# KLEE: Effective Testing of Systems Programs


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# Writing Systems Code Is Hard

- Code complexity
  - Tricky control flow
  - Complex dependencies
  - Abusive use of pointer operations
- Environmental dependencies
  - Code has to anticipate all possible interactions
  - Including malicious ones
- 

# Program Path

- Program Path
  - A path in the control flow of the program
    - Can start and end at any point
    - Appropriate for imperative programs
- Feasible program path
  - There exists an input that leads to the execution of this path
- Infeasible program path
  - No input that leads to the execution

# Concrete vs. Symbolic Executions

- Real programs have many infeasible paths
  - Ineffective concrete testing
- Symbolic execution aims to find rare errors

# Symbolic Testing Tools

- EFFIGY [King, IBM 76]
- PEX [MSR]
- SAGE [MSR]
- SATURN[Stanford]
- KLEE[Stanford]
- Java pathfinder[NASA]
- Bitscope [Berkeley]
- Cute [UIUC, Berkeley]
- Calysto [UBC]

# Symbolic Exploration

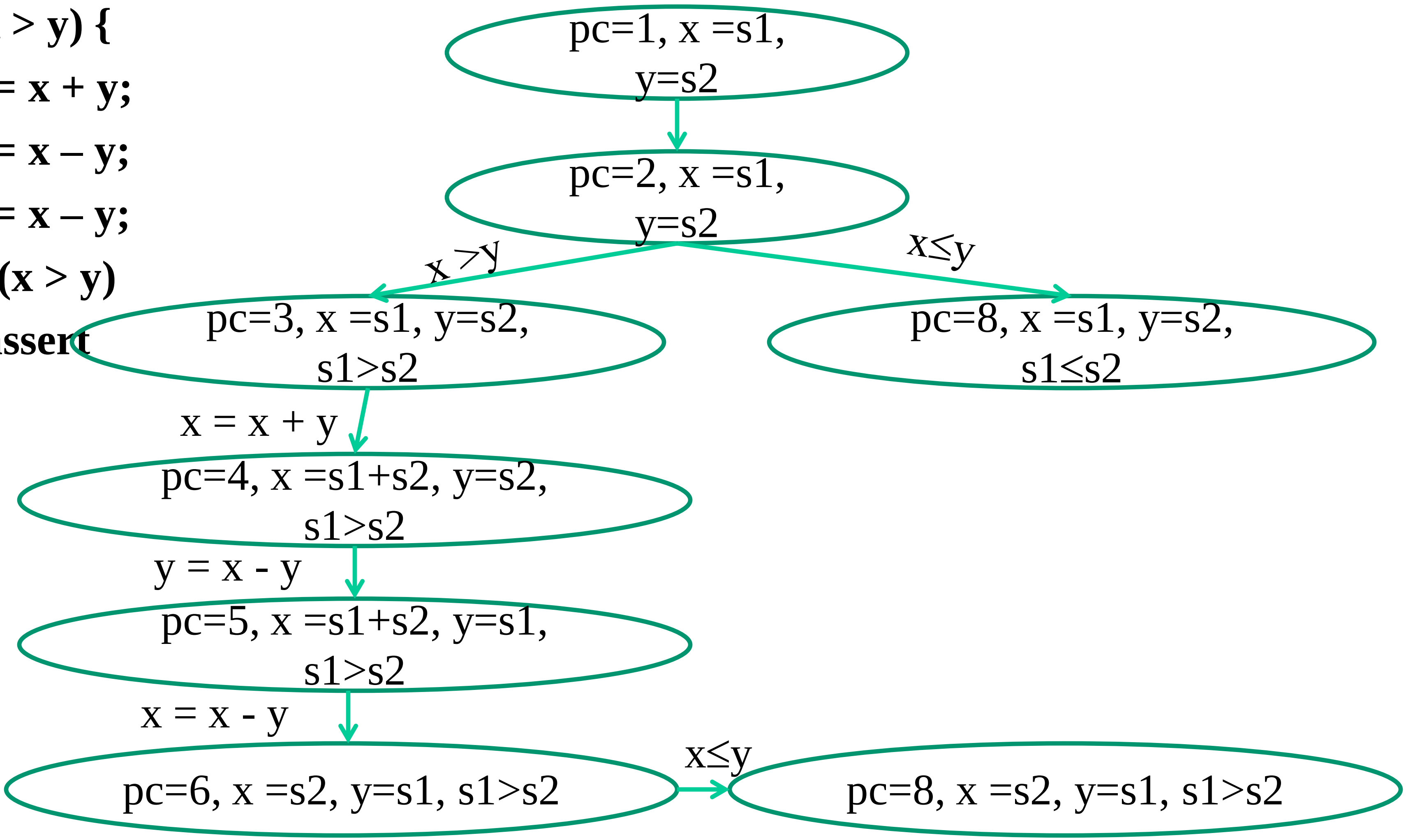
- Execute a program on symbolic inputs
- Track set of values symbolically
- Update symbolic states when instructions are executed
- Whenever a branch is encountered check if the path is feasible using a theorem prover call

# Symbolic Execution Tree

- The constructed symbolic execution paths
- Nodes
  - Symbolic Program States
- Edges
  - Potential Transitions
- Constructed during symbolic evaluation
- Each edge requires a theorem prover call

# Simple Example

```
1)int x, y;
2)if (x > y) {
  3) x = x + y;
  4) y = x – y;
  5) x = x – y;
  6) if (x > y)
    7) assert
false;
8)}
```



# Challenge 1: Limitations of Theorem Provers

```
foobar(int  x, int y) {
if (x * x * x > 0) {
   if  (x>0 && y ==10) {
       abort() ; }
}
   else {
        if (x > 0 && y == 20)  {
            abort  ;}
         }
}
```

# Challenge 2: External Calls

```
FILE *fp;
fp = fopen(“test.txt", “w");
if (fp) {
    struct stat buffer;
    if (stat (“text.txt”, &buffer) != 0) {
        abort();
    }
}
```

# Challenge 3: #Theorem prover calls

```
1) int i = 0;
2) while  i < n {
      i = i + 1;
     }
3) if (n==10^6) {
4)     abort();
5) }
```

# Concolic Testing

## **Conc**rete + Symb**olic** = Concolic

- Combine concrete testing (concrete execution) and symbolic testing (symbolic execution)
- Trade coverage (miss bugs) for scalability
- Reduce the number of theorem prover calls
- Reduce the complexity of path formulas
- Can cope with external calls

# Concolic Testing Approach

```
int double (int v) {

    return 2*v;
}

void testme (int x, int y) {

    z = double (y);

    if (z == x) {

      if (x > y+10) {

          ERROR;
      }
    }

}
```

concrete state

symbolic state

path condition

# Concolic Testing Approach

```
int double (int v) {

   return 2*v;
}

void testme (int x, int y) {

   z = double (y);

   if (z == x) {

     if (x > y+10) {

        ERROR;
     }
   }

}
```

concrete state | symbolic state | path condition

# Concolic Testing Approach

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int double (int v) {

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    z = double (y);

