Symbolic Crosschecking of Data-Parallel Code

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Joint work with **Peter Collingbourne** and **Paul Kelly**

[EuroSys 2011, HVC 2011]

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David Dill, Junfeng Yang, Peter Boonstoppel, Can Sar, Paul Twohey,
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Dynamic Symbolic Execution

- Renewed interest in the last few years:
  - **Software testing**: high-coverage test generation
  - **Automatic bug-finding**
  - **Security**: automatic vulnerability signature generation, security testing
- Main enablers:
  - Recent advances in constraint solving
  - Mixed concrete and symbolic execution

Dynamic SymEx in Practice

- Many dynamic symbolic execution/concolic tools available as open-source:
  - **CREST, KLEE, SYMBOLIC JPF**, etc.

- Started to be adopted by the industry:
  - Microsoft (**SAGE, PEX**), IBM (**APOLLO**), Fujitsu (**KLEE/KLOVER, SYMBOLIC JPF**), NASA (**SYMBOLIC JPF**), etc.

Dynamic Symbolic Execution

Let the code generate its own (complex) test cases!

- Dynamic symbolic execution can ***automatically explore multiple paths*** through a program
  - Determine the feasibility of a particular path by reasoning about all possible values using a constraint solver
- Before each dangerous operation, can check if there are ***any*** values that can cause an error
- For each path, can usually generate a ***concrete input triggering the path***

Scalability Challenges

Path exploration challenges

- Employing search heuristics
- Dynamically eliminating redundant paths
- Statically merging paths
- Using existing regression test suites to prioritize execution
- etc.

