# FPChecker

## Detecting Floating-Point Exceptions in GPUs


Ignacio Laguna, Harshitha Menon
**Lawrence Livermore National Laboratory**

Michael Bentley, Ian Briggs, Pavel Panchekha, Ganesh Gopalakrishnan
**University of Utah**

Hui Guo, Cindy Rubio González
**University of California at Davis**

Michael O. Lam
**James Madison University**

http://fpanalysistools.org/

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# Trapping Floating-Point Exceptions in CPU Code

**Floating-Point Arithmetic Standard (IEEE 754)**

1. Invalid operation
2. Division by zero
3. Overflow
4. Underflow
5. Inexact calculation

- When an exceptions occurs, it is signaled
  - System sets a flag or takes a trap
  - Status flag FPSCR set by default
- The system (e.g., Linux) can also cause the floating-point exception signal to be raised
  - SIGFPE

Source: https://www.ibm.com/support/knowledgecenter/en/ssw_aix_71/com.ibm.aix.genprogc/floating-point_except.htm

# CUDA has Limited Support for Detecting Floating-Point Exceptions

- CUDA: programming language of NVIDIA GPUs
- CUDA has no mechanism to detect exceptions
  - As of CUDA version: 10
- All operations behave as if exceptions are masked

You may have **“hidden”** exceptions in your CUDA program

# Detecting the Result of Exceptions in a CUDA Program

- Place **printf** statements in the code (as many a possible)

```
double x = 0;
x = x/x;
printf("res = %e\n", x);
```

- Programming checks are available in CUDA:

```
__device__  int isnan ( float  a );
__device__  int isnan ( double  a );
```

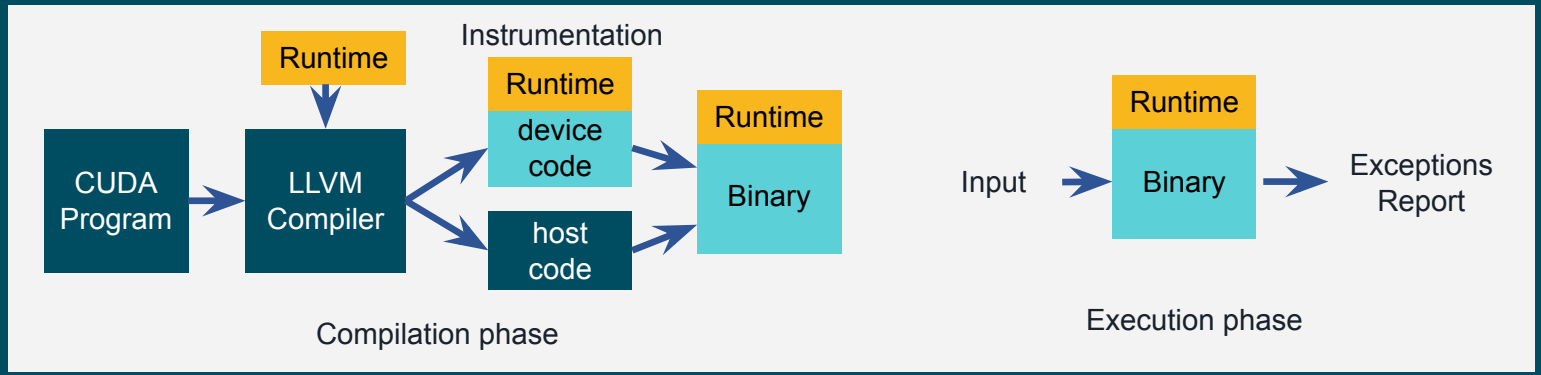
  - Also available isinf

These solutions are not ideal;  they require significant programming effort

# Goals of FPChecker

- Automatically detect the location of FP exceptions in NVIDIA GPUs
  - Report file & line number
  - No extra programming efforts required
- Report input operands
- Use software-based approach (compiler)
- Analyze optimized code

# Workflow of FPChecker



# How to Use FPChecker

1. Use clang as compiler for CUDA

2. Include path of FPChecker runtime system

3. Tell clang to load the instrumentation library

# Example of Compilation Configuration

Use clang instead of NVCC

```
#CXX = nvcc
CXX = /path/to/clang++
CUFLAGS = -std=c++11 --cuda-gpu-arch=sm_60 -g
FPCHECK_FLAGS = -Xclang -load -Xclang /path/libfpchecker.so \
  -include Runtime.h -I/path/fpchecker/src
CXXFLAGS += $(FPCHECK_FLAGS)
```