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      if (x > y+10) {

          ERROR;
      }
    }
}
```

concrete state | symbolic state | path condition

Solve: $2*y_0 == x_0$

Solution: $x_0 = 2$, $y_0 = 1$

# Concolic Testing Approach

```
int double (int v) {

    return 2*v;
}

void testme (int x, int y) {

    z = double (y);

    if (z == x) {

      if (x > y+10) {

          ERROR;
      }
    }

}
```

| concrete state | symbolic state | path condition |
|---|---|---|
| Concrete Execution | Symbolic Execution | |
| x = 2, y = 1 | $x = x_0$, $y = y_0$ | |

# Concolic Testing Approach

```
int double (int v) {

    return 2*v;
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void testme (int x, int y) {

    z = double (y);

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concrete state | symbolic state | path condition

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int double (int v) {

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void testme (int x, int y) {

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    if (z == x) {

      if (x > y+10) {

          ERROR;
      }
    }

}
```

concrete state

$x = 2, y = 1,$
$z = 2$

symbolic state

$x = x_0,$
$y = y_0,$
$z = 2*y_0$

path condition

$2*y_0 == x_0$

# Concolic Testing Approach

```
int double (int v) {
    return 2*v;
}

void testme (int x, int y) {
    z = double (y);
    if (z == x) {
      if (x > y+10) {
          ERROR;
      }
    }
}
```

Concrete Execution

Symbolic Execution

concrete state

symbolic state

path condition

$2*y_0 == x_0$

$x_0 > y_0+10$

x = 2, y = 1, z = 2

$x = x_0$, $y = y_0$, $z = 2*y_0$

# Concolic Testing Approach

```
int double (int v) {

    return 2*v;
}

void testme (int x, int y) {

    z = double (y);

    if (z == x) {

      if (x > y+10) {

          ERROR;
      }
    }
}
```

Concrete Execution | Symbolic Execution

concrete state | symbolic state | path condition

Solve: $(2*y_0 == x_0) \wedge (x_0 > y_0 + 10)$

Solution: $x_0 = 30$, $y_0 = 15$

Path condition: $2*y_0 == x_0$, $x_0 > y_0+10$

Concrete state: $x = 2$, $y = 1$, $z = 2$

Symbolic state: $x = x_0$, $y = y_0$, $z = 2*y_0$

# Concolic Testing Approach

```
int double (int v) {

    return 2*v;
}

void testme (int x, int y) {

    z = double (y);

    if (z == x) {

      if (x > y+10) {

          ERROR;
      }
    }

}
```

concrete state | symbolic state | path condition

# Concolic Testing Approach

```
int double (int v) {

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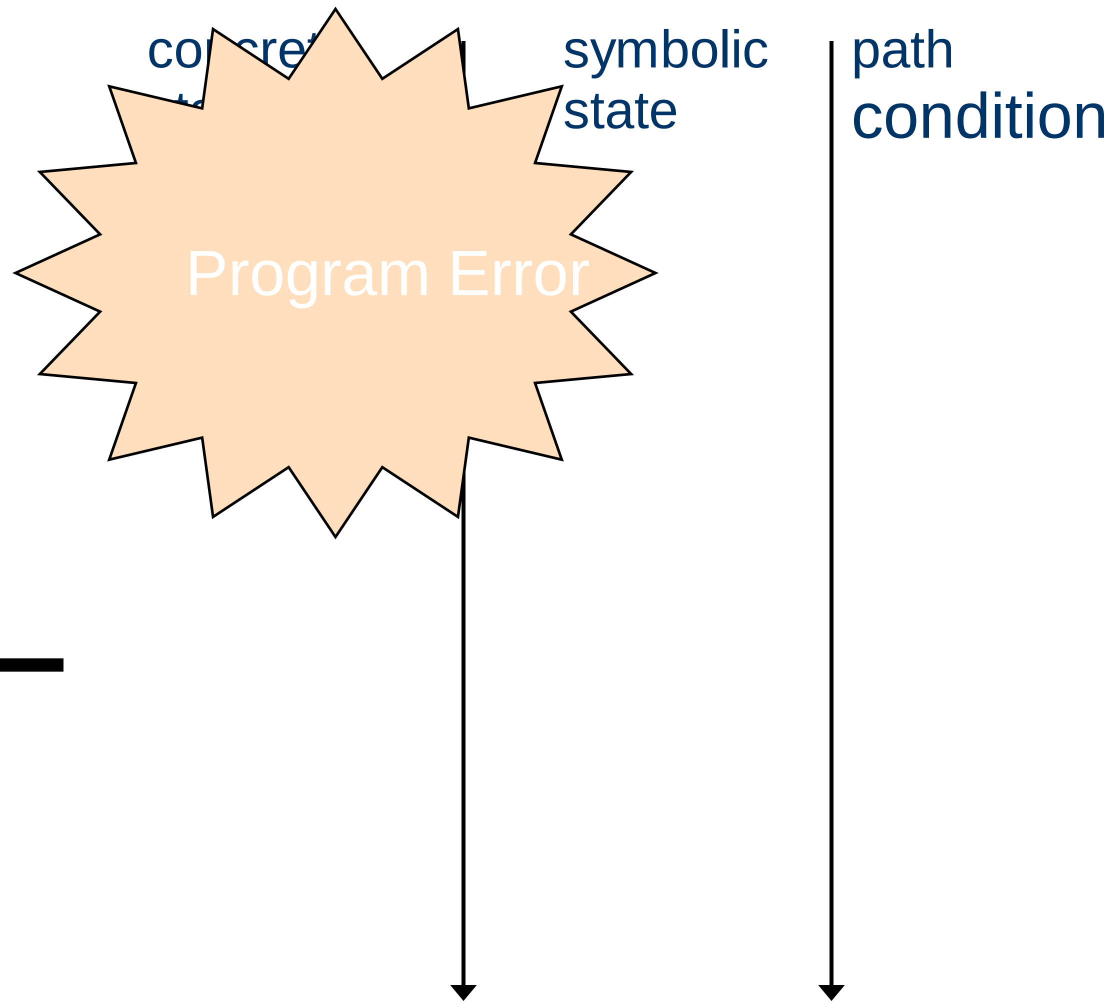
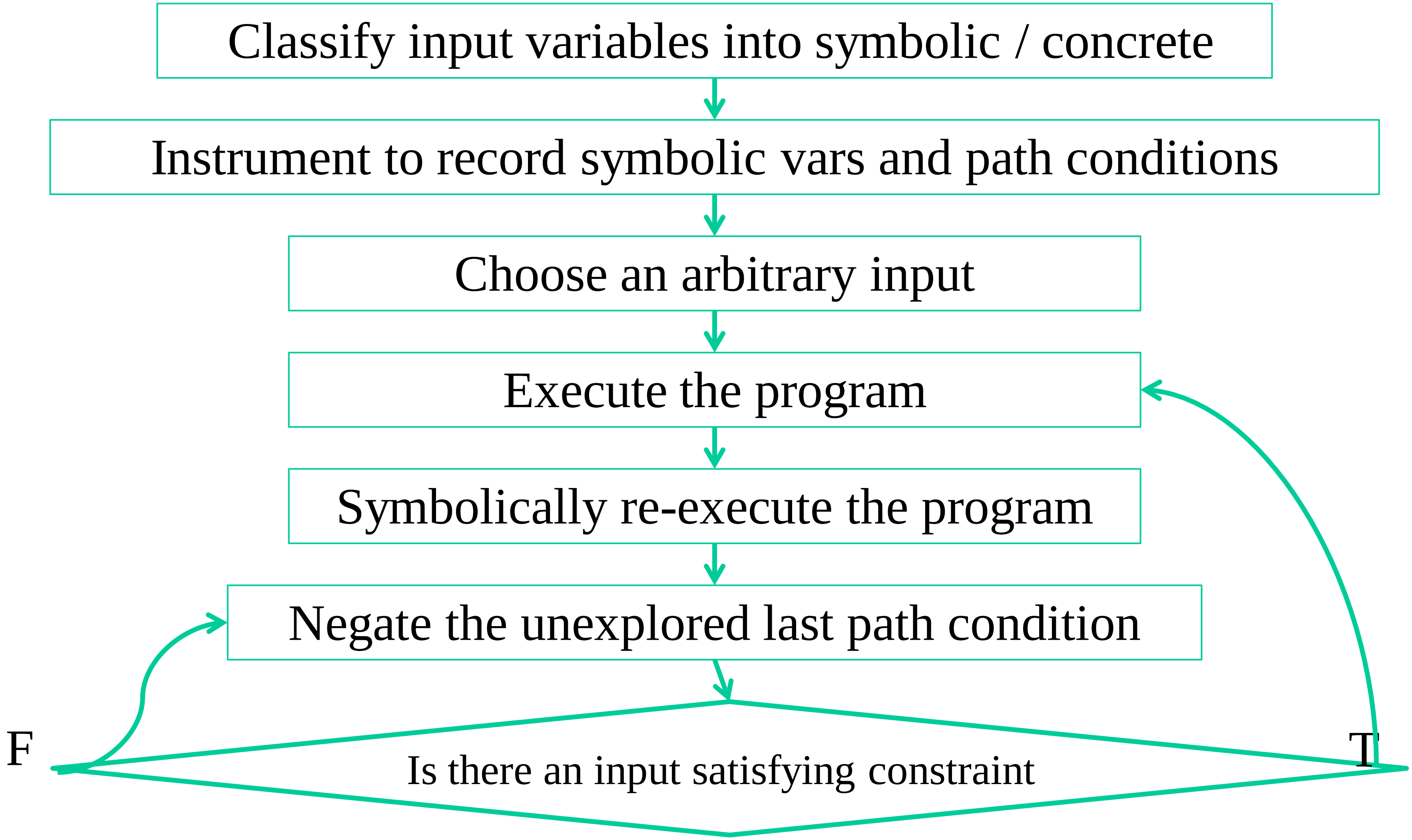
      }
    }

