Symbolic Execution

for finding bugs

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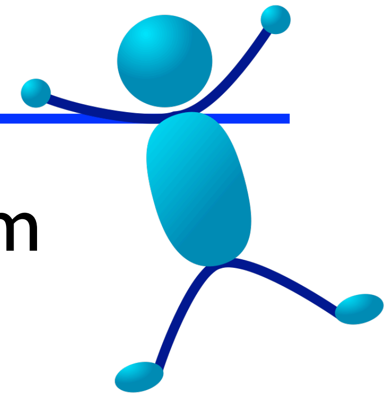
Software has bugs

- To find them, we use testing and code reviews

- But some bugs are still missed
  - Rare features
  - Rare circumstances
  - Nondeterminism

Static analysis



- Can analyze all possible runs of a program
  - Lots of interesting ideas and tools
  - Commercial companies sell, use static analysis
  - It all looks good on paper, and in papers

- But can developers use it?
  - Our experience: Not easily
  - Results in papers describe use by static analysis experts
  - Commercial viability implies you must deal with developer confusion, false positives, error management,..

One Issue: Abstraction

- Abstraction lets us scale and model all possible runs
  - But it also introduces conservatism
  - *-sensitivities attempt to deal with this
    - * = flow-, context-, path-, field-, etc
  - But they are never enough

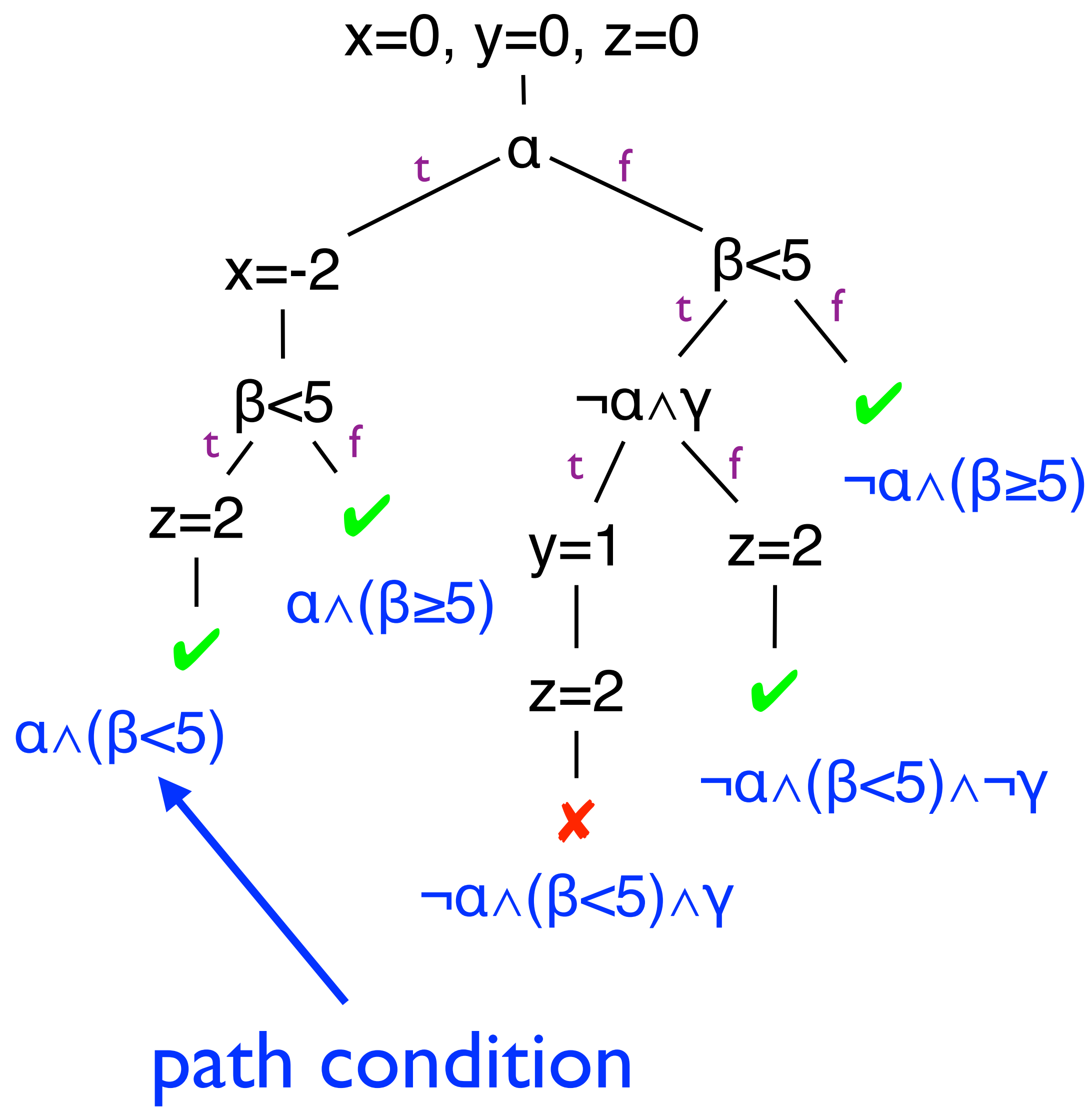
- Static analysis abstraction ≠ developer abstraction
  - Because the developer didn't have them in mind

