a difference
 SOURCE += ${MFEM_SRC}/linalg/densemat.cpp # where the bug is

+# a few more files to make the search space a bit more interesting
+SOURCE += ${MFEM_SRC}/linalg/matrix.cpp
+SOURCE += ${MFEM_SRC}/fem/gridfunc.cpp
+SOURCE += ${MFEM_SRC}/fem/linearform.cpp
+SOURCE += ${MFEM_SRC}/mesh/point.cpp
+SOURCE += ${MFEM_SRC}/mesh/quadrilateral.cpp
+
 CC_REQUIRED += - I${MFEM_SRC}
 CC_REQUIRED += - I${MFEM_SRC}/examples
 CC_REQUIRED += - isystem ${HYPRE_SRC}/src/hypre/include
```

Exercise 2 - ./step - 08.sh

Again, we need to regenerate the Makefile

```
exercise - 2 $ flit update
Creating ./Makefile
```

Before we bisect, remember which compilation caused a problem:

g++- 7 - O3 - mfma

Exercise 2 - ./step - 09.sh

```
exercise -2$ flit bisect --precision=double "g++-7 -O3 -mfma" Mfeml3
Updating ground-truth results - ground-truth.csv - done
Searching for differing source files:
  Created ./bisect-04/bisect-make-01.mk - compiling and running - score 193.00735125466363
  Created ./bisect-04/bisect-make-02.mk - compiling and running - score 193.00735125466363
  Created ./bisect-04/bisect-make-03.mk - compiling and running - score 0.0
  Created ./bisect-04/bisect-make-04.mk - compiling and running - score 193.00735125466363
    Found differing source file /home/user1/Module-FLiT/packages/mfem/linalg/densemat.cpp: score
193.00735125466363
[...]
All variability inducing symbols:
  /home/user1/Module-FLiT/packages/mfem/linalg/densemat.cpp :3692
_ZN4mfem13AddMult_a_AAtEdRKNS_11DenseMatrixERS0_ -- mfem::AddMult_a_AAt (double, mfem::DenseMatrix
const&, mfem::DenseMatrix&) (score 193.00735125466363)
```

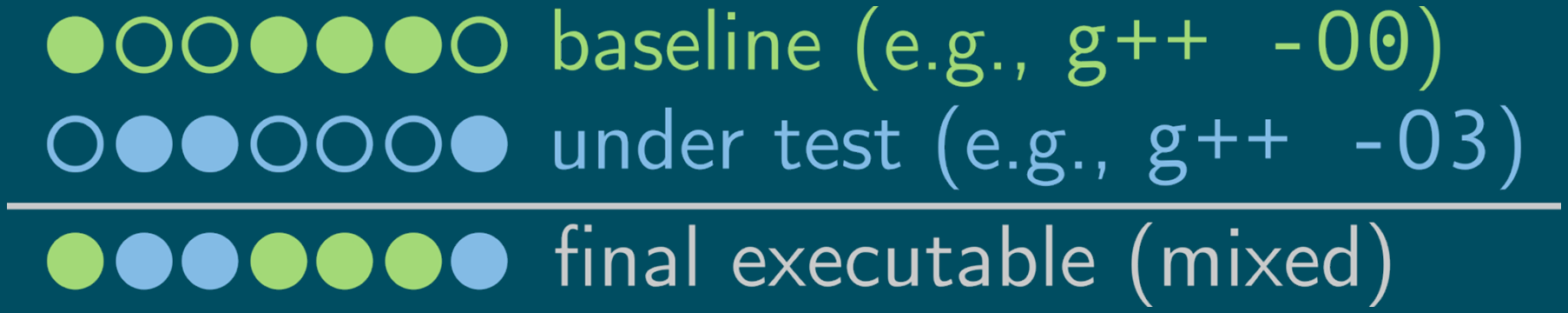
(takes approximately 1 minute 30 seconds)

- Finds the file: `densemat.cpp`
- Finds the function: `mfem::AddMult_a_AAt()`

Exercise 2 - Bisect Details

First locate variability files

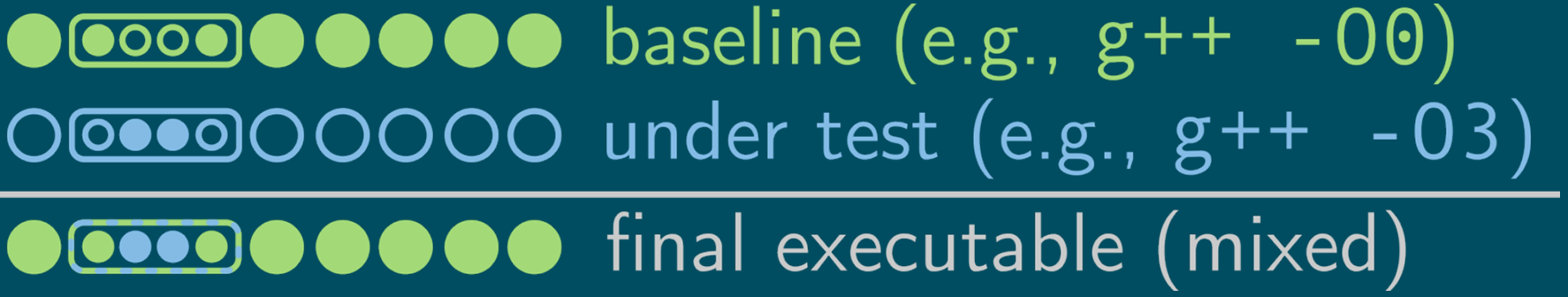
Approach: combine object files from the two compilations



Exercise 2 - Bisect Details

Approach: combine symbols **after compilation**

Convert function symbols into weak symbols



Downside: Requires recompiling with -fPIC

Exercise 2 - ./step - 10.sh

