How is Dynamic Symbolic Execution Different from Manual Testing?

An Experience Report on KLEE

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Outline

- Background
- Research Goal
- Study Setup
- Quantitative Analysis
- Qualitative Analysis
- Summary and Future Work

Background

- Dynamic Symbolic Execution (DSE)
  - A promising approach to automated test generation
  - Aims to explore all/specific paths in a program
  - Generates and solves path constraints at runtime
- KLEE
  - A state-of-the-art DSE tool for C programs
  - Specially tuned for Linux Coreutils
  - Reported higher coverage than manual testing

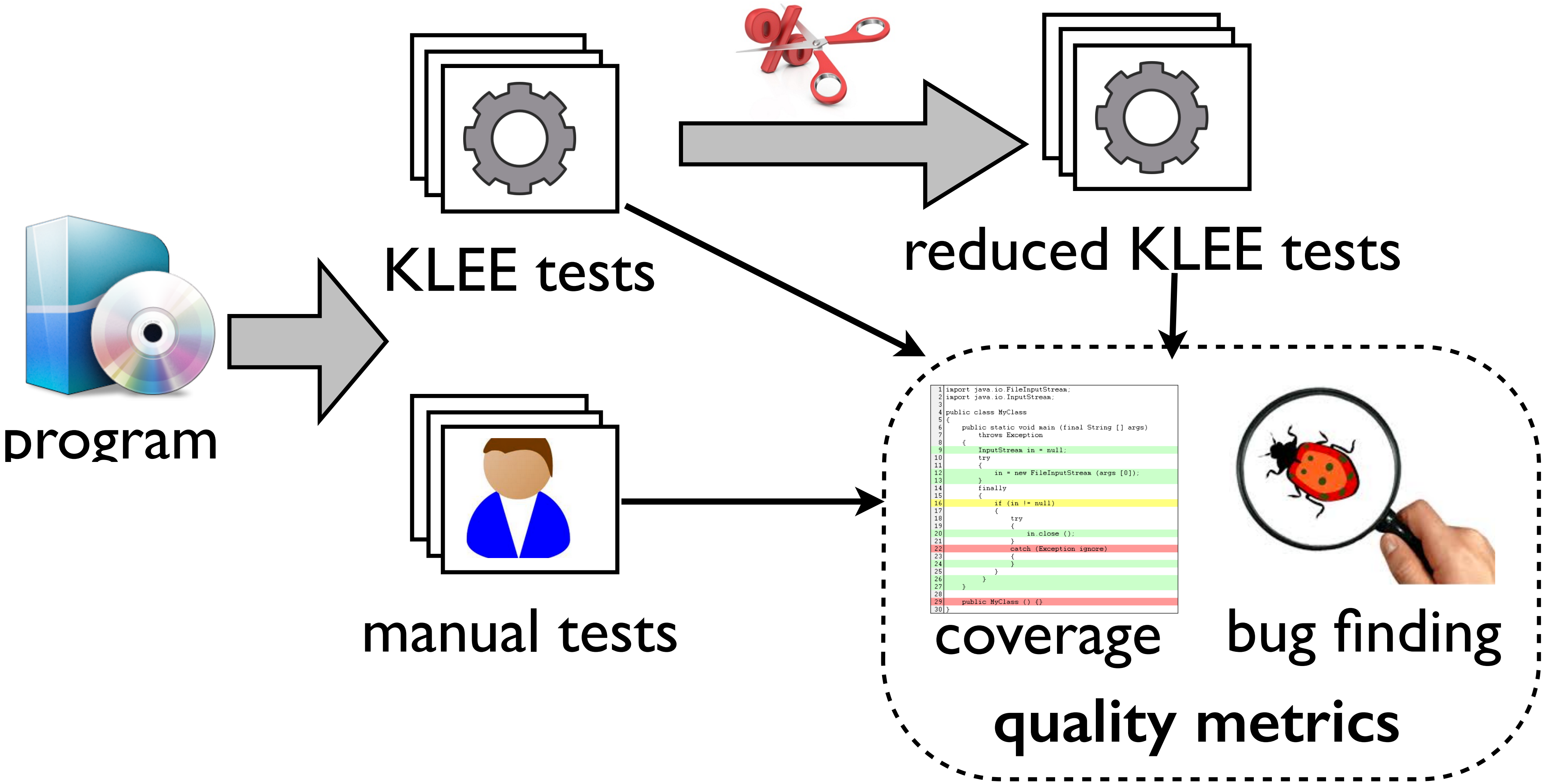
Research Goal

- Understand the ability of state-of-art DSE tools
- Identify proper scenarios to apply DSE tools
- Discover potential opportunities for enhancement

Research Questions

- Are KLEE-based test suites comparable with manually developed test suites on test sufficiency?
- How do KLEE-based test suites compare with manually test suites on harder testing problems?
- How much extra value can KLEE-based test suites provide to manually test suites?
- What are the characteristics of the code/mutants covered/killed by one type of test suites, but not by the other?

Study Process



Study Setup: Tools

- KLEE
  - Default setting for test generation
  - Execute each program for 20 minutes

- GCOV
  - Statement coverage collection

- MutGen
  - Generates 100 mutation faults for each program
  - 4 mutation operators