Symbolic execution: a middle ground

- Testing works
  - But, each test only explores one possible execution
    - assert(f(3) == 5)
  - We *hope* test cases generalize, but no guarantees
- Symbolic execution generalizes testing
  - Allows *unknown* symbolic variables in evaluation
    - y = α; assert(f(y) == 2*y-1);
  - If execution path depends on unknown, conceptually *fork* symbolic executor
    - int f(int x) { if (x > 0) then return 2*x - 1; else return 10; }

Symbolic Execution Example

```
int a = α, b = β, c = γ;
                 // symbolic
int x = 0, y = 0, z = 0;
if (a) {
  x = -2;
}
if (b < 5) {
  if (!a && c)  { y = 1; }
  z = 2;
}
assert(x+y+z!=3)
```



Insight

- Each symbolic execution path stands for *many* actually program runs
  - In fact, exactly the set of runs whose concrete values satisfy the path condition

- Thus, we can cover a lot more of the program's execution space than testing

Early work on symbolic execution

- Robert S. Boyer, Bernard Elspas, and Karl N. Levitt. SELECT–a formal system for testing and debugging programs by symbolic execution. In ICRS, pages 234–245, 1975.
- James C. King. Symbolic execution and program testing. CACM, 19(7):385–394, 1976. **(most cited)**
- Leon J. Osterweil and Lloyd D. Fosdick. Program testing techniques using simulated execution. In ANSS, pages 171–177, 1976.
- William E. Howden. Symbolic testing and the DISSECT symbolic evaluation system. IEEE Transactions on Software Engineering, 3(4):266–278, 1977.

