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

KLEE

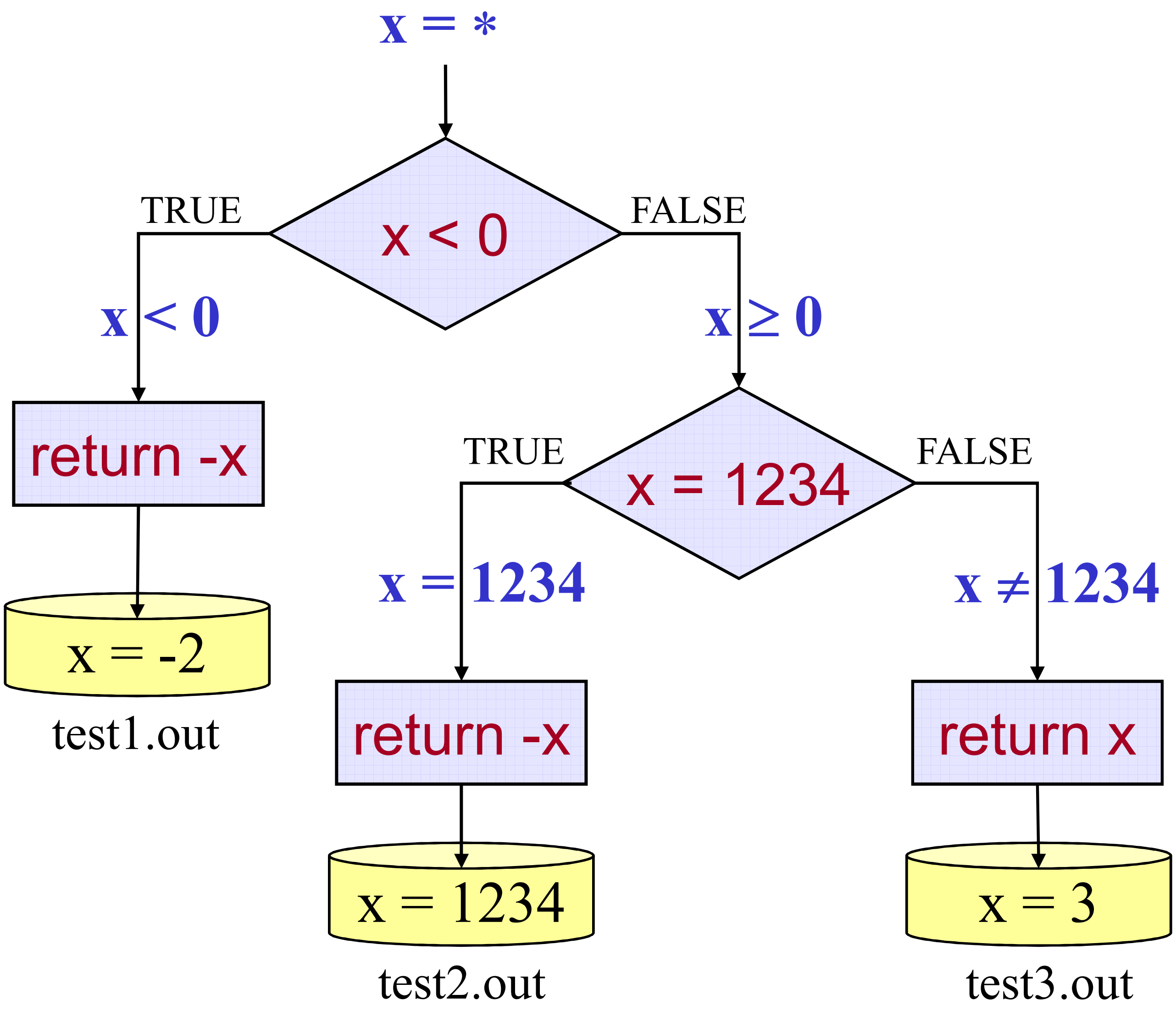
[OSDI 2008, Best Paper Award]

- Based on symbolic execution and constraint solving techniques

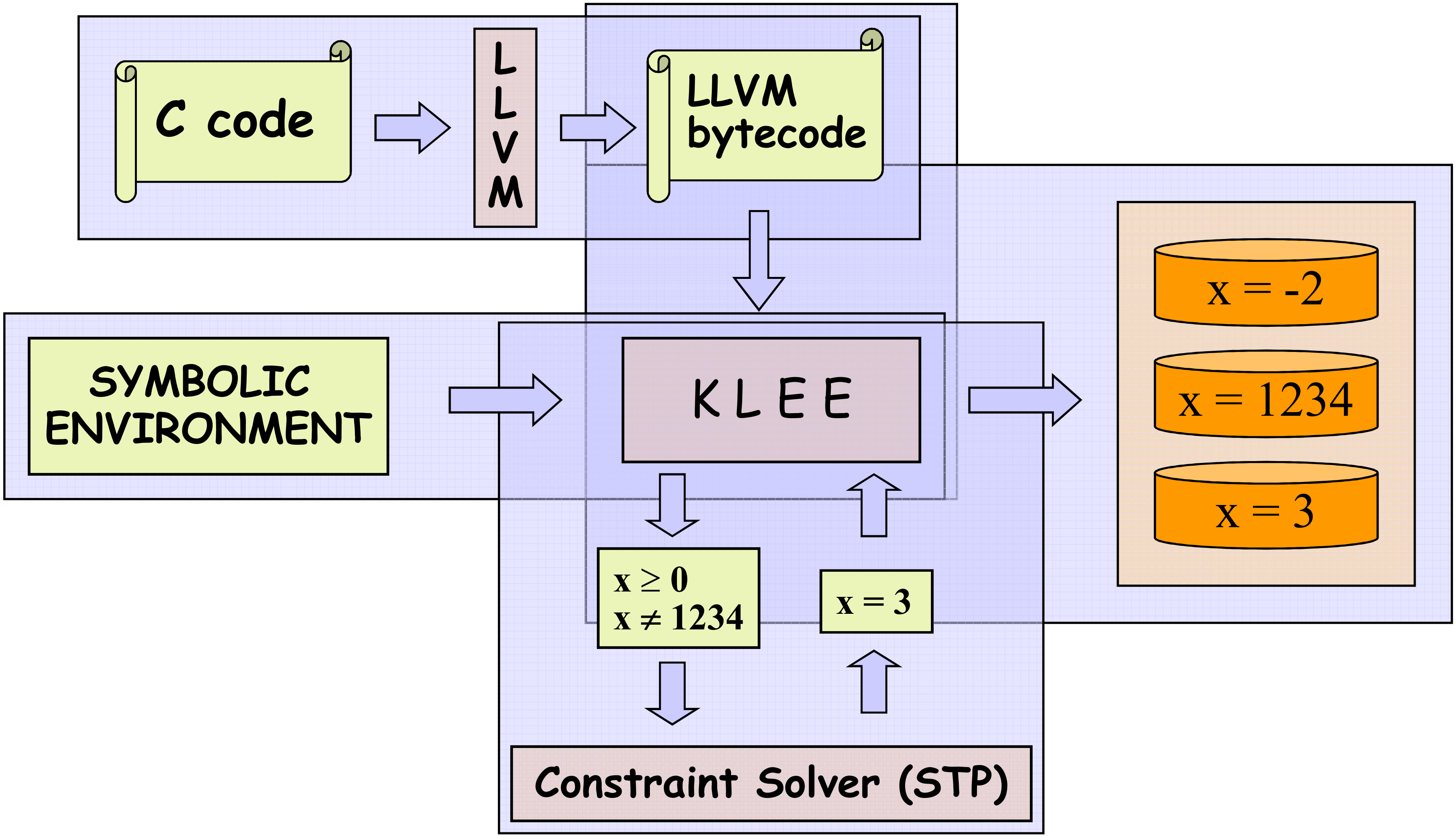