Study Setup: Subjects

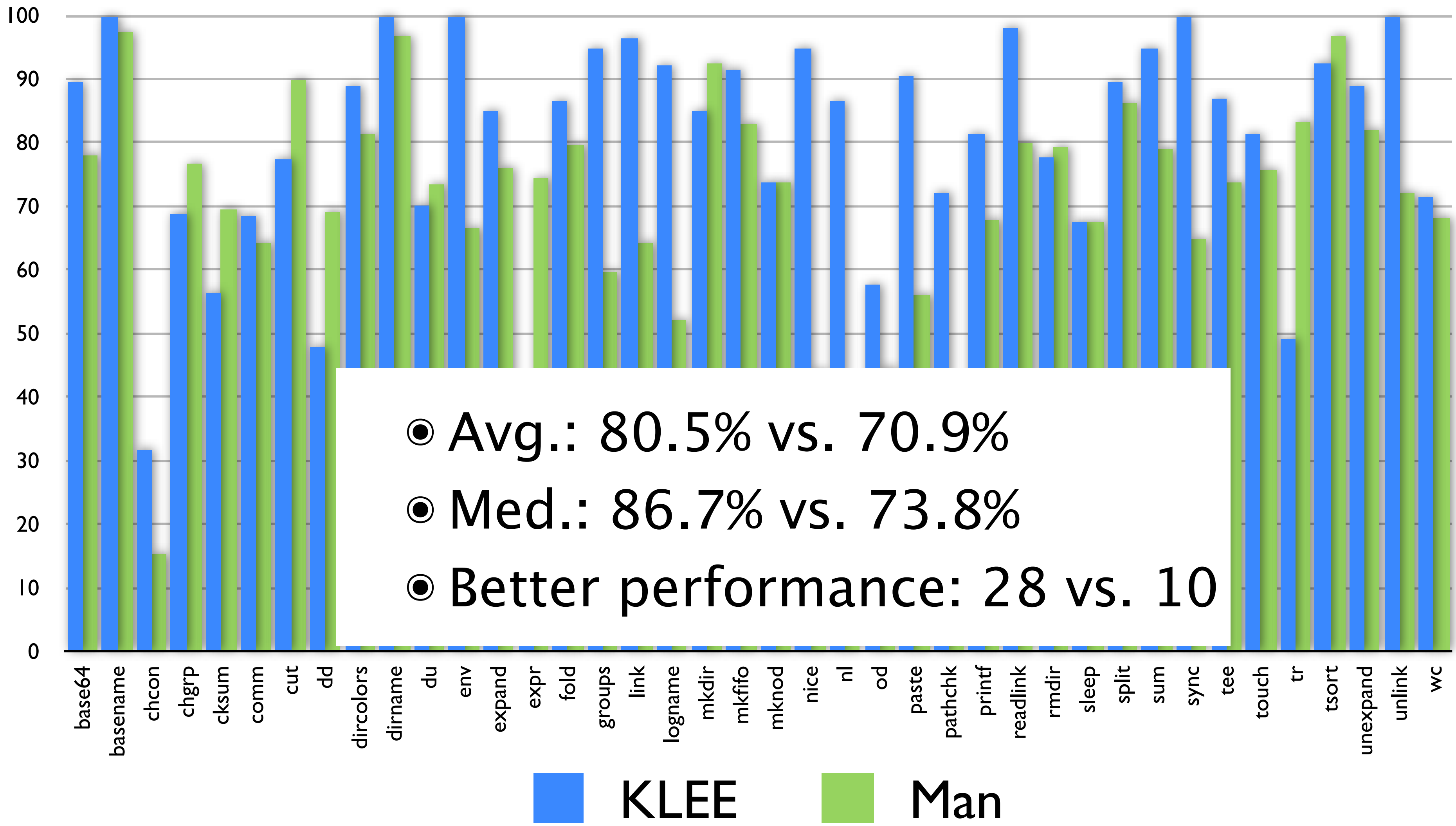
- CoreUtils Programs
  - Linux utilities programs
  - KLEE includes API modeling and turning of them
  - Used by KLEE in its evaluation

  - We did not include CoreUtils programs:
    - Do not generate any output
    - Output is not deterministic

Study Setup: Measurements

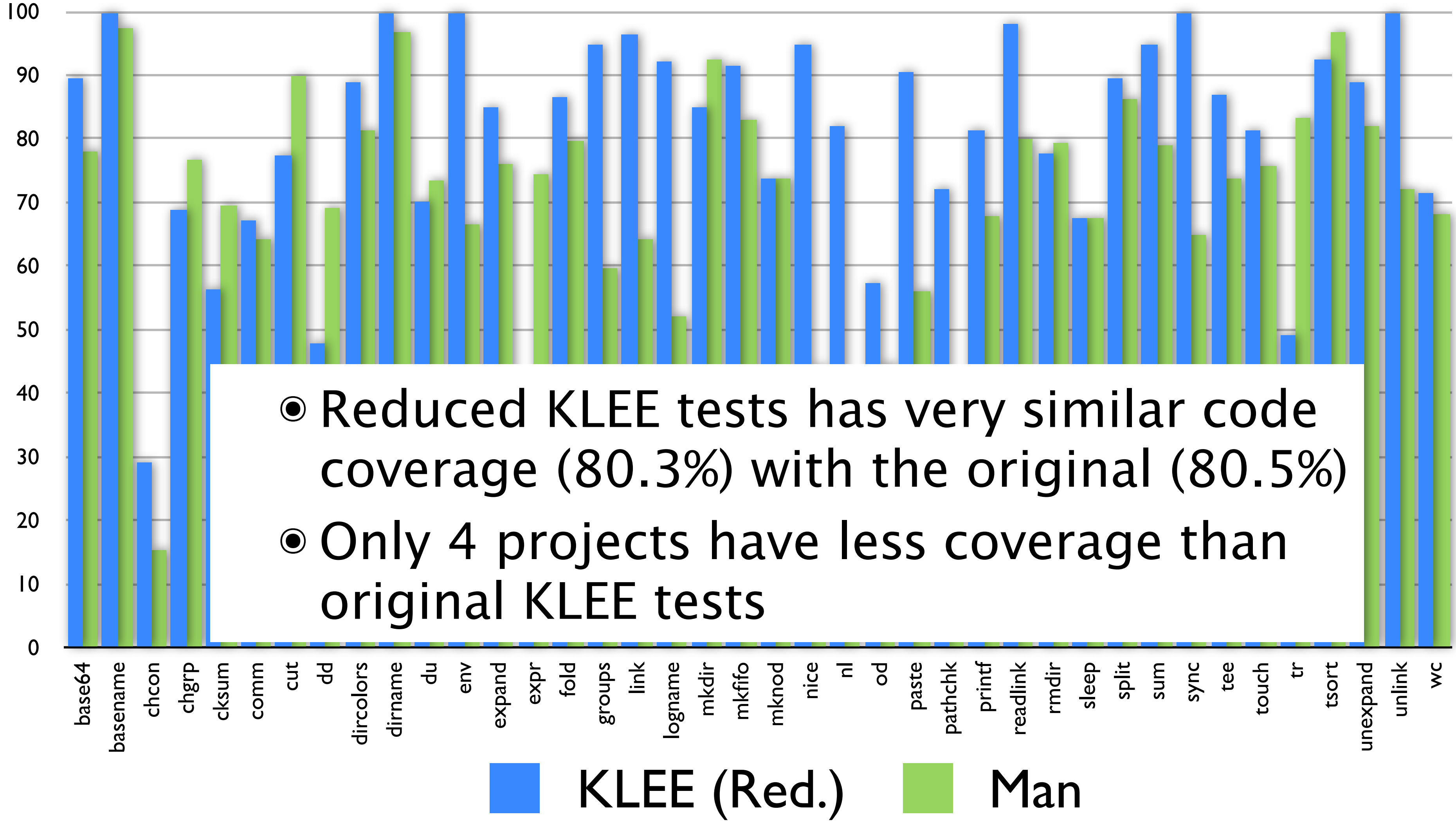
- Code coverage
  - Statement coverage
- Fault detection rate
  - Compare the command-line output of the original program and mutated programs to check if the mutation faults can be detected