}
```



# The Concolic Testing Algorithm



# KLEE

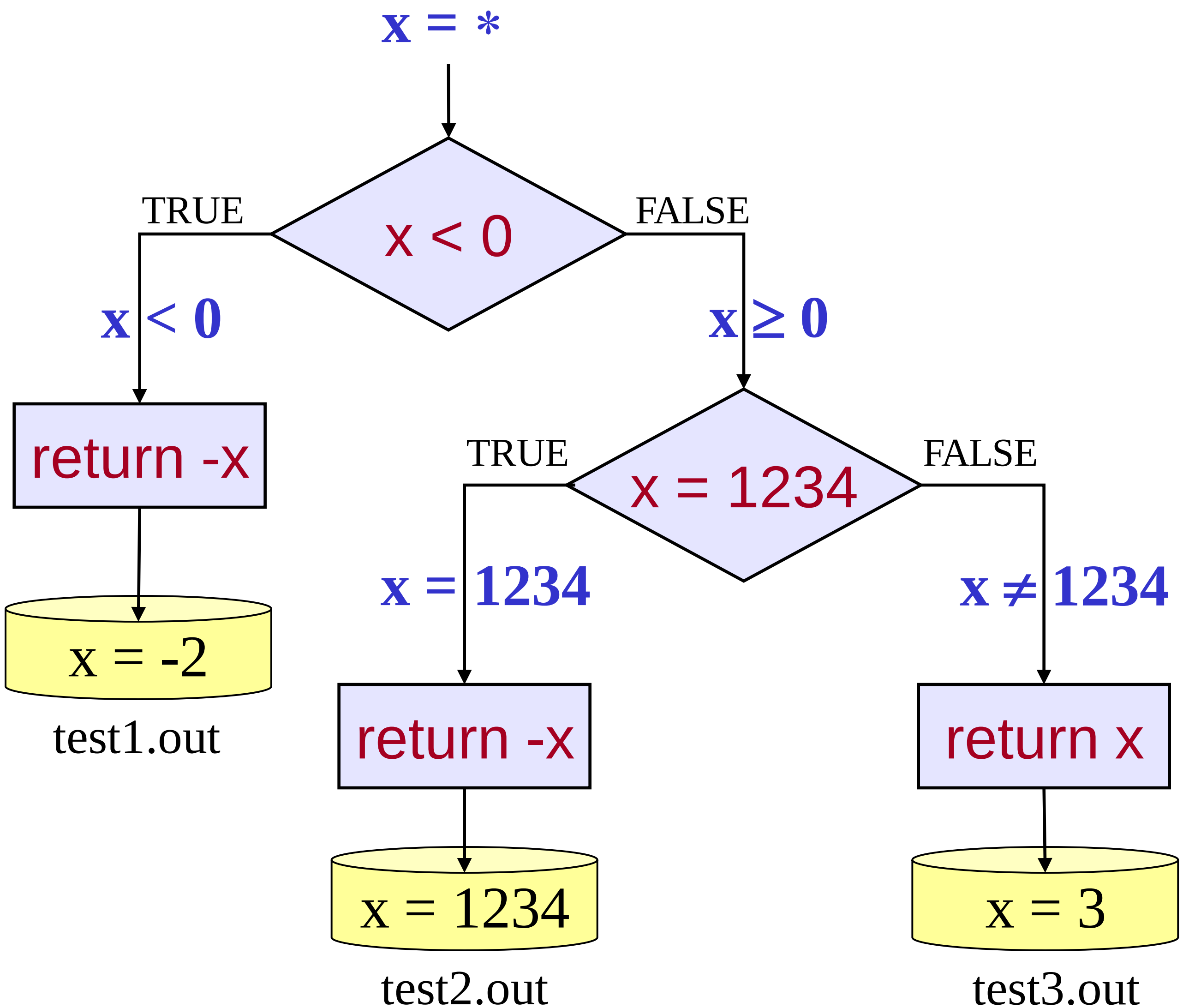
[OSDI 2008, Best Paper Award]

- Based on symbolic execution and constraint solving techniques

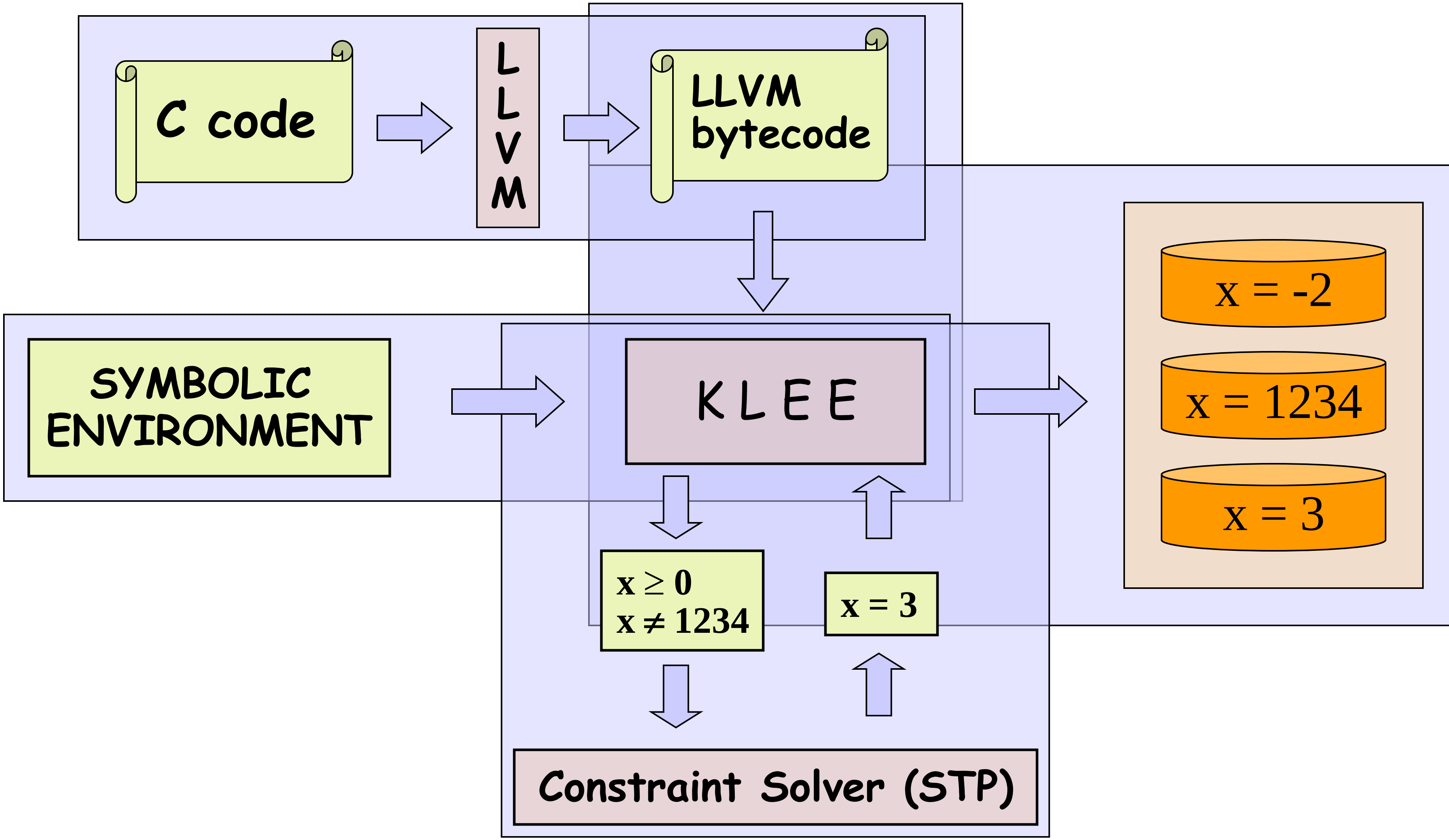
- Automatically generates high coverage test suites
  - Over 90% on average on ~160 user-level apps
- Finds deep bugs in complex systems programs
  - Including higher-level correctness ones

# Toy Example

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



# KLEE Architecture



# Outline

- Motivation
- Example and Basic Architecture
- Scalability Challenges
- Experimental Evaluation

# Three Big Challenges

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

# Exponential Search Space

Naïve exploration can easily get “stuck”

Use search heuristics:

- Coverage-optimized search
  - Select path closest to an uncovered instruction
  - Favor paths that recently hit new code
- Random path search
  - See [KLEE – OSDI’08]

# Three Big Challenges

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# Constraint Solving

- Dominates runtime
  - Inherently expensive (NP-complete)
  - Invoked at every branch
- Two simple and effective optimizations
  - Eliminating irrelevant constraints
  - Caching solutions
    - Dramatic speedup on our benchmarks

# Eliminating Irrelevant Constraints

- In practice, each branch usually depends on a small number of variables