- Automatically generates high coverage test suites
  - Over 90% on average on ~160 user-level apps
- Finds deep bugs in complex systems programs
  - Including higher-level correctness ones

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]

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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) {
    …
}
```

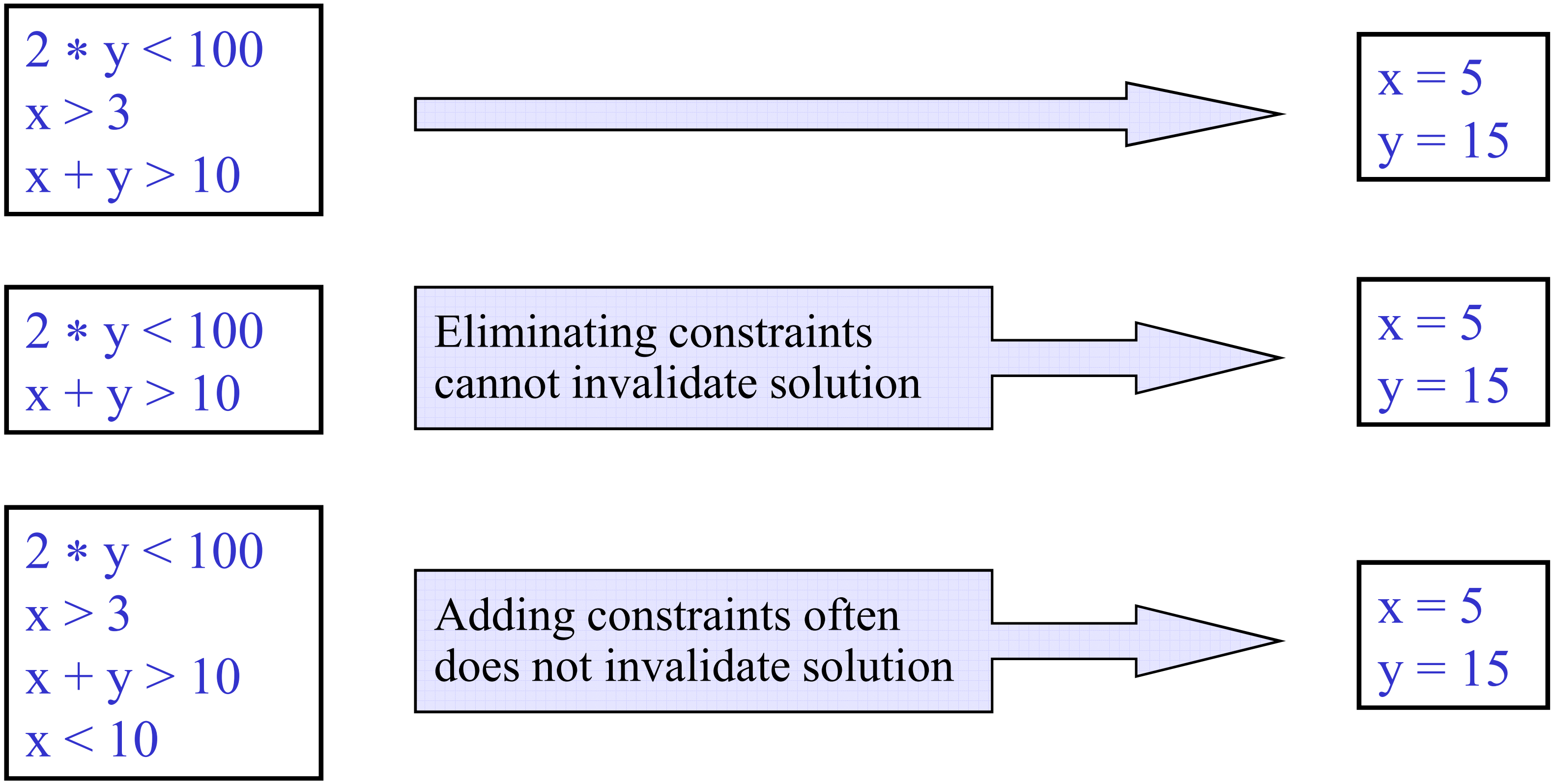
$x + y > 10$

~~$z \& -z = z$~~

$x < 10$?

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

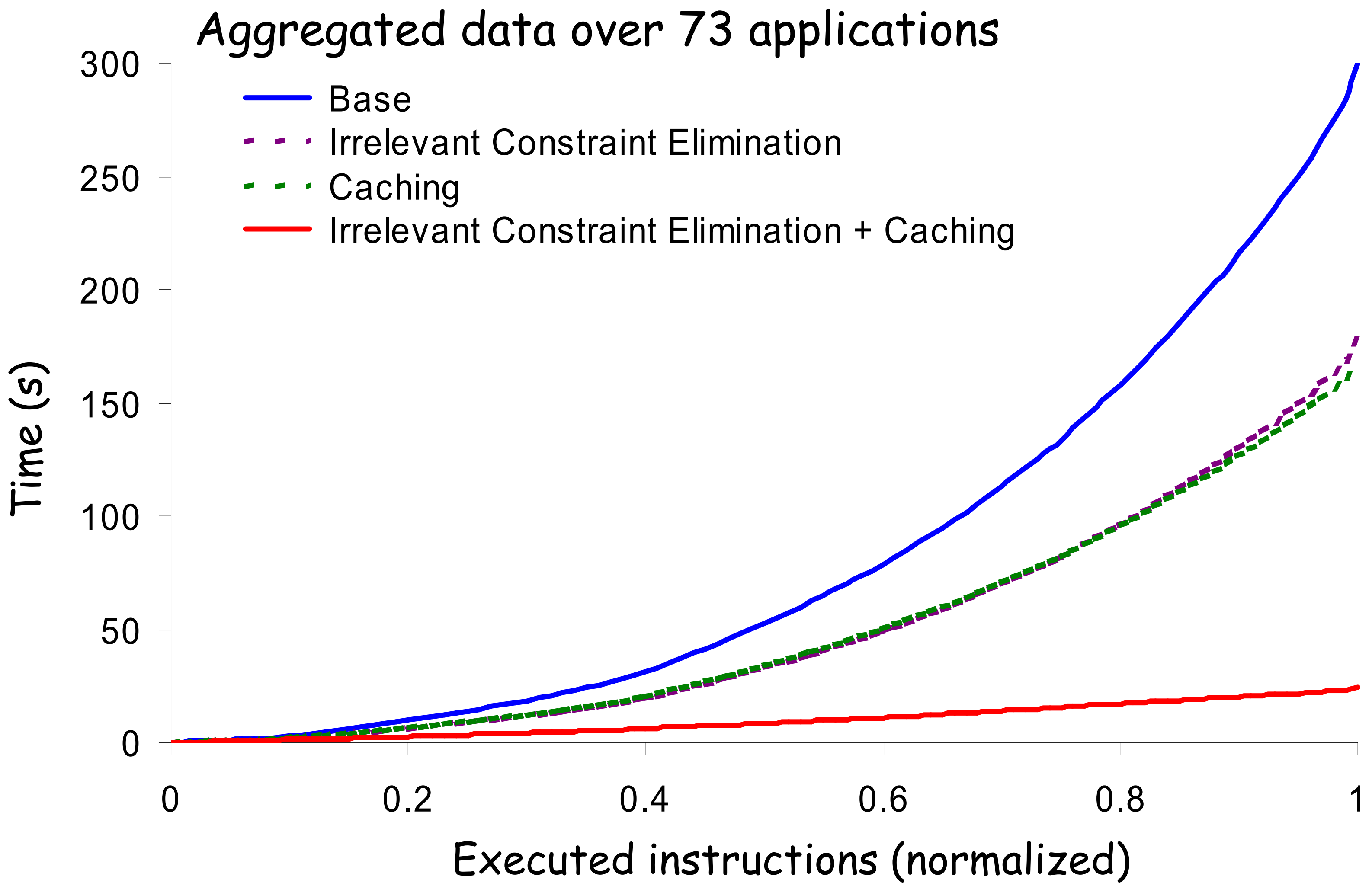