Quantitative Analysis: Coverage



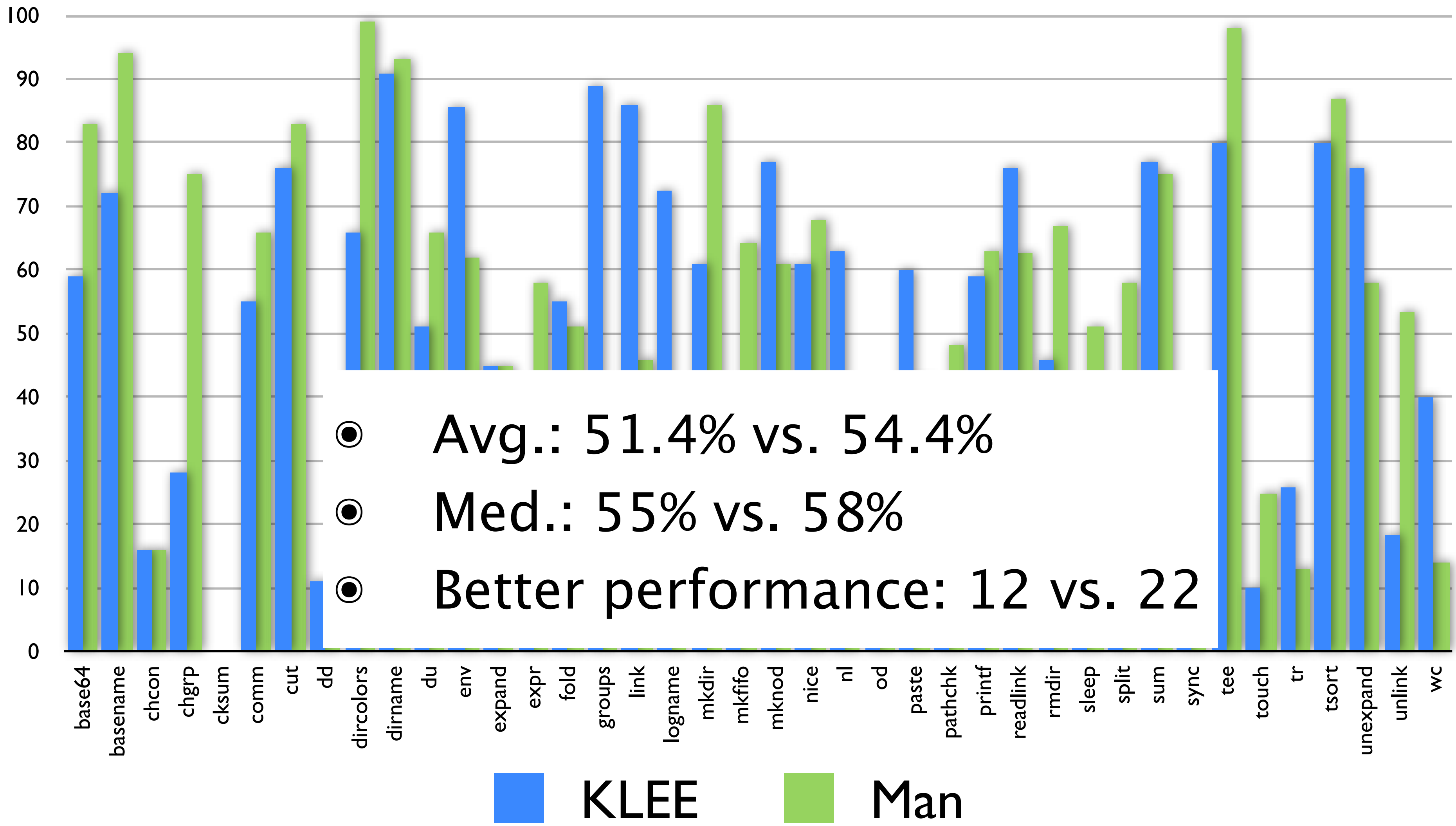
- Avg.: 80.5% vs. 70.9%
- Med.: 86.7% vs. 73.8%
- Better performance: 28 vs. 10