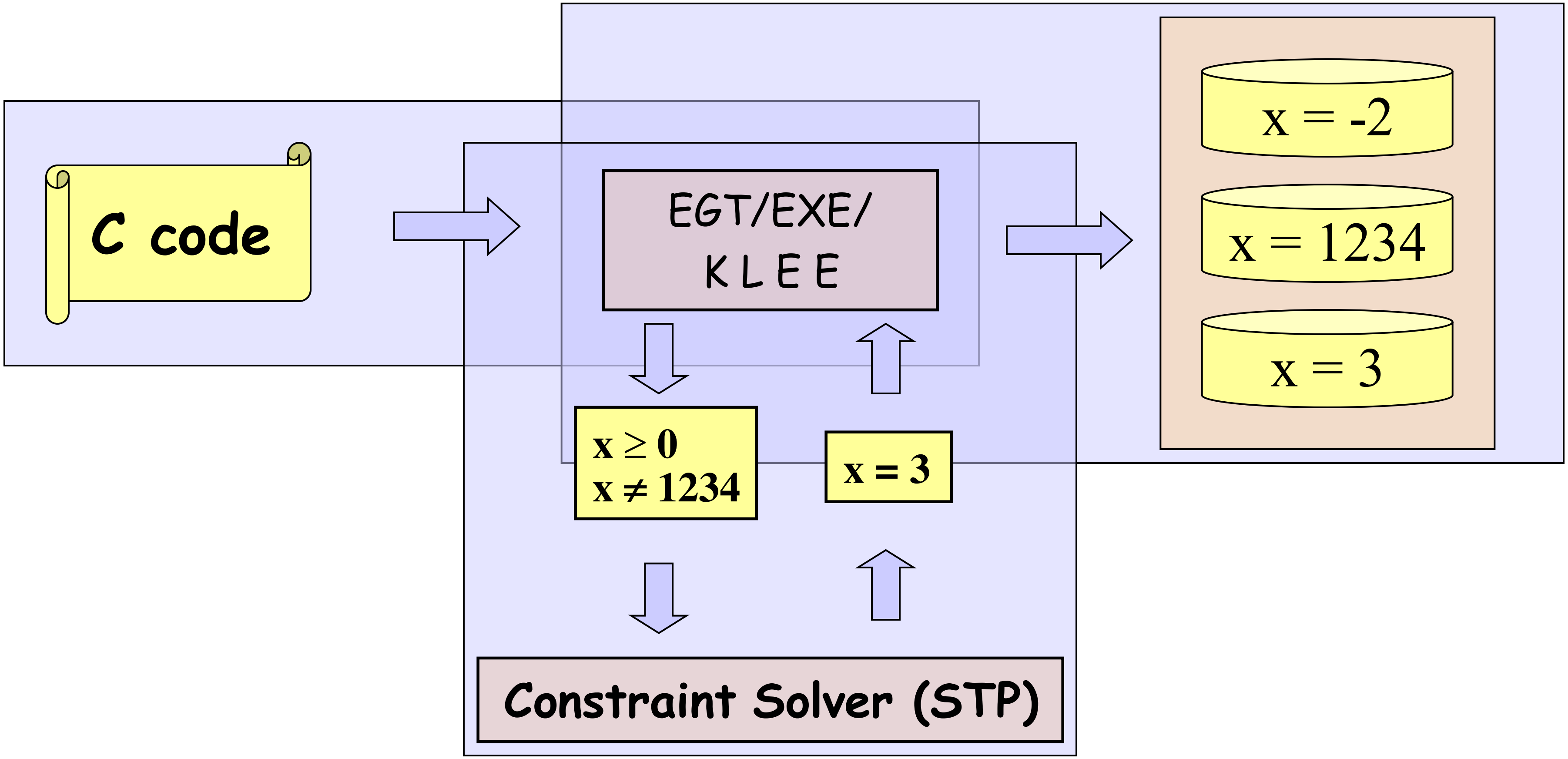
Constraint solving challenges

Exploit the characteristics of constraints generated by symex

- Eliminating irrelevant constraints
- Exploiting similarity between constraints
- etc.

[Joint work with Engler, Dunbar, Collingbourne, Kelly, Pawlowski, Sar, Twohey, Yang, Boonstoppel, Ganesh, Dill, Song, Pietzuch, Marinescu]

Three tools: EGT, EXE, KLEE



[Joint work with Dawson Engler, Daniel Dunbar, Peter Pawlowski, Peter Boonstoppel, Vijay Ganesh, David Dill]

EGT, EXE, KLEE

Successfully used our tools to:

- Automatically generate high-coverage test suites

- Find bugs and security vulnerabilities in complex software

Bug Finding with EGT, EXE, KLEE:
Focus on Systems and Security Critical Code

	Applications
UNIX utilities	Coreutils, Busybox, Minix (over 450 apps)
UNIX file systems	ext2, ext3, JFS
Network servers	Bonjour, Avahi, udhcpd, WsMp3
Library code	libdwarf, libelf, PCRE, uClibc, Pintos
Packet filters	FreeBSD BPF, Linux BPF
MINIX device drivers	pci, lance, sb16
Kernel code	HiStar kernel
Computer vision code	OpenCV (filter, remap, resize, etc.)
OpenCL code	Parboil, Bullet, OP2

- Most bugs fixed promptly

JFS, Linux 2.6.10: Disk of death

Offset	Hex Values							
00000	0000	0000	0000	0000	0000	0000	0000	0000
. . .	. . .							
08000	464A	3135	0000	0000	0000	0000	0000	0000
08010	1000	0000	0000	0000	0000	0000	0000	0000
08020	0000	0000	0100	0000	0000	0000	0000	0000
08030	E004	000F	0000	0000	0002	0000	0000	0000
08040	0000	0000	0000	. . .				

- **64^{th} sector of a 64K disk image**
- **Mount it and PANIC your kernel**

[Joint work with Junfeng Yang, Dawson Engler, Can Sar, Paul Twohey]

Bonjour: Packet of Death

Offset	Hex Values							
0000	0000	0000	0000	0000	0000	0000	0000	0000
0010	003E	0000	4000	FF11	1BB2	7F00	0001	E000
0020	00FB	0000	14E9	002A	0000	0000	0000	0001
0030	0000	0000	0000	055F	6461	6170	045F	7463
0040	7005	6C6F	6361	6C00	000C	0001		

- **Causes Bonjour to abort, potential DoS attack**
- **Apple confirmed it and released a security update**

[Joint work with JaeSeung Song and Peter Pietzuch]

Kerberized Telnet: Packet of Death

Offset	Hex Values							
0000	001E	8C97	BBD9	001B	FC40	5983	0800	4500
0010	0040	8930	4000	4006	7E39	9BC6	7DE0	9BC6
0020	7DE1	AAA9	0017	7FBE	B5A2	494D	6AF4	8018
0030	005C	4FAE	0000	0101	080A	014E	3CCD	1115
0040	029A	FFFD	25FF	FA25	03FF	F0FF	F800	

- **Crashes the telnet daemon**
- **Reported and confirmed by developers**

[Joint work with JaeSeung Song and Peter Pietzuch]

Semantic Bugs

- Bugs shown before were all generic errors
- What about semantic bugs?

