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

Presented by Jordan Gillard

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- The authors use KLEE to generate tests for the GNU Core Utilities suite.
- KLEE beats the line coverage of the developers own hand-written tests.
- KLEE is an effective bug-finding tool.

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- Researchers doubt that automatic test generation tools like KLEE can consistently work with real applications.
- Concerns:
  - Number of paths through code grows exponentially
  - Dealing with code that interacts with the surrounding environment

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- Researchers present KLEE - a new symbolic execution tool.
- Researchers show that KLEE performs well on real environmentally-intensive programs.

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- KLEE is not limited to low-level errors.
- KLEE works with non-application code.

Overview

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- Complexity

```
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: }
```

Overview

- Complexity
- Environmental Dependencies

Overview Con’t

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- Hit every line of executable code in the program.

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- Hit every line of executable code in the program.
- Detect at each line potential dangerous operations.

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- KLEE has a unique way of handling state.
- KLEE optimizes queries.

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Optimizations	Queries	Time (s)	STP Time (s)
None	13717	300	281
Independence	13717	166	148
Cex. Cache	8174	177	156
All	699	20	10

Table 1: Performance comparison of KLEE's solver optimizations on COREUTILS. Each tool is run for 5 minutes without optimization, and rerun on the same workload with the given optimizations. The results are averaged across all applications.

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- Example 1: Modeling the file system
- Failing system calls

Evaluation

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- Line coverage as measure of KLEE test case effectiveness.
- KLEE minimizes the number of generated test cases.

KLEE Performance - GNU Coreutils

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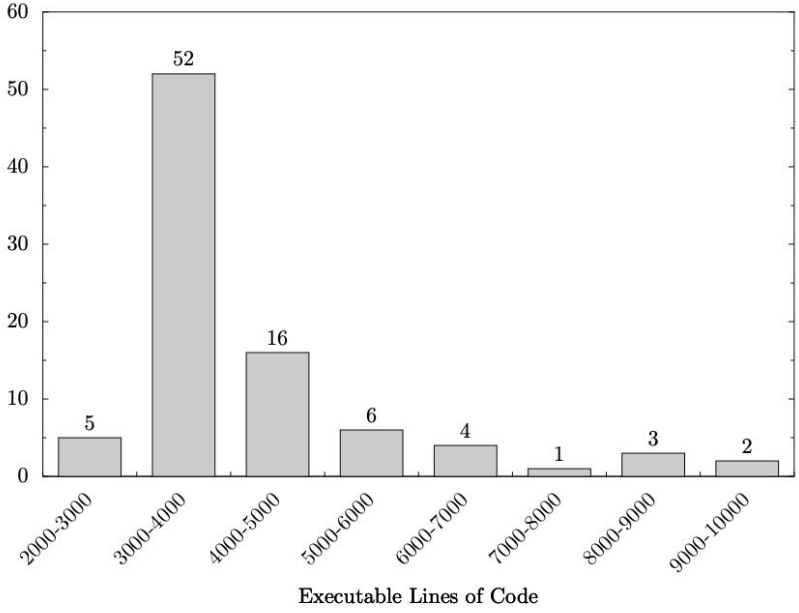

Figure 4: Histogram showing the number of COREUTILS tools that have a given number of executable lines of code (ELOC).

KLEE Performance - GNU Coreutils

	COREUTILS		BUSYBOX	
Coverage (w/o lib)	**KLEE tests**	**Devel. tests**	**KLEE tests**	**Devel. tests**
100%	16	1	31	4
90-100%	40	6	24	3
80-90%	21	20	10	15
70-80%	7	23	5	6
60-70%	5	15	2	7
50-60%	-	10	-	4
40-50%	-	6	-	-
30-40%	-	3	-	2
20-30%	-	1	-	1
10-20%	-	3	-	-
0-10%	-	1	-	30
Overall cov.	84.5%	67.7%	90.5%	44.8%
Med cov/App	94.7%	72.5%	97.5%	58.9%
Ave cov/App	90.9%	68.4%	93.5%	43.7%

