

Symbolic Execution

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Outline

- ▶ What is *symbolic execution*?
- ▶ Applications
- ▶ History
- ▶ Internal Design: The three challenges
 - ▶ Path explosion
 - ▶ Modeling statements and environments
 - ▶ Constraint solving
- ▶ Implementation and symbolic execution tools

Concrete execution vs. symbolic execution

```
int foo(int i){  
    int j = 2*i;  
    i = i++;  
    i = i * j;  
    if ( i < 1 )  
        i = -i;  
    return i;  
}
```

```
i = 1  
i = 1, j = 2  
i = 2, j = 2  
i = 4, j = 2  
  
return 4
```

Concrete execution vs. symbolic execution

```
int foo(int i){  
    int j = 2*i;  
    i = i++;  
    i = i * j;  
    if ( i < 1 )  
        i = -i;  
    return i;  
}
```

i_{input}

$i = i_{input}, j = 2 * i_{input}$

$i = i_{input} + 1, j = 2 * i_{input}$

$i = 2 * i_{input}^2 + 2 * i_{input}$

Concrete execution vs. symbolic execution

```
int foo(int i){  
    int j = 2*i;  
    i = i++;  
    i = i * j;  
    if ( i < 1 )  
        i = -i;  
    return i;  
}
```

i_{input}

$i = i_{input}, j = 2 * i_{input}$

$i = i_{input} + 1, j = 2 * i_{input}$

$i = 2 * i_{input}^2 + 2 * i_{input}$

$i = - 2 * i_{input}^2 - 2 * i_{input}$
 $(2 * i_{input}^2 + 2 * i_{input} < 1)$

OR

$i = 2 * i_{input}^2 + 2 * i_{input}$
 $(2 * i_{input}^2 + 2 * i_{input} \geq 1)$

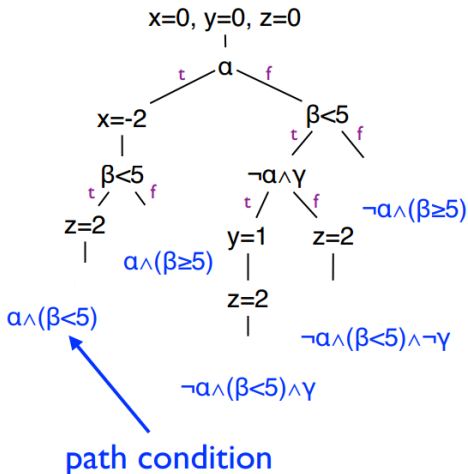
Intuitive understanding of symbolic execution

- ▶ 'Execute' programs with symbols: we track symbolic state rather than concrete input
- ▶ 'Execute' many program paths simultaneously: when execution path diverges, fork and add constraints on symbolic values
- ▶ When 'execute' one path, we actually simulate many test runs, since we are considering all the inputs that can exercise the same path
- ▶ System calls and library calls: the symbolic execution engine creates an environment to mimic real executions, e.g., by supplying concrete inputs
- ▶ Other variants
 - ▶ *Symbolic Analysis*: Model library and system calls rather than 'executing' it [Le2013]
 - ▶ *Concolic Testing*: Mixture of symbolic and concrete inputs [Sen2005]

Symbolic execution tree

```
int a =  $\alpha$ , b =  $\beta$ , c =  $\gamma$ ;  
// 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)
```



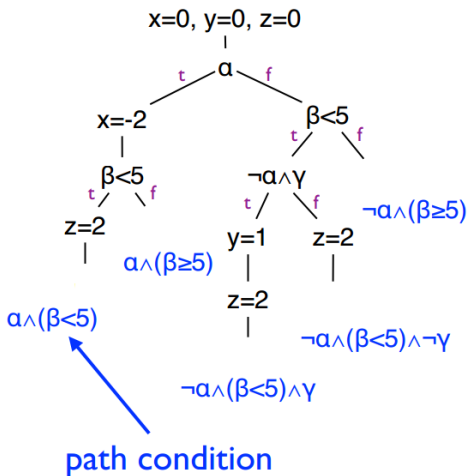
Applications

- ▶ Generating test inputs
- ▶ Finding bugs and vulnerabilities
- ▶ Detecting infeasible paths
- ▶ Proving two code segments are equivalent
- ▶ Repair programs
- ▶ Compare two programs
- ▶ Generate program specifications
- ▶ ...