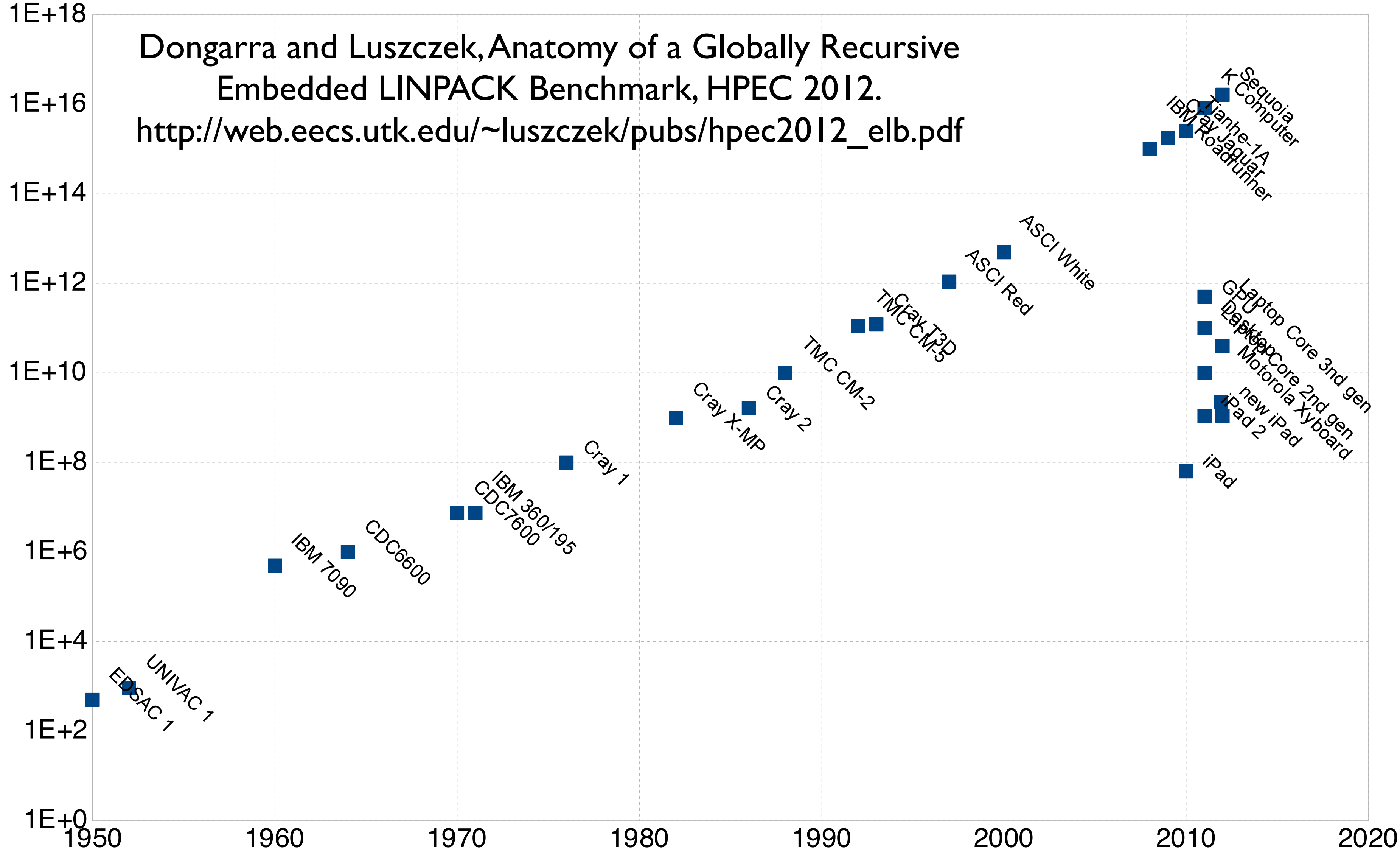
The problem

- Computers were small (not much memory) and slow (not much processing power)
  - Apple's iPad 2 is as fast as a Cray-2 from the 1980's

- Symbolic execution can be extremely expensive
  - Lots of possible program paths
  - Need to query solver a lot to decide which paths are feasible, which assertions could be false
  - Program state has many bits

Today

- Computers are much faster, memory is cheap
- There are very powerful SMT/SAT solvers today
  - SMT = Satisfiability Modulo Theories = SAT++
  - Can solve very large instances, very quickly
    - Lets us check assertions, prune infeasible paths
  - We've used Z3, STP, and Yices
- Recent success: bug finding
  - Heuristic search through space of possible executions
  - Find really interesting bugs


Dongarra and Luszczek, Anatomy of a Globally Recursive Embedded LINPACK Benchmark, HPEC 2012.
http://web.eecs.utk.edu/~luszczek/pubs/hpec2012_elb.pdf
1E+18
1E+16
1E+14
1E+12
1E+10
1E+8
1E+6
1E+4
1E+2
1E+0
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EDSAC 1
UNIVAC 1
IBM 7090
CDC6600
CDC7600
IBM 360/195
Cray 1
Cray X-MP
Cray 2
TMC CM-2
TMC CM-5
Cray T3D
ASCI Red
ASCI White
IBM Roadrunner
Cray Jaguar
Tianhe-1A
K Computer
Sequoia
Laptop Core 3nd gen
Motorola Xyboard
new iPad
iPad 2
iPad

Remainder of the tutorial

- The basics, in code
- Scaling up
  - The search space
  - Hard-to-handle features
- Existing tools
  - KLEE: one industrial grade tool
- KLEE lab: using KLEE to find bugs
  - Including vulnerabilities