Quantitative Analysis: Coverage



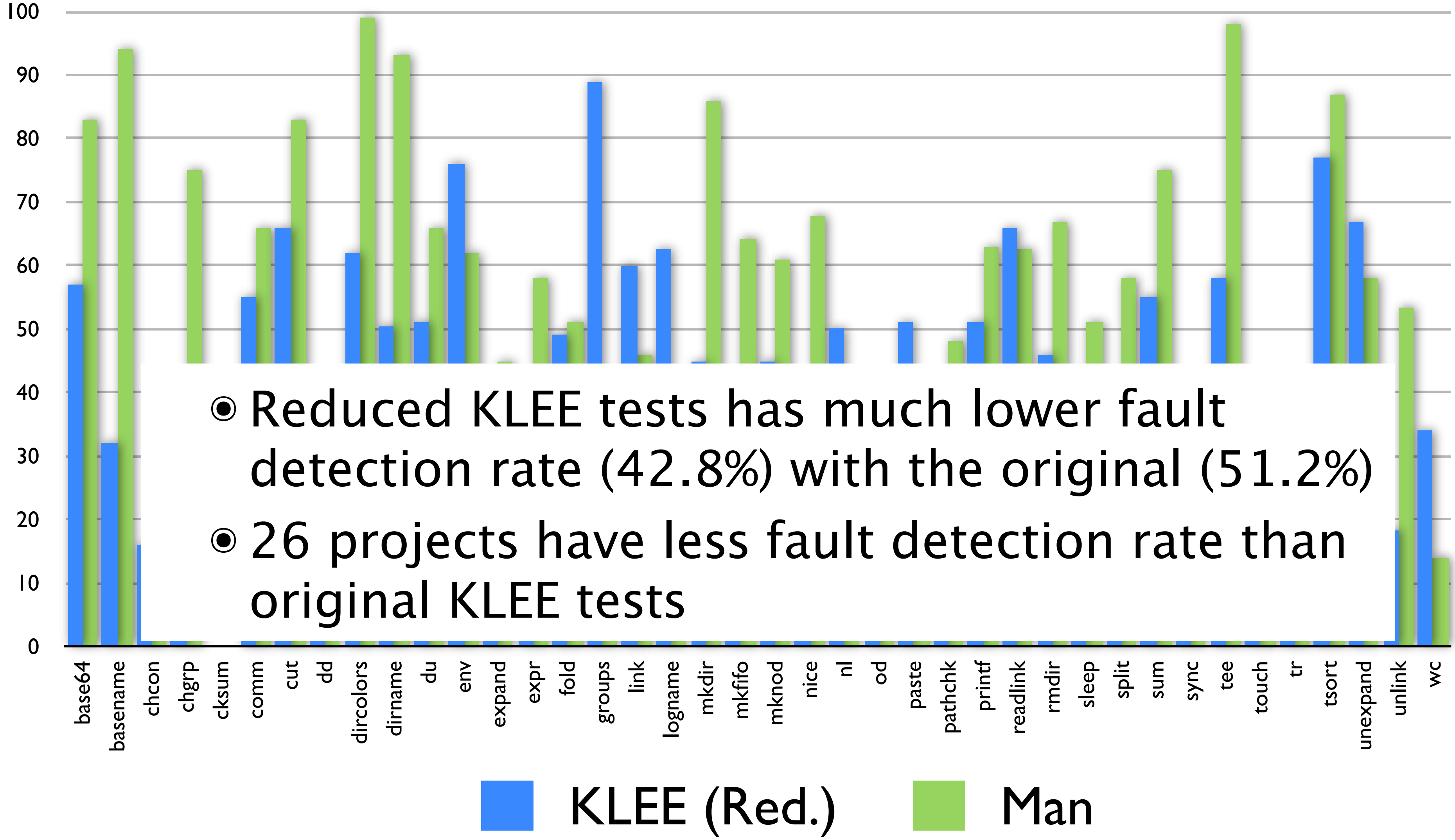
- Reduced KLEE tests has very similar code coverage (80.3%) with the original (80.5%)
- Only 4 projects have less coverage than original KLEE tests

Quantitative Analysis: Fault Detection



- Avg.: 51.4% vs. 54.4%
- Med.: 55% vs. 58%
- Better performance: 12 vs. 22

Quantitative Analysis: Fault Detection



- Reduced KLEE tests has much lower fault detection rate (42.8%) with the original (51.2%)
- 26 projects have less fault detection rate than original KLEE tests

