Program Testing via Symbolic Execution

Daniel Dunbar

Introduction

- Motivation
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    - Requires knowledge of code
    - Requires constant maintenance
  - Random testing is ineffective
    - Hard to deeply probe programs
- Symbolic execution?
  - Automatic
  - Can check for error conditions
  - Can reach deep code paths

Overview

- KLEE: A Symbolic Virtual Machine
  - Basic Architecture
  - Constraint Solver Optimizations

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- KLEE: A Symbolic Virtual Machine
  - Basic Architecture
  - Constraint Solver Optimizations
- A Modeling Environment for UNIX
- Case Study: Coreutils
  - Over 80% coverage on majority of tools
  - Overall coverage better than developer tests

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- Also:

  Record branch choices in a *path condition*

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void escape(char *s,
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  while (*s != 0) {
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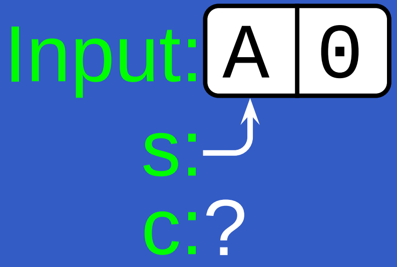

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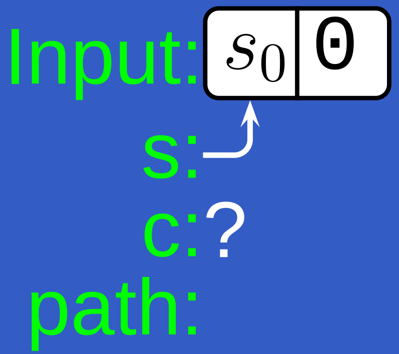

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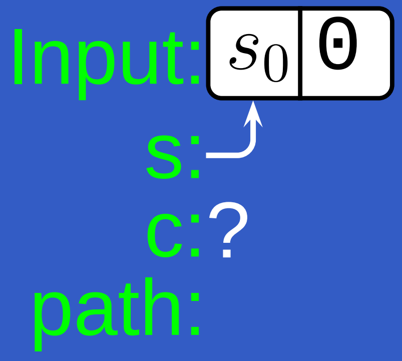

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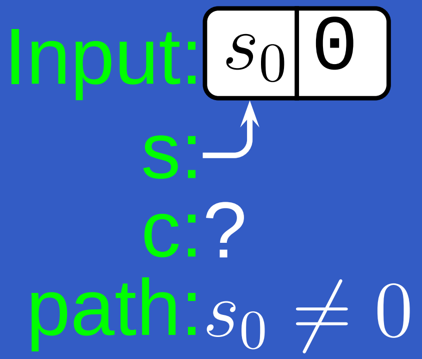

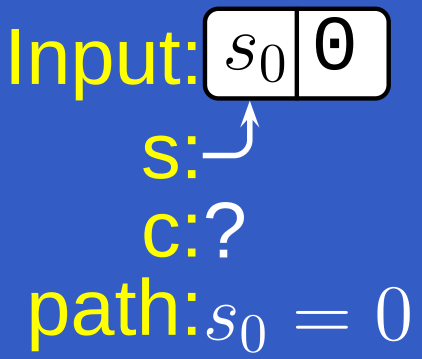

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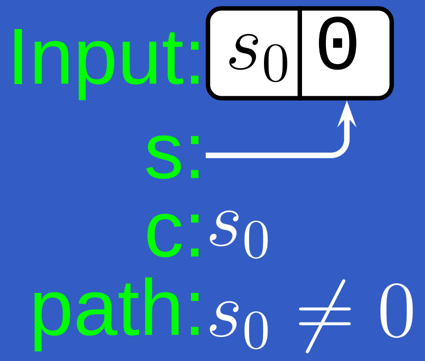