- Load instrumentation library
- Include runtime header file

# What Happens At Runtime?

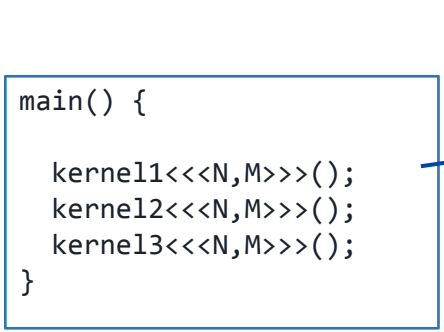
**Mode 1**
**Errors abort**

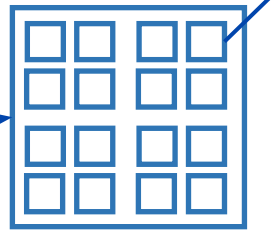
- If exception is detected, we signal a trap instruction
- Kernel aborts execution

**Mode 2**
**Errors don't abort**

- If exception is detected, we store the location in global memory
- At the end of kernels, we check if exceptions occurred
  - If so, it prints a report
- Slightly higher overhead than mode 1

# Errors Abort Mode



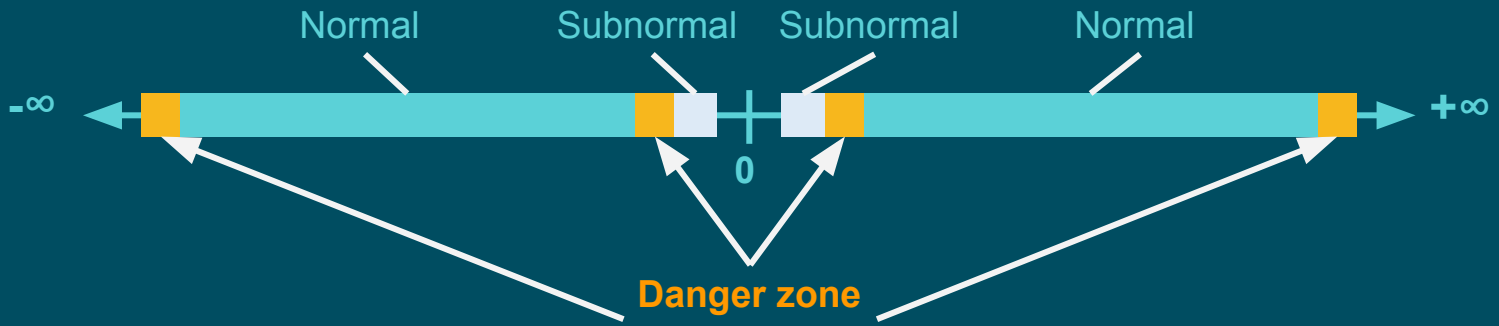




**Interrupt routine:**
- Threads (in block) get a lock
- First thread signals trap instruction

**Given a floating-point operation**
- Resulted in +INF or -INF?
- Resulted in NaN?
- Is an underflow?
- Is an overflow?
- Is latent underflow/overflow?

No synchronization when checking

# We report **Warnings** for Latent Underflows/Overflows



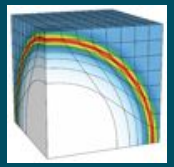

- -D **FPC_DANGER_ZONE_PERCENT**=x.x:
  a. Changes the size of the danger zone.
  b. By default, x.x is 0.10, and it should be a number between 0.0 and 1.0.

# Example of Error Report

```
+------------------------- FPChecker Error Report -------------------------+
Error          : Underflow
Operation      : MUL (9.999888672e-321)
File           : dot_product_raja.cpp
Line           : 32
+--------------------------------------------------------------------------+
```

# Example of Overflow

**Laghos** (LAGrangian High-Order Solver) is a miniapp that solves the time-dependent Euler equations of compressible gas dynamics.



```
388             const double pinv = 1.0 / p;
389             // det(pinv*(gradv-q*I))
390             const double r = (0.5*pinv*pinv*pinv *
391                               ((gradv_q00*gradv_q11*gradv_q22) +
392                                (2.0*gradv10*gradv21*gradv20) -
393                                (gradv_q11*gradv20*gradv20) -
394                                (gradv_q22*gradv10*gradv10) -
395                                (gradv_q00*gradv21*gradv21)));
396
397             double phi = 0;
398             if (r <= -1.0)
399             {
400                phi = M_PI / 3.0;
401             }
402             else if (r < 1.0)
403             {
404                phi = acos(r) / 3.0;
405             }
```

