

FPChecker

Detecting Floating-Point Exceptions in GPUs



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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.genprog/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

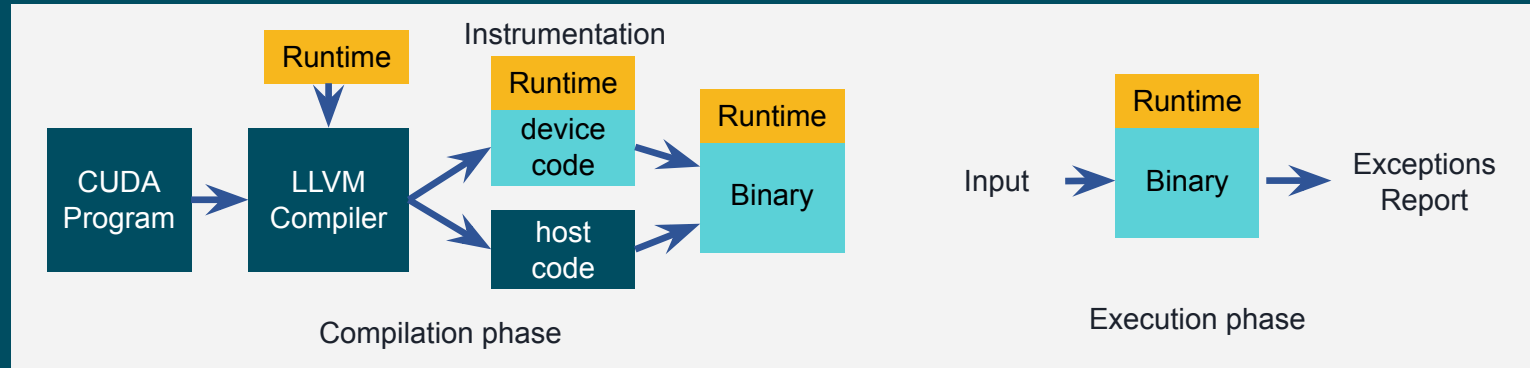
These solutions are not ideal; they require significant programming effort



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
- Kernel aborts execution

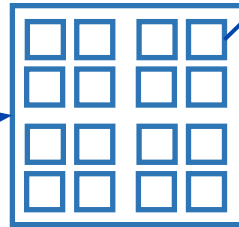
Mode 2: Errors don't abort

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

Errors Abort Mode

```
main() {  
    kernel1<<<N,M>>>();  
    kernel2<<<N,M>>>();  
    kernel3<<<N,M>>>();  
}
```

GPU Kernel



Interrupt routine:

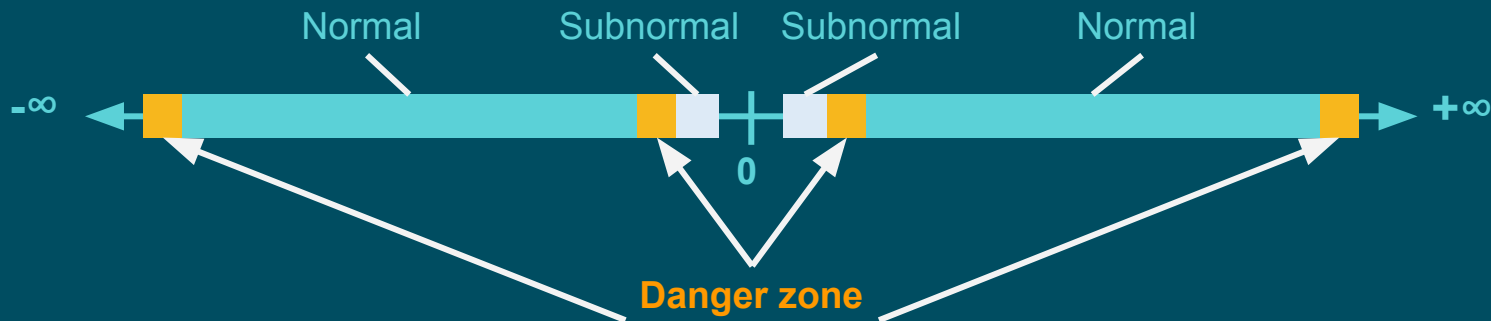
- Threads (in block) get a lock
- First thread signals trap instruction

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
+-----+
```

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

Questions?

Exercises



Exercises with FPChecker

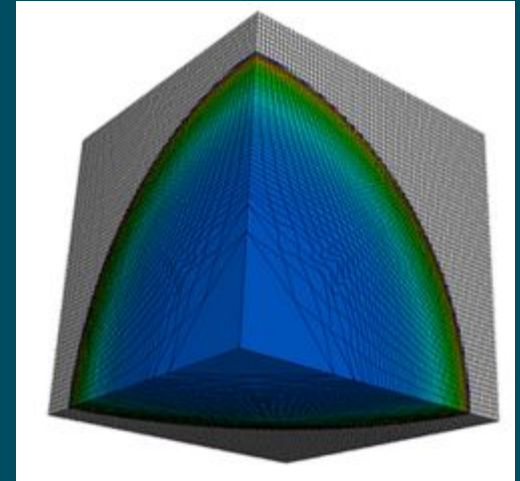
1. Compile and run CUDA application with Clang
2. Compile application with Clang & FPChecker
3. ERRORS_ABORT: NaN exception
4. ERRORS_DONT_ABORT: INF exception

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 10`
 - Runs a 10x10x10 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 10`

```
$ ./run_lulesh.sh
Host ip-172-31-37-229 using GPU 0: Tesla K80
Running until t=0.010000, Problem size=10x10x10
cycle = 1, time = 6.042222e-05, dt=6.042222e-05
cycle = 2, time = 1.329289e-04, dt=7.250667e-05
cycle = 3, time = 1.577814e-04, dt=2.485252e-05
cycle = 4, time = 1.785352e-04, dt=2.075378e-05
...
cycle = 231, time = 1.000000e-02, dt=3.744566e-05
Run completed:
  Problem size      = 10
  MPI tasks         = 1
  Iteration count   = 231
  Final Origin Energy = 2.720531e+04
  Testing Plane 0 of Energy Array on rank 0:
    MaxAbsDiff      = 5.456968e-12
    TotalAbsDiff    = 2.286042e-11
    MaxRelDiff      = 3.296482e-14

Elapsed time        = 0.05 (s)
Grind time (us/z/c) = 0.21277922 (per dom) (0.21277922 overall)
FOM                 = 4699.707 (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_S_
#FPCHECKER: Entering main loop in instrumentFunction
#FPCHECKER: Instrumented operations: 4
```

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 10
```

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=10x10x10
cycle = 1, time = 6.042222e-05, dt=6.042222e-05
cycle = 2, time = 1.329289e-04, dt=7.250667e-05

#FPCHECKER: INF Error at lulesh.cu:2871 (code: #-2, tid:0)
cycle = 3, time = 1.577814e-04, dt=2.485252e-05
cycle = 4, time = 1.785352e-04, dt=2.075378e-05

#FPCHECKER: Warning at lulesh.cu:2871 (-1.213789e+308, tid:0)
cycle = 5, time = 1.970364e-04, dt=1.850120e-05
cycle = 6, time = 2.142156e-04, dt=1.717920e-05
cycle = 7, time = 2.305486e-04, dt=1.633299e-05
cycle = 8, time = 2.463245e-04, dt=1.577590e-05
cycle = 9, time = 2.617391e-04, dt=1.541457e-05
cycle = 10, time = 2.769363e-04, dt=1.519719e-05
cycle = 11, time = 2.951729e-04, dt=1.823663e-05
...
```