CS 5/6110, Software Correctness Analysis, Spring 2023

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Lecture 13 : Dynamic Symbolic Execution (also known as “Concolic Execution” standing for Concrete + Symbolic Execution)

- There is so much C codes out there
- How to even make a dent in verifying them?
- How do DSE or Concolic tools help?
  - An amazing success story in this area: KLEE – OSDI 2008
- How do they compare with fuzzers (what are they?)
  - Mention about American Fuzzy Lop or AFL
  - Study by Dr. Peng Li (my former student) is very good – slides uploaded on Canvas
- How does all of this apply to parallel computing
  - Say GPUs?
  - Test of Time Award Honorable Mention for Dr. Guodong Li (my former student) and me at FSE 2020
    - Work on PUG (2010) and work on GKLEE (2012) – Guodong was VERY foresightful to have keyed off KLEE in 4 years!
- Dr. Guodong Li is with Google Research now, and Dr. Peng Li is with ByteDance Inc. now

KLEE: Unassisted and Automatic Generation of High-Coverage Tests for Complex Systems Programs

Cristian Cadar, Daniel Dunbar, Dawson Engler *
Stanford University

KLEE
OSDI
2008

```
1 : void expand(char *arg, unsigned char *buffer) {          8
2 :   int i, ac;                                             9
3 :   while (*arg) {                                         10*
4 :     if (*arg == '\\') {                                  11*
5 :       arg++;
6 :       i = ac = 0;
7 :       if (*arg >= '0' && *arg <= '7') {
8 :         do {
9 :           ac = (ac << 3) + *arg++ - '0';
10:          i++;
11:        } while (i<4 && *arg>='0' && *arg<='7');
12:        *buffer++ = ac;
13:      } else if (*arg != '\0')
14:        *buffer++ = *arg++;
15:    } else if (*arg == '[') {                             12*
16:      arg++;                                              13
17:      i = *arg++;                                         14
18:      if (*arg++ != '-') {                                15!
19:        *buffer++ = '[';
20:        arg --= 2;
21:        continue;
22:      }
23:      ac = *arg++;
24:      while (i <= ac) *buffer++ = i++;
25:      arg++;       /* Skip ']' */
26:    } else
27:      *buffer++ = *arg++;
28:  }
29: }
30: ...
31: int main(int argc, char* argv[]) {                        1
32:   int index = 1;                                         2
33:   if (argc > 1 && argv[index][0] == '-') {               3*
34:     ...                                                  4
35:   }                                                      5
36:   ...                                                    6
37:   expand(argv[index++], index);                          7
38:   ...
39: }
```

Figure 1: Code snippet from MINIX's `tr`, representative of the programs checked in this paper: tricky, non-obvious, difficult to verify by inspection or testing. The order of the statements on the path to the error at line 18 are numbered on the right hand side.

1 KLEE constructs symbolic command line string arguments whose contents have no constraints other than zero-termination. It then constrains the number of arguments to be between 0 and 3, and their sizes to be 1, 10 and 10 respectively. It then calls `main` with these initial path constraints.

2 When KLEE hits the branch `argc > 1` at line 33, it uses its constraint solver STP [23] to see which directions can execute given the current path condition. For this branch, both directions are possible; KLEE forks execution and follows both paths, adding the constraint `argc` > 1 on the false path and `argc` ≤ 1 on the true path.

3 Given more than one active path, KLEE must pick which one to execute first. We describe its algorithm in Section 3.4. For now assume it follows the path that reaches the bug. As it does so, KLEE adds further constraints to the contents of `arg`, and forks for a total of five times (lines denoted with a "*"): twice on line 33, and then on lines 3, 4, and 15 in `expand`.

4 At each dangerous operation (e.g., pointer dereference), KLEE checks if any possible value allowed by the current path condition would cause an error. On the annotated path, KLEE detects no errors before line 18. At that point, however, it determines that input values exist that allow the read of `arg` to go out of bounds: after taking the true branch at line 15, the code increments `arg` twice without checking if the string has ended. If it has, this increment skips the terminating `'\0'` and points to invalid memory.

5 KLEE generates concrete values for `argc` and `argv` (i.e., `tr [ "" ""`) that when rerun on a raw version of `tr` will hit this bug. It then continues following the current path, adding the constraint that the error does not occur (in order to find other errors).

Why can’t we crank through all inputs/states?

Your answer here for a C program that has exactly one 32-bit register

How about a 64-bit register?

Your answer here for a C program with 1k bytes of state and 64 bits of input

How about a C program with 5 threads with 5 sequential steps? How many interleavings?

How about something larger?

The main technology!

- Progress in Boolean Satisfiability is central to the magic I'm going to demo
  - SAT-solving increased by 1000x or more (in performance)
- SAT alone is not sufficient
  - SMT-solving was essential
    - Think of the SEND + MORE = MONEY problem!
- Progress in SMT-solving happened this way
  - Nelson/Oppen methods of the 1980's and Shostak's method
  - SVC and CVC and Yices
  - Then Z3, and now CVC4 and a whole array of others!

- Rides on the power of SAT-solving but their "theory-solving" is key
- KLEE uses "STP", an SMT solver that can handle bit-arrays and uninterpreted functions well
- This is why we must study mathematical logic
  - took 1000s of years since Euclid, 170 years since Boole, 100 years since Shannon, and 120 years since Russell, Peano and others to get here!
  - in addition to all those other "cool topics" to which students are flocking these days!
    - (What are some of those?!)

Publication on KLEE for enhancing its coverage

https://arxiv.org/pdf/2211.14592.pdf

2.2 Klee

Klee [6] is a popular test-case generation tool for C programs based on dynamic symbolic execution, developed and maintained at Imperial College London. Klee is open-source, has a large community of contributors, and a large user base, both in industry and in academia. Klee operates on LLVM bitcode, which is an intermediate representation of the executable program: this enables it to mix concrete and symbolic executions. Klee internally makes use of various (configurable)

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cutions. Klee internally makes use of various (configurable) strategies to explore the path space of the program under test, and is able to produce a test case for each path found to be feasible. Such a test case consists of concrete input values on which the program executes along this path. By design, Klee's only coverage criterion is *all-path*: as a result, the user

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Klee's only coverage criterion is *all-path*: as a result, the user often must configure a timeout or specify preconditions to the program in order to ensure Klee's termination within reasonable time bounds. More precisely, Klee aims at covering all paths of the LLVM bitcode, which means in particular that compound conditions are decomposed according to lazy evaluation semantic of Boolean operators in C.

The tutorial at https://adalogics.com/blog/symbolic-execution-with-klee
mentions that even a dozen lines of a Regexp code has about 7000 paths
This "path explosion" is an issue. But this also points to the futility of fuzzing such programs
(a point vividly brought out by Peng Li's study)

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Concretely, when launched on a given program, Klee tries to produce a test case for each executable path that reaches a return statement of the main function, an assertion, or an instruction that may raise a runtime error (RTE), e.g. division by 0, overshift, invalid pointer access. A path that reaches a return statement is called a *complete path*, whereas other paths are called *partially completed paths*. In Klee's output directory, a test case generated for a partially completed path comes with an additional file that ends with *.xxx*`.err`, where *xxx* gives information about the premature end of the path, e.g. `assert` (for assertion failure), or `ptr` (for pointer error). Klee can replay generated test cases in a separate step.

Publication on KLEE for enhancing its coverage

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Since Klee aims at covering all paths of the LLVM bitcode, it sometimes produces more test cases than needed to cover only decisions or conditions for example. Its path-oriented approach is not directly adapted to more advanced coverage criteria like multiple conditions, boundary tests or weak mutations (cf. Section 2.3). The purpose of this work is to adapt and optimize Klee for a large range of coverage criteria expressed using coverage labels.

Demo-1 : a hard-to-test program under conventional testing and then KLEE

```c
/*
 * An error that is hard to hit
 */

#include <stdio.h>
#include <assert.h>
#include <stdlib.h>
#include "klee/klee.h"

int rare(int x) {
  if (x < RAND_MAX/2) {
    if (x > RAND_MAX/2 - 3) {
          assert(0);
      }
  }
  else
    return(1);
}

int main() {
  int a, i;

  #ifdef KLEEON
  klee_make_symbolic(&a, sizeof(a), "a");
  rare(a);
  #endif


  #ifdef PRINTON
  #ifndef KLEEON
  printf("randmax = %d\n", RAND_MAX);
  for (i=0; i < 10000000; i++) {
  a = rand(); //% 100000000;
  rare(a);
  }
  #endif
  #endif
}
```

```
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ gcc -DINITON -DPRINTO
N -I ../../include hardToHit.c
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ ./a.out
randmax = 2147483647
rare() called withx = 1028600000
rare() called withx = 1845200000
rare() called withx = 1276300000
rare() called withx = 1784500000
rare() called withx = 2085600000
rare() called withx = 882700000
rare() called withx = 345800000
rare() called withx = 2114900000
rare() called withx = 803300000
rare() called withx = 1710400000
rare() called withx = 910000000
rare() called withx = 334300000
rare() called withx = 468700000
rare() called withx = 1130600000
rare() called withx = 439100000
rare() called withx = 1751800000
rare() called withx = 447800000
rare() called withx = 1277300000
rare() called withx = 1241200000
rare() called withx = 1272500000
rare() called withx = 1431200000
rare() called withx = 1961900000
rare() called withx = 557700000
rare() called withx = 895600000
rare() called withx = 1026900000
rare() called withx = 69700000
rare() called withx = 1711500000
rare() called withx = 1009100000
rare() called withx = 449700000
rare() called withx = 1316300000
rare() called withx = 384800000
rare() called withx = 1764000000
rare() called withx = 551000000
rare() called withx = 943400000
rare() called withx = 803900000
rare() called withx = 1348100000
rare() called withx = 557500000
rare() called withx = 614500000
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$
```

Demo-1 : a hard-to-test program under conventional testing and then KLEE

```c
/*
 * An error that is hard to hit
 */

#include <stdio.h>
#include <assert.h>
#include <stdlib.h>
#include "klee/klee.h"

int rare(int x) {
  if (x < RAND_MAX/2) {
    if (x > RAND_MAX/2 - 3) {
          assert(0);
      }
  }
  else
    return(1);
}

int main() {
  int a, i;

  #ifdef KLEEON
  klee_make_symbolic(&a, sizeof(a), "a");
  rare(a);
  #endif


  #ifdef PRINTON
  #ifndef KLEEON
  printf("randmax = %d\n", RAND_MAX);
  for (i=0; i < 10000000; i++) {
  a = rand(); //% 100000000;
  rare(a);
  }
  #endif
  #endif
}
```

```
$ clang -DKLEEON -I ../../include -emit-llvm -g -c -O0 -Xclang -disa
ble-O0-optnone hardToHit.c
sh: 3: clang: not found
$
Script done, file is typescript
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ clear

klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ gcc -DINITON -DPRINTO
N -I ../../include hardToHit.c
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ which clang
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ alias clang
alias clang='/usr/lib/llvm-11/bin/clang'
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ clang -DKLEEON -I ../
../include -emit-llvm -g -c -O0 -Xclang -disable-O0-optnone hardToHi
t.c
hardToHit.c:18:1: warning: non-void function does not return a value
 in all control paths [-Wreturn-type]
}
^
```

Demo-1 : a hard-to-test program under conventional testing and then KLEE

```c
/*
 * An error that is hard to hit
 */

#include <stdio.h>
#include <assert.h>
#include <stdlib.h>
#include "klee/klee.h"

int rare(int x) {
  if (x < RAND_MAX/2) {
    if (x > RAND_MAX/2 - 3) {
          assert(0);
      }
  }
  else
    return(1);
}

int main() {
  int a, i;

  #ifdef KLEEON
  klee_make_symbolic(&a, sizeof(a), "a");
  rare(a);
  #endif


  #ifdef PRINTON
  #ifndef KLEEON
  printf("randmax = %d\n", RAND_MAX);
  for (i=0; i < 10000000; i++) {
  a = rand(); //% 100000000;
  rare(a);
  }
  #endif
  #endif
}
```

```
1 warning generated.
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ klee hardToHit.bc
KLEE: WARNING: Module and host target triples do not match: 'x86_64-
pc-linux-gnu' != 'x86_64-unknown-linux-gnu'
This may cause unexpected crashes or assertion violations.
KLEE: output directory is "/home/klee/klee_src/examples/6110exs/kle
-out-3"
KLEE: Using STP solver backend
KLEE: ERROR: hardToHit.c:13: ASSERTION FAIL: 0
KLEE: NOTE: now ignoring this error at this location

KLEE: done: total instructions = 27
KLEE: done: completed paths = 2
KLEE: done: partially completed paths = 1
KLEE: done: generated tests = 3
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ ktest-tool klee-last/
test000001.ktest
ktest file : 'klee-last/test000001.ktest'
args       : ['hardToHit.bc']
num objects: 1
object 0: name: 'a'
object 0: size: 4
object 0: data: b'\xfd\xff\xff?'
object 0: hex : 0xfdffff3f
object 0: int : 1073741821
object 0: uint: 1073741821
object 0: text: ...?
```

Demo-1 : a hard-to-test program under conventional testing and then KLEE

```c
/*
 * An error that is hard to hit
 */

#include <stdio.h>
#include <assert.h>
#include <stdlib.h>
#include "klee/klee.h"

int rare(int x) {
  if (x < RAND_MAX/2) {
    if (x > RAND_MAX/2 - 3) {
          assert(0);
      }
  }
  else
    return(1);
}

int main() {
  int a, i;

  #ifdef KLEEON
  klee_make_symbolic(&a, sizeof(a), "a");
  rare(a);
  #endif


  #ifdef PRINTON
  #ifndef KLEEON
  printf("randmax = %d\n", RAND_MAX);
  for (i=0; i < 10000000; i++) {
  a = rand(); //% 100000000;
  rare(a);
  }
  #endif
  #endif
}
```

```
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ ktest-tool klee-last/
test000002.ktest
ktest file : 'klee-last/test000002.ktest'
args       : ['hardToHit.bc']
num objects: 1
object 0: name: 'a'
object 0: size: 4
object 0: data: b'\x00\x00\x00\x00'
object 0: hex : 0x00000000
object 0: int : 0
object 0: uint: 0
object 0: text: ....
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ ls klee-last
assembly.ll   run.stats              test000002.ktest
info          test000001.assert.err  test000003.ktest
messages.txt  test000001.kquery      warnings.txt
run.istats    test000001.ktest
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ ls -lgd klee-last
lrwxrwxrwx 1 klee 47 Feb 21 04:41 klee-last -> /home/klee/klee_src/e
xamples/6110exs/klee-out-3
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ ls klee-out-0/
assembly.ll  messages.txt  run.stats         warnings.txt
info         run.istats    test000001.ktest
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ ktest-tool klee-last/
test000002.ktest
ktest file : 'klee-last/test000002.ktest'
args       : ['hardToHit.bc']
num objects: 1
object 0: name: 'a'
object 0: size: 4
```