```
…
…
if (x < 10) {
    …
}
```

→

**x + y > 10**

~~**z & -z = z**~~

**x < 10 ?**

# Caching Solutions

- Static set of branches: lots of similar constraint sets

$2 * y < 100$
$x > 3$
$x + y > 10$

→

$x = 5$
$y = 15$

$2 * y < 100$
$x + y > 10$

Eliminating constraints cannot invalidate solution →

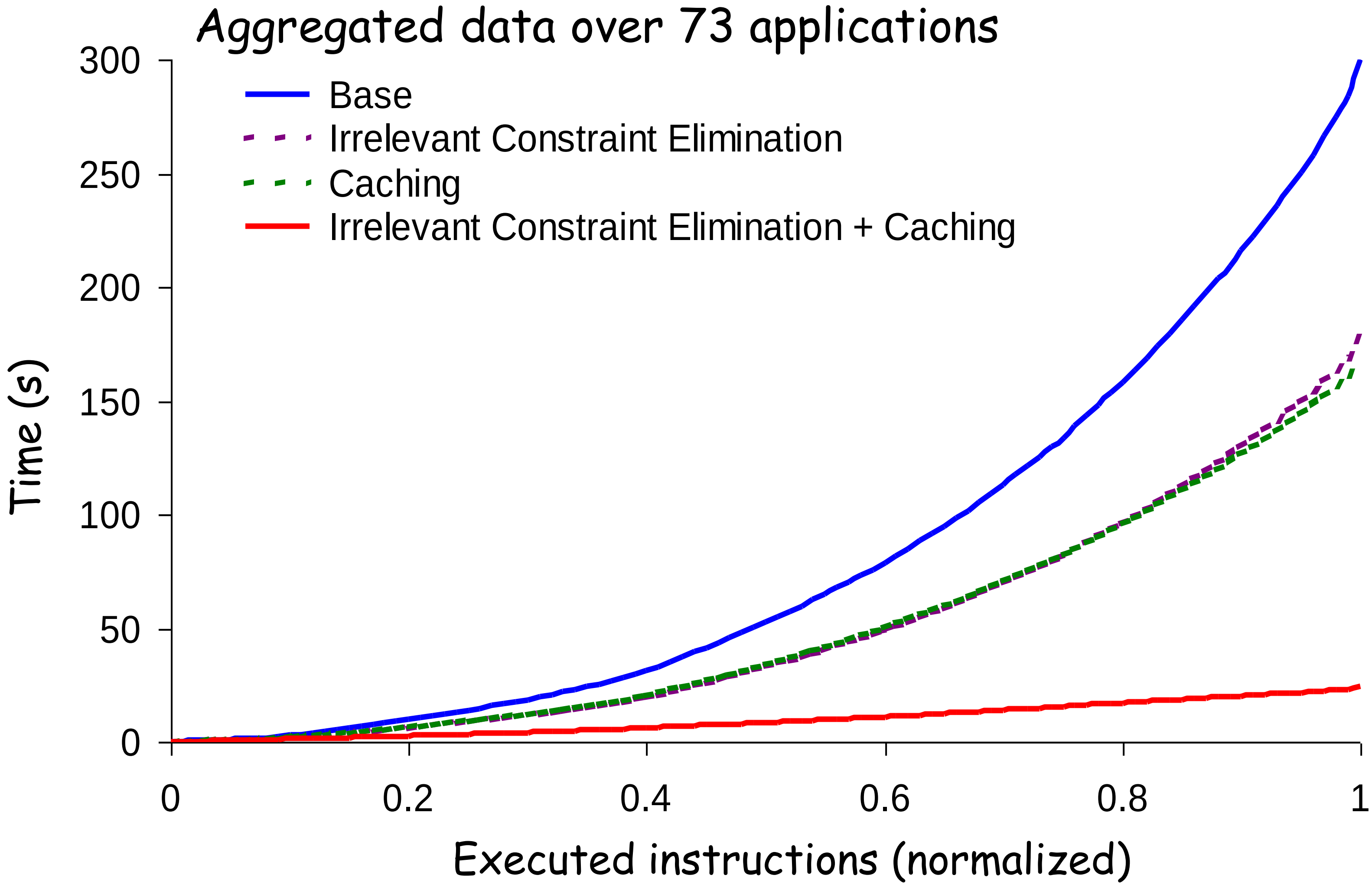
$x = 5$
$y = 15$

$2 * y < 100$
$x > 3$
$x + y > 10$
$x < 10$

Adding constraints often does not invalidate solution →

$x = 5$
$y = 15$

# Dramatic Speedup



# Three Big Challenges

- Motivation
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# Environment: Calling Out Into OS