Symbolic Execution for IMP

a ::= n | X | a0+a1 | a0-a1 | a0×a1

b ::= bv | a0=a1 | a0≤a1 | ¬b | b0∧b1 | b0∨b1

c ::= skip | X:=a | goto pc | if b then pc | assert b

p ::= c; ...; c

- n ∈ N = integers, X ∈ Var = variables, bv ∈ Bool = {true, false}
- This is a typical way of presenting a language
  - Notice grammar is for ASTs
    - Not concerned about issues like ambiguity, associativity, precedence
- Syntax stratified into commands (c) and expressions (a,b)
  - Expressions have no side effects
- No function calls (and no higher order functions)

Interpretation for IMP

- See main.ml

- How to extend this to be a symbolic executor?

Symbolic Variables

- Add a new kind of expression

```
type aexpr = ... | ASym of string
type bexpr = ... | BSym of string
```

  - The string is the variable name
  - Naming variables is useful for understanding the output of the symbolic executor

Symbolic Expressions

- Now change aeval and beval to work with symbolic expressions

```
let rec aeval sigma = function
  | ASym s -> new_symbolic_variable 32 s (* 32-bit *)
  | APlus (a1, a2) ->
    symbolic_plus (aeval sigma a1) (aeval sigma a2)
  | ...

let rec beval sigma = function
  | BSym s -> new_symbolic_variable 1 s (* 1 bit *)
  | BLeq (a1, a2) ->
    symbolic_leq (aeval sigma a1) (aeval sigma a2)
  | ...
```

Symbolic State

- Previous step function, roughly speaking

```
cstep : sigma -> pc -> (sigma', pc')
```

- Now we have a couple of issues:
  - We need to keep track of the path condition
  - There may be more than one pc if we fork execution
- Convenient to package all this up in a record, and change cstep appropriately

```
type state = {
  sigma : (string * symbolic_expr) list;
  pc : int;
  path : symbolic_expr;
}
cstep : state -> state * (state option)
```

Forking Execution

- How to decide which branches are *feasible*?
  - Combine path condition with branch cond and ask solver!

```
let cstep st = function
 | CIf (b, pc') ->
   let b' = beval st.sigma b in
   let t_path_cond = symbolic_and st.path b' in
   let f_path_cond = symbolic_and st.path (symbolic_not b') in
   let maybe_t = satisfiable t_path_cond in
   let maybe_f = satisfiable f_path_cond in
   match maybe_t, maybe_f with
   | true, true -> (* true path *), Some (* false path *)
   | true, false -> (* true path *), None
   | false, true -> (* false path *), None
   | false, false -> (* impossible *)
```

Top-level Driver

```
1. create initial state
   - pc = 0, path cond = true, state = empty
2. push state onto worklist
3. while (worklist is not empty)
  3a. st = pull some state from worklist
  3b. st', st'' = cstep st
  3c. add st' to worklist
  3d. add st''' to worklist if st'' = Some st'''
```

Path explosion

- Usually can't run symbolic execution to exhaustion
  - Exponential in branching structure

```
int a = α, b = β, c = γ;    // symbolic
if (a) ... else ...;
if (b) ... else ...;
if (c) ... else ...;
```

    - Ex: 3 variables, 8 program paths

  - Loops on symbolic variables even worse

```
int a = α;    // symbolic
while (a) do ...;

```

    - Potentially 2^31 paths through loop!

Basic search

- Simplest ideas: algorithms 101
  - Depth-first search (DFS)
  - Breadth-first search (BFS)

- Potential drawbacks
  - Neither is guided by any higher-level knowledge
    - Probably a bad sign
  - DFS could easily get stuck in one part of the program
    - E.g., it could keep going around a loop over and over again
  - Of these two, BFS is a better choice

Search strategies

- Need to prioritize search
  - Try to steer search towards paths more likely to contain assertion failures
  - Only run for a certain length of time
    - So if we don't find a bug/vulnerability within time budget, too bad

- Think of program execution as a DAG
  - Nodes = program states
  - Edge(n1,n2) = can transition from state n1 to state n2
- Then we need some kind of graph exploration strategy
  - At each step, pick among all possible paths