Option 1: Write specifications!

- Can find assert() violations

(Can verify **assert()** statements on a per-path basis)

Crosschecking (Equivalence Checking)

Option 2: Crosschecking!

- Successfully used in the past
- Great match for symbolic execution

Lots of available opportunities:

- Different implementations of the same functionality: e.g., libraries, servers, compiler
- Optimized versions of a reference implementation
- Refactored code
- Reverse computations: e.g., compress and uncompress

New Platforms, New Code

- Recent years have seen the emergence of new computing platforms which provide many opportunities for optimizations

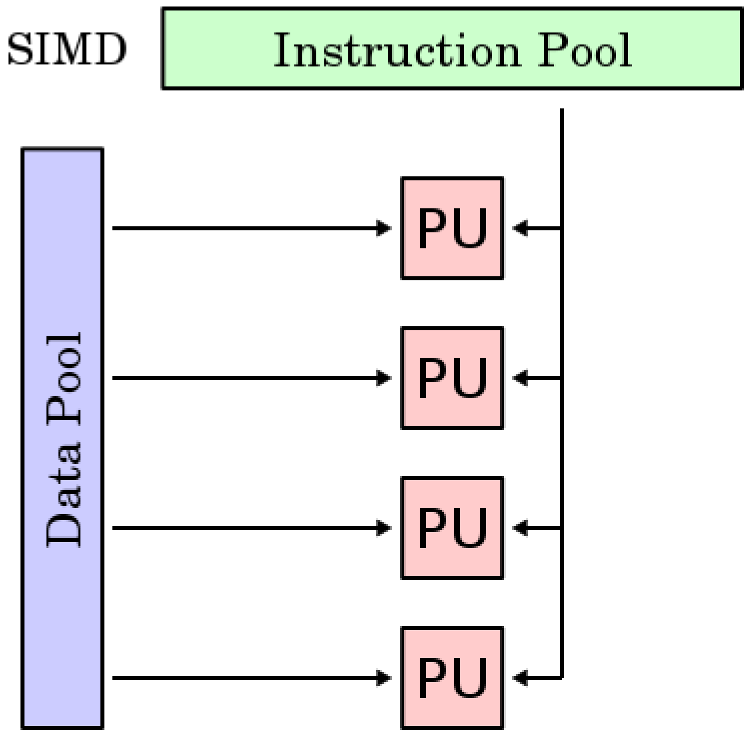
- Code is often adapted manually to benefit from these platforms

***Error-prone*, as any manual process**

SIMD Optimizations

Most processors offer support for SIMD instructions

- Can operate on multiple data concurrently
- Many algorithms can make use of them (e.g., computer vision algorithms)