```
int fd  = open("t.txt", O_RDONLY);
```

- If all arguments are concrete, forward to OS

```
int fd  = open(sym_str, O_RDONLY);
```

- Otherwise, provide *models* that can handle symbolic files
  - Goal is to explore all possible *legal* interactions with the environment

# Environmental Modeling

```
// actual implementation: ~50 LOC
ssize_t read(int fd, void *buf, size_t count) {
        exe_file_t *f = get_file(fd);
        …
        memcpy(buf, f->contents + f->off, count)
        f->off += count;
        …
}
```

- Plain C code run by KLEE
  - Users can extend/replace environment w/o any knowledge of KLEE internals
- Currently: effective support for symbolic command line arguments, files, links, pipes, ttys, environment vars

# Does KLEE work?

- Motivation
- Example and Basic Architecture
- Scalability Challenges
- Evaluation
  - Coverage results
  - Bug finding
  - Crosschecking

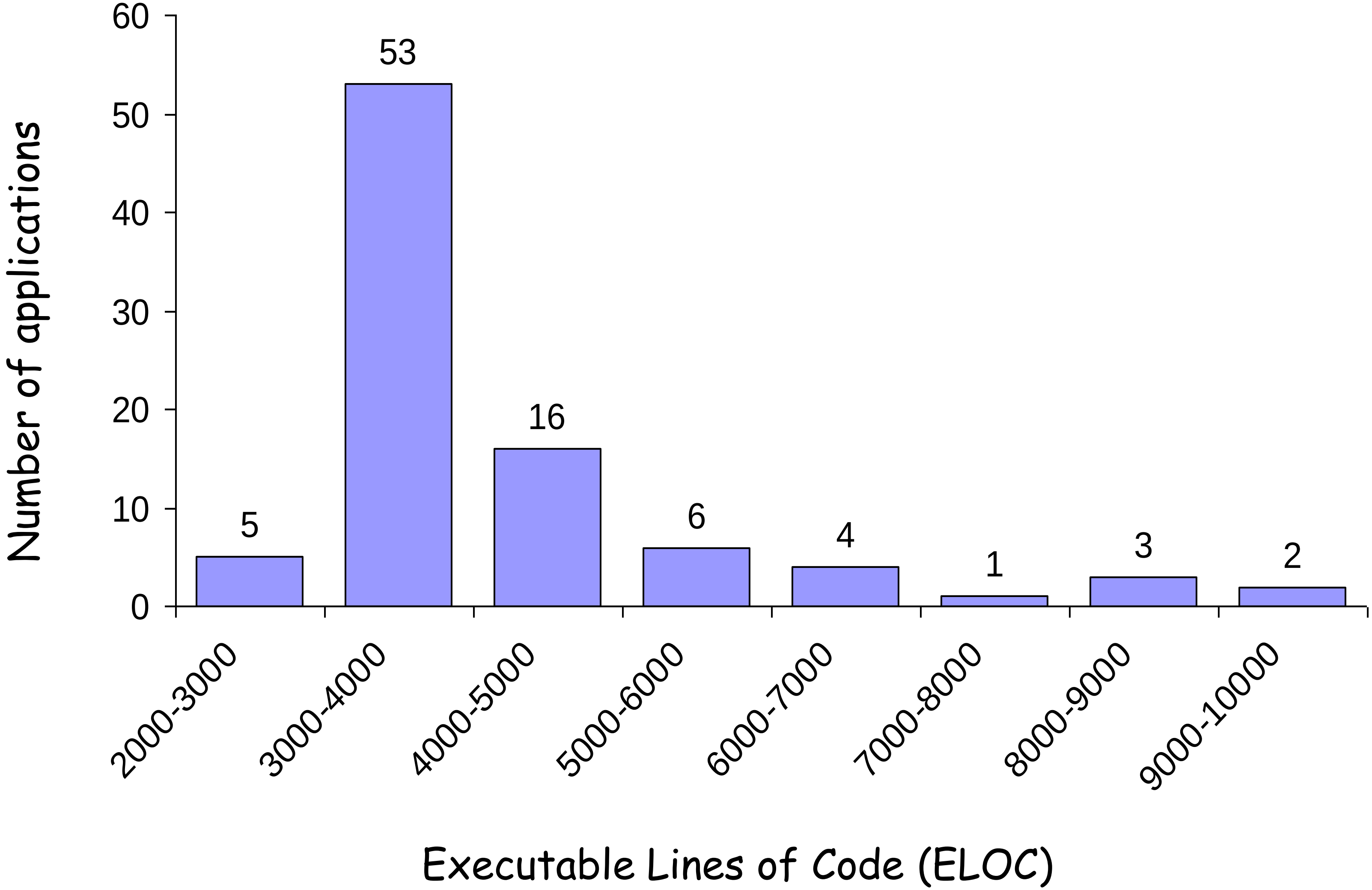
# GNU Coreutils Suite

- Core user-level apps installed on many UNIX systems
- 89 stand-alone (i.e. excluding wrappers) apps (v6.10)
  - File system management: ls, mkdir, chmod, etc.
  - Management of system properties: hostname, printenv, etc.
  - Text file processing : sort, wc, od, etc.