```
exercise - 2 $ cat - n ../packages/mfem/linalg/densemat.cpp | tail - n +3688 | head - n 24
3688  void AddMult_a_AAt( double a, const DenseMatrix &A, DenseMatrix &AAt)
3689  {
3690     double d;
3691
3692     for ( int i = 0; i < A.Height(); i++)
3693     {
3694        for ( int j = 0; j < i; j++)
3695        {
3696           d = 0. ;
3697           for ( int k = 0; k < A.Width(); k++)
3698           {
3699              d += A(i,k) * A(j,k);
3700           }
3701           AAt(i, j) += (d *= a);
3702           AAt(j, i) += d;
3703        }
3704        d = 0. ;
3705        for ( int k = 0; k < A.Width(); k++)
3706        {
3707           d += A(i,k) * A(i,k);
3708        }
3709        AAt(i, i) += a * d;
3710     }
3711  }
```

Computes

$$M = M + aAA^\top$$

CONCLUDING REMARKS

- Using FLiT and its bisect feature, we can root-cause files/functions whose numerical results can affect the final results
- For additional details, please see the CACM article authored by the presenters
  - https://cacm.acm.org/magazines/2021/2/250083-keeping-science-on-keel-when-software-moves/fulltext

Advanced exercises now follow (including LULESH)

Exercise 3

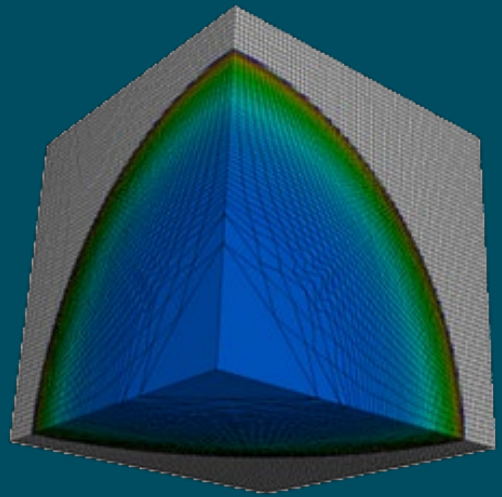
```
exercise - 2 $ cd ../exercise - 3
```

Exercise 3 Application: LULESH

- Proxy application developed at LLNL
- Models a shock hydrodynamics problem

Goal: explore more FLiT Bisect functionality

- Auto-Bisect all from results.sqlite
- Bisect-Biggest instead of Bisect-All



Exercise 3 - ./step - 11.sh

```
exercise - 3 $ sqlite3 results.sqlite
SQLite version 3.22.0 2018 - 01- 22 18:45:57
Enter ".help" for usage hints.
sqlite> .headers on
sqlite> .mode column
sqlite> select compiler, optl, switches, comparison, nanosec from tests;
compiler    optl       switches         comparison          nanosec
----------  ---------  ---------------  ------------------  ---------
clang++ - 6.0  - O3  - freciprocal - math  5.52511478433538e - 05  432218541
clang++ - 6.0  - O3  - funsafe - math - opt  5.52511478433538e - 05  432185456
clang++ - 6.0  - O3        0.0               433397072
g++- 7         - O3  - freciprocal - math  5.52511478433538e - 05  441362811
g++- 7         - O3  - funsafe - math - opt  7.02432004920159  436202864
g++- 7         - O3  - mavx2 - mfma  1.02330009691563  416599918
g++- 7         - O3        0.0               432654778
sqlite> .q
```

Five variability compilations.

Let's investigate!

Exercise 3 - ./step - 12.sh