Demo-1 : a hard-to-test program under conventional testing and then KLEE

```c
/*
 * An error that is hard to hit
 */

#include <stdio.h>
#include <assert.h>
#include <stdlib.h>
#include "klee/klee.h"

int rare(int x) {
  if (x < RAND_MAX/2) {
    if (x > RAND_MAX/2 - 3) {
          assert(0);
      }
  }
  else
    return(1);
}

int main() {
  int a, i;

  #ifdef KLEEON
  klee_make_symbolic(&a, sizeof(a), "a");
  rare(a);
  #endif


  #ifdef PRINTON
  #ifndef KLEEON
  printf("randmax = %d\n", RAND_MAX);
  for (i=0; i < 10000000; i++) {
  a = rand(); //% 100000000;
  rare(a);
  }
  #endif
  #endif
}
```

```
args       : ['hardToHit.bc']
num objects: 1
object 0: name: 'a'
object 0: size: 4
object 0: data: b'\x00\x00\x00\x00'
object 0: hex : 0x00000000
object 0: int : 0
object 0: uint: 0
object 0: text: ....
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ gcc -DKLEEON -DPRINTO
N -I ../../include -L /home/klee/klee_build/lib hardToHit.c -lkleeRu
ntest
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ KTEST_FILE=klee-last/
test000001.ktest ./a.out
a.out: hardToHit.c:13: rare: Assertion `0' failed.
Aborted
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ KTEST_FILE=klee-last/
test000002.ktest ./a.out
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ gcc -DINITON -DPRINTO
N -I ../../include hardToHit.c
klee@dc563dc0bfd1:~/klee_src/examples/6110exs$ ./a.out
randmax = 2147483647
```

Enter

KLEE !!

```c
/*
 * An error that is hard to hit
 */

#include <stdio.h>
#include <assert.h>
#include <stdlib.h>
#include "klee/klee.h"

int rare(int x) {
  if (x < RAND_MAX/2) {
    if (x > RAND_MAX/2 - 3) {
        assert(0);
      }
  }
  else
    return(1);
}

int main() {
  int a, i;

  #ifdef KLEEON
  klee_make_symbolic(&a, sizeof(a), "a");
  rare(a);
  #endif


  #ifdef PRINTON
  #ifndef KLEEON
  printf("randmax = %d\n", RAND_MAX);
  for (i=0; i < 10000000; i++) {
  a = rand(); //% 100000000;
  rare(a);
  }
  #endif
  #endif
}
```

```
klee@f88364af576a:~/klee_src/examples/hardToHit$ clang -DKLEEON -I ../../include -emit-llvm -g -c -O0 -Xclang -disable-O0-optnone hardToHit.c
hardToHit.c:18:1: warning: control may reach end of non-void function [-Wreturn-type]
}
^
1 warning generated.
klee@f88364af576a:~/klee_src/examples/hardToHit$ klee hardToHit.bc
KLEE: output directory is "/home/klee/klee_src/examples/hardToHit/klee-out-3"
KLEE: Using STP solver backend
KLEE: ERROR: hardToHit.c:13: ASSERTION FAIL: 0
KLEE: NOTE: now ignoring this error at this location

KLEE: done: total instructions = 27
KLEE: done: completed paths = 3
KLEE: done: generated tests = 3
klee@f88364af576a:~/klee_src/examples/hardToHit$ echo "see we already hit the assert in concolic"
see we already hit the assert in concolic
klee@f88364af576a:~/klee_src/examples/hardToHit$ echo "now to see the tests synthesized"
now to see the tests synthesized
klee@f88364af576a:~/klee_src/examples/hardToHit$ ls -ld klee-last
lrwxrwxrwx 1 klee klee 49 Feb 10 18:34 klee-last -> /home/klee/klee_src/examples/hardToHit/klee-out-3
klee@f88364af576a:~/klee_src/examples/hardToHit$ echo "this directory has the tests"
this directory has the tests
klee@f88364af576a:~/klee_src/examples/hardToHit$ ktest-tool klee-last/test000002.ktest
ktest file : 'klee-last/test000002.ktest'
args       : ['hardToHit.bc']
num objects: 1
object 0: name: 'a'
object 0: size: 4
object 0: data: b'\x00\x00\x00\x00'
object 0: hex : 0x00000000
object 0: int : 0
object 0: uint: 0
object 0: text: ....
klee@f88364af576a:~/klee_src/examples/hardToHit$ ktest-tool klee-last/test000001.ktest
ktest file : 'klee-last/test000001.ktest'
args       : ['hardToHit.bc']
num objects: 1
object 0: name: 'a'
object 0: size: 4
object 0: data: b'\xfd\xff\xff?'
object 0: hex : 0xfdffff3f
object 0: int : 1073741821
object 0: uint: 1073741821
object 0: text: ...?
klee@f88364af576a:~/klee_src/examples/hardToHit$ ls klee-last
assembly.ll  messages.txt  run.stats             test000001.kquery  test000002.ktest  warnings.txt
info         run.istats    test000001.assert.err  test000001.ktest   test000003.ktest
klee@f88364af576a:~/klee_src/examples/hardToHit$ echo "ah ha , test 000001 is the one that hit assert"
ah ha , test 000001 is the one that hit assert
```

Enter

KLEE !!

```c
/*
 * An error that is hard to hit
 */

#include <stdio.h>
#include <assert.h>
#include <stdlib.h>
#include "klee/klee.h"

int rare(int x) {
  if (x < RAND_MAX/2) {
    if (x > RAND_MAX/2 - 3) {
        assert(0);
      }
  }
  else
    return(1);
}

int main() {
  int a, i;

  #ifdef KLEEON
  klee_make_symbolic(&a, sizeof(a), "a");
  rare(a);
  #endif


  #ifdef PRINTON
  #ifndef KLEEON
  printf("randmax = %d\n", RAND_MAX);
  for (i=0; i < 10000000; i++) {
  a = rand(); //% 100000000;
  rare(a);
  }
  #endif
  #endif
}
```

```
klee@f88364af576a:~/klee_src/examples/hardToHit$ gcc -DKLEEON -DPRINTON -I ../../include -L /home/klee/klee_build/lib hardToHit.c -lkleeRuntest
klee@f88364af576a:~/klee_src/examples/hardToHit$ KTEST_FILE=klee-last/test000002.ktest ./a.out
klee@f88364af576a:~/klee_src/examples/hardToHit$ KTEST_FILE=klee-last/test000001.ktest ./a.out
a.out: hardToHit.c:13: rare: Assertion `0' failed.
Aborted
klee@f88364af576a:~/klee_src/examples/hardToHit$ echo "BOOM - we hit the assert "
BOOM - we hit the assert
klee@f88364af576a:~/klee_src/examples/hardToHit$
```

Demo-2
Binary
Search

Looks
OK?

Ship it?!

```c
#include <klee/klee.h>
#include <stdio.h>
#include <assert.h>
#include <stdlib.h>

void print_data(int arr[], int size, int target) {
  printf("searching for %d in:\n[", target);
    for (int i=0; i < size-1; i++) {
      printf("%d, ", arr[i]);
    }
    printf("%d]\n", arr[size-1]);
}

int binary_search(int arr[], int size, int target) {
  #ifdef PRINTON
    print_data(arr, size, target);
  #endif
    int low = 0;
    int high = size - 1;
    int mid;
    while (low <= high) {
        mid = (low + high)/2;
        if (arr[mid] == target) {
            return mid;
        }
        if (arr[mid] < target) {
            low = mid + 1;
        }
        if (arr[mid] > target) {
            high = mid - 1;
        }
    }
    return -1;
}
```

```c
int main() {

  int a[4]; // was a[10]

  #ifdef KLEEON
  klee_make_symbolic(&a, sizeof(a), "a");
  klee_assume(a[0] <= a[1]);
  klee_assume(a[1] <= a[2]);
  klee_assume(a[2] <= a[3]);

  klee_make_symbolic(&x, sizeof(x), "x");
  #endif

  #ifdef INITON
  a[0]=rand()%30;
  a[1]=a[0]+rand()%30;
  a[2]=a[1]+rand()%30;
  a[3]=a[2]+rand()%30;
  #endif

  int result = binary_search(a, 4, x); // was 10

  #ifdef PRINTON
  printf("result = %d\n", result);
  #endif
  // check correctness

  if (result != -1) {
    assert(a[result] == x);
  } else {
    // if result == -1, then we didn't find it.
rray
    for (int i = 0; i < 3; i++) { // was 10

      assert(a[i] != x);
    }
  }
  return 1;
}
```

Demo-2 Binary Search

Looks OK?

```c
#include <klee/klee.h>
#include <stdio.h>
#include <assert.h>
#include <stdlib.h>

void print_data(int arr[], int size, int target) {
  printf("searching for %d in:\n[", target);
    for (int i=0; i < size-1; i++) {
      printf("%d, ", arr[i]);
    }
    printf("%d]\n", arr[size-1]);
}

int binary_search(int arr[], int size, int target) {
  #ifdef PRINTON
    print_data(arr, size, target);
  #endif
    int low = 0;
    int high = size - 1;
    int mid;
    while (low <= high) {
        mid = (low + high)/2;
        if (arr[mid] == target) {
            return mid;
        }
        if (arr[mid] < target) {
            low = mid + 1;
        }
        if (arr[mid] > target) {
            high = mid - 1;
        }
    }
    return -1;
}
```

```c
int main() {

  int a[4]; // was a[10]

  #ifdef KLEEON
  klee_make_symbolic(&a, sizeof(a), "a");
```

```
klee@f88364af576a:~/klee_src/examples/binsrch$ gcc -DINITON -DPRINTON -I ../../include binsrch.c
klee@f88364af576a:~/klee_src/examples/binsrch$ ./a.out
searching for -336381299 in:
[13, 29, 56, 81]
result = -1
klee@f88364af576a:~/klee_src/examples/binsrch$ clang -DKLEEON -I ../../include -emit-llvm -g -c -O0 -Xclang -disable-O0-optnone binsrch.c
klee@f88364af576a:~/klee_src/examples/binsrch$ klee binsrch.bc
KLEE: output directory is "/home/klee/klee_src/examples/binsrch/klee-out-18"
KLEE: Using STP solver backend
KLEE: WARNING: undefined reference to function: printf

KLEE: done: total instructions = 638
KLEE: done: completed paths = 9
KLEE: done: generated tests = 9
```

Demo-2 Binary Search

Looks OK?

Ship it?!

```c
#include <klee/klee.h>
#include <stdio.h>
#include <assert.h>
#include <stdlib.h>

void print_data(int arr[], int size, int target) {
  printf("searching for %d in:\n[", target);
    for (int i=0; i < size-1; i++) {
      printf("%d, ", arr[i]);
    }
    printf("%d]\n", arr[size-1]);
}

int binary_search(int arr[], int size, int target) {
  #ifdef PRINTON
    print_data(arr, size, target);
  #endif
    int low = 0;
    int high = size - 1;
    int mid;
    while (low <= high) {
        mid = (low + high)/2;
        if (arr[mid] == target) {
            return mid;
        }
        if (arr[mid] < target) {
            low = mid + 1;
        }
        if (arr[mid] > target) {
            high = mid - 1;
        }
    }
    return -1;
}
```

```c
int main() {

  int a[4]; // was a[10]

  #ifdef KLEEON
  klee_make_symbolic(&a, sizeof(a), "a");
  klee_assume(a[0] <= a[1]);
  klee_assume(a[1] <= a[2]);
  klee_assume(a[2] <= a[3]);

  klee_make_symbolic(&x, sizeof(x), "x");
  #endif

  #ifdef INITON
  a[0]=rand()%30;
  a[1]=a[0]+rand()%30;
  a[2]=a[1]+rand()%30;
  a[3]=a[2]+rand()%30;
  #endif

  int result = binary_search(a, 4, x); // was 10

  #ifdef PRINTON
  printf("result = %d\n", result);
  #endif
  // check correctness

  if (result != -1) {
    assert(a[result] == x);
  } else {
    // if result == -1, then we didn't find it.
rray
    for (int i = 0; i < 3; i++) { // was 10

      assert(a[i] != x);
    }
  }
  return 1;
}
```

```
KLEE: done: generated tests = 9
klee@f88364af576a:~/klee_src/examples/binsrch$ ls klee-last
assembly.ll  messages.txt  run.stats        test000002.ktest  test000004.ktest  test000006.ktest  test000008.ktest  warnings.txt
info         run.istats    test000001.ktest  test000003.ktest  test000005.ktest  test000007.ktest  test000009.ktest
klee@f88364af576a:~/klee_src/examples/binsrch$ ktest-tool klee-last/test000001.ktest
ktest file : 'klee-last/test000001.ktest'
args       : ['binsrch.bc']
num objects: 2
object 0: name: 'a'
object 0: size: 16
object 0: data: b'\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00\x00'
object 0: hex : 0x00000000000000000000000000000000
object 0: text: ................
object 1: name: 'x'
object 1: size: 4
object 1: data: b'\x00\x00\x00\x00'
object 1: hex : 0x00000000
object 1: int : 0
object 1: uint: 0
object 1: text: ....
klee@f88364af576a:~/klee_src/examples/binsrch$ ktest-tool klee-last/test000002.ktest
ktest file : 'klee-last/test000002.ktest'
args       : ['binsrch.bc']
num objects: 2
object 0: name: 'a'
object 0: size: 16
object 0: data: b'\x00\x00\x00\x00\x00\x00\x00\x01\x00\x00\x00\x00\x01\x00\x00\x00\x01'
object 0: hex : 0x00000000000000010000000100000001
object 0: text: ................
object 1: name: 'x'
object 1: size: 4
object 1: data: b'\x00\x00\x00\x00'
object 1: hex : 0x00000000
object 1: int : 0
object 1: uint: 0
object 1: text: ....
klee@f88364af576a:~/klee_src/examples/binsrch$ ktest-tool klee-last/test000009.ktest
ktest file : 'klee-last/test000009.ktest'
args       : ['binsrch.bc']
num objects: 2
object 0: name: 'a'
object 0: size: 16
object 0: data: b'\x00\x00\x00\x006\x00\x00\x00\xfe\x00\x00\x00\x00\x00\x00\x03'
object 0: hex : 0x0000000036000000fe00000000000003
object 0: text: ....6...........
object 1: name: 'x'
object 1: size: 4
object 1: data: b'\x00\x01\x00\x00'
object 1: hex : 0x00010000
object 1: int : 256
object 1: uint: 256
object 1: text: ....
klee@f88364af576a:~/klee_src/examples/binsrch$
```

Demo-2 Binary Search Looks OK. Closer to shipping.