Input: $\boxed{s_0 \mid 0}$

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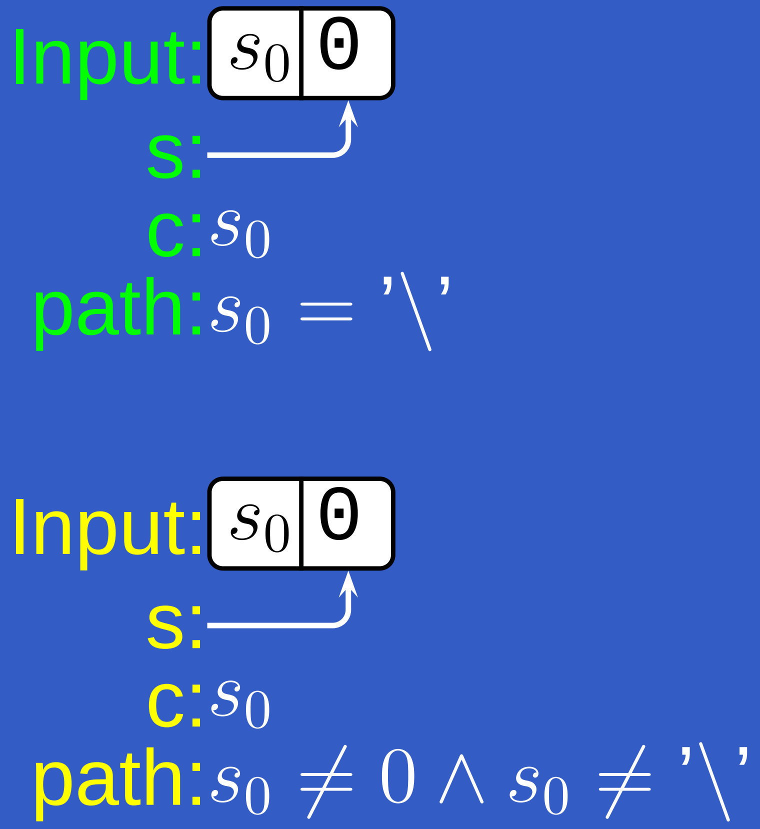

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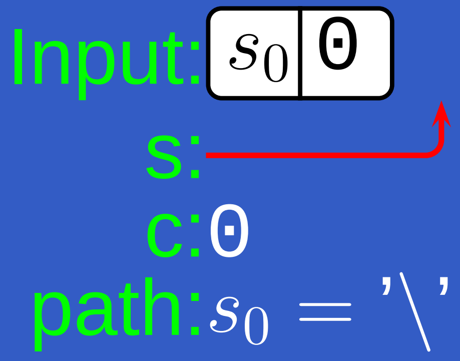

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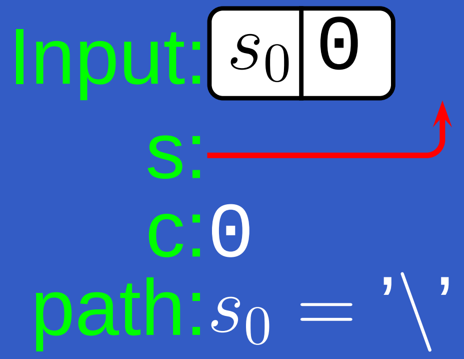

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The KLEE Architecture

- Based on experience with EXE system
- Goals
  - Simplicity
  - Scalability
  - Speed

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- Interpreter for LLVM Assembly Language
    - Precise semantics
    - Multiple language support
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- Easy to understand
    - Simple interpreter loop
    - Explicit process representation
    - Modular search & constraint solving

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- Handle over 100k processes for small programs

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- Optimize constraint solving

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- Program decomposition
  - Queries deal with distinct input variables
- Considerable redundancy
  - Processes *accrue* constraints
  - Static set of branches

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- Path constraints may refer to many variables
  - Path: $s_0 = \text{'A'} \wedge s_1 = 0 \wedge y_0 < 100$

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- Individual expressions only refer to a few
  - Branch condition: $y = 10$
- Independent constraint optimization:
  - Group constraints into disjoint subsets based on referenced variables
  - Only pass dependent constraints to solver
  - Query: $y < 100 \Rightarrow y = 10$

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2. If $(C', \perp), C' \subset C$ in cache, return $\perp$
3. If $(C', A), C' \supset C$ in cache, return A
4. Otherwise, for each $(C', A), C' \subset C$ in cache, *speculatively* evaluate C using A