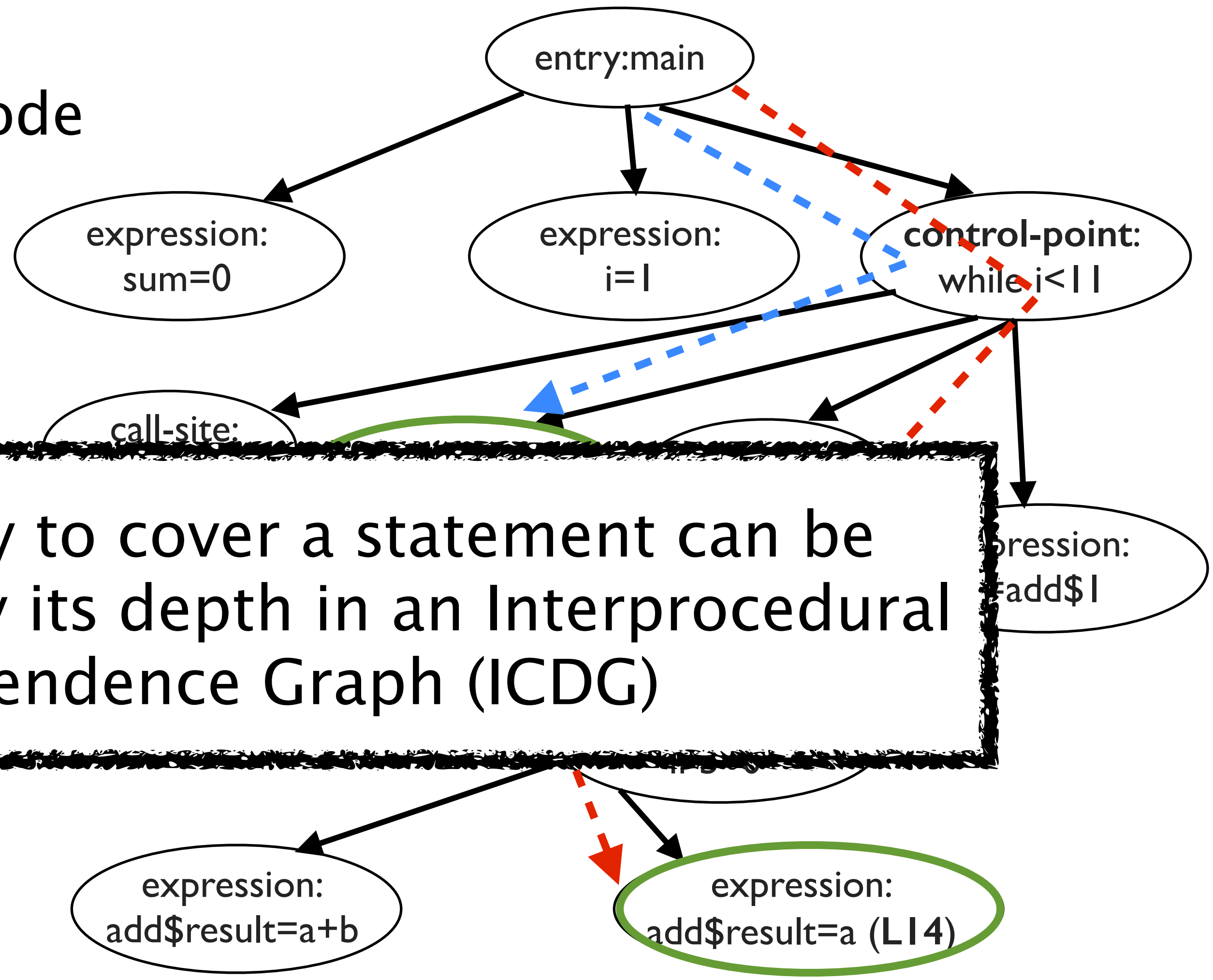
Quantitative Analysis: Harder Tasks (Code)

- Hard-to-cover code

```
void main() {
        int sum, i;
  sum = 0;
  i = 1;
  while ( i<11 ) {
    s
    i
  }
}
int a
  if
    r
  els
    return a;
}
```

Example

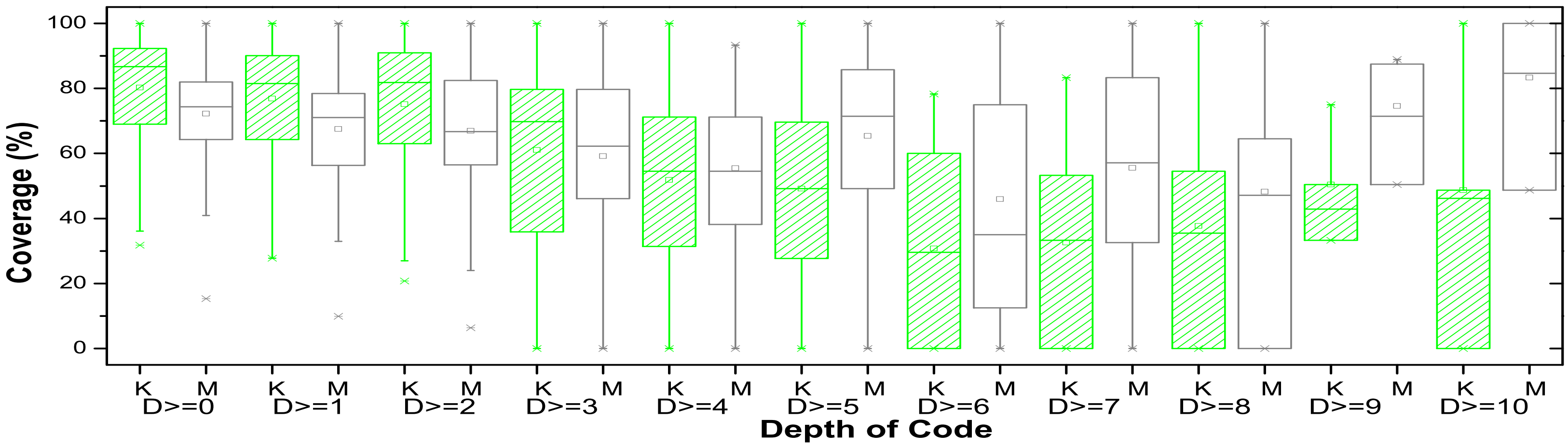
The difficulty to cover a statement can be measured by its depth in an Interprocedural Control Dependence Graph (ICDG)



Interprocedural Control Dependence Graph (ICDG)

Quantitative Analysis: Harder Tasks (Code)