```
exercise - 3 $ flit update
Creating ./Makefile
```

Nothing surprising here...

Exercise 3 - ./step - 13.sh

```
exercise - 3 $ flit bisect -- auto - sqlite - run results.sqlite -- parallel=1 -- jobs=1
Before parallel bisect run, compile all object files
   (1 of 5) clang++ - O3 - freciprocal - math: done
   (2 of 5) clang++ - O3 - funsafe - math - optimizations: done
   (3 of 5) g++ - O3 - freciprocal - math: done
   (4 of 5) g++ - O3 - funsafe - math - optimizations: done
   (5 of 5) g++ - O3 - mavx2 - mfma: done
Updating ground - truth results - ground - truth.csv - done

Run 1 of 5
flit bisect -- precision double "clang++ - O3 - freciprocal - math" LuleshTest
Updating ground - truth results - ground - truth.csv - done
Searching for differing source files:
[...]
```

(takes approximately 3 min 10 sec)

Will automatically run all rows with comparison > 0.0

Let's look at the Bisect algorithm

How to Perform the Search

- **Problem:** search space is exponential
- **Problem:** floating-point errors combine in non-intuitive ways

Assumption 1: errors do not exactly cancel

- **Delta Debugging:** old but good idea $O(n \log n)$

Assumption 2: variability sites act alone

- **Linear Search:** simple $O(n)$
- **Logarithmic Search:** find one at a time $O(k \log n)$

Bisect Algorithm

- Simple divide and conquer
- Guaranteed to have no false positives
- False negatives identified automatically

Algorithm 1 Bisect Algorithm

```
1:  procedure BisectAll(Test, items)
2:      found ← { }
3:      T ← Copy(items)
4:      while Test(T) > 0 do
5:          G, next ← BisectOne(Test, T)
6:          found ← found ∪ next
7:          T ← T \ G
8:      assert Test(items) = Test(found)
9:      return found
```

```
1:  procedure BisectOne(Test, items)
2:      if Size(items) = 1 then                    ▷ base case
3:          assert Test(items) > 0
4:          return items, items
5:      Δ1, Δ2 ← SplitInHalf(items)
6:      if Test(Δ1) > 0 then
7:          return BisectOne(Test, Δ1)
8:      else
9:          G, next ← BisectOne(Test, Δ2)
10:         return G ∪ Δ1, next
```

Exercise 3 - ./step - 14.sh

```
exercise - 3 $ head - n 3 auto - bisect.csv
testid,bisectnum,compiler,optl,switches,precision,testcase,type,name,return
1,1,clang++, - O3, - freciprocal - math,double,LuleshTest,completed,"lib,src,sym",0
1,1,clang++, - O3, - freciprocal - math,double,LuleshTest,src,"('tests/LuleshTest.cpp',
0.33294020544031533)",0
```

Results are placed in a CSV file for easy access

Exercise 3 - Bonus

Exercise 3 - efficiency

The 4th run (from auto-run) took 34 compilation / run steps.

```
Run 4 of 5
flit bisect          --  precision double "g++          - O3  - funsafe    - math - optimizations" LuleshTest
    [...]
All variability inducing symbols:
    ../packages/LULESH/lulesh          - init.cc:16 _ZN6DomainC1Eiiiiiiiii                    --    Domain::Domain(int, int, int, int,
int, int, int, int, int) (score 2.3302358973548727)
    ../packages/LULESH/lulesh          - init.cc:219 _ZN6Domain9BuildMeshEiii                 --    Domain::BuildMesh(int, int,
int) (score 1.4315005606175104)
    ../packages/LULESH/lulesh.cc:1362 _Z14CalcElemVolumePKdS0_S0_                  --    CalcElemVolume(double const*,
double const*, double const*) (score 0.9536115035892543)
    ../packages/LULESH/lulesh.cc:1507 _Z22CalcKinematicsForElemsR6Domaindi                      --
CalcKinematicsForElems(Domain&, double, int) (score 0.665781828022106)
    ../packages/LULESH/lulesh.cc:2651 _Z11lulesh_mainiPPc                  --    lulesh_main(int, char**) (score
0.3328909140110529)
```

Can we do better?

What if we only want the **top contributing function**?

Exercise 3 - ./step - 15.sh