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  if (x < 100)
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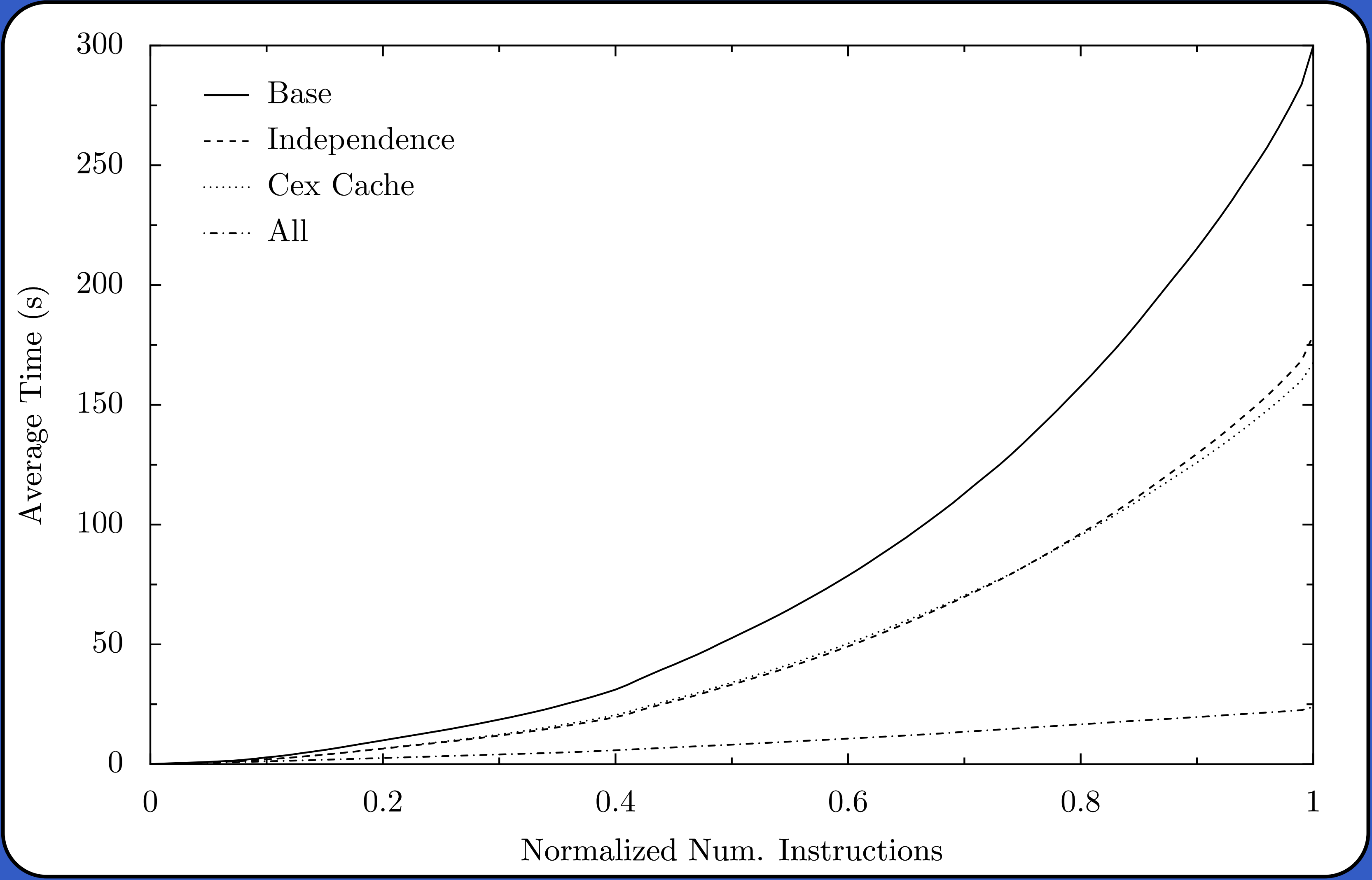
- Query: $x < 100$, Cache: $\{(x < 100, \{x : 0\})\}$
- Query: $x < 100 \wedge x \neq 50$
  - Evaluate with $\{x : 0\}$
  - $0 < 100 \wedge 0 \neq 50$
  - Found assignment