What was achieved?
* tests that cover every path

* default C-level checks such as array out of bounds, null de reference

i.e. FEWER BUGS

```
#include <klee/klee.h>
#include <stdio.h>
#include <assert.h>
#include <stdlib.h>

void print_data(int arr[], int size, int target) {
  printf("searching for %d in:\n[", target);
```

```
klee@f88364af576a:~/klee_src/examples/binsrch$ ktest-tool klee-last/test000009.ktest
ktest file : 'klee-last/test000009.ktest'
args       : ['binsrch.bc']
num objects: 2
object 0: name: 'a'
object 0: size: 16
object 0: data: b'\x00\x00\x00\x006\x00\x00\x00\xfe\x00\x00\x00\x00\x00\x00\x03'
object 0: hex : 0x0000000036000000fe00000000000003
object 0: text: ....6...........
object 1: name: 'x'
object 1: size: 4
object 1: data: b'\x00\x01\x00\x00'
object 1: hex : 0x00010000
object 1: int : 256
object 1: uint: 256
object 1: text: ....
klee@f88364af576a:~/klee_src/examples/binsrch$ gcc -DKLEEON -DPRINTON -I ../../include -L /home/klee/klee_build/lib binsrch.c -lkleeRuntest
klee@f88364af576a:~/klee_src/examples/binsrch$ KTEST_FILE=klee-last/test000001.ktest ./a.out
searching for 0 in:
[0, 0, 0, 0]
result = 1
klee@f88364af576a:~/klee_src/examples/binsrch$ KTEST_FILE=klee-last/test000002.ktest ./a.out
searching for 0 in:
[0, 16777216, 16777216, 16777216]
result = 0
klee@f88364af576a:~/klee_src/examples/binsrch$ KTEST_FILE=klee-last/test000009.ktest ./a.out
searching for 256 in:
[0, 54, 254, 50331648]
result = -1
klee@f88364af576a:~/klee_src/examples/binsrch$
```

What does KLEE do? (Cadar's slides)

KLEE

[OSDI 2008, Best Paper Award]

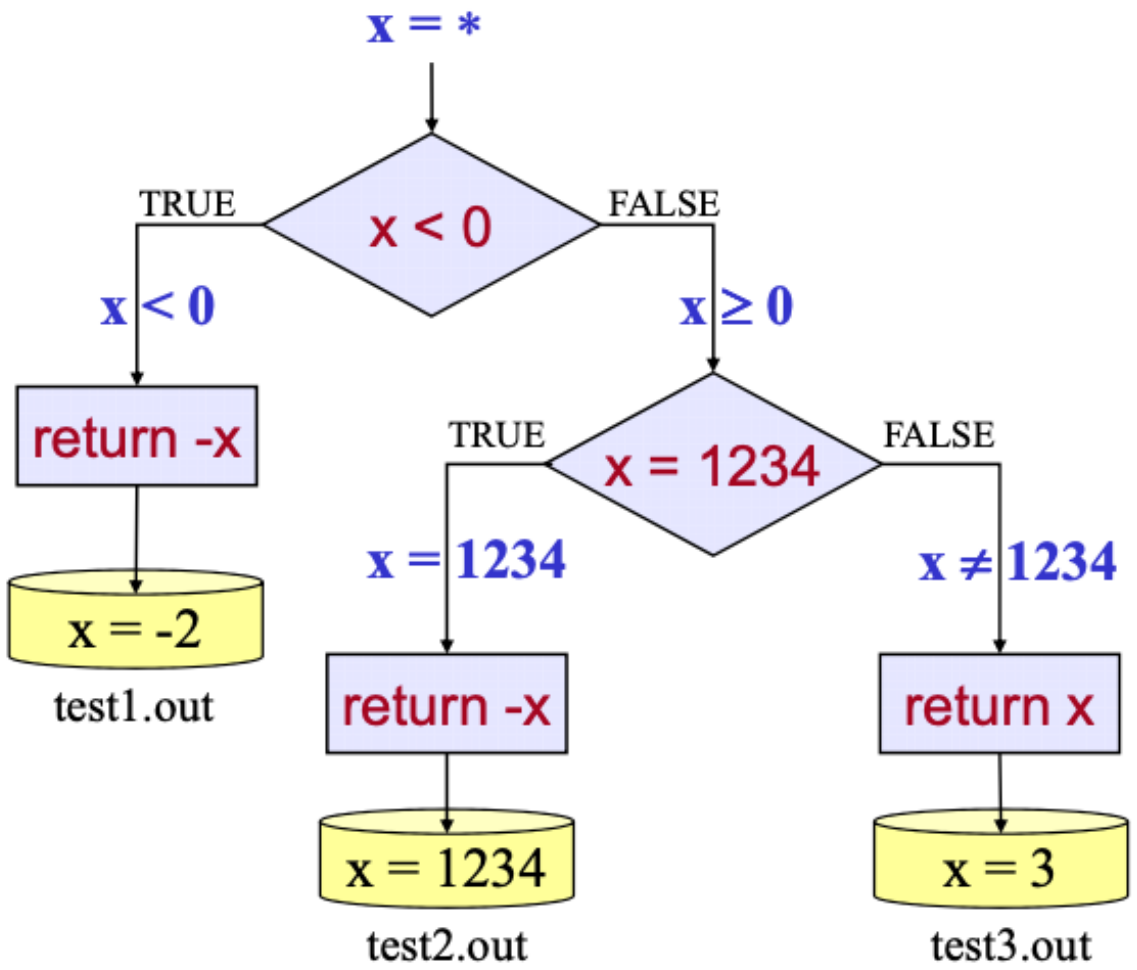
- Based on symbolic execution and constraint solving techniques

- Automatically generates high coverage test suites
  - Over 90% on average on ~160 user-level apps
- Finds deep bugs in complex systems programs
  - Including higher-level correctness ones

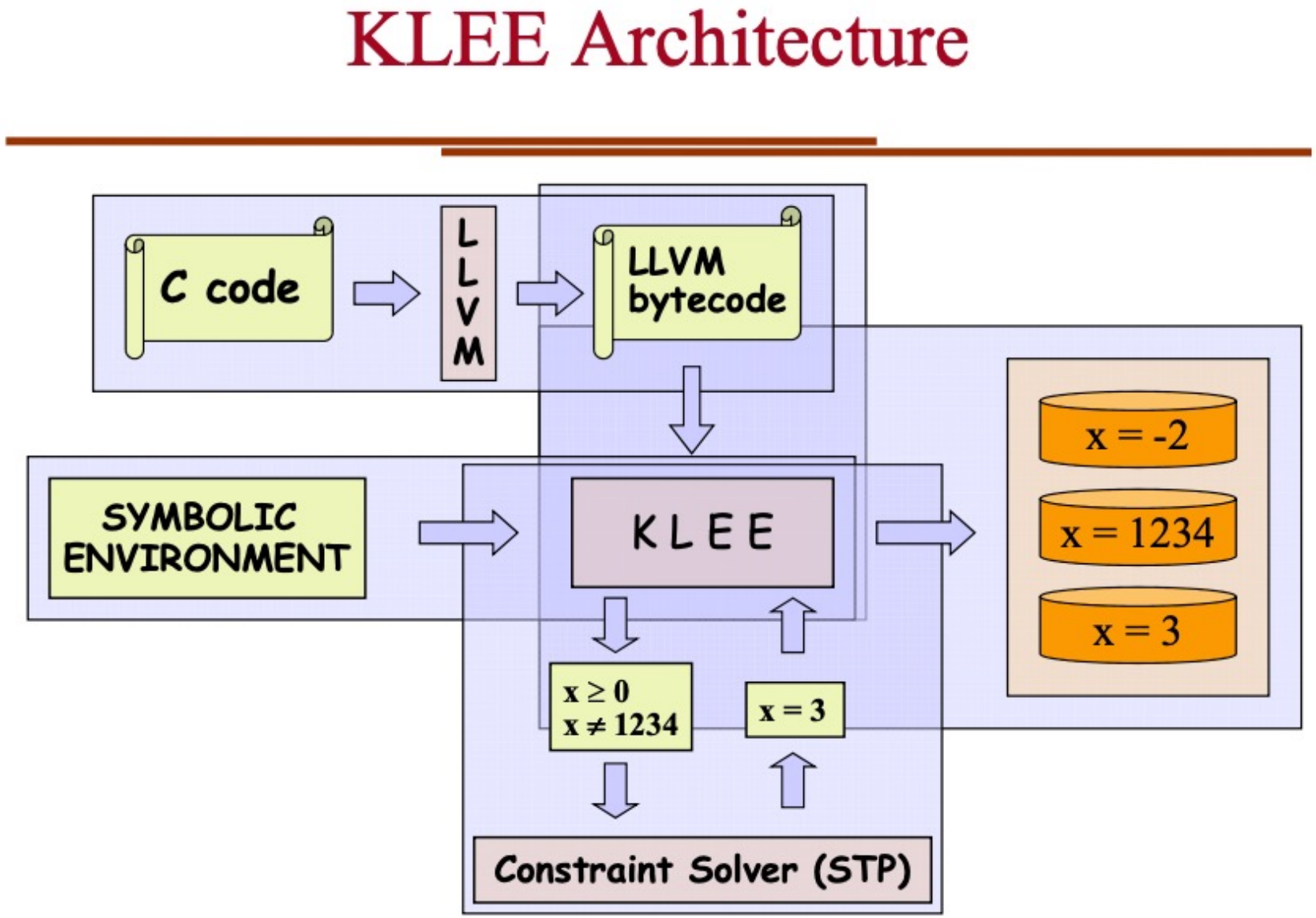
How does KLEE work? (Cadar's slides)

Toy Example

```
int bad_abs(int x)
{
    if (x < 0)
        return -x;
    if (x == 1234)
        return -x;
    return x;
}
```



How does KLEE work? (Cadar's slides)



Engineering KLEE to be efficient (Cadar)

Three Big Challenges

- Motivation
- Example and Basic Architecture
- **Scalability Challenges**
  - Exponential number of paths
  - Expensive constraint solving
  - Interaction with environment
- Experimental Evaluation

How good is KLEE (Dr. Peng Li's slides)

ConcFuzzer: a sanitizer guided hybrid fuzzing framework leveraging greybox fuzzing and concolic execution

Peng Li, Rundong Zhou, Yaohui Chen,

Yulong Zhang, Tao (Lenx) Wei

lipeng28@baidu.com

Baidu X-Lab

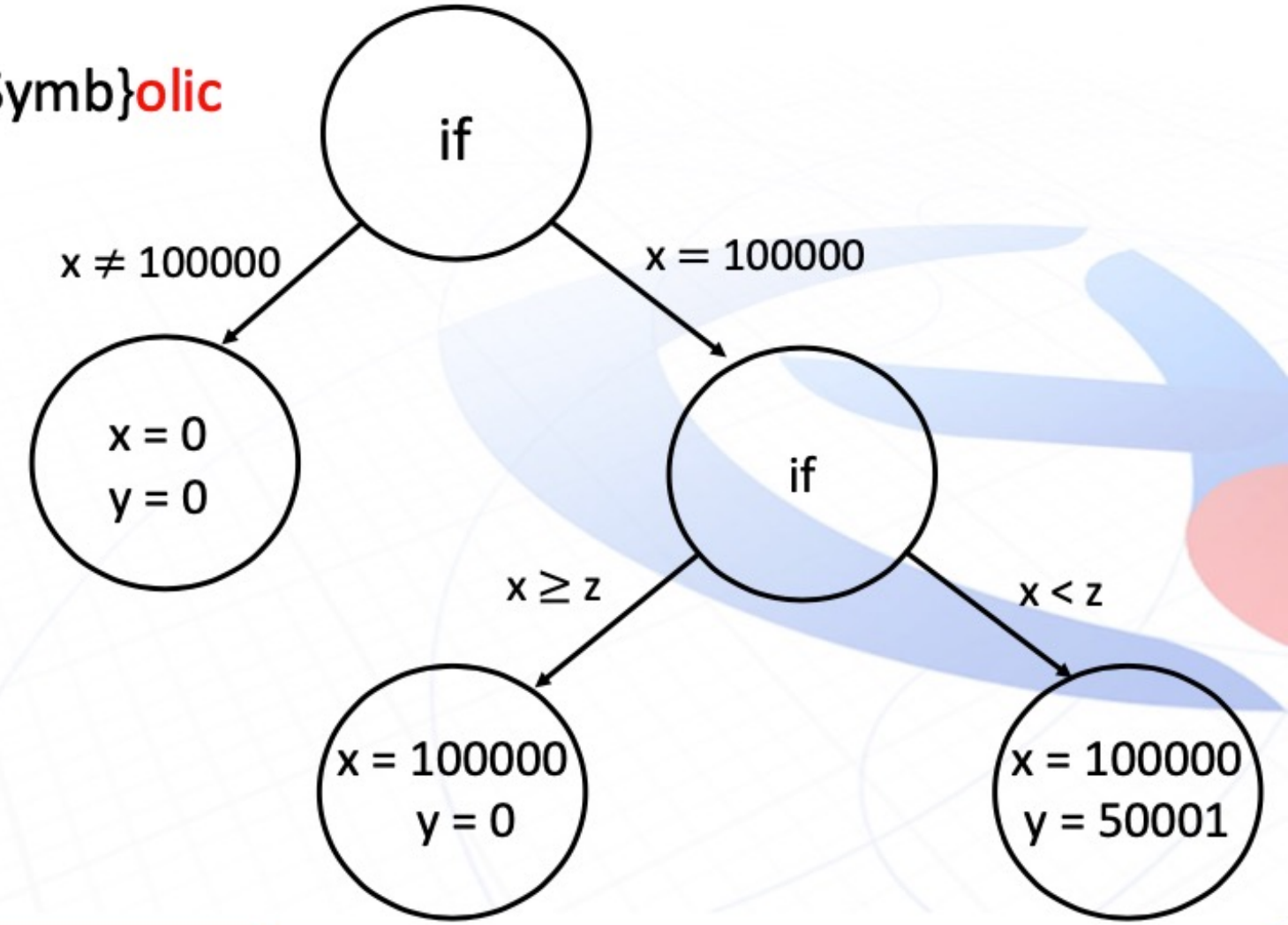
How good is KLEE (Dr. Peng Li's slides)