  - …

**Variety of functions, different authors, intensive interaction with environment**

**Heavily tested, mature code**

# Coreutils ELOC (incl. called lib)

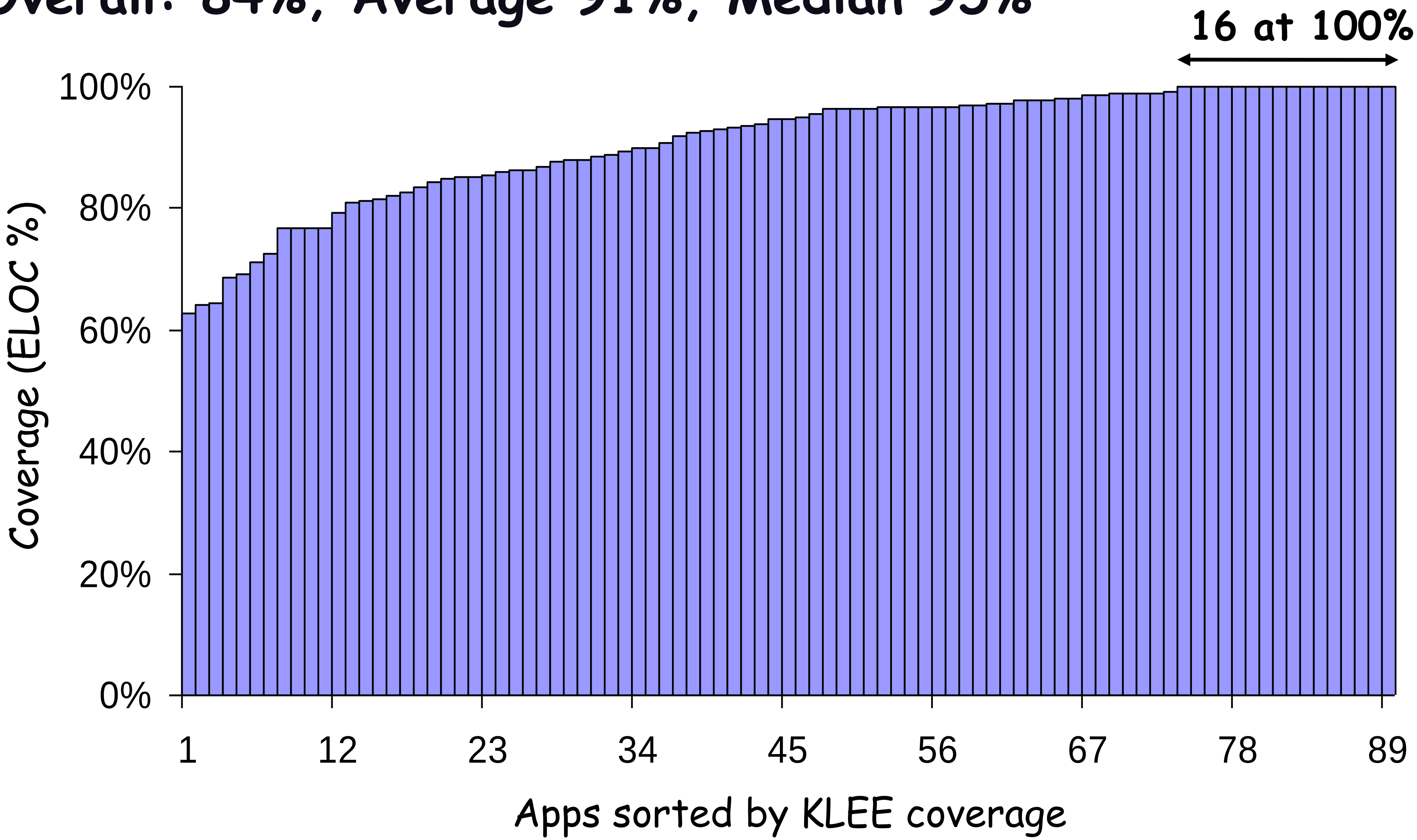


# Methodology

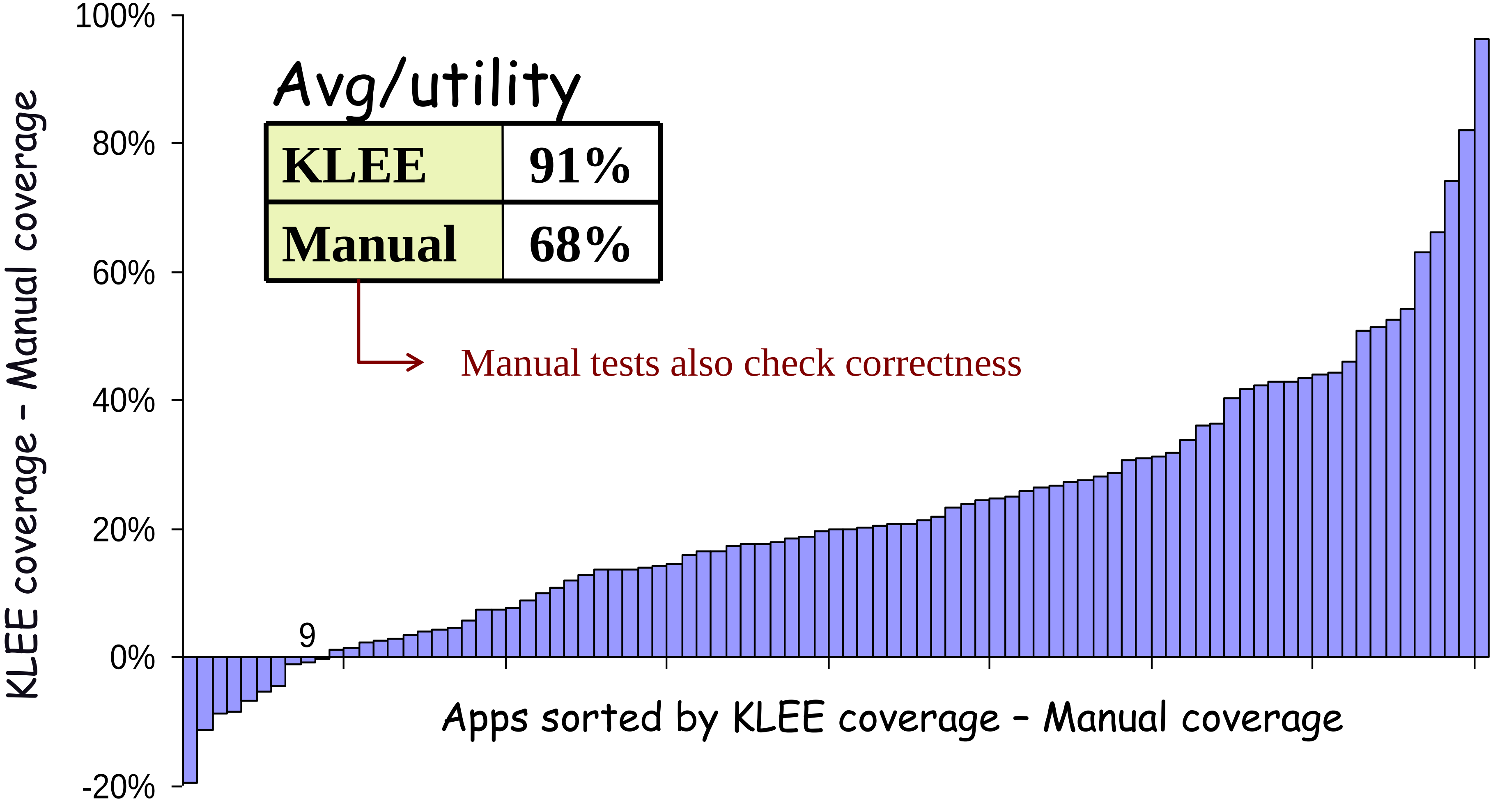
- Fully automatic runs
- Run KLEE one hour per utility, generate test cases
- Run test cases on *uninstrumented* version of utility
- Measure line coverage using `gcov`
  - Coverage measurements not inflated by potential bugs in our tool

# High Line Coverage
## (Coreutils, non-lib, 1h/utility = 89 h)

**Overall: 84%, Average 91%, Median 95%**



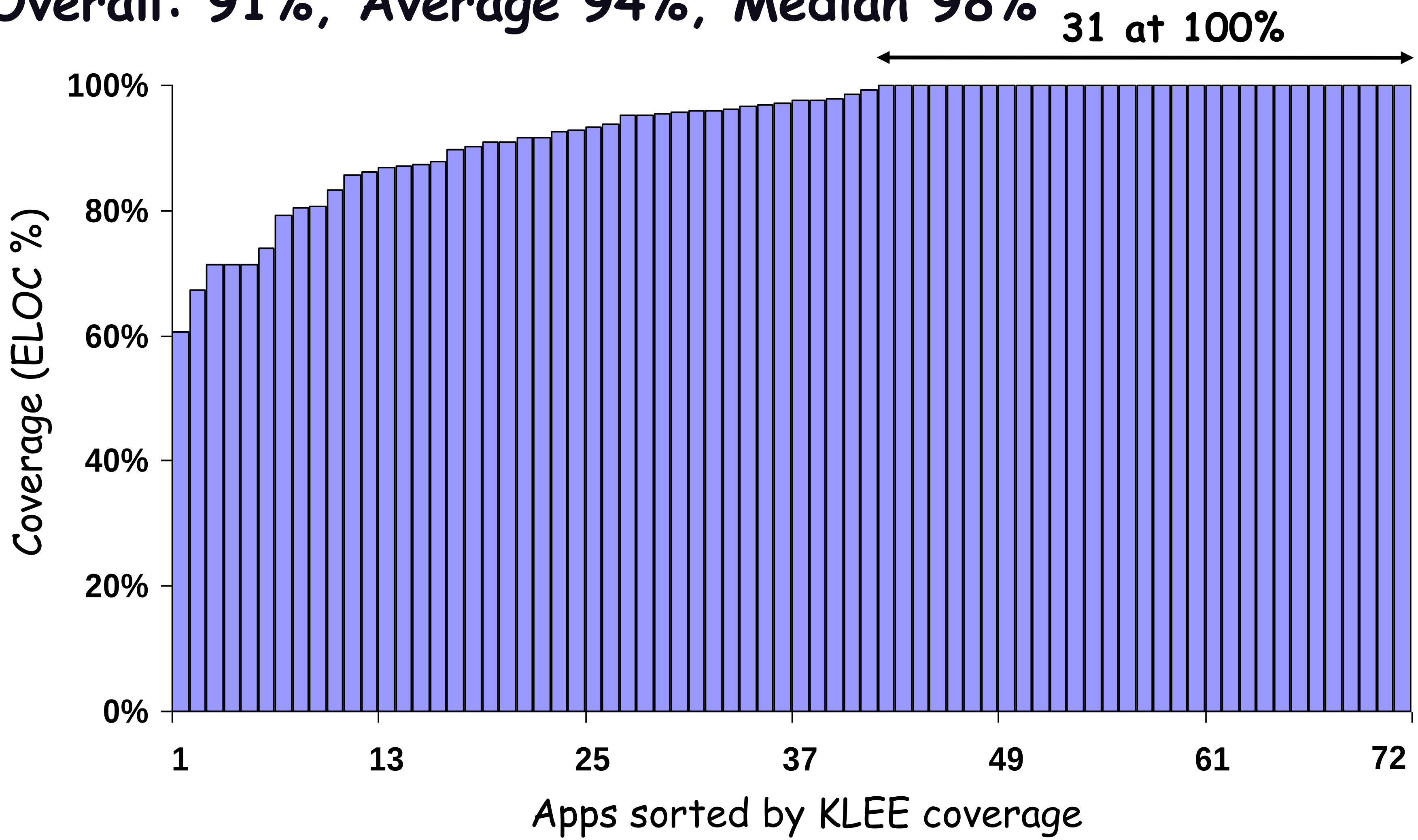
# Beats 15 Years of Manual Testing



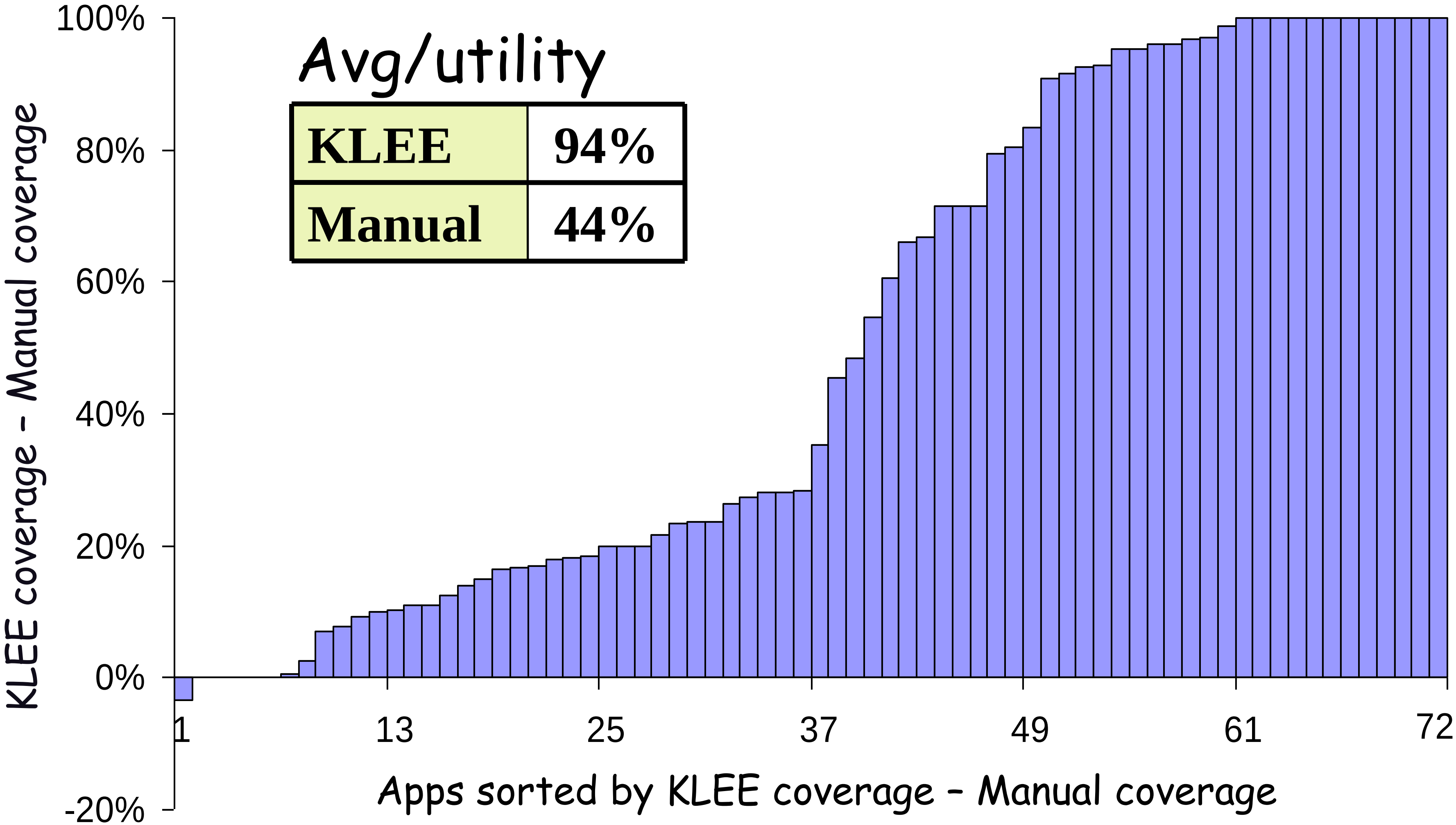

| | |
|---|---|
| **KLEE** | **91%** |
| **Manual** | **68%** |

# Busybox Suite for Embedded Devices

**Overall: 91%, Average 94%, Median 98%**



# Busybox – KLEE vs. Manual



# Does KLEE work?

- Motivation
- Example and Basic Architecture
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- Evaluation
  - Coverage results
  - Bug finding
  - Crosschecking

# GNU Coreutils Bugs

- Ten crash bugs
  - More crash bugs than approx last three years combined