Test input generation

```
int a =  $\alpha$ , b =  $\beta$ , c =  $\gamma$ ;  
// 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)
```



Path 1: $\alpha = 1, \beta = 1$

Path 2: $\alpha = 1, \beta = 6$

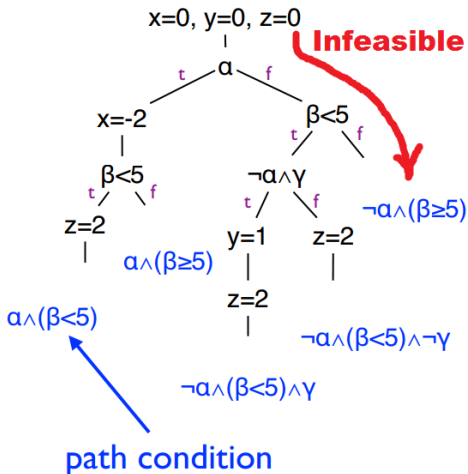
Path 3:

Detecting infeasible paths

Suppose we require $\alpha = \beta$

```
int a =  $\alpha$ , b =  $\beta$ , c =  $\gamma$ ;  
// symbolic
```

```
int x = 0, y = 0, z = 0;  
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```



Finding bugs

```
int foo(int i){  
    int j = 2*i;  
    i = i++;  
    i = i * j;  
    if ( i < 1 )  
        i = -i;  
    i = j/i;  
    return i;  
}
```

i_{input}

True branch:

$$2 * i_{input}^2 + 2 * i_{input} < 1$$

$$i = -2 * i_{input}^2 - 2 * i_{input}$$

$$i == 0$$

False Branch:

$$2 * i_{input}^2 + 2 * i_{input} \geq 1$$

$$i = 2 * i_{input}^2 + 2 * i_{input}$$

$$i == 0$$

Finding bugs

```
int foo(int i){  
    int j = 2*i;  
    i = i++;  
    i = i * j;  
    if ( i < 1 )  
        i = -i;  
    i = j/i;  
    return i;  
}
```

i_{input} i_{input} = -1 Trigger the bug

True branch:

$$2 * \underline{i}_{input}^2 + 2 * \underline{i}_{input} < 1$$

$$\underline{i} = - 2 * \underline{i}_{input}^2 - 2 * \underline{i}_{input}$$

$$\underline{i} == 0$$

False Branch: always safe

$$2 * \underline{i}_{input}^2 + 2 * \underline{i}_{input} \geq 1$$

$$\underline{i} = 2 * \underline{i}_{input}^2 + 2 * \underline{i}_{input}$$

$$\underline{i} == 0$$


Comparing equivalence of the code: CodeHunt

Secret Implementation

```
class Secret {  
    public static int Puzzle(int x) {  
        return 2*x-1;  
    }  
}
```

Player Implementation

```
class Player {  
    public static int Puzzle(int x) {  
        return x;  
    }  
}
```



```
class Test {  
    public static void Driver(int x) {  
        if (Secret.Puzzle(x) != Player.Puzzle(x))  
            throw new Exception("Mismatch");  
    }  
}
```