Concolic Execution

- Concolic = Conc{rete + Symb}olic

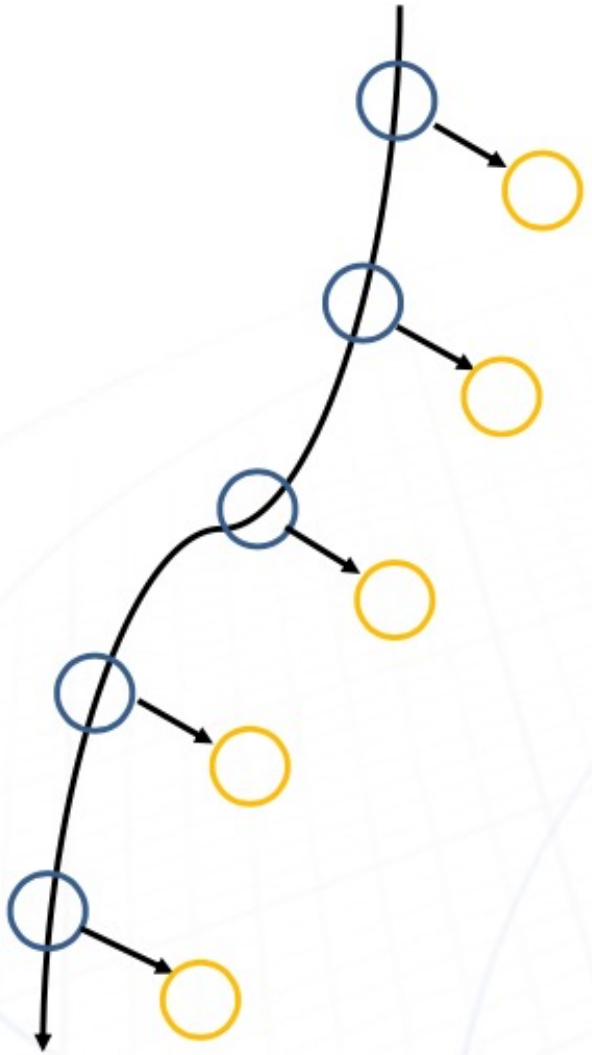
```
void foo (int x, int y) {
  int z = 2*y;
  if (x == 100000) {
    if (x < z) {
      /* error */
      assert(0);
    }
  }
}
```

Snippet of C code from wikipedia



How good is KLEE (Dr. Peng Li's slides)

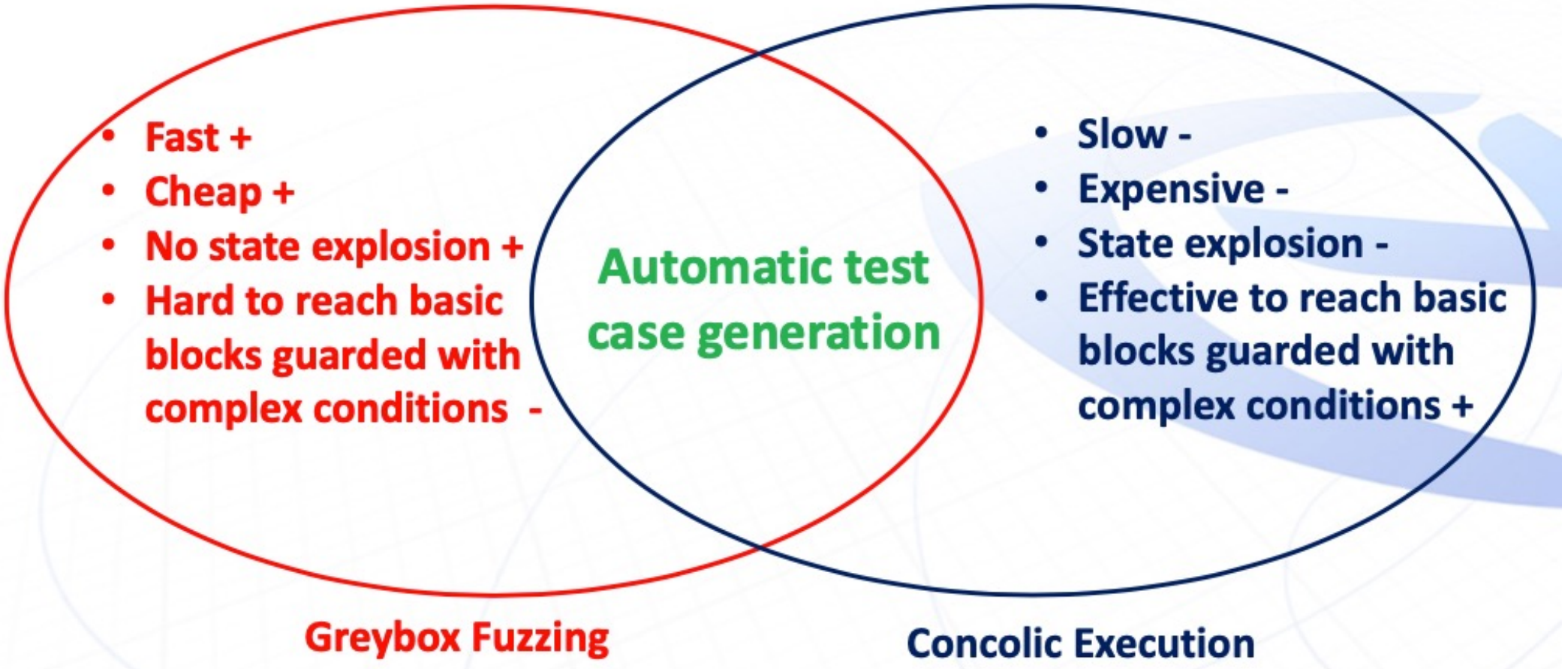
Concolic Execution on top of KLEE



1. Delay constraint solving until the state get scheduled
2. If the state's path constraint is satisfiable, compute the input
3. Otherwise, discard the state

How good is KLEE (Dr. Peng Li's slides)

Concolic execution



How good is KLEE (Dr. Peng Li's slides)

MbedTLS X509 Certificate Parser

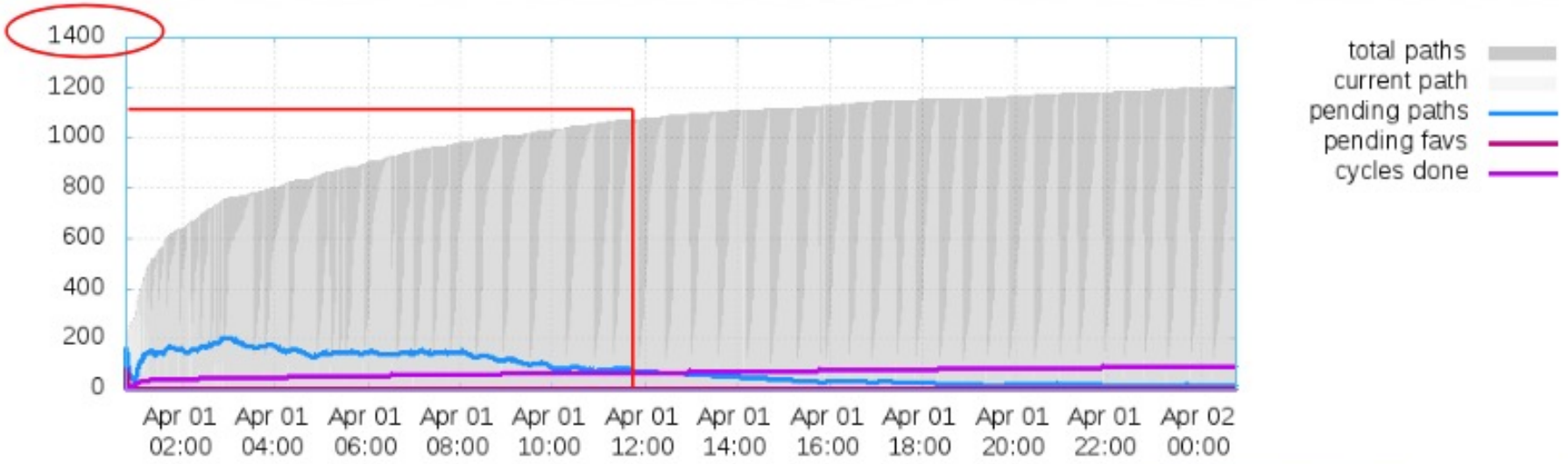


Fig 5. concfuzzer's 24 hours running results for mbedtls x509 certificate parser

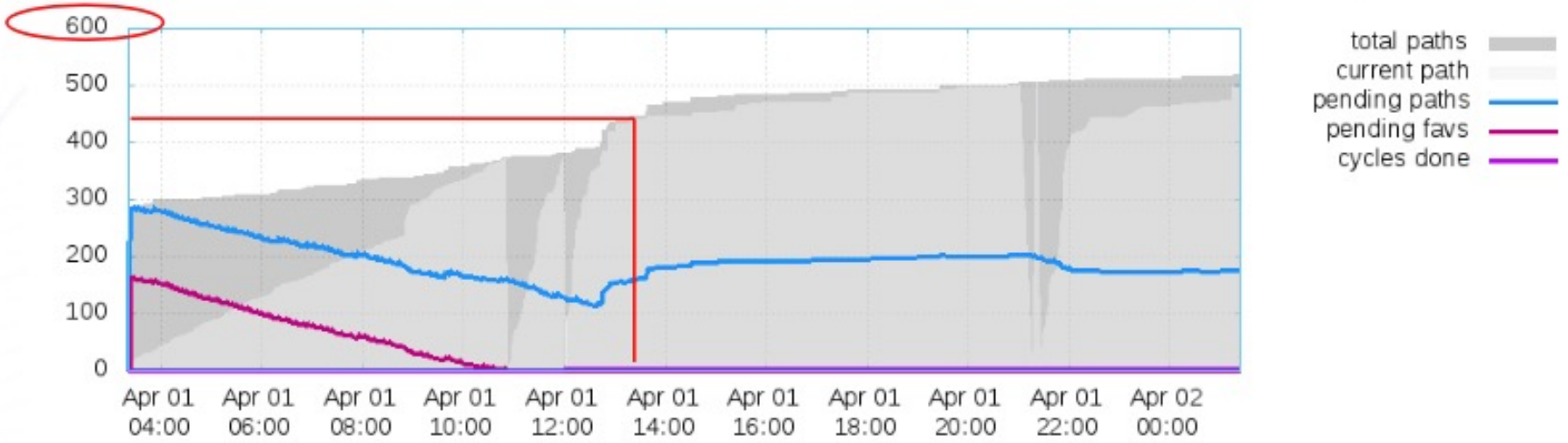


Fig 6. AFL's 24 hours running results for mbedtls x509 certificate parser

How good is KLEE (Dr. Peng Li's slides)

djpeg (Libjpeg-9b)

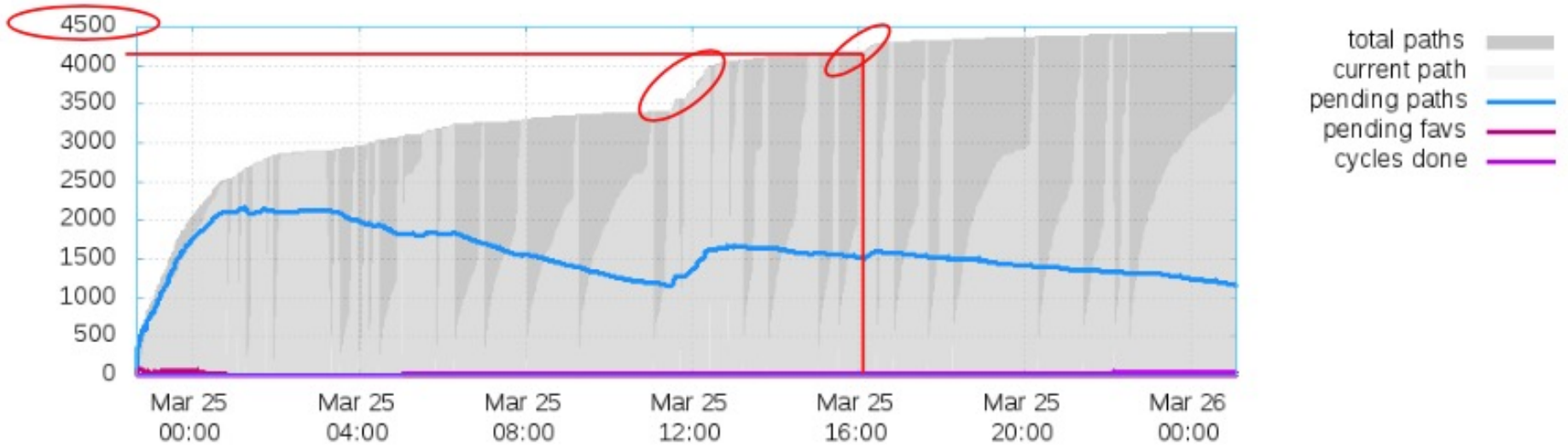


Fig 1. ConcFuzzer's 24 hours running results for djpeg

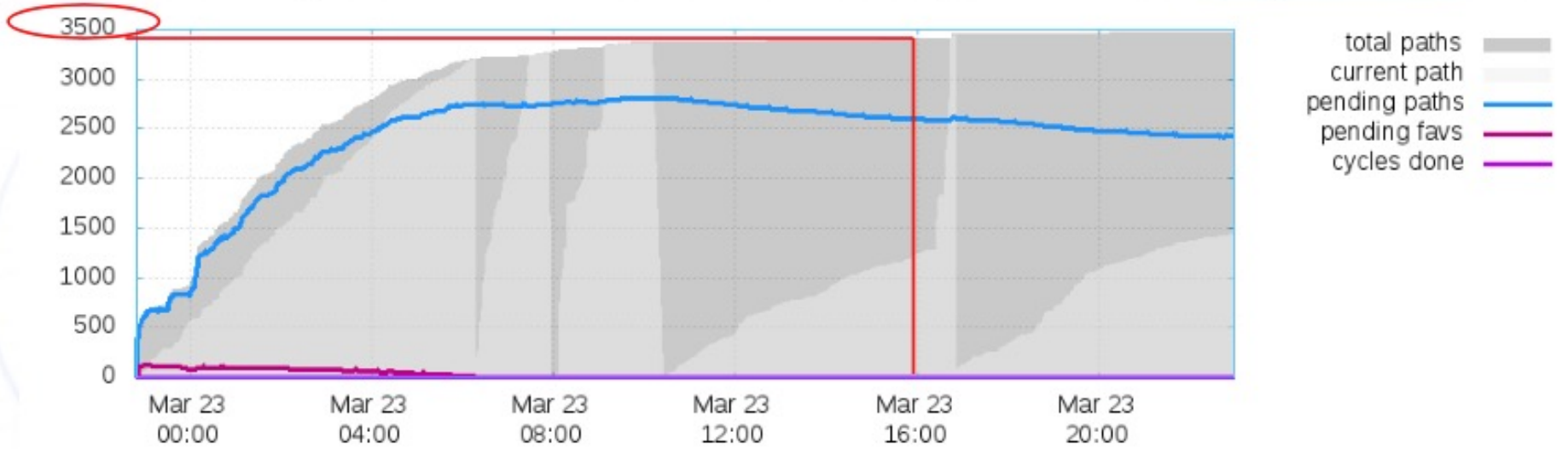


Fig 2. AFL's 24 hours running results for djpeg

Dr. Guodong Li's and Dr. Peng Li's FANTASTIC work on GKLEE follows

See also Guodong's work on PUG on the FSE 2010 publication site!
It was followed by GPUVerify, another fantastic verifier from Alastair Donaldson's groups at Imperial College, London

Summary

This is a huge field now – symbolic execution

You get to study this in projects

Even the MSR python Dyn Symb Executor – good project!