- **p** is initially zero
- **pinv** is INF
- **r** becomes -INF

This branch is taken

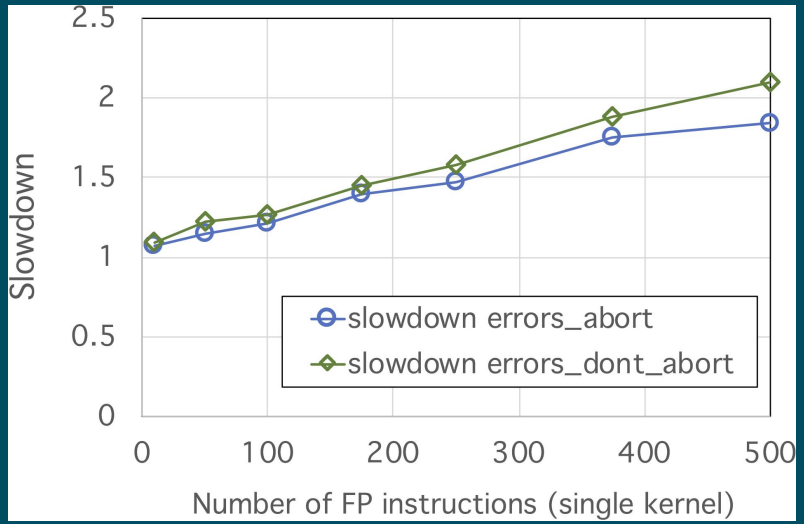
May not be detected with printf

# Overhead of FPChecker

Average slowdown observed in three mini applications: **1.3x - 1.5x**

Slowdown depends on:

- Mode of operation
- Floating-point instructions per kernel
- Kernel execution frequency



Source code available:
https://github.com/LLNL/FPChecker

# Questions?

# Exercises

# Exercises with FPChecker

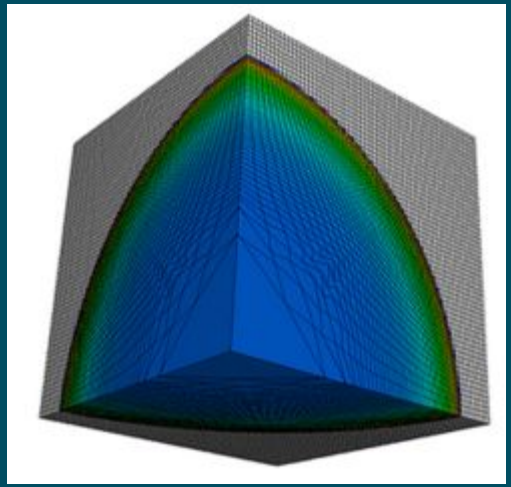
1. Compile and run CUDA application with Clang
2. Compile application with Clang & FPChecker
3. ERRORS_ABORT: NaN exception
4. ERRORS_DONT_ABORT: INF exception

**Directory Structure**

```
/Module-FPChecker
     |---/exercise-1
     |---/exercise-2
     |---/exercise-3
     |---/exercise-4
```

# Application: LULESH

- Proxy application developed at LLNL
- Models a shock hydrodynamics problem
- LULESH version 2.0.2 for CUDA
  - Input: -s N
  - N: integer
  - Example: ./lulesh -s 5
    - Runs a 5x5x5 problem
- https://computation.llnl.gov/projects/co-design/lulesh



# Exercise 1

# **Exercise 1:** Compiling CUDA with Clang

- Open Makefile file
- Take a look at this compilation options:
  - NVCC = clang++
    - Indicates to use clang as the CUDA compiler
  - FLAGS = -g --cuda-gpu-arch=sm_35
    - Use debug information (-g)
    - Use CUDA compute capability (architecture) sm_35
- Execute:
  - $ make clean
  - $ make