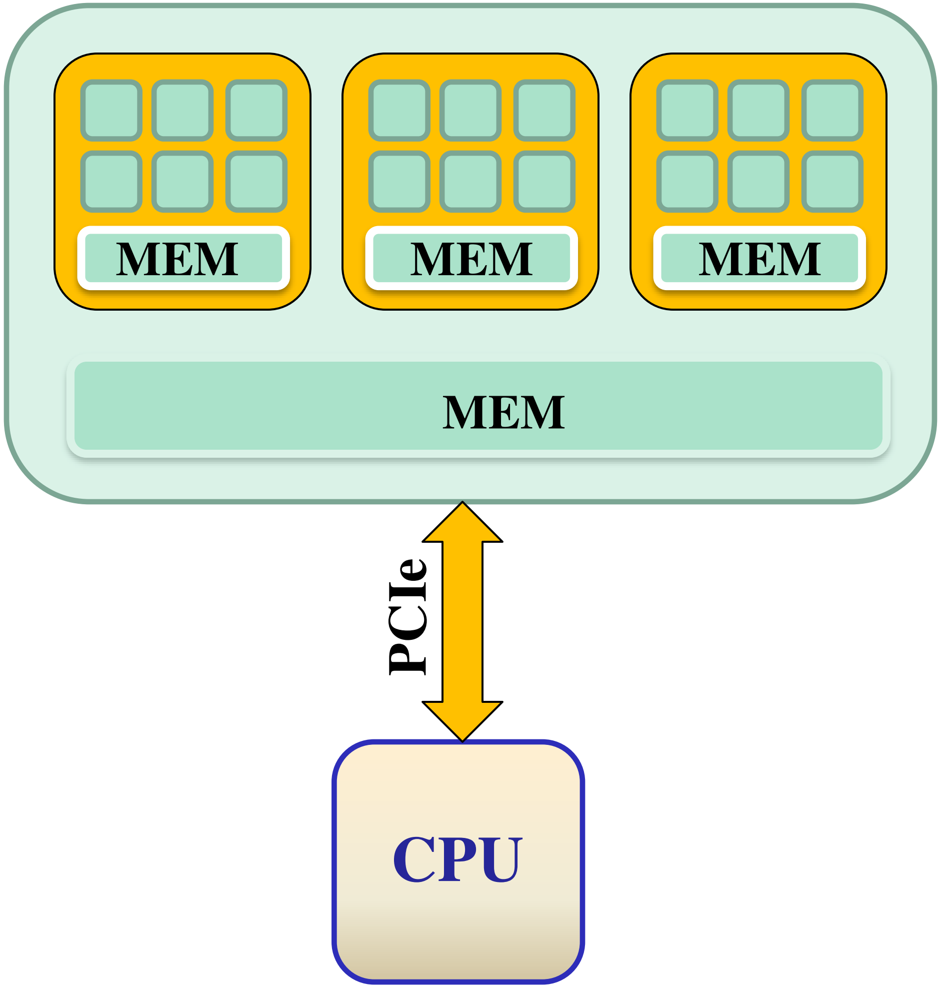


General Purpose GPU Computing

(2006) NVIDIA CUDA

(2008) OpenCL

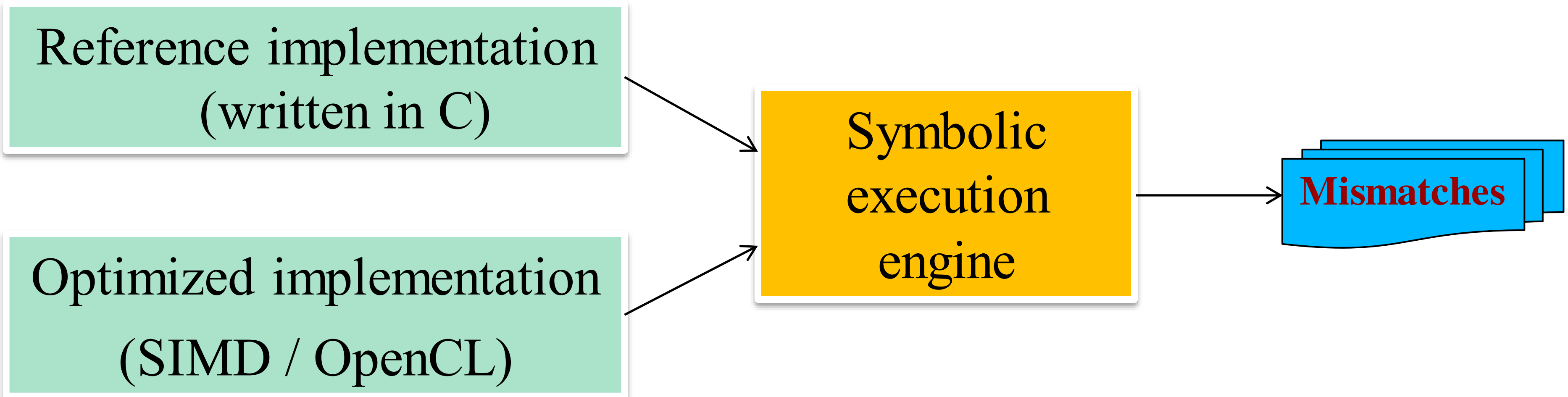
General Purpose GPU Computing



New programming model:

- Large number of threads
- Hierarchical execution and memory model

Crosschecking (Equivalence Checking)



We can find any mismatches in their behavior by:

1. Using symbolic execution to explore multiple paths
2. Comparing the path constraints across implementations

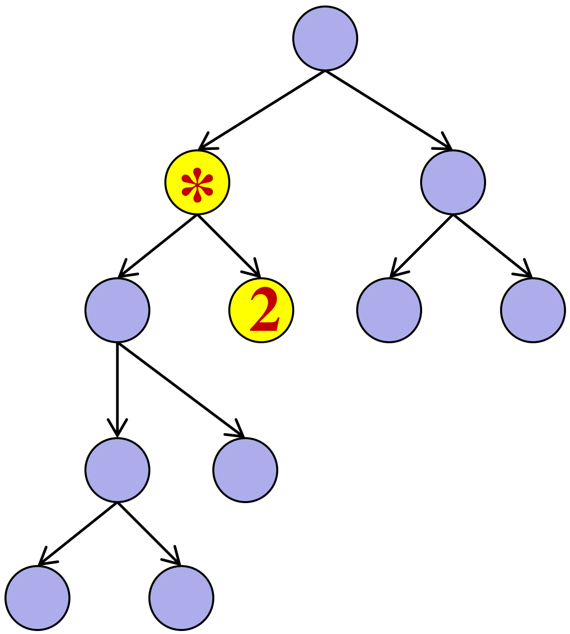
Crosschecking: Advantages

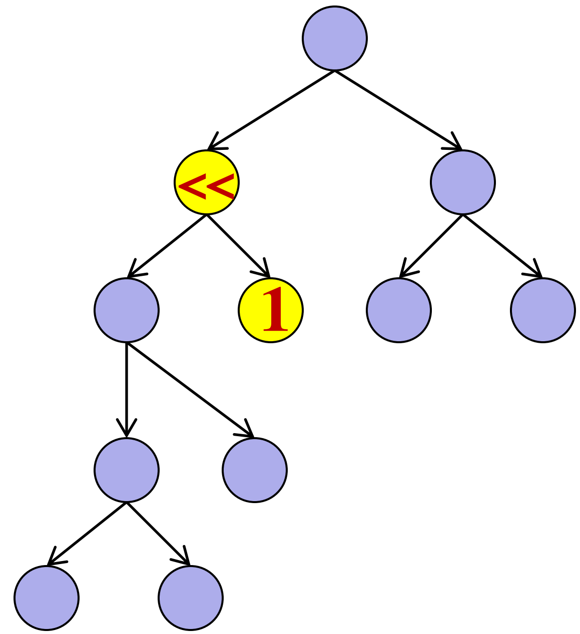
- No need to write any specifications

- Constraint solving queries can be solved faster
- Can support constraint types not (efficiently) handled by the underlying solver, e.g., floating-point

Many crosschecking queries can be *syntactically* proved to be equivalent

Crosschecking: Advantages



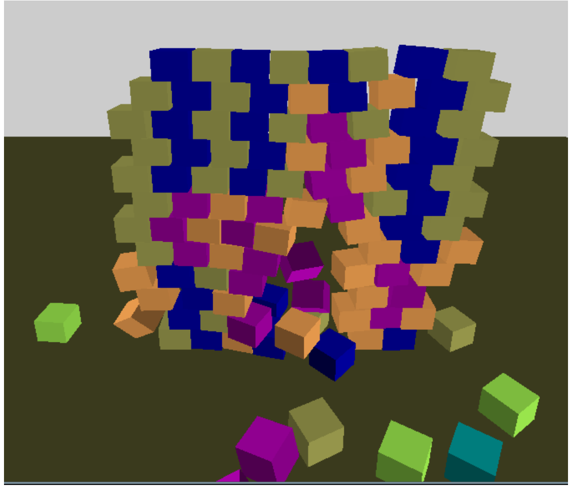


Many crosschecking queries can be *syntactically* proved to be equivalent

OpenCL Optimizations

- Parboil:
  - GPU benchmark suite, originally written in CUDA
- OP2
  - Library for applications on unstructured grids
- Bullet open-source physics library
  - Popular library used movie studios and professional game developers
  - Analyzed soft body engine