Correctness is central to Energy-Efficient Computing

The more performance per watt we can obtain (e.g. TeraFlop in 30W, Exaflop in 25 MW) … that is $25 Million In electricity costs alone !!

… the less we need to depend on dirty fuels,
… the faster we can innovate in science and engineering

Intrepid supercomputer (Image courtesy of Argonne)

pogoprinciple.wordpress.com

Emerging Heterogeneous Parallel Systems, and Role of Formal Methods in them

Problem Solving Environment based **User Applications**

Problem-Solving Environments e.g. Uintah, Charm++, ADLB

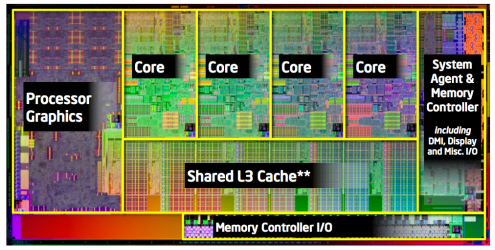
(1) Formal Methods at the User Application Level

Infiniband style interconnect

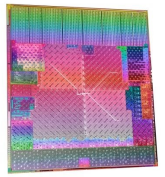
High Performance MPI Libraries

Concurrent Data Structures

(2) Formal Dynamic Methods for MPI



Sandybridge (courtesy anandtech.com)



AMD Fusion APU

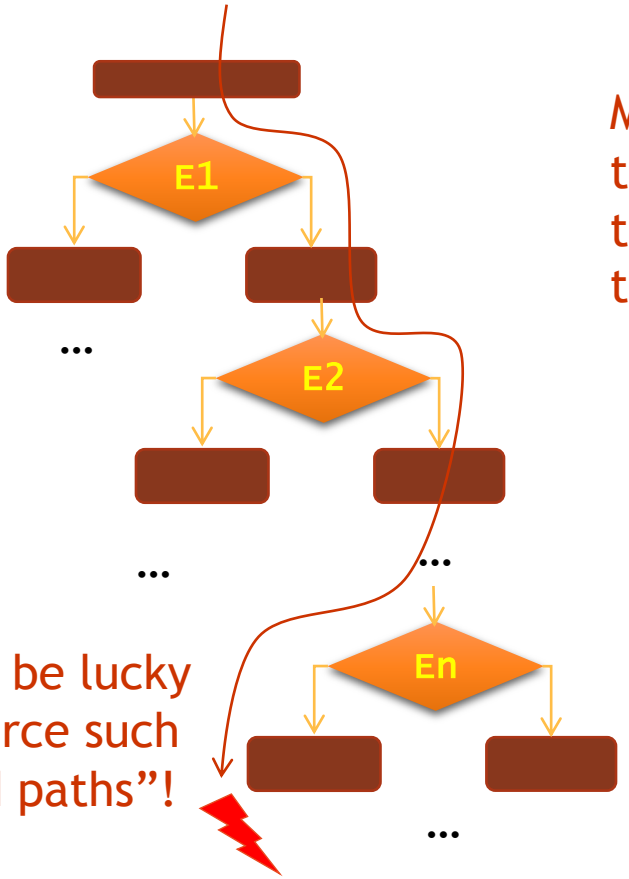
Geoforce GTX 480 (Nvidia)

(3) Formal Analysis for CUDA Programs

Why conventional testing is inadequate

Exponential number of paths;

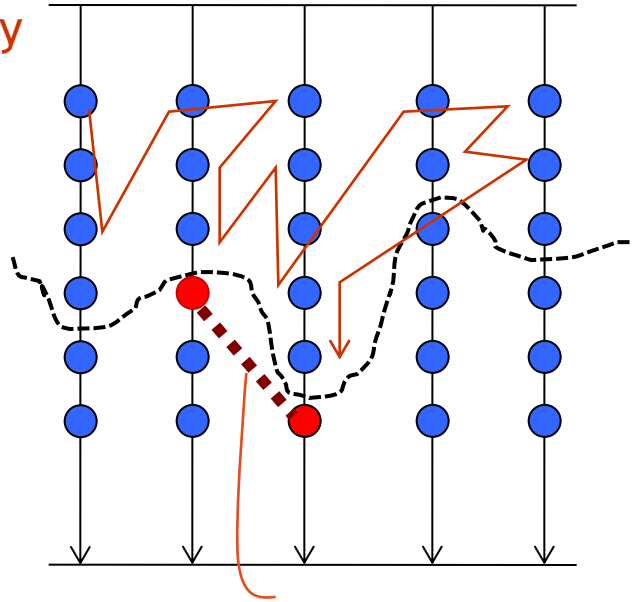
the bug may be deeply hidden



Must be lucky to force such "bad paths"!

Exponential number of schedules; the bug may be triggered only by one particular interleaving

Must be lucky to schedule threads in this manner!

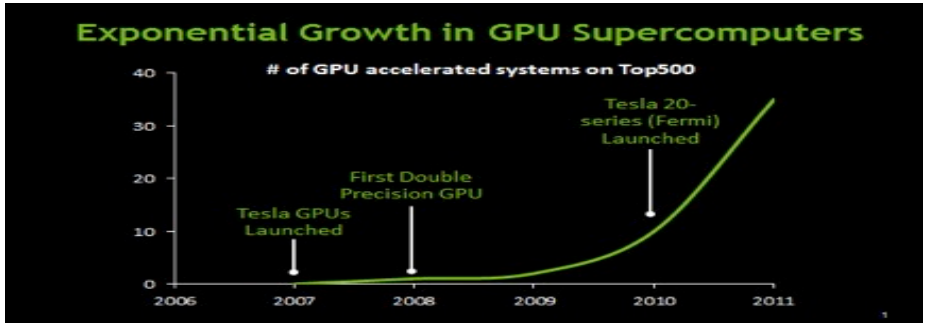


Some bad interaction, such as a data race may depend on the schedule…

GPU-based Computing

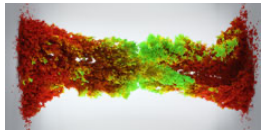
- About 40 of the top 500 machines were (in 2012) GPU-based

(courtesy of Nvidia, www.engadget.com)



- Personal supercomputers used for scientific research (biology, physics, …) increasingly based on GPUs

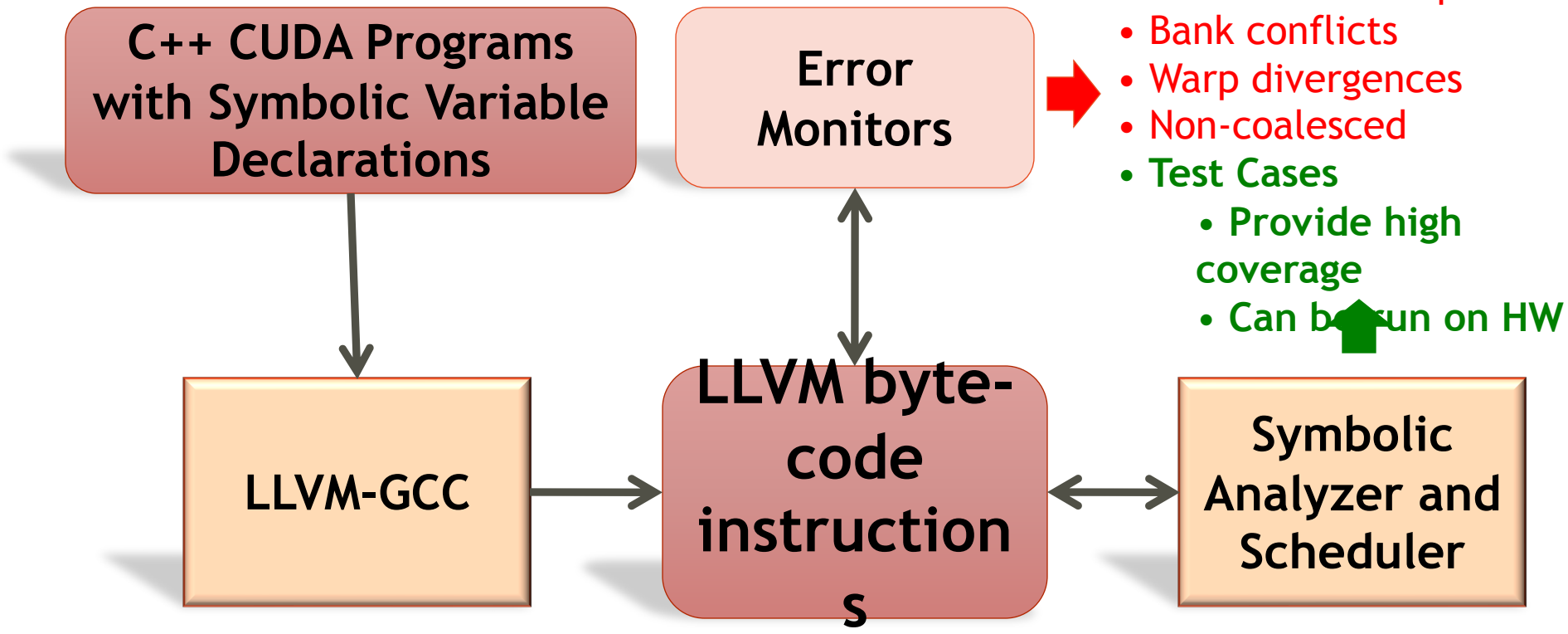
(courtesy of AMD)



(courtesy of Nvidia)

GKLEE (see PPoPP 2012)

```
__input__ int *values = (int *)malloc(sizeof(int) * NUM);

klee_make_symbolic(values, sizeof(int)*NUM, "values");

int *dvalues;
cudaMalloc((void **)&dvalues, sizeof(int) * NUM);
cudaMemcpy(dvalues, values, sizeof(int) * NUM, cudaMemcpyHostToDevice);

BitonicKernel <<< … >>> (dvalues);
```



Our Formal Verification of CUDA builds on top of *Sequential Program* Verification by KLEE [OSDI '08]

```
#include "stdio.h"
#include "cutil.h"
#include "string.h"
#include "klee.h"

#define STRLEN 5
int main(){
 char item;
 char str[STRLEN];
 int lo=0;
 int hi;

 int mid, found=0;
 //  printf("Please give char to be searched: \n");
 //  scanf("%c", &item);
klee_make_symbolic(&item, sizeof(item), "item");
 //  printf("Please give string within which to search: \n");
 //  scanf("%s", str);
klee_make_symbolic(str, sizeof(str), "str");
klee_assume(str[0] <= str[1]);
klee_assume(str[1] <= str[2]);
klee_assume(str[2] <= str[3]);
klee_assume(str[3] <= str[4]);
str[4] = '\0';
hi=  4; //strlen(str)-1; // strlen ignores null at the end of string
                // hi points to last char in a 0 based array

while(!found && lo <= hi) {
  mid = (lo+hi)/2;

  if (item == str[mid])
   { printf("*");
     found = 1; }
  else
   if (item < str[mid])
    { hi = mid-1;
                printf("L"); }
   else
    { lo = mid+1;
                printf("H"); }
 }
 if (found) printf("found\n");//printf("\nitem %c found at posn %d\n", item, mid);
 else printf("not found\n");//printf("\nitem %c not in str %s\n", item, str);
 return found;
}
```

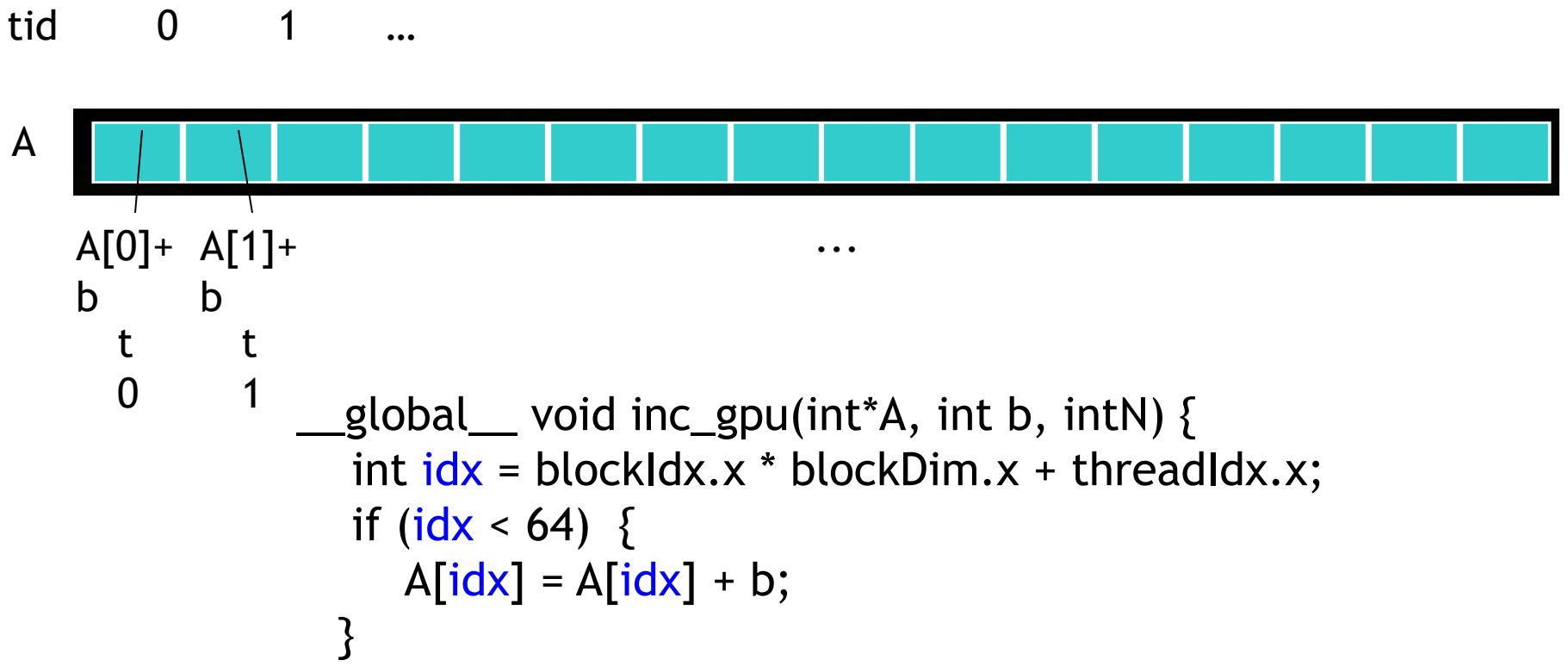
A simple Binary Search being prepared for formal symbolic analysis

This will force path coverage !!