$x = 5$
$y = 15$

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

Adding constraints often does not invalidate solution

$x = 5$
$y = 15$

Dramatic Speedup



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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

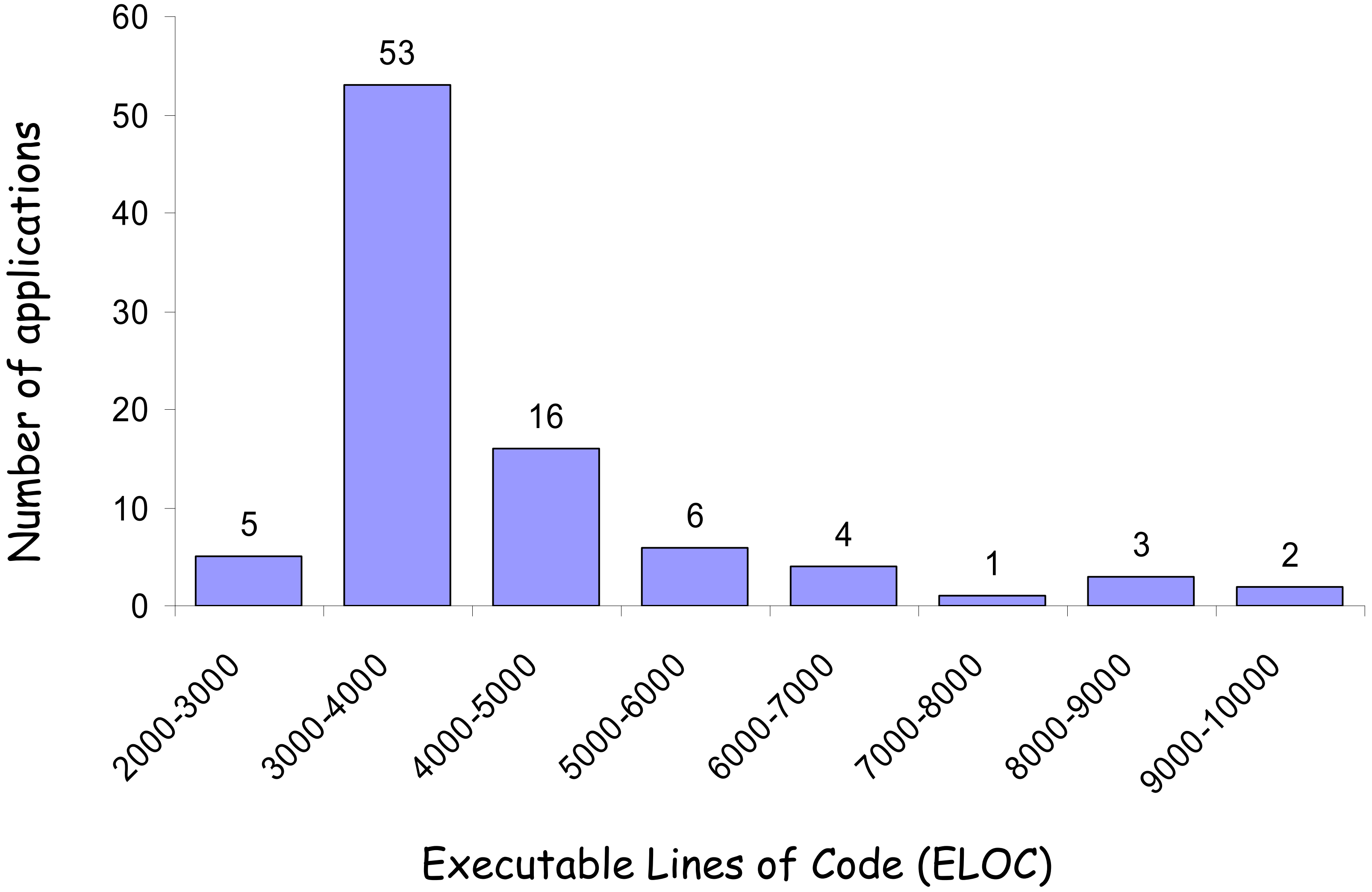
GNU Coreutils Suite

- 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)



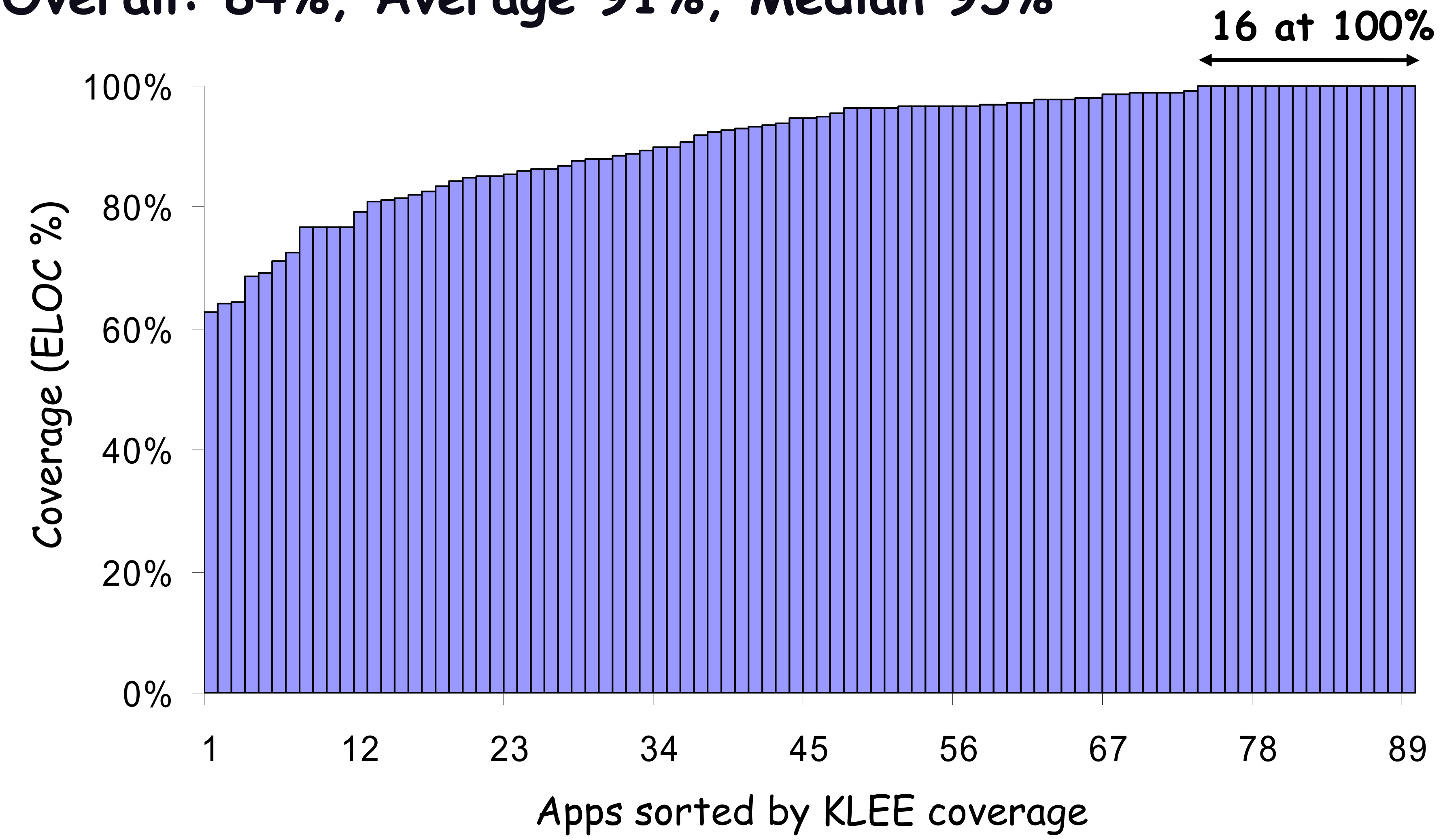
Methodology

- 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