Bullet library



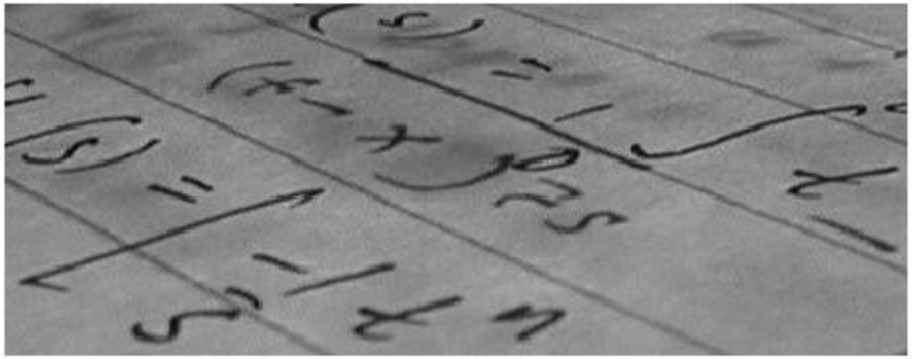
OpenCL Benchmarks: Bugs and Mismatches

Several bugs and mismatches:

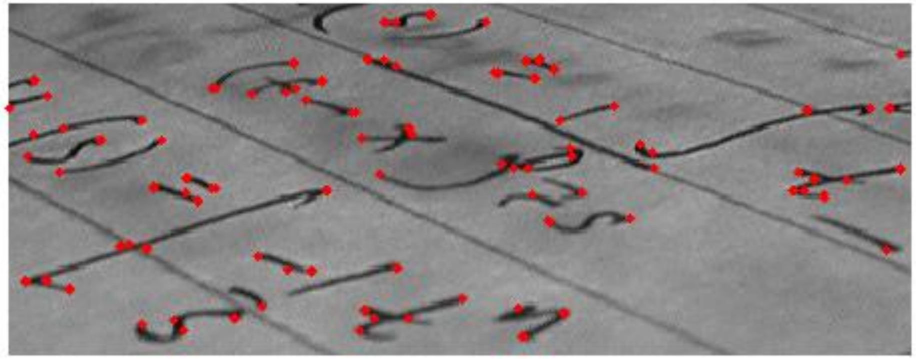
- 2 mismatches between C and OpenCL code
  - Incorrect FP associativity and distributivity assumptions (CP in Parboil)
- 3 memory errors
  - Buffer overflows (MRI-Q&MRI-FHD in Parboil)
  - Use-after-free: incorrect synchronization between host and kernel code (MRI-Q in Parboil)
  - Uninitialized memory (MRI-FHD in Parboil)
- 1 race condition
  - Missing synchronization barrier (OP2)
- 1 compiler bug
  - NVidia compiler bug (incorrect optimization)

SIMD Optimizations

OpenCV: popular computer vision library from Intel and Willow Garage



[Corner detection algorithm]



OpenCV Results

- Crosschecked 51 SIMD-optimized versions against their reference scalar implementations
  - Proved the bounded equivalence of 41
  - Found mismatches in 10
- Most mismatches due to tricky FP-related issues:
  - Precision
  - Rounding
  - Associativity
  - Distributivity
  - NaN values

OpenCV Results

Surprising find: min/max not commutative nor associative!

```
min(a,b) = a < b ? a : b

a < b (ordered) → always returns false if one
                  of the operands is NaN

min(NaN, 5) = 5
min(5, NaN) = NaN

min(min(5, NaN),  100) = min(NaN, 100) = 100
min(5, min(NaN, 100))  = min(5, 100) = 5
```

Integrating Crosschecking into Development Process

Semantic mismatches not always errors

- Underspecified behavior

Two (anecdotal) insights:

1. Provide developers the **ability to add "assumptions"** eg:
   - Floating-point associativity holds:
     - A+(B+C) = (A+B)+C
   - Disregard the difference between 0_- and 0_+:
     - A+0 = A
2. All things being equal, developers **prefer to keep the behavior of the reference implementation**
   - Particularly if we can provide some guarantees
     - bounded equivalence

KLEE: Freely Available as Open-Source

http://klee.llvm.org

- Over 200 subscribers to the klee-dev mailing list
- Extended in many interesting ways by several research groups, in the areas of:
  - wireless sensor networks
  - schedule memoization in multithreaded code
  - automated debugging
  - exploit generation
  - online gaming, etc.