Concurrency errors

Example: Increment Array Elements

Increment N-element array A by scalar b




```
__global__ void inc_gpu(int*A, int b, intN) {
    int idx = blockIdx.x * blockDim.x + threadIdx.x;
    if (idx < 64)  {
        A[idx] = A[idx] + b;
    }
```

Data Races in GPU Programs

The usual definition of a race:

"Two accesses, one of which is a write, that occur without a happens-before edge between them."

In GPUs, the happens-before is provided by
- Barriers (_syncthreads())
- Atomics

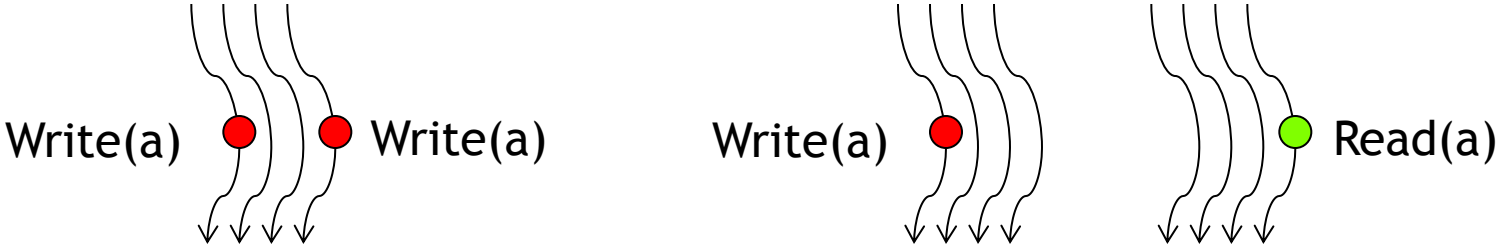
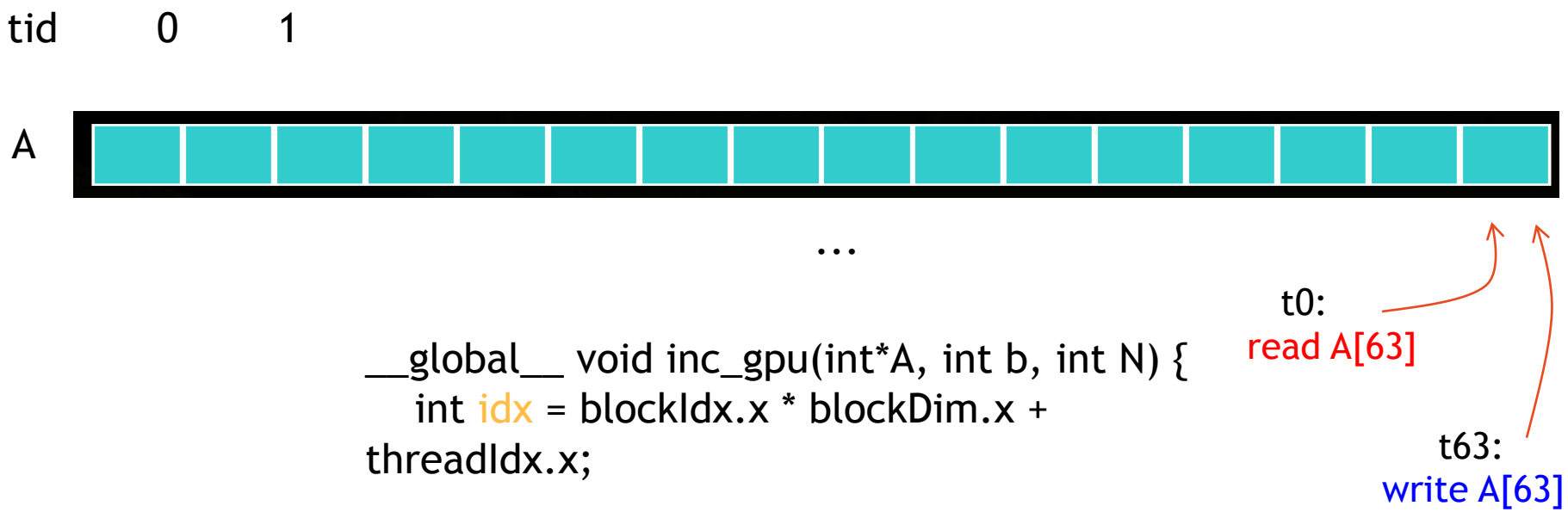


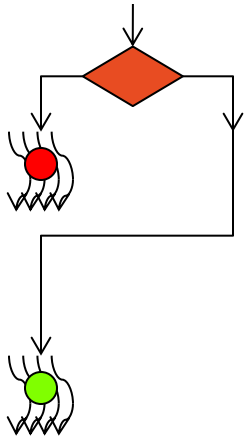
Illustration of Race

Increment N-element vector A by scalar b

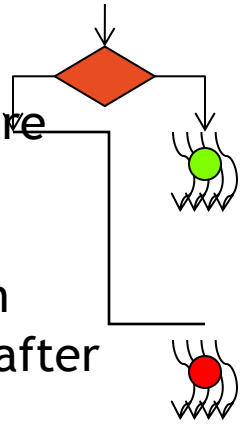


Porting Race: A Race-type Identified by us

- Some hardware platforms may evaluate “then” before “else” – others may reverse this order



If we have a divergent warp where a variable is **READ** in one path and **WRITTEN** in another path, then depending on the execution order, the **READ** may be before/after the **WRITE**

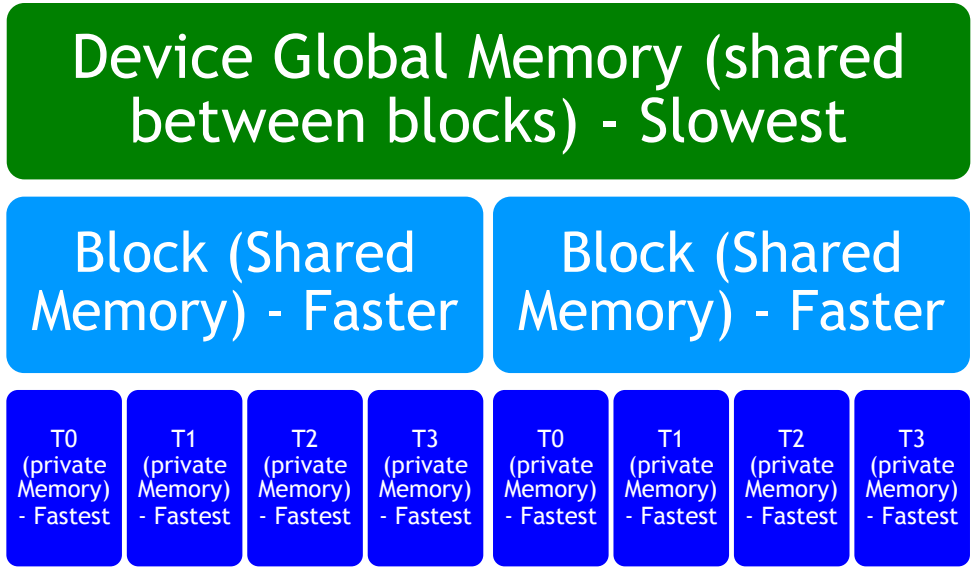


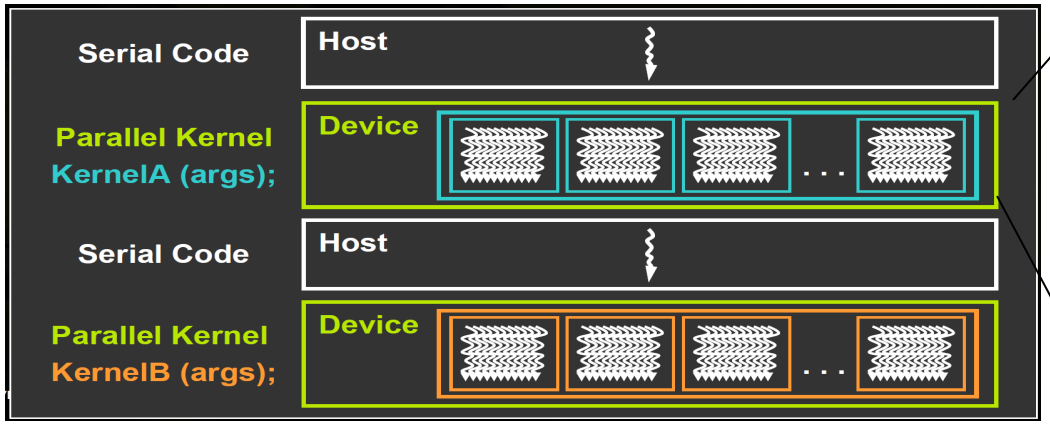
Example of Porting Race

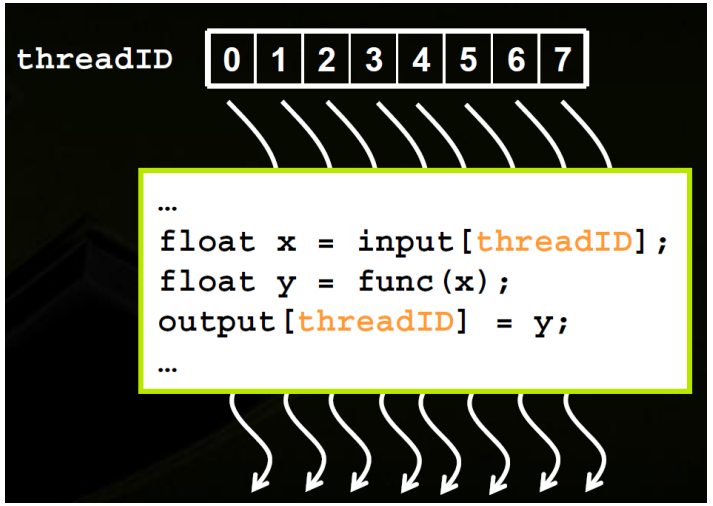
```
#include <stdio.h>

#define NUM 32

__shared__ int v[NUM];

__global__ void PortingRace() {
  if (threadIdx.x % 2) {
    v[threadIdx.x] = v[ (NUM + threadIdx.x - 1) % NUM ] + 1; // W:even;
R:odd
  }
  else {
    v[threadIdx.x] = v[ (NUM + threadIdx.x + 1) % NUM ] - 1; // W:odd;
R:even
  }
}
int main() {
  PortingRace<<<1,NUM>>>();
  return 0;
}
```

CUDA-based GPU Programming Basics

- A simple dialect of C++ with CUDA directives
- Synchronization within Block through Barriers
- (__syncthread())
- Threads within block scheduled in *warps*
- **Don't rely on warps for correctness!**







Conventional GPU Debuggers are Inadequate

- Based on platform testing
- Full generality of executions not reflected
- Hard to cause races (input selection)
- Hard to observe races
  - vector-clock based solutions that run on GPUs exist
  - (last time we checked) only for shared memory races

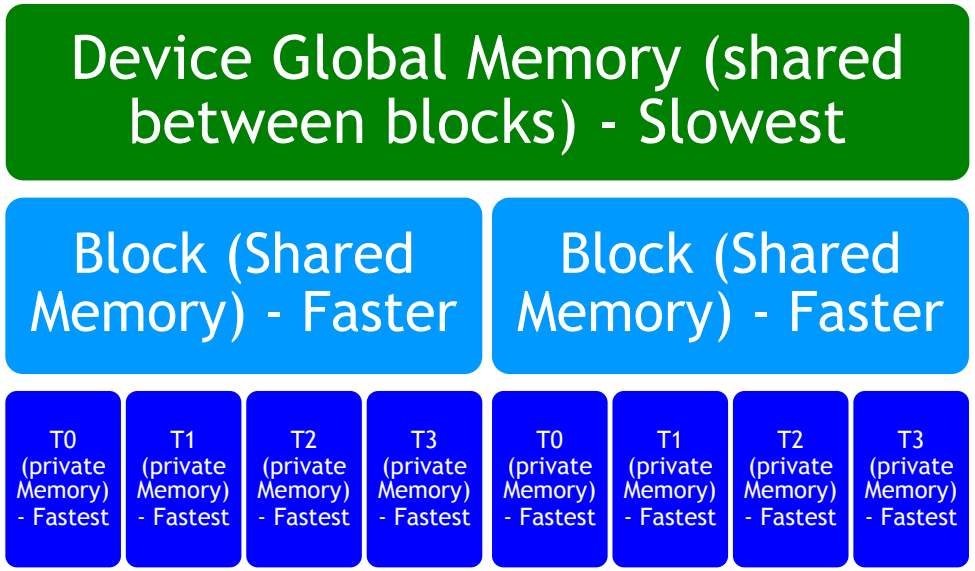
Some of the GPU Program Bugs

- Data races
  - Cause unpredictable outputs
  - Cause compilers to misbehave
- Incorrectly used synchronizations
  - Syncthreads not used with textual barriers
  - Syncthreads causing deadlocks
- Misunderstood memory consistency models
  - When updates are visible across threads
- Incorrectly used atomics (synchronization)
  - Due to incorrect synchronization, invariants get broken
- Erroneous computational results – esp. with floating-point
  - Due to unpredictable computational order, results may diverge

Why are Data Races Highly Problematic?