```
exercise -3$ flit bisect --biggest=1 --precision=double "g++-7 -O3 -funsafe-math-optimizations"
LuleshTest
Updating ground-truth results - ground-truth.csv - done
Looking for the top 1 different symbol(s) by starting with files
  [...]
    Found differing source file ../packages/LULESH/lulesh-init.cc: score 3.7609285311270604
    Searching for differing symbols in: ../packages/LULESH/lulesh-init.cc
      [...]
        Found differing symbol on line 16 -- Domain::Domain(int, int, int, int, int, int, int, int,
int) (score 2.3302358973548727)
  [...]
  Created ./bisect-06/bisect-make-20.mk - compiling and running - score 0.022750390077923448
    Found differing source file tests/LuleshTest.cpp: score 0.022750390077923448
[...]
The 1 highest variability symbol:
  ../packages/LULESH/lulesh-init.cc:16 _ZN6DomainC1Eiiiiiiiii -- Domain::Domain (int, int, int, int,
int, int, int, int, int) (score 2.3302358973548727)
```

- Found the same highest variability function: `Domain::Domain()`
- Found it in 20 compile/run cycles instead of 34
- Searches for symbols after each file

Thank You!
Questions?

pruners.github.io/flit

Details of test creation now follow

Exercise 1 - Create MFEM Test

tests/MFEM13.cpp

```
 6  // Redefine main() to avoid name clash.  This is the function we will test
 7  #define main mfem_13p_main
 8  #include      "ex13p.cpp"
 9  #undef main
10  // Register it so we can use it in call_main() or call_mpi_main()
11  FLIT_REGISTER_MAIN(mfem_13p_main);
```

Things to notice:

- Include ex13p.cpp from MFEM without modification
- Rename main() to mfem_13p_main() to avoid name clash
- Register mfem_13p_main() with FLiT to be called as a separate process

Exercise 1 - Create MFEM Test

tests/MFEM13.cpp

```
14  template    <typename   T>
15  class   Mfem13 :    public    flit::TestBase<T> {
16 public    :
17      Mfem13(std::string id) : flit::TestBase<T>(std::move(id)) {}
18      virtual     size_t    getInputsPerRun()       override     {   return     0; }
19      virtual     std::vector<T> getDefaultInput()              override     {   return     { }; }
20
21      virtual     long   double   compare(  const    std::vector<std::string> &ground_truth,
22                                             const    std::vector<std::string> &test_results)                 const    override     {
23- 50   [...]
 51     }
```

- A simple test setup with no floating-point inputs
- compare() does L2 norm and returns % relative difference (skipped)

Exercise 1 - Create MFEM Test

tests/MFEM13.cpp

```
64  // Only implement the test for double precision
65  template    <>
66  flit::Variant Mfem13<           double  >::run_impl(      const     std::vector<       double  > &ti) {
67      FLIT_UNUSED(ti);
68
69      // Run in a temporary directory so output files don't clash
70      std::string start_dir = flit::curdir();
71      flit::TempDir exec_dir;
72      flit::PushDir pusher(exec_dir.name());
```

- Only double precision is implemented
- Create a temporary directory and go there (for out files)

Exercise 1 - Create MFEM Test

tests/MFEM13.cpp

```
74    // Run the example's main under MPI
75    auto   meshfile = flit::join(start_dir,                    "data"    ,   "beam - tet.mesh"    );
76    auto   result = flit::call_mpi_main(
77                                  mfem_13p_main,
78                                  "mpirun    - n 1   --  bind  - to none"    ,
79                                  "Mfem13" ,
80                                  " --  no - visualization          --  mesh "    + meshfile);
```

- Call mfem_13p_main() as a child process with MPI
- Command-line arguments for mpirun are given
- For this tutorial, only one MPI process, but can use many
- Command-line arguments for mfem_13p_main() are given

Exercise 1 - Create MFEM Test

tests/MFEM13.cpp

```
82   // Output debugging information
83   std::ostream &out = flit::info_stream;
84   out << id <<         " stdout: "         << result.out <<         " \ n" ;
85   out << id <<         " stderr: "         << result.err <<         " \ n" ;
86   out << id <<         " return: "         << result.ret <<         " \ n" ;
87   out.flush();
88
89   if    (result.ret !=          0) {
90       throw    std::logic_error(          "Failed to run my main correctly"                );
91   }
```

- Result from call_mpi_main() have out , err , and ret
- We check for an error using the return code, ret

Exercise 1 - Create MFEM Test

tests/MFEM13.cpp