  - KLEE generates actual command lines exposing crashes

# Ten command lines of death

| | |
|---|---|
| `md5sum -c t1.txt` | `pr -e t2.txt` |
| `mkdir -Z a b` | `tac -r t3.txt t3.txt` |
| `mkfifo -Z a b` | `paste -d\\ abcdefghijklmnopqrstuvwxyz` |
| `mknod -Z a b p` | `ptx -F\\ abcdefghijklmnopqrstuvwxyz` |
| `seq -f %0 1` | `ptx x t4.txt` |

*t1.txt:* `\t \tMD5(`

*t2.txt:* `\b\b\b\b\b\b\b\t`

*t3.txt:* `\n`

*t4.txt:* `A`

# Does KLEE work?

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# Finding Correctness Bugs

- KLEE can prove asserts on a per path basis
  - Constraints have no approximations
  - An assert is just a branch, and KLEE proves feasibility/infeasibility of each branch it reaches
  - If KLEE determines infeasibility of false side of assert, the assert was <u>proven</u> on the current path

# Crosschecking

Assume f(x) and f'(x) implement the same interface

1. Make input x symbolic
2. Run KLEE on `assert(f(x) == f'(x))`
3. For each explored path:
   a) KLEE terminates w/o error: paths are equivalent
   b) KLEE terminates w/ error: mismatch found

Coreutils vs. Busybox:

1. UNIX utilities should conform to *IEEE Std.1003.1*
2. Crosschecked pairs of Coreutils and Busybox apps