KLEE Performance - GNU Coreutils

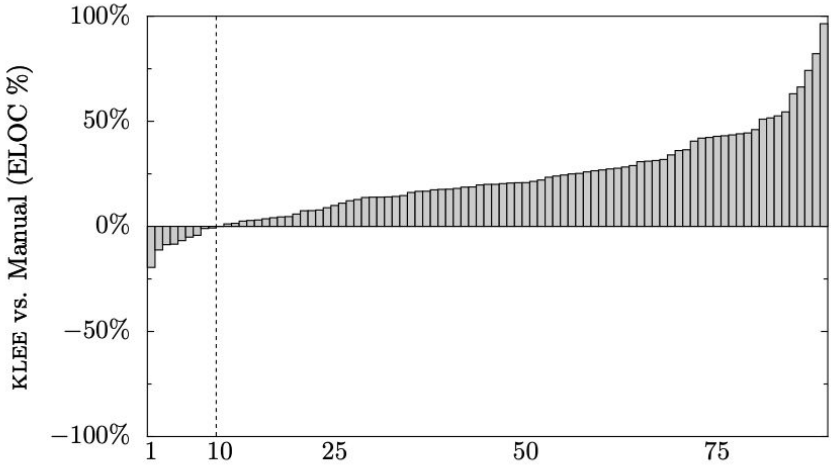

Figure 6: Relative coverage difference between KLEE and the COREUTILS manual test suite, computed by subtracting the executable lines of code covered by manual tests (L_{man}) from KLEE tests (L_{klee}) and dividing by the total possible: $(L_{klee} - L_{man})/L_{total}$. Higher bars are better for KLEE, which beats manual testing on all but 9 applications, often significantly.

KLEE as a bug finder

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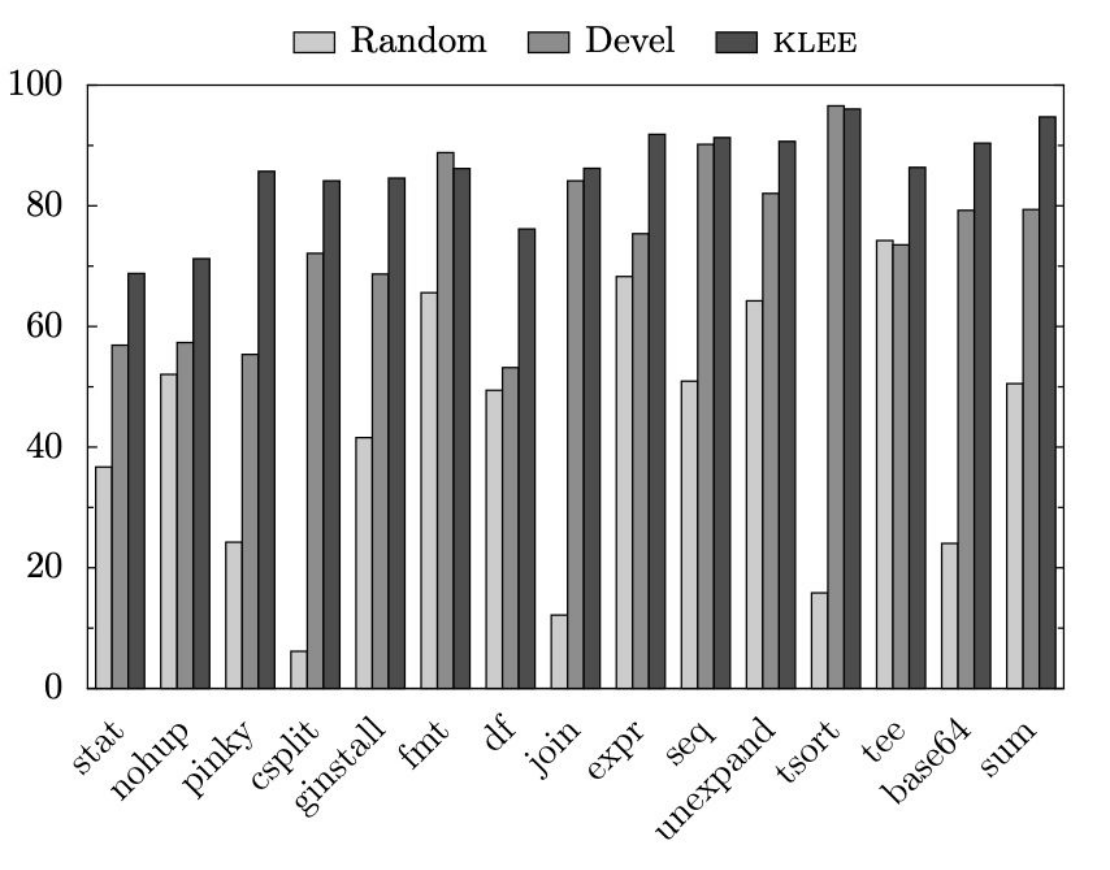
```
paste -d\\ abcdefghijklmnopqrstuvwxyz
pr -e t2.txt
tac -r t3.txt t3.txt
mkdir -Z a b
mkfifo -Z a b
mknod -Z a b p
md5sum -c t1.txt
ptx -F\\ abcdefghijklmnopqrstuvwxyz
ptx x t4.txt
seq -f %0 1
```

t1.txt: "\t \tMD5("
t2.txt: "\b\b\b\b\b\b\t"
t3.txt: "\n"
t4.txt: "a"

KLEE tests vs random tests

KLEE tests vs random tests



KLEE usage on BusyBox Utilities

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- Researchers ran KLEE on the 75 utilities that make up BusyBox’s coreutils - with great success.
- Researchers used KLEE to find bugs in BusyBox.

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- More recent tools can interact with the environment but are limited.
- More related work is interested in the path-explosion problem.

Concluding Remarks

Discussion