```
 93    // We will be returning a vector of strings that hold the mesh data
 94    std::vector<std::string> retval;
95- 111  [...]
112    // Return the mesh and mode files as strings
113    return      flit::Variant(retval);
```

- We skip the details here
- Return value is a vector<string> used by compare()

Exercise 1 - Create MFEM Test

tests/MFEM13.cpp

```
116  REGISTER_TYPE(Mfem13)
```

Finally, we register the test class with FLiT

Now, let's look at how the FLiT configuration looks
This has config about compilers and the search space

```
exercise - 1 $ vim flit - config.toml
```

Exercise 1 - FLiT Configuration

flit - config.toml

```
1 [run]
2 enable_mpi = true
```

- Needed to get the compiler and linker flags for MPI
- Grabs the flags from mpic++

Exercise 1 - FLiT Configuration

flit - config.toml

```
4  [dev_build]
5  compiler_name     = 'g++'
6  optimization_level          = ' - O3'
7  switches     = ' - mavx2  - mfma'
8
9  [ground_truth]
10 compiler_name     = 'g++'
11 optimization_level          = ' - O2'
12 switches     = ''
```

Defines the compilations for make dev and make gt

Exercise 1 - FLiT Configuration

flit - config.toml

```
14 [[compiler]]
15 binary = 'g++ - 7'
16 name = 'g++'
17 type = 'gcc'
18 optimization_levels = [
19     ' - O3' ,
20 ]
21 switches_list = [
22     ' - ffast - math' ,
23     ' - funsafe - math - optimizations' ,
24     ' - mfma' ,
25 ]
```

- Defines the “g++” compiler
- Defines the compilation search space

Exercise 1 - FLiT Configuration

flit - config.toml

```
27 [[compiler]]
28 binary = 'clang++ - 6.0'
29 name = 'clang++'
30 type = 'clang'
31 optimization_levels = [
32     ' - O3' ,
33 ]
34 switches_list = [
35     ' - ffast - math' ,
36     ' - funsafe - math - optimizations' ,
37     ' - mfma' ,
38 ]
```

- Defines the “clang++” compiler
- Defines the compilation search space

Exercise 1 - Makefile Configuration

A second configuration file: custom.mk

- FLiT autogenerates a Makefile
- custom `.mk` is included in the `Makefile`
- Tells FLiT how to compile your test(s)

```
exercise - 1 $ vim custom.mk
```

Exercise 1 - Makefile Configuration

custom.mk

```
 4 PACKAGES_DIR   :=  $( abspath    ../packages)
 5 MFEM_SRC       :=  $(PACKAGES_DIR)/mfem
 6 HYPRE_SRC      :=  $(PACKAGES_DIR)/hypre
 7 METIS_SRC      :=  $(PACKAGES_DIR)/metis   - 4.0
 8
 9 SOURCE         :=
10 SOURCE         +=  $( wildcard     *.cpp)
11 SOURCE         +=  $( wildcard     tests/*.cpp)
12
13 # Compiling all sources of MFEM into the tests takes too long for a tutorial
14 # skip it.  Instead, we link in the MFEM static library
15 #SOURCE        += $(wildcard ${MFEM_SRC}/fem/*.cpp)
16 #SOURCE        += $(wildcard ${MFEM_SRC}/general/*.cpp)
17 #SOURCE        += $(wildcard ${MFEM_SRC}/linalg/*.cpp)
18 #SOURCE        += $(wildcard ${MFEM_SRC}/mesh/*.cpp)
19
20 # just the one source file to see there is a difference
21 SOURCE         +=  ${MFEM_SRC}/linalg/densemat.cpp          # where the bug is
```

Exercise 1 - Makefile Configuration

custom.mk

```
23 CC_REQUIRED    += -I ${MFEM_SRC}
24 CC_REQUIRED    += -I ${MFEM_SRC}/examples
25 CC_REQUIRED    += -isystem ${HYPRE_SRC}/src/hypre/include
26
27 LD_REQUIRED    += -L${MFEM_SRC} -lmfem
28 LD_REQUIRED    += -L${HYPRE_SRC}/src/hypre/lib -lHYPRE
29 LD_REQUIRED    += -L${METIS_SRC} -lmetis
```

That's all there is to it

Let's run it!