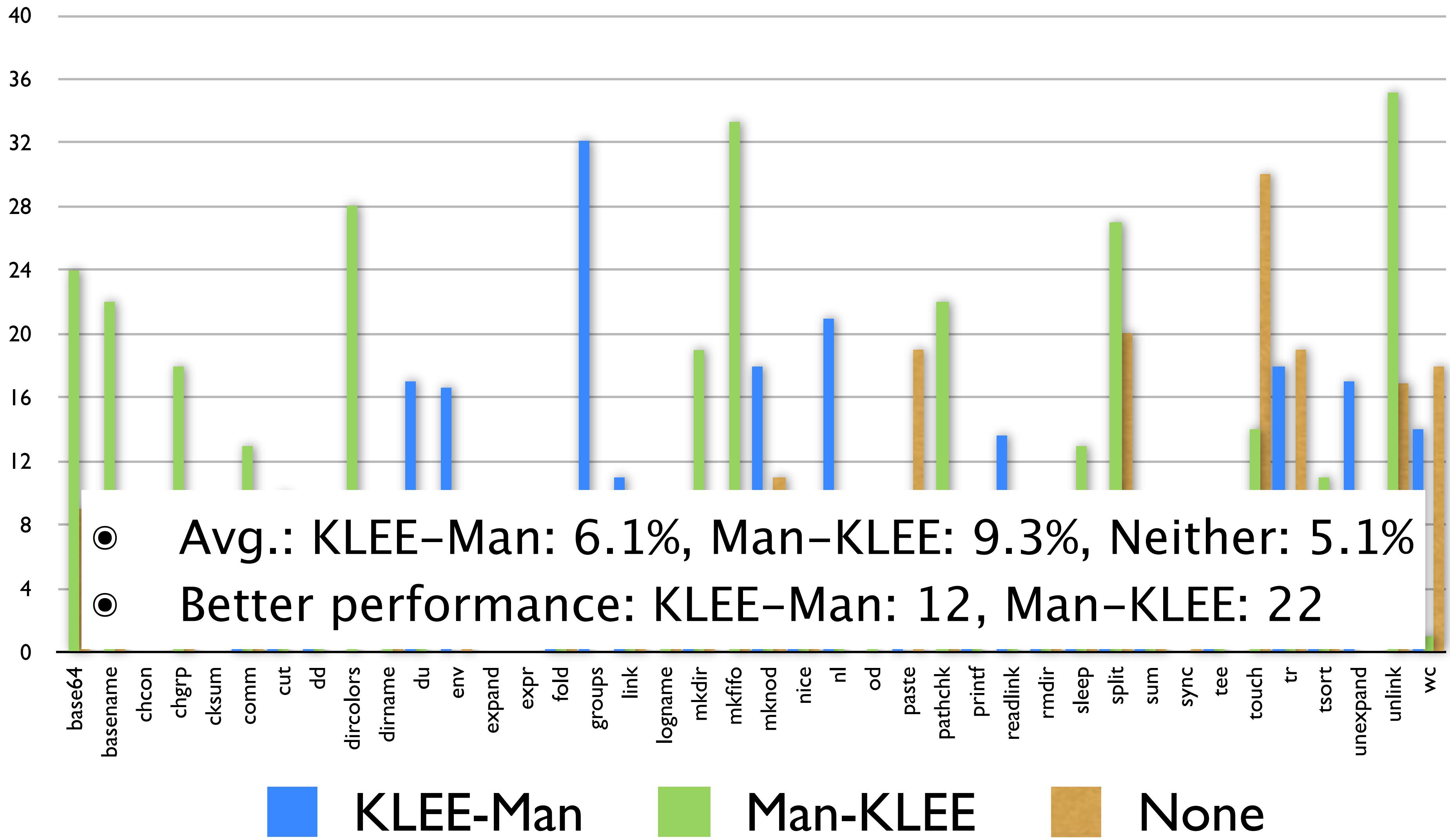
- Hard-to-cover code:



- Coverage of KLEE tests drops dramatically as depth goes lar… the same cover…

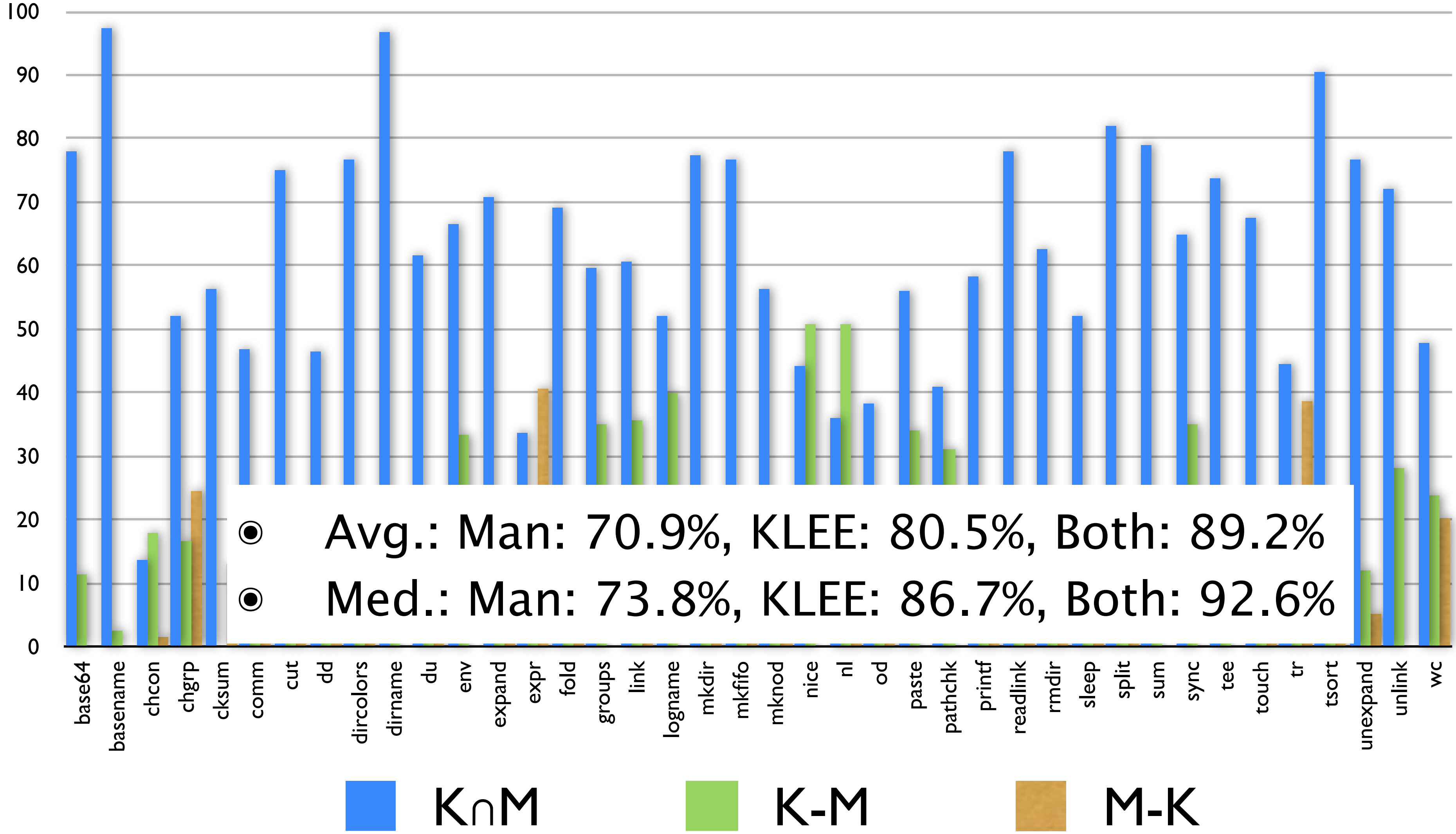
A hint of where human developers should help