Randomness

- We don't know a priori which paths to take, so adding some randomness seems like a good idea
  - Idea 1: pick next path to explore uniformly at random (Random Path, RP)
  - Idea 2: randomly restart search if haven't hit anything interesting in a while
  - Idea 3: when have equal priority paths to explore, choose next one at random
    - All of these are good ideas, and randomness is very effective
- One drawback: reproducibility
  - Probably good to use psuedo-randomness based on seed, and then record which seed is picked
  - (More important for symbolic execution implementers than users)

Coverage-guided heuristics

- Idea: Try to visit statements we haven't seen before
- Approach
  - Score of statement = # times it's been seen and how often
  - Pick next statement to explore that has lowest score
- Why might this work?
  - Errors are often in hard-to-reach parts of the program
  - This strategy tries to reach everywhere.
- Why might this not work?
  - Maybe never be able to get to a statement if proper precondition not set up
- KLEE = RP + coverage-guided

Generational search

- Hybrid of BFS and coverage-guided
- Generation 0: pick one program at random, run to completion
- Generation 1: take paths from gen 0, negate *one* branch condition on a path to yield a new path prefix, find a solution for that path prefix, and then take the resulting path
  - Note will semi-randomly assign to any variables not constrained by the path prefix
- Generation n: similar, but branching off gen n-1
- Also uses a coverage heuristic to pick priority

Combined search

- Run multiple searches at the same time
- Alternate between them
  - E.g., Fitnext

- Idea: no one-size-fits-all solution
  - Depends on conditions needed to exhibit bug
  - So will be as good as "best" solution, which a constant factor for wasting time with other algorithms
  - Could potentially use different algorithms to reach different parts of the program

SMT solver performance

- SAT solvers are at core of SMT solvers
  - In theory, could reduce all SMT queries to SAT queries
  - In practice, SMT and higher-level optimizations are critical

- Some examples
  - Simple identities (x + 0 = x, x * 0 = 0)
  - Theory of arrays (read(42, write(42, x, A)) = x)
    - 42 = array index, A = array, x = element
  - Caching (memoize solver queries)
  - Remove useless variables
    - E.g., if trying to show path feasible, only the part of the path condition related to variables in guard are important

Libraries and native code

- At some point, symbolic execution will reach the “edges” of the application
  - Library, system, or assembly code calls
- In some cases, could pull in that code also
  - E.g., pull in libc and symbolically execute it
  - But glibc is insanely complicated
    - Symbolic execution can easily get stuck in it
  - ⇒ pull in a simpler version of libc, e.g., newlib
    - libc versions for embedded systems tend to be simpler
- In other cases, need to make models of code
  - E.g., implement ramdisk to model kernel fs code
  - This is a lot of work!

Concolic execution

- Also called *dynamic symbolic execution*
- Instrument the program to do symbolic execution as the program runs
  - I.e., shadow concrete program state with symbolic variables
- Explore one path at a time, start to finish
  - Always have a concrete underlying value to rely on

Concretization

- Concolic execution makes it really easy to concretize
  - Replace symbolic variables with concrete values that satisfy the path condition
    - Always have these around in concolic execution
- So, could actually do system calls
  - But we lose symbolic-ness at such calls
- And can handle cases when conditions too complex for SMT solver
  - But can do the same in pure symbolic system

Resurgence of symbolic exection

- Two key systems that triggered revival of this topic:
  - DART — Godefroid and Sen, PLDI 2005
    - Godefroid = model checking, formal systems background
  - EXE — Cadar, Ganesh, Pawlowski, Dill, and Engler, CCS 2006
    - Ganesh and Dill = SMT solver called "STP" (used in implementation)
      - Theory of arrays
    - Cadar and Engler = systems

Recent successes, run on binaries

- SAGE
  - Microsoft (Godefroid) concolic executor
  - Symbolic execution to find bugs in file parsers
    - E.g., JPEG, DOCX, PPT, etc
  - Cluster of *n* machines continually running SAGE
- Mayhem
  - Developed at CMU (Brumley et al), runs on binaries
  - Uses BFS-style search and native execution
  - Automatically generates exploits when bugs found

KLEE

- Symbolically executes LLVM bitcode
  - LLVM compiles source file to .bc file
  - KLEE runs the .bc file
- Works in the style of our example interpreter
  - Uses fork() to manage multiple states
  - Employs a variety of search strategies
  - Mocks up the environment to deal with system calls, file accesses, etc.