# Exercise 1: Output

```
$ make
clang++ -g --cuda-gpu-arch=sm_35  -Wno-mismatched-new-delete -Wno-format-extra-args -O3 -DNDEBUG
allocator.cu -I ./ -c -o allocator.o
clang++ -g --cuda-gpu-arch=sm_35  -Wno-mismatched-new-delete -Wno-format-extra-args -O3 -DNDEBUG
lulesh.cu -I ./   -c -o lulesh.o
clang++ -g --cuda-gpu-arch=sm_35  -Wno-mismatched-new-delete -Wno-format-extra-args -O3 -DNDEBUG
lulesh-comms.cu -I ./ -c -o lulesh-comms.o
clang++ -g --cuda-gpu-arch=sm_35  -Wno-mismatched-new-delete -Wno-format-extra-args -O3 -DNDEBUG
lulesh-comms-gpu.cu -I ./ -c -o lulesh-comms-gpu.o
clang++ -L/usr/local/cuda-8.0/lib64/ -lcuda -lcudart allocator.o lulesh.o lulesh-comms.o
lulesh-comms-gpu.o -o lulesh
```

# **Exercise 1:** Running LULESH

- Run LULESH:
  - ./run_lulesh.sh
- Internally the scripts runs:
  - ./lulesh -s 5

```
$ ./run_lulesh.sh
Host ip-172-31-37-229 using GPU 0: Tesla K80
Running until t=0.010000, Problem size=5x5x5
cycle = 1, time = 3.417997e-04, dt=3.417997e-04
cycle = 2, time = 7.519594e-04, dt=4.101597e-04
cycle = 3, time = 8.925464e-04, dt=1.405871e-04
cycle = 4, time = 1.009948e-03, dt=1.174011e-04
...
...
cycle = 72, time = 1.000000e-02, dt=1.193338e-04
Run completed:
   Problem size        =  5
   MPI tasks           =  1
   Iteration count     =  72
   Final Origin Energy = 7.853665e+03
   Testing Plane 0 of Energy Array on rank 0:
        MaxAbsDiff   = 4.547474e-13
        TotalAbsDiff = 1.405569e-12
        MaxRelDiff   = 4.974166e-15

Elapsed time         =       0.02 (s)
Grind time (us/z/c)  =  1.6841111 (per dom)  ( 1.6841111 overall)
FOM                  =  593.78505 (z/s)
```

# Exercise 2

# **Exercise 2:** Compile Application with FPChecker

1. Open Makefile
2. Take a look at FPChecker flags

```
FPCHECKER_PATH  = /opt/fpchecker/install
LLVM_PASS       = -Xclang -load -Xclang $(FPCHECKER_PATH)/lib/libfpchecker.so \
-include Runtime.h -I$(FPCHECKER_PATH)/src

OTHER_FLAGS = $(LLVM_PASS) -Wno-mismatched-new-delete -Wno-format-extra-args

NVCC            = clang++
FLAGS           = -g --cuda-gpu-arch=sm_35
DFLAGS  = $(OTHER_FLAGS) -lineinfo
RFLAGS  = $(OTHER_FLAGS) -O3 -DNDEBUG
```

# **Exercise 2:** Compile Application with FPChecker

- Run make:
  - make

FPChecker output

Some instructions are instrumented

```
$ make
clang++ -g --cuda-gpu-arch=sm_35  -Xclang -load -Xclang
/opt/fpchecker/install/lib/libfpchecker.so -include Runtime.h
-I/opt/fpchecker/install/src -Wno-mismatched-new-delete -Wno-format-extra-args -O3
-DNDEBUG  allocator.cu -I ./ -c -o allocator.o
#FPCHECKER: Initializing instrumentation
#FPCHECKER: Pointer value (fp32_check_add_function): 0
...
clang++ -g --cuda-gpu-arch=sm_35  -Xclang -load -Xclang
/opt/fpchecker/install/lib/libfpchecker.so -include Runtime.h
-I/opt/fpchecker/install/src -Wno-mismatched-new-delete -Wno-format-extra-args -O3
-DNDEBUG  lulesh.cu -I ./   -c -o lulesh.o
#FPCHECKER: Initializing instrumentation
#FPCHECKER: Pointer value (fp32_check_add_function): 0
#FPCHECKER: Found _FPC_DEVICE_CODE_FUNC_
#FPCHECKER: Found _FPC_PRINT_ERRORS_
...
#FPCHECKER: Entering main loop in instrumentFunction
#FPCHECKER: Instrumented operations: 15
#FPCHECKER: Leaving main loop in instrumentFunction
#FPCHECKER: Instrumenting function: _Z31CalcAccelerationForNodes_kerneliPdS_S_S_S_S_
#FPCHECKER: Entering main loop in instrumentFunction
#FPCHECKER: Instrumented operations: 4
```