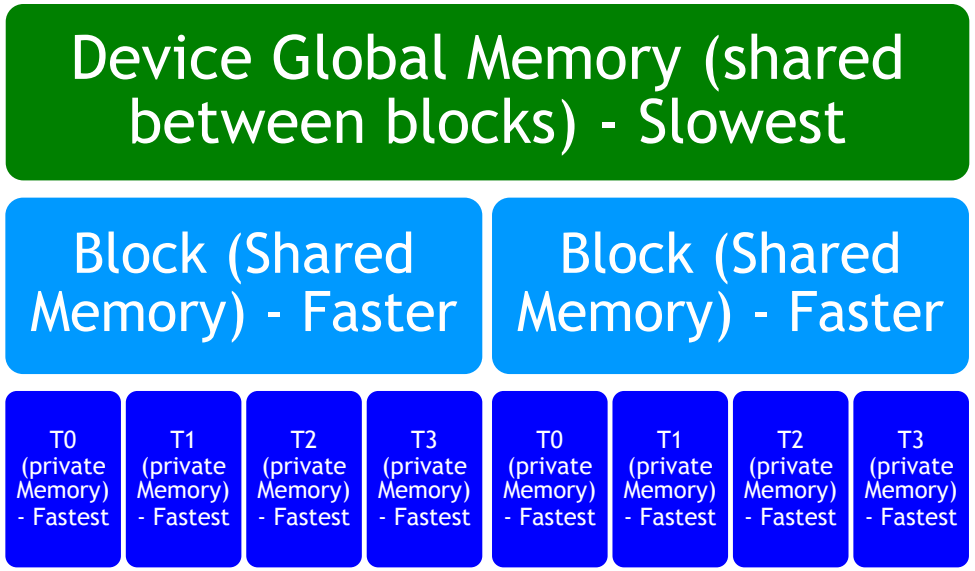
- Testing is seldom conclusive
  - Must infer a race indirectly (e.g. corrupted results)
- Races manifest when code is ported or optimized
  - Scheduling can change
- Data races make compiled results suspect
  - Compilers optimize assuming the absence of races in the most general setting

Synchronization Primitives in CUDA




```
__kernel__ void deadlock() {
  if (threadIdx.x > 0) {
    v[threadIdx.x]++;
  }
  else {
    v[threadIdx.x]--;
  }
  __syncthreads(); // Barrier
}
```

Synchronization Primitives in CUDA

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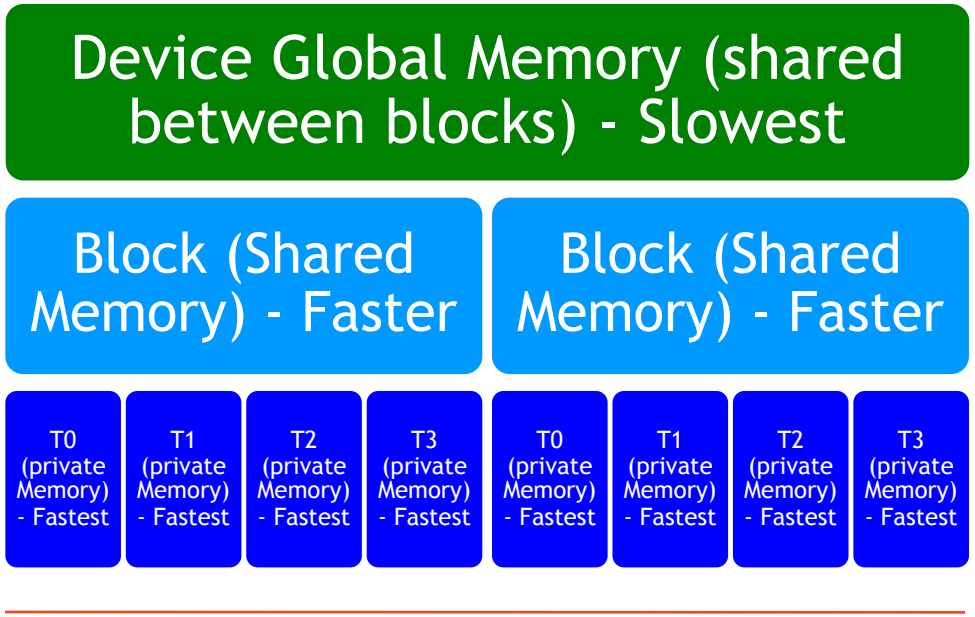
Threads within a block can synchronize using __syncthreads(). (This call synchronizes threads, also gives the effect of the stronger fence “thread_fence”.)

Synchronization Primitives in CUDA

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  }
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  }
  __syncthreads(); // Barrier
}
```

For synchronization across blocks, we must use one of the CUDA Atomics **(Zvonimir will present our NFM'13 work)**

Threads within a block can synchronize using __syncthreads(). (This call synchronizes threads, also gives the effect of the stronger fence "thread_fence".)

Deadlocks caused by misused __syncthreads()

- Cause a “hang” or unspecified behavior

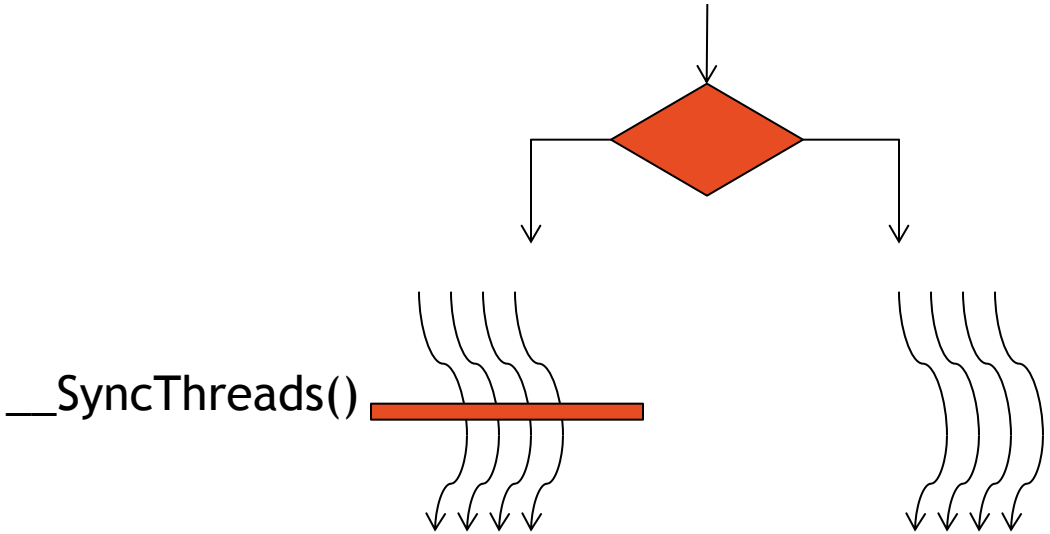
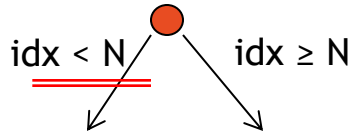


Illustration of “Deadlock” (conceptual deadlock; behavior is really undefined)

```
__global__ void kernelName (args) {

    int idx = blockIdx.x * blockDim.x +
threadIdx.x;

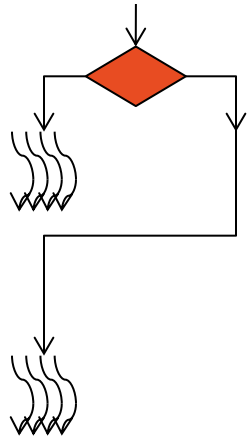
   if (idx == 3) {
  ….
       __syncthreads();
  }
```




```
__kernel__ void deadlock() {
  if (threadIdx.x > 0) {
    v[threadIdx.x]++;
    __syncthreads();
  }
  else {
    v[threadIdx.x]--;
    __syncthreads();
  }
}
```

Suffers from Textually Non-aligned Barriers (example Deadlock1.C)

Warp Divergence



```
__global__ void kernelName (args) {

    int idx = blockIdx.x * blockDim.x +
threadIdx.x;