Optimization Results



Environment Modeling

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  - system libraries
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  - system libraries
  - operating system
- Our approach:
  - Compile and execute using μlibc
  - Implement UNIX systems calls in separate modeling library

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- Idea: Overlay *symbolic* environment onto operating system
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- Idea: Overlay *symbolic* environment onto operating system
  - Program sees “virtual” symbolic resources and actual OS resources
- Implemented by routing system calls through model routines
  - Symbolic resources are handled in model
  - Actual resources are forwarded to OS

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- Supports `open()`, `close()`, `read()`, `write()`, `lseek()`, `stat()`, `fstat()` as well as simple stubs for several more
- Implementation is about 800 lines of C code

Testing Process

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    - Additional arguments specify what parts of environment to make symbolic
    - KLEE generates test cases for any errors and for coverage

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  - Protects against modeling and system errors

Coreutils Background

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- GNU implementation of standard UNIX utilities
- Core of most Linux installations
- Encompasses 90 applications of varying size and focus
    - File system: `ls, dd, chmod`
    - Numeric: `factor, seq`
    - System: `printenv, hostname`
    - Text Processing: `sort, head, od`

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- Focused on tool front-ends
- Covers 20k combined executable lines of code
- Mostly automatic
  - One source code modification required
  - Most programs tested using a generic configuration

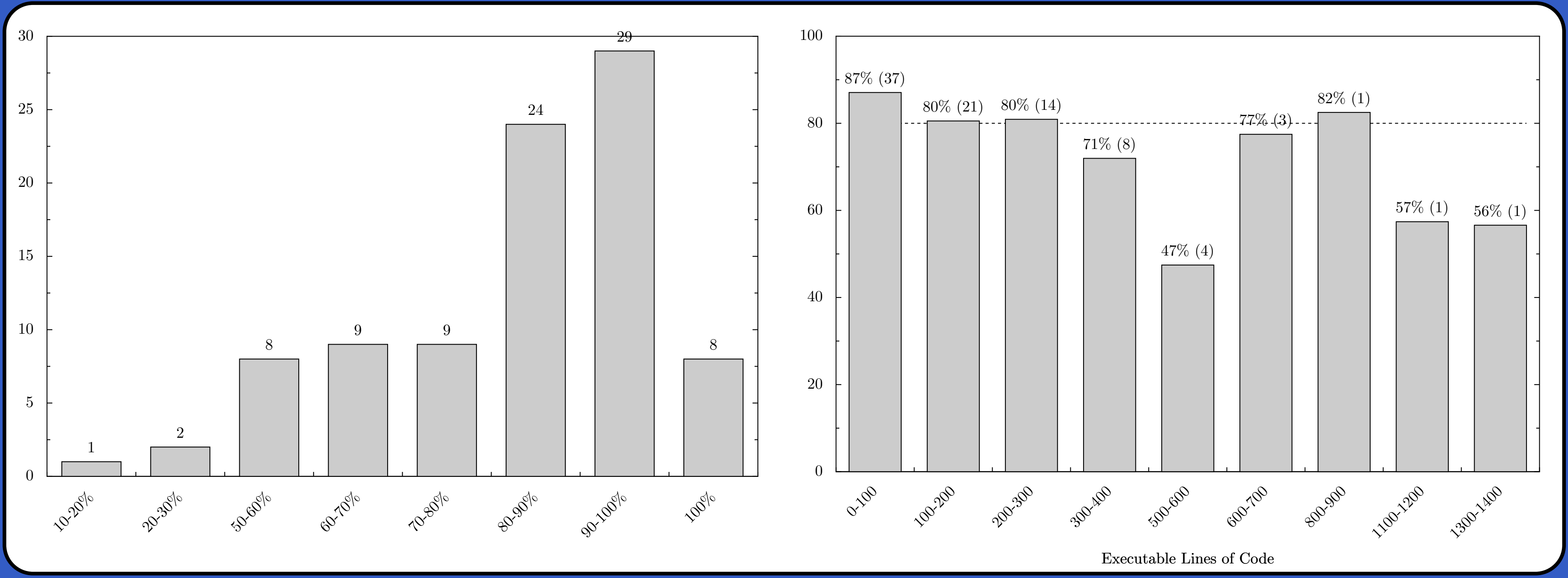
Results: Bugs

- Six bugs found
  - One fixed in developer repository
  - Three resulted in segmentation fault
  - Two allowed arbitrary heap smashing

```
ptx -F\\ abcdefghijklmnopqrstuvwxyz
paste -d\\ abcdefghijklmnopqrstuvwxyz
seq -f %0 1
mkdir -Z a b
mkfifo -Z a b
mknod -Z a b p
```