Quantitative Analysis: Harder Tasks (Faults)



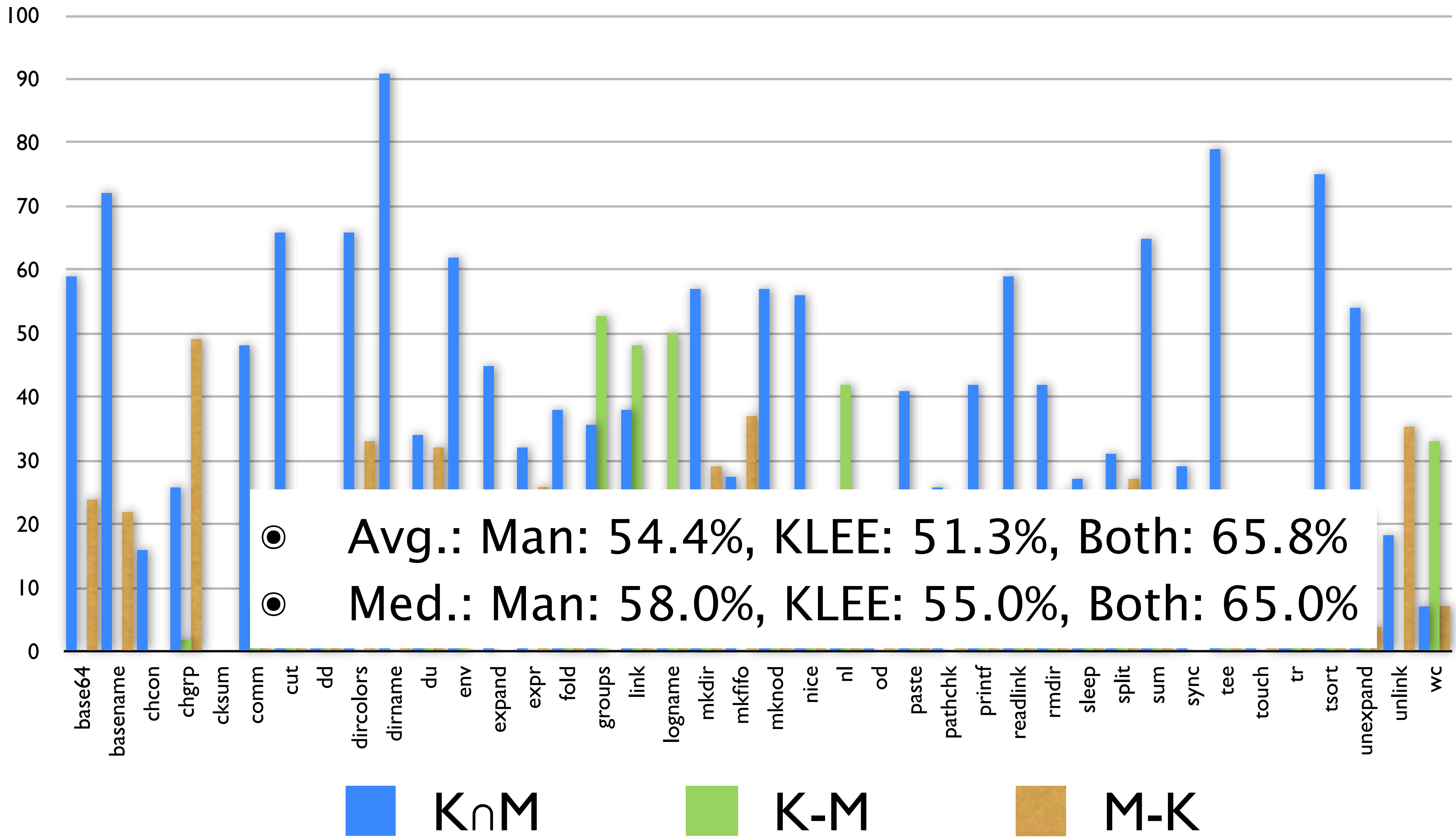
- Avg.: KLEE–Man: 6.1%, Man–KLEE: 9.3%, Neither: 5.1%
- Better performance: KLEE–Man: 12, Man–KLEE: 22

Quantitative Analysis: KLEE's Extra Value (Coverage)



- Avg.: Man: 70.9%, KLEE: 80.5%, Both: 89.2%
- Med.: Man: 73.8%, KLEE: 86.7%, Both: 92.6%

Quantitative Analysis: KLEE's Extra Value (Fault Detection)