    if ( odd(idx) ) {

      <Statements1>

    } else  {

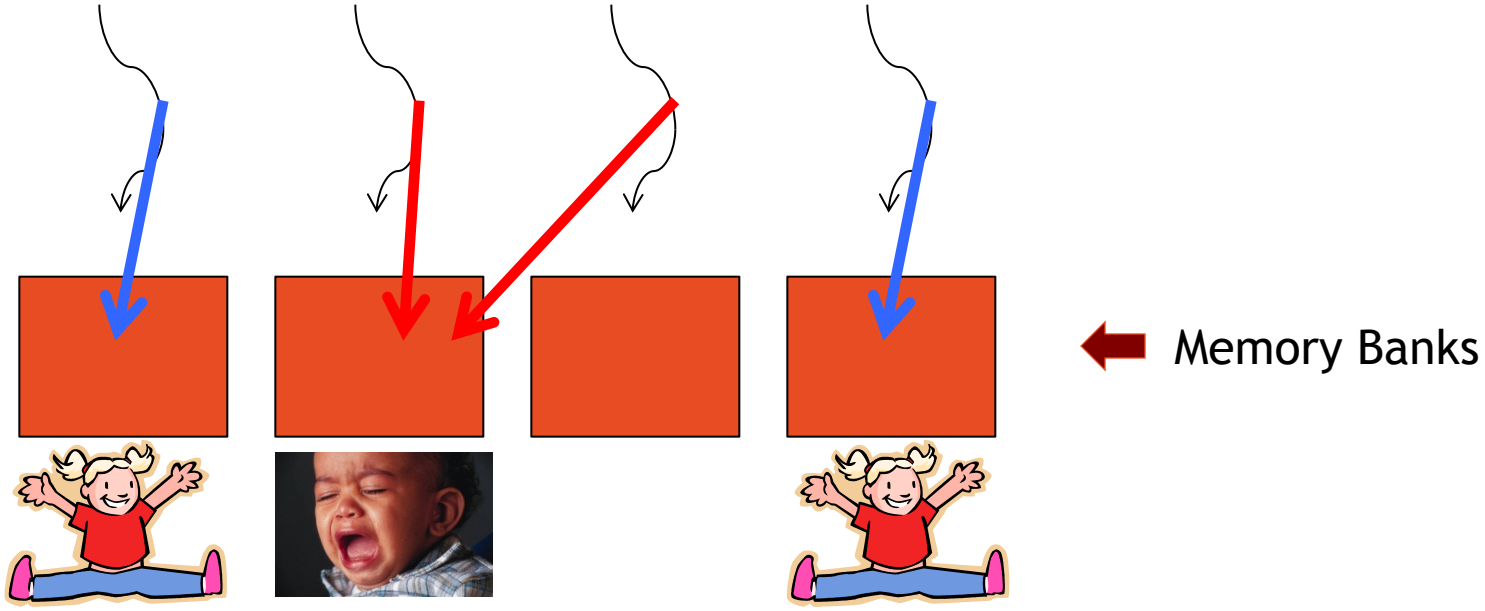
      <Statements2>

    }
```

This is a performance bug – but can be detected through formal symbolic analysis

Memory-bank Conflicts

Happen when two threads generate addresses that fall into the same memory bank



This is a performance bug – but can be detected through formal symbolic analysis

Non-coalesced Memory Fetches

Happen when threads generate global memory addresses that do not fully utilize the bus

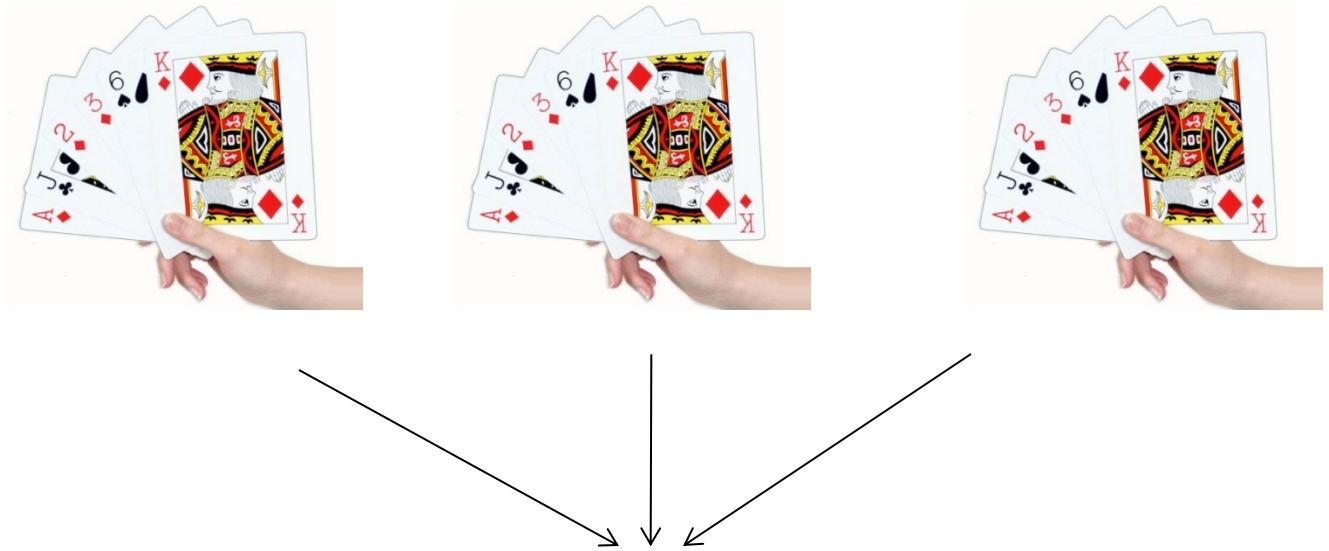
This is a performance bug – but can be detected through formal symbolic analysis (10 x more severe than bank conflicts)

Two approaches to modeling

- Through interleaving
  - Followed in most works
- Through lock-step synchronous execution
  - Pioneered in GPUVerify

How bad is the interleaving problem?

It is like shuffling decks of cards

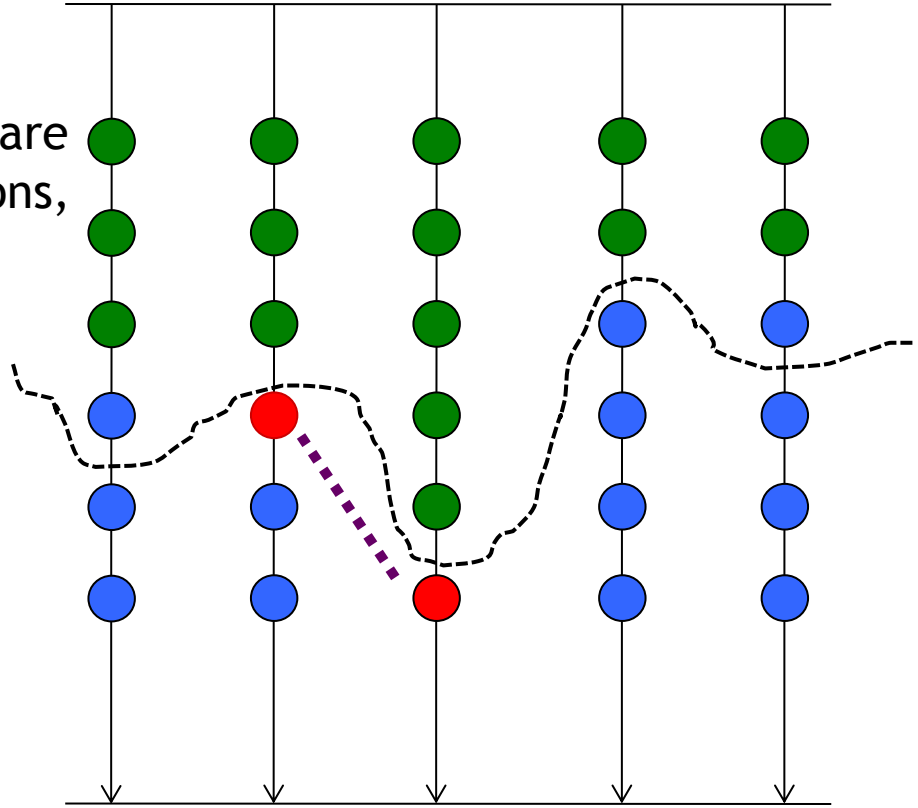


> 6 * 10^14 interleavings for 5 threads with 5 instructions

Avoiding Interleaving Explosion

Solution to the interleaving problem: Find *representative* interleavings

For Example:
If the green dots are local thread actions, then all schedules that arrive at the "cut line" are equivalent!



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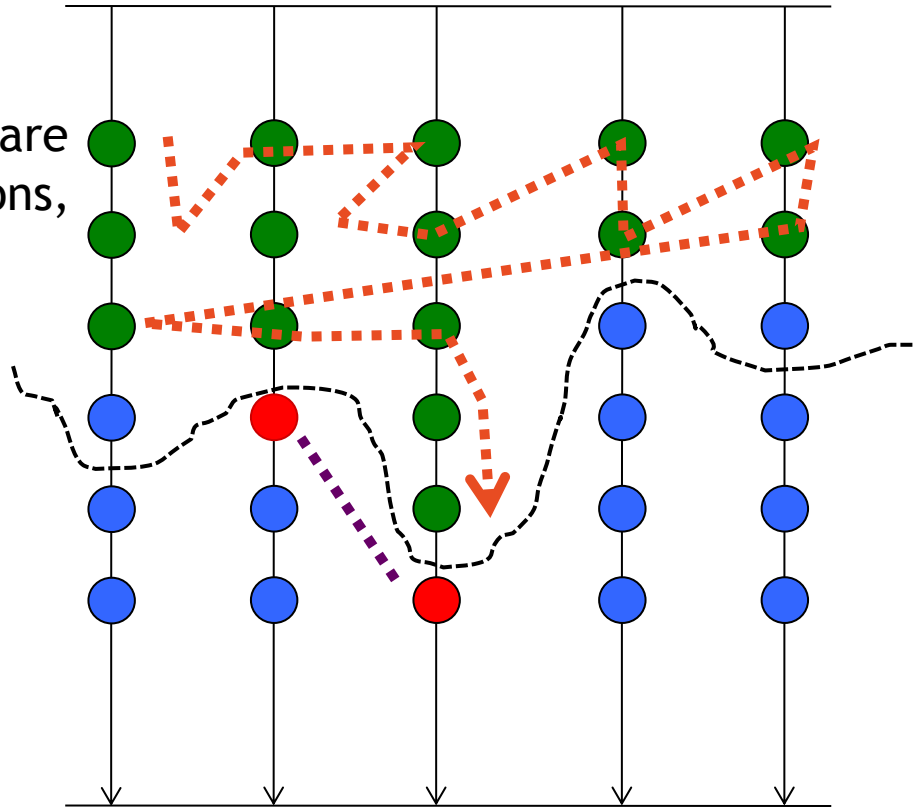

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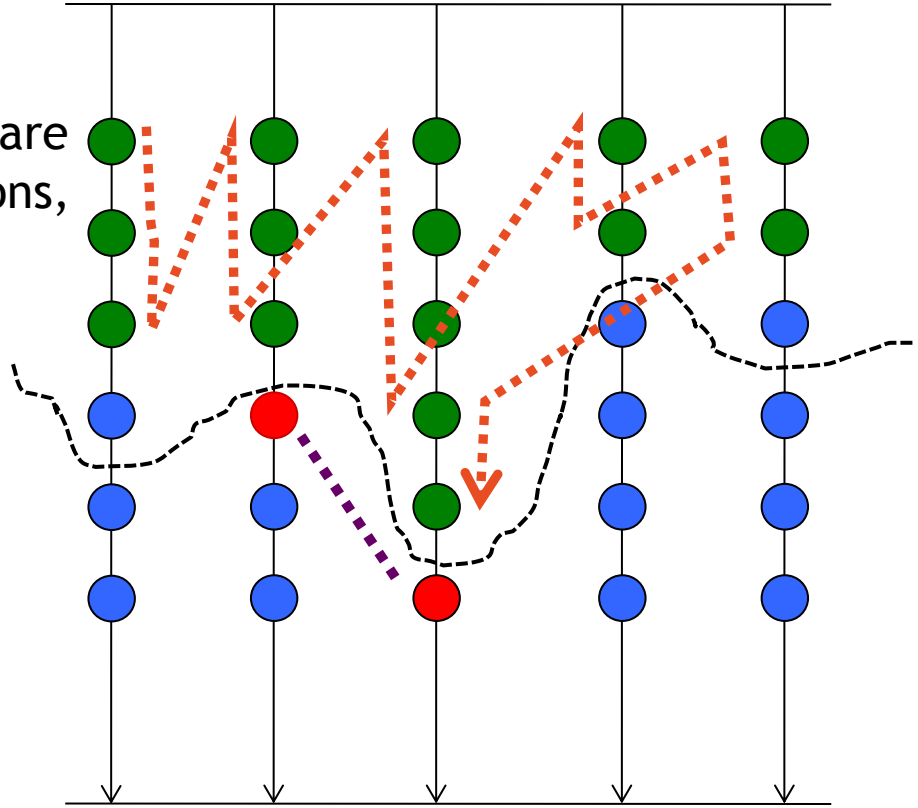
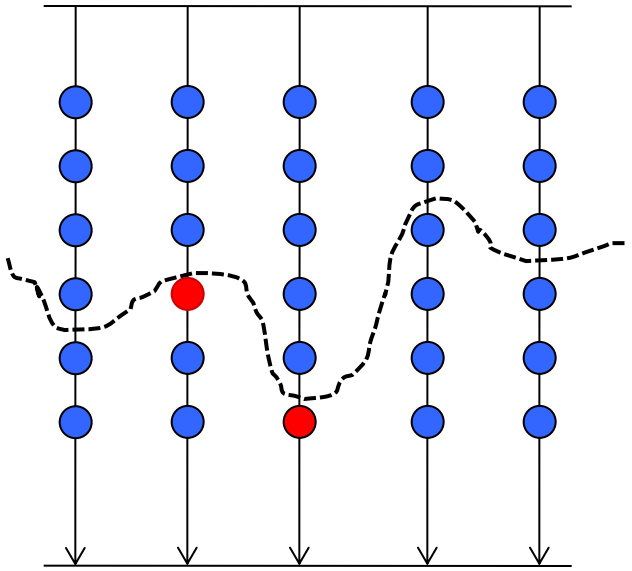
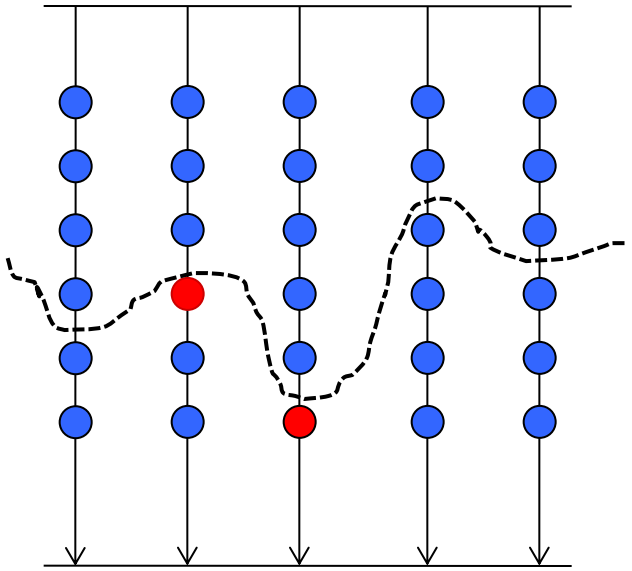


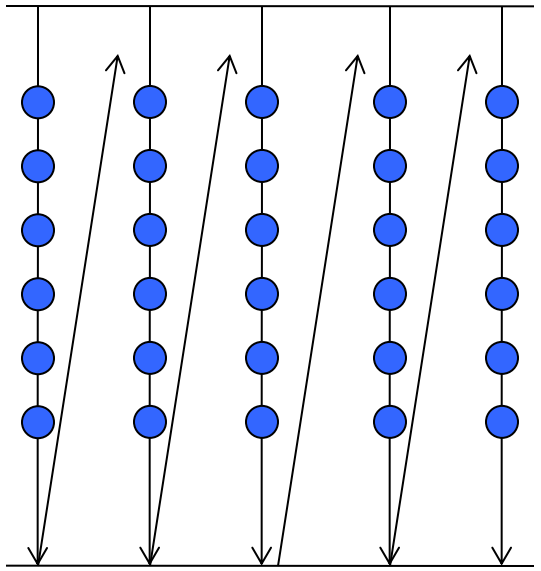
GKLEE Avoids Examining Exp. Schedules !!



Instead of considering all
Schedules and
All Potential Races…

GKLEE Avoids Examining Exp. Schedules !!



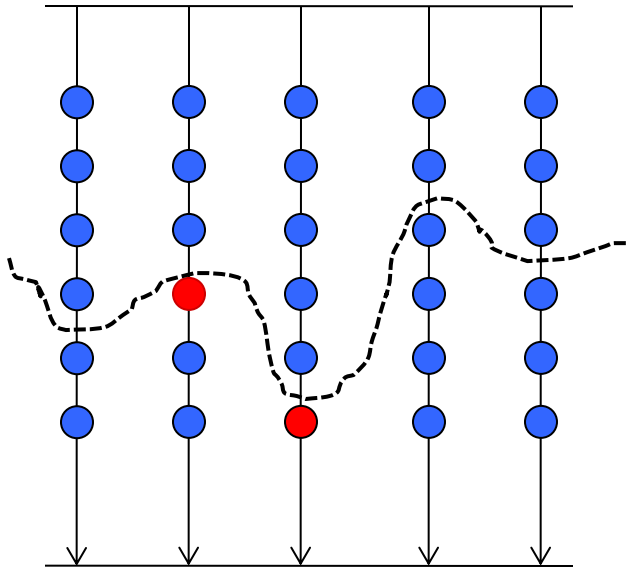


Instead of considering all
Schedules and
All Potential Races…

Consider JUST THIS SINGLE
CANONICAL SCHEDULE !!

Folk Theorem (proved in our paper):
"We will find A RACE
If there is ANY race" !!

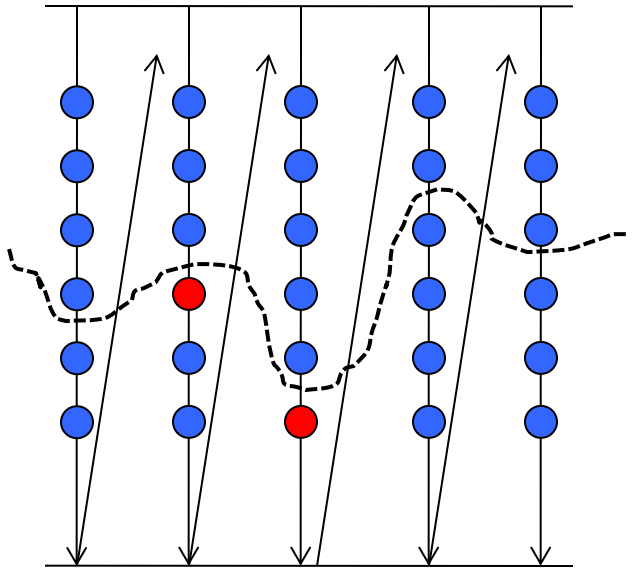
Why does a sequential run suffice?



If the red pair is the only race, then it occurs after the cut-line

So all the ways to reach the cut-line are EQUIVALENT !!

So this sequential run is equivalent too.



You my complain saying:
“But, the sequential run
Inches Past the Cutline !!”

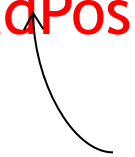
But hey, you told me that
this is the ONLY race!

If there were some other
race encountered before,
then that will be caught.

… there is a “first race”
and that will be caught !

Concolic execution helps find witnesses to data races

```
__global__ void histogram64Kernel(unsigned *d_Result, unsigned *d_Data, int
dataN) {
  const int threadPos = ((threadIdx.x & (~63)) >> 0)
                      | ((threadIdx.x & 15) << 2)
                      | ((threadIdx.x & 48) >> 4);
  ...
  __syncthreads();
  for (int pos = IMUL(blockIdx.x, blockDim.x) + threadIdx.x; pos < dataN;
        pos += IMUL(blockDim.x, gridDim.x))  {
    unsigned data4 = d_Data[pos];
    ...
    addData64(s_Hist, threadPos, (data4 >> 26) & 0x3FU); }
    __syncthreads(); ...
}
inline void addData64(unsigned char *s_Hist, int threadPos, unsigned int data)
{  s_Hist[ threadPos + IMUL(data, THREAD_N) ]++; }
```



"GKLEE: Is there a Race ?"

69

Concolic execution helps find witnesses to data races

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```

GKLEE

Threads 5 and and 13 have a WW race

when d_Data[5] = 0x04040404 and d_Data[13] = 0.

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Summary

This is a huge field now – symbolic execution

You get to study this in projects

Even the MSR python Dyn Symb Executor – good project!