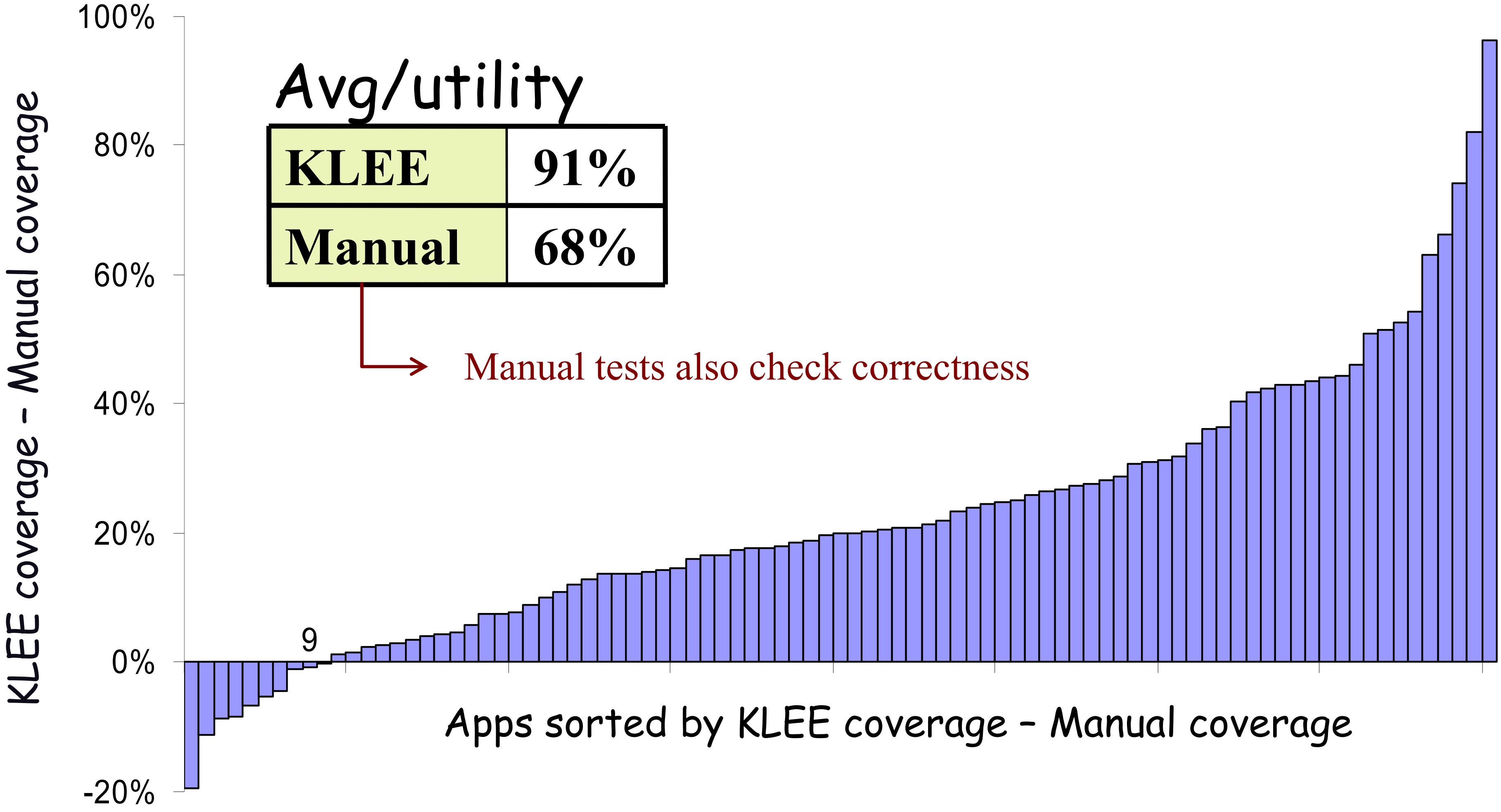
High Line Coverage

(Coreutils, non-lib, 1h/utility = 89 h)

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



Beats 15 Years of Manual Testing



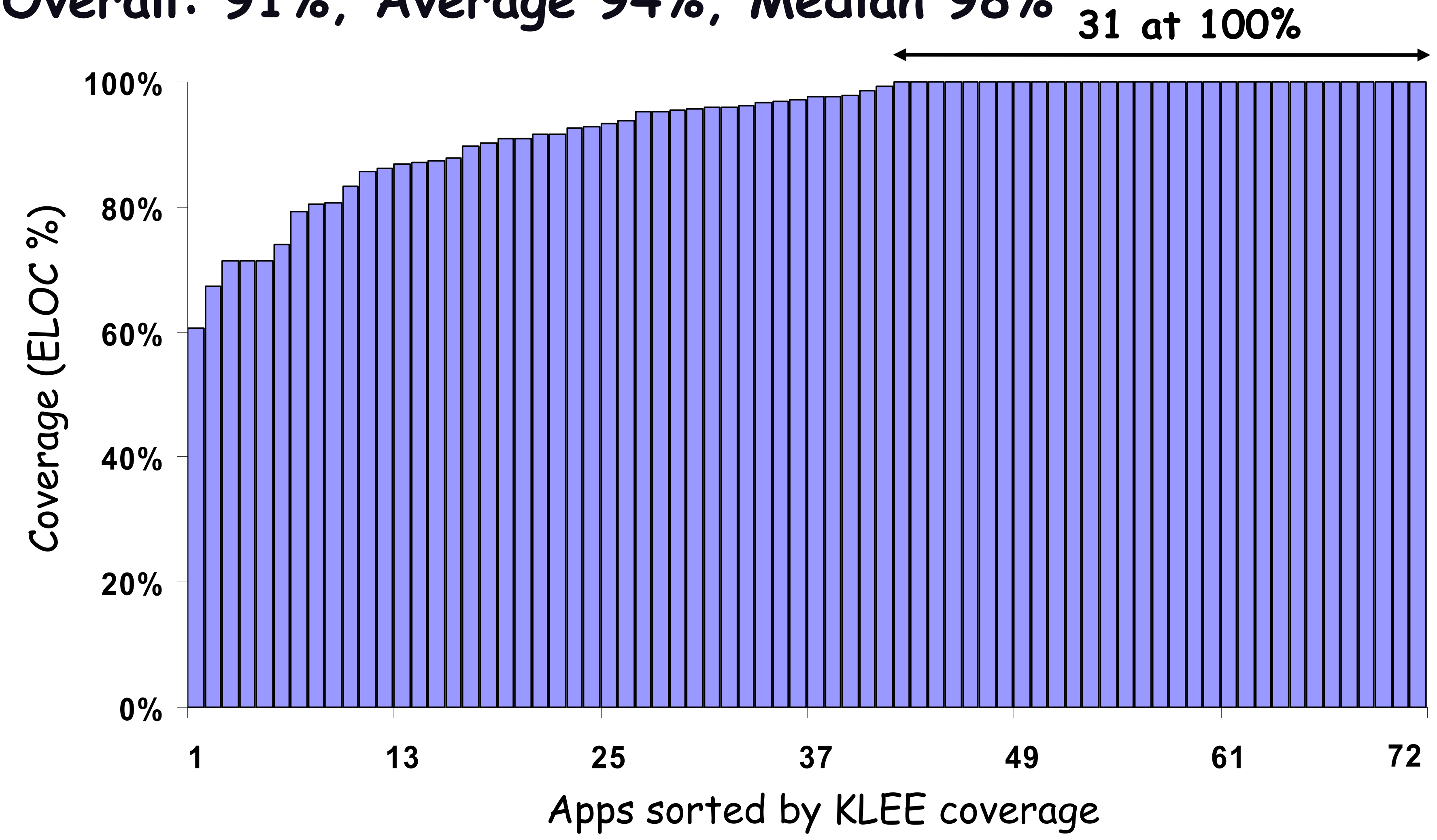
Avg/utility

KLEE	**91%**
Manual	**68%**