- Avg.: Man: 54.4%, KLEE: 51.3%, Both: 65.8%
- Med.: Man: 58.0%, KLEE: 55.0%, Both: 65.0%

Qualitative Analysis

- Selection of code portion and mutation faults
  - KLEE-Man code:
    - 5 subjects with highest KLEE-Man code proportion
    - 5 longest code chunks
  - Man-KLEE code
    - 10 longest Man-KLEE code chunks
  - KLEE-Man / Man-KLEE mutation faults:
    - 10 Randomly selected mutants (at most 1 in each subject project)
    - Covered by both test suites

KLEE-Man Code

- Error Handling Code
  - Examples
    - **expr**: Manual tests fail to generate a bracket mismatch
    - **paste**: Manual tests fail to generate a file read error
- Exhausting all options
  - Example:
    - **nl**: Manual tests cover only 8 of 11 command options
    - **printf**: Manual tests fail to cover most escape characters

Man–KLEE Code

- Complex input structures:
  - Example:
    - **expr**: KLEE tests fail to include an expression containing a ":" operation and parsed correctly
    - **rmdir**: KLEE tests fail to generate a valid path
    - **tsort**: KLEE tests fail to include a tree structure requiring double rotation in balancing

KLEE-Man Mutants

- Why not detected by manual tests?
  - Major Reason: mutation affects only uncovered code
  - Example:

covered

```
if(optind + 1 < argc){     //mutate to “optind + 2”
    error (0, 0, ("extra operand \%s"), quote (…));
}
```

Fault detection condition:

$$(optind+1<argc) \mathrel{!=} (optind+2<argc)$$

$$optind+2 == argc$$

$$optind+1 < argc$$

Error Condition Not Covered by Manual Tests

Man-KLEE Mutants

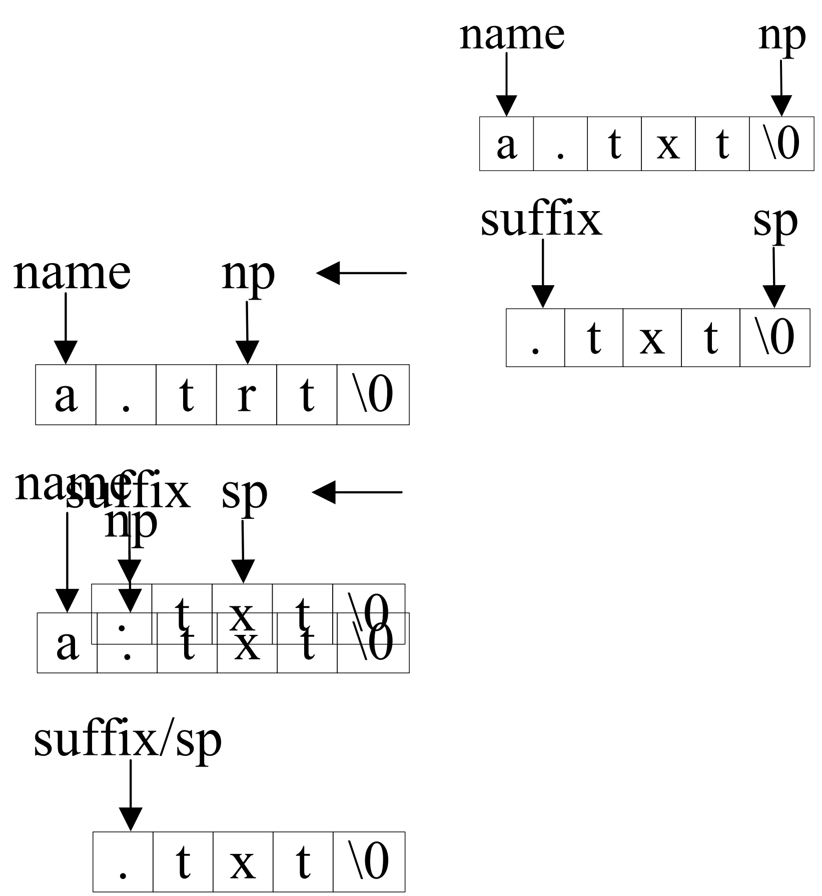
- Why not detected by KLEE tests?
  - Major reason: meaningful path not covered
  - Example: **basename**, try to remove suffix of a file name

```
char *np;
const char *sp;
```

```
np = name + strlen (name);
sp = suffix + strlen (suffix);
```

```
while (np > name && sp > suffix)
    if (*--np != *--sp)
        return;
```

```
if (np > name)
    *np = '$\slash$0';
```



Man-KLEE Mutants

- Why not detected by KLEE tests?
  - E.g., meaningful path not covered
  - Example: **basename**, try to remove suffix of a file name

```
char *np;
const char *sp;

np = name + strlen (name);
sp = suffix + strlen (suffix);

while (np > name && sp > suffix)
    if (*--np != *--sp)
        return;

if (np > name)
    *np = '$\slash$0';
```

KLEE Tests

np="a.txt" sp=""	np="a.txt" sp="bc"

KLEE tests: Although covering all statements, cannot execute the valid path

DANGER

Take-Home Message (Summary)

- While KLEE tests provide competitive coverage, their fault detection rates are lower
- Manual tests are better in covering hard-to-cover code and detecting hard-to-detect faults
- KLEE tests can provide non-trivial extra supports to manual tests in both coverage and fault detection
- KLEE is better at covering error handling code and exhausting a large number of options
- KLEE is worse at handling input with complicated structures, and may miss meaningful paths

Future Work

- Larger-scale quantitative and qualitative study
  - Larger and more subject programs
  - More test termination criteria
  - More measurements of code-coverage difficulty
  - Real-world faults
- More studies on other DSE tools
- Improving state-of-the-art DSE techniques
  - Knowledge of input formats
  - Integration of string constraint solvers
  - Guiding test-generation towards meaningful paths
  - …

Thanks! Questions?