May take a few minutes

# Exercise 3

# **Exercise 3:** NaN Exception & ERRORS_ABORT

- We inject a synthetic a NaN exception in LULESH
- FPChecker is run in ERRORS_ABORT mode
  - Detects the first exception
  - Reports the exception
  - Aborts

# **Exercise 3:** Synthetic NaN Exception

- We inject a synthetic NaN exception in LULESH
  - See file: lulesh.cu
  - Line: 2868

```
2857 __global__
2858 void CalcAccelerationForNodes_kernel(int numNode,
2859                                       Real_t *xdd, Real_t *ydd, Real_t *zdd,
2860                                       Real_t *fx, Real_t *fy, Real_t *fz,
2861                                       Real_t *nodalMass)
2862 {
2863   int tid=blockDim.x*blockIdx.x+threadIdx.x;
2864   if (tid < numNode)
2865   {
2866       Real_t one_over_nMass = Real_t(1.)/nodalMass[tid];
2867       // NaN
2868       one_over_nMass = (one_over_nMass-one_over_nMass) / (one_over_nMass-one_over_nMass);
2869       xdd[tid]=fx[tid]*one_over_nMass;
2870       ydd[tid]=fy[tid]*one_over_nMass;
```

# **Exercise 3:** FPChecker Detects NaN Exception

- Run lulesh:
  - ./run_lulesh.sh
- See FPChecker report
- Aborts after report is printed

```
$ ./run_lulesh.sh

========================================
 FPChecker (v0.1.0, Jun 23 2019)
========================================

Host ip-172-31-37-229 using GPU 0: Tesla K80
Running until t=0.010000, Problem size=10x10x10
+--------------------------- FPChecker Error Report ---------------------------+
 Error         : NaN
 Operation     : DIV
 File          : lulesh.cu
 Line          : 2868
+------------------------------------------------------------------------------+
terminate called after throwing an instance of 'thrust::system::detail::bad_alloc'
  what():  std::bad_alloc: an illegal instruction was encountered
./run_lulesh.sh: line 3:  3344 Aborted                 (core dumped) ./lulesh -s 5
```

# Exercise 4

# **Exercise 4:** INF Exception & ERRORS_DONT_ABORT

- We inject a synthetic a INF exception in LULESH
- FPChecker is run in ERRORS_DONT_ABORT mode
  - Reports the exception
  - It doesn't aborts on the first exception
  - Program continues running

# **Exercise 4:** INF Exception & ERRORS_DONT_ABORT

Makefile

```
FPCHECKER_PATH  = /opt/fpchecker/install
LLVM_PASS       = -Xclang -load -Xclang $(FPCHECKER_PATH)/lib/libfpchecker.so \
-include Runtime.h -I$(FPCHECKER_PATH)/src -DFPC_ERRORS_DONT_ABORT

OTHER_FLAGS = $(LLVM_PASS) -Wno-mismatched-new-delete -Wno-format-extra-args

NVCC            = clang++
FLAGS           = -g --cuda-gpu-arch=sm_35
DFLAGS  = $(OTHER_FLAGS) -lineinfo
RFLAGS  = $(OTHER_FLAGS) -O3 -DNDEBUG
```

Flag

# **Exercise 4:** FPChecker Detects INF Exception

- Run lulesh:
  - ./run_lulesh.sh
- FPChecker report is a single line
- Program continues to run after the error report
- A warning is also reported

```
$ ./run_lulesh.sh

========================================
 FPChecker (v0.1.0, Jun 23 2019)
========================================

Host ip-172-31-37-229 using GPU 0: Tesla K80
Running until t=0.010000, Problem size=5x5x5
cycle = 1, time = 3.417997e-04, dt=3.417997e-04
cycle = 2, time = 7.519594e-04, dt=4.101597e-04

#FPCHECKER: INF Error at lulesh.cu:2871 (code:#-2, tid:0)
cycle = 3, time = 8.925464e-04, dt=1.405871e-04
cycle = 4, time = 1.009948e-03, dt=1.174011e-04

#FPCHECKER: Warning at lulesh.cu:2871 (#2.805864e+304, tid:0)
cycle = 5, time = 1.114606e-03, dt=1.046586e-04
cycle = 6, time = 1.211786e-03, dt=9.718025e-05
cycle = 7, time = 1.304180e-03, dt=9.239337e-05
cycle = 8, time = 1.393422e-03, dt=8.924197e-05
cycle = 9, time = 1.480620e-03, dt=8.719797e-05
cycle = 10, time = 1.566588e-03, dt=8.596832e-05
...
```