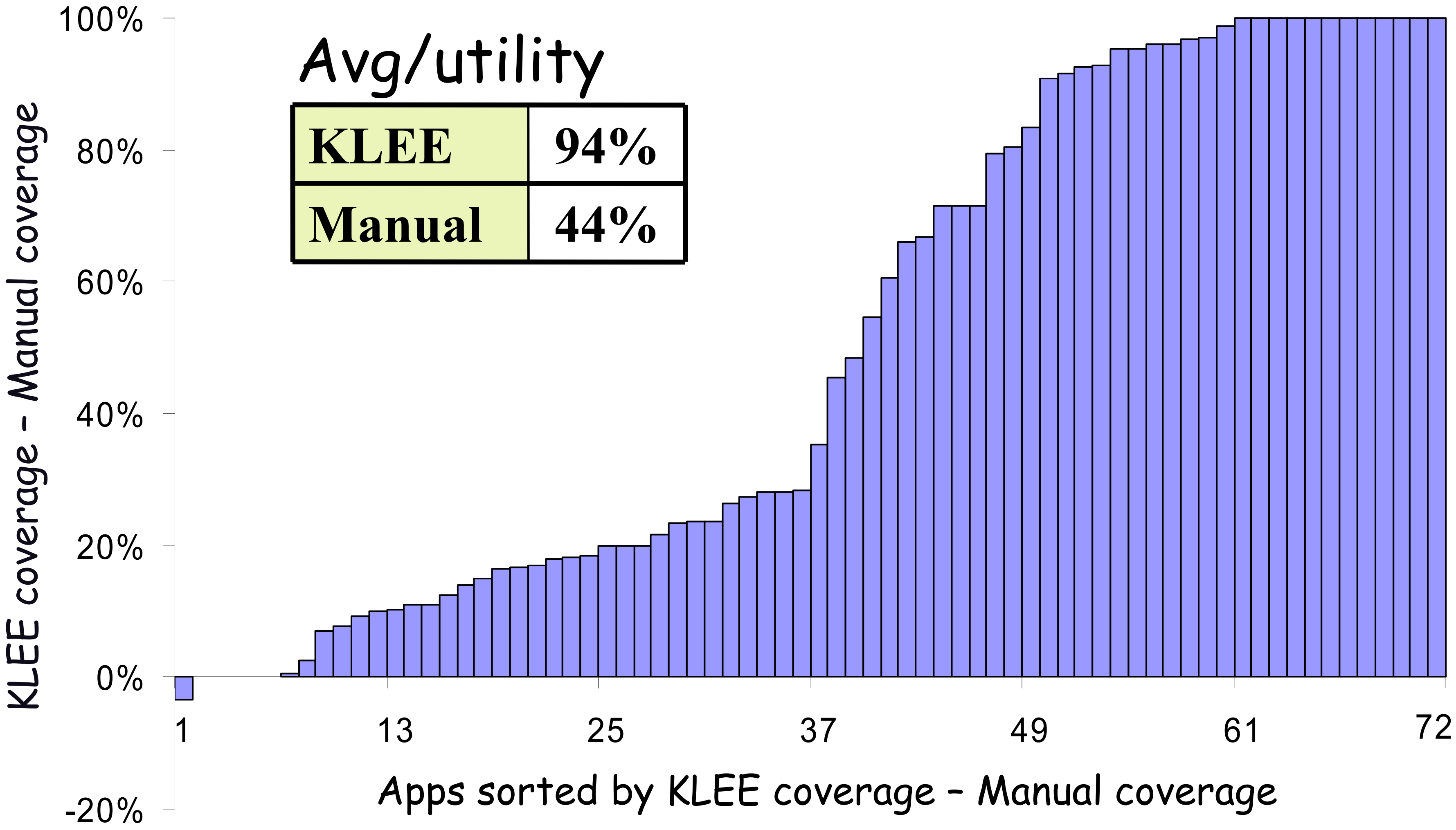
Manual tests also check correctness

Busybox Suite for Embedded Devices

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



Busybox – KLEE vs. Manual



Avg/utility

KLEE	**94%**
Manual	**44%**

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  - Bug finding
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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`

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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