KLEE: Coverage for Coreutils

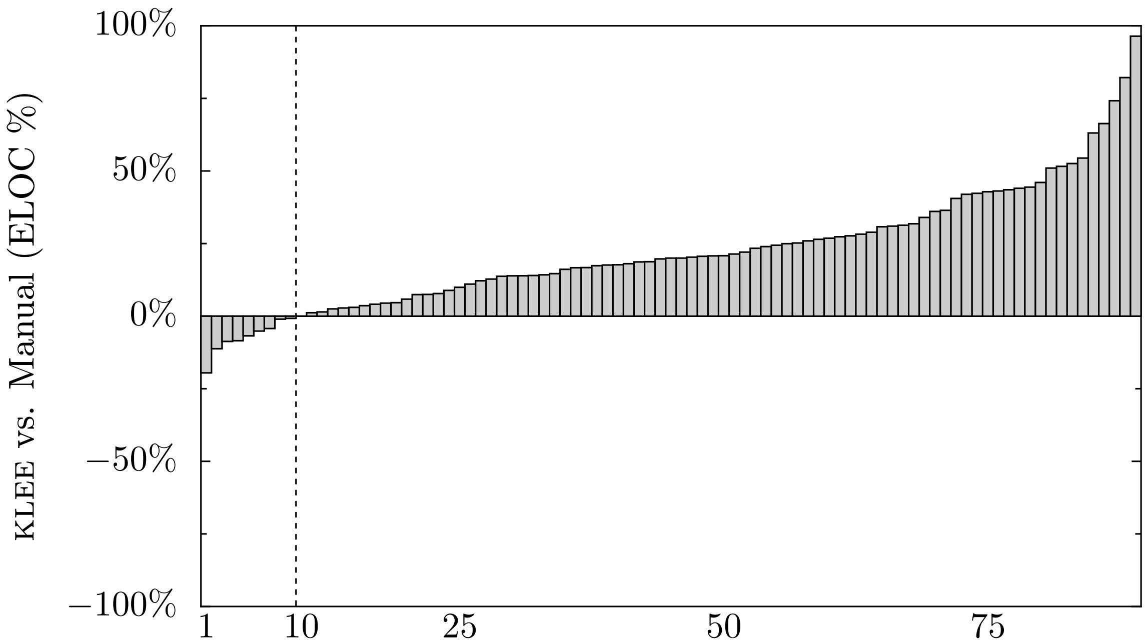

Figure 6: Relative coverage difference between KLEE and the COREUTILS manual test suite, computed by subtracting the executable lines of code covered by manual tests (L_{man}) from KLEE tests (L_{klee}) and dividing by the total possible: $(L_{klee} - L_{man})/L_{total}$. Higher bars are better for KLEE,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

Cadar, Dunbar, and Engler. KLEE: Unassisted and Automatic Generation of High-Coverage Tests for Complex Systems Programs, OSDI 2008

KLEE: Coreutils crashes

```
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\b\t"`
t3.txt: `"\n"`
t4.txt: `"a"`

Figure 7: KLEE-generated command lines and inputs (modified for readability) that cause program crashes in COREUTILS version 6.10 when run on Fedora Core 7 with SELinux on a Pentium machine.

Cadar, Dunbar, and Engler. KLEE: Unassisted and Automatic Generation of High-Coverage Tests for Complex Systems Programs, OSDI 2008

Other symbolic executors

- Cloud9 — parallel symbolic execution, also supports threads
- Pex — symbolic execution for .NET
- jCUTE — symbolic execution for Java
- Java PathFinder — a model checker that also supports symbolic execution

Research tools at UMD

- Otter — symbolic executor for C
  - Better library model than KLEE, support for multiprocess symbolic execution
  - Supports directed symbolic execution: give the tool a line number, and it try to generate a test case to get there
- RubyX — symbolic executor for Ruby
- SymDroid — symbolic executor for Dalvik bytecode

Lab

- Now will try out KLEE
- To get started, go to
  - http://www.cs.umd.edu/~mwh/se-tutorial/
- We will get the basics working and then try to reproduce some of the coreutils bugs