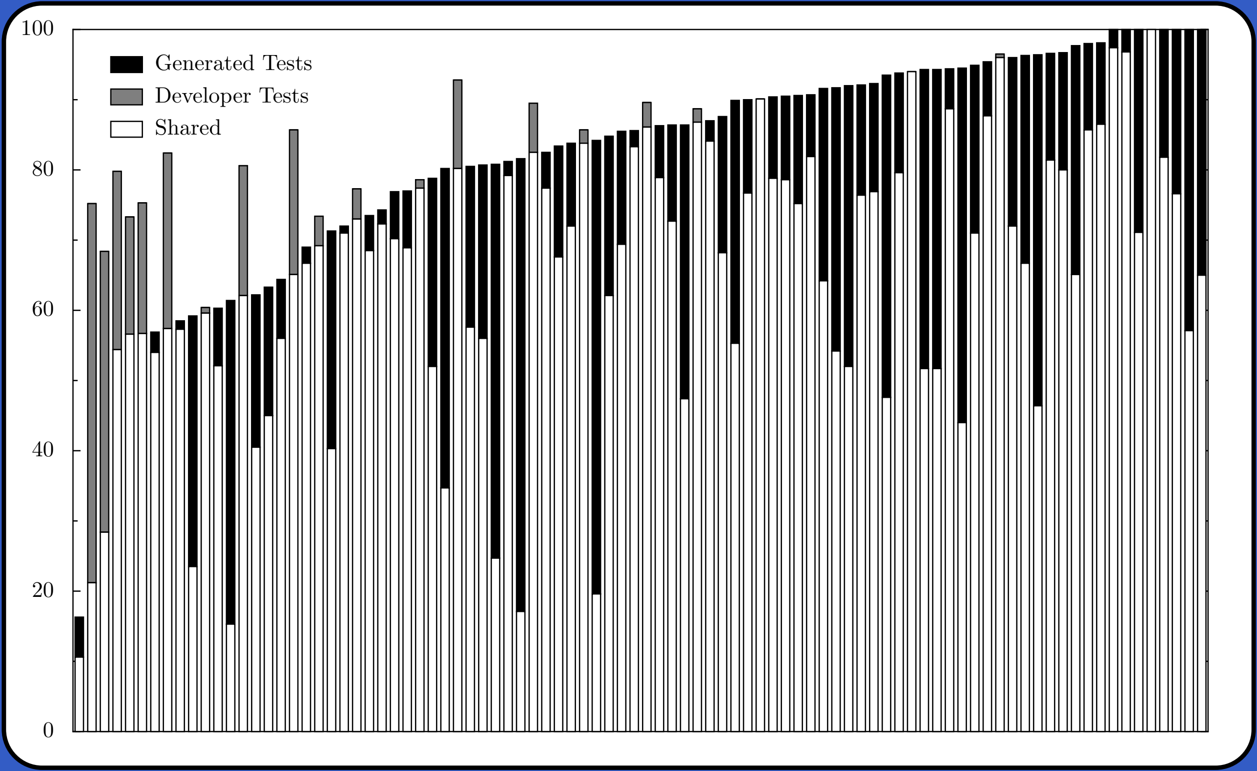
Results: Coverage

Overall coverage: 70.6%
Over 80% on $61/90$



Results: Vs. Manual

Developers tests overall coverage: 67.4%.
Generated tests outperform on majority of tools.



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  - Careful attention to scalability
  - Take advantage of specialized domain to optimize constraint solving
- Requires only modest amount of effort to construct an adequate model
- Can beat manual testing out-of-the-box

Questions?