3. Verified paths, found mismatches

# Mismatches Found

| **Input** | **Busybox** | **Coreutils** |
|---|---|---|
| tee "" <t1.txt | [infinite loop] | [terminates] |
| tee - | [copies once to stdout] | [copies twice] |
| comm t1.txt t2.txt | [doesn't show diff] | [shows diff] |
| cksum / | "4294967295 0 /" | "/: Is a directory" |
| split / | "/: Is a directory" | |
| tr | [duplicates input] | "missing operand" |
| [ 0 "<" 1 ] | | "binary op. expected" |
| tail –2l | [rejects] | [accepts] |
| unexpand –f | [accepts] | [rejects] |
| split – | [rejects] | [accepts] |

t1.txt: a   t2.txt: b   (no newlines!)

# Related Work

Very active area of research. E.g.:

- EGT / EXE / KLEE [Stanford]
- DART [Bell Labs]
- CUTE [UIUC]
- SAGE, Pex [MSR Redmond]
- Vigilante [MSR Cambridge]
- BitScope [Berkeley/CMU]
- CatchConv [Berkeley]
- JPF [NASA Ames]

KLEE

- Hundred distinct benchmarks
- Extensive coverage numbers
- Symbolic crosschecking
- Environment support

# KLEE
# Effective Testing of Systems Programs

- KLEE can effectively:
  - Generate high coverage test suites
    - Over 90% on average on ~160 user-level applications
  - Find deep bugs in complex software
    - Including higher-level correctness bugs, via crosschecking