```
class Test {  
    public static void Driver(int x) {  
        if (2*x-1 != x)  
            throw new Exception("Mismatch");  
    }  
}
```

	x	your result	secret implementation result	Output/Exception
✓	1	1	1	
✗	3	3	5	Mismatch

Dynamic Symbolic Execution for Test input generation

DART: see ppt slides from Patrice for another example

History of 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.

Resurgence of symbolic execution

The block issues in the past:

- ▶ Not scalable: program state has many bits, there are many program paths
- ▶ Not able to go through loops and library calls
- ▶ Constraint solver is slow and not capable to handle advanced constraints

The two key projects that enable the advance:

- ▶ DART — Godefroid and Sen, PLDI 2005 (introduce dynamic information to symbolic execution)
- ▶ EXE — Cadar, Ganesh, Pawlowski, Dill, and Engler, CCS 2006 (STP: a powerful constraint solver that handles *array*)

Moving forward:

- ▶ More powerful computers and clusters
- ▶ Techniques of mixture concrete and symbolic executions
- ▶ Powerful constraint solvers

Today: two important tools

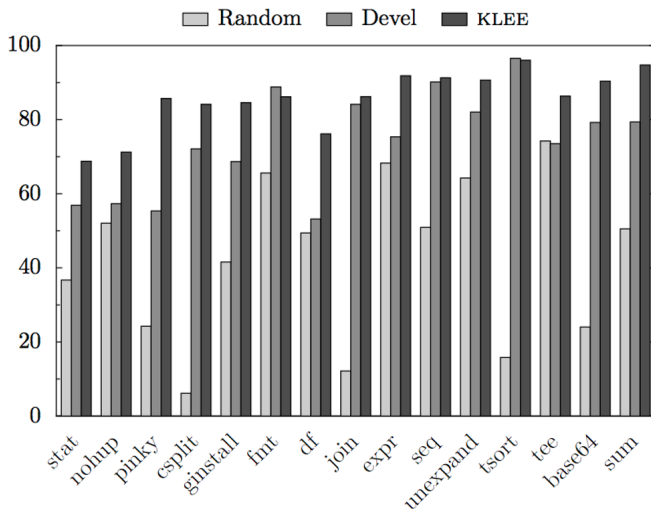
KLEE [2008:OSDI:Cadar]

- ▶ Open source symbolic executor
- ▶ Runs on top of LLVM
- ▶ Has found lots of problems in open-source software

SAGE [PLDI:Godefroid:2008]

- ▶ Microsoft internal tool
- ▶ Symbolic execution to find bugs in file parsers - E.g., JPEG, DOCX, PPT, etc
- ▶ Cluster of n machines continually running SAGE

KLEE vs. random



Bug Detection Results: KLEE

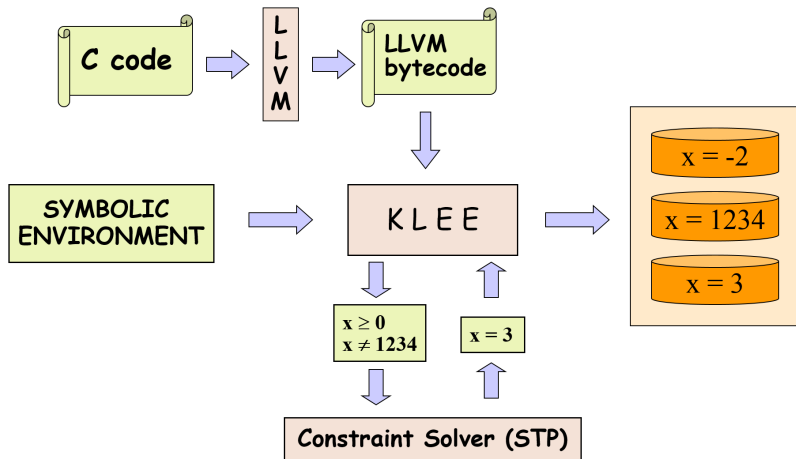
Mismatch of CoreUtils and BusyBox

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!)		

Other symbolic executors

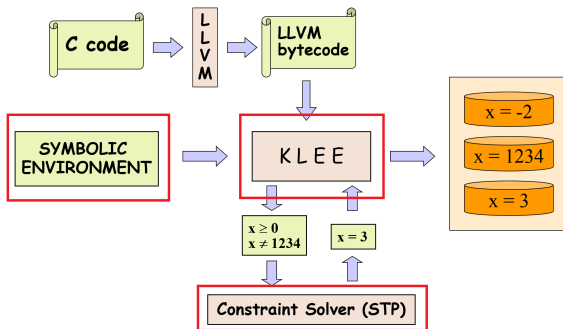
- ▶ Cloud9: parallel symbolic execution, also supports threads
- ▶ Pex, Code Hunt: Microsoft tools, symbolic execution for .NET
- ▶ Cute: concolic testing
- ▶ jCUTE: symbolic execution for Java
- ▶ Java PathFinder: NASA tools, a model checker that also supports symbolic execution
- ▶ SymDroid: symbolic execution on Dalvik Bytecode
- ▶ Kleenet: testing interaction protocols for sensor network

Internal of symbolic executors: KLEE



Three Challenges

- ▶ Path explosion
- ▶ Modeling program statements and environment
- ▶ Constraint solving



Challenge 1: Path Explosion

- Exponential in branching structure

```
1. int a =  $\alpha$ , b =  $\beta$ , c =  $\gamma$ ; // symbolic
2. if (a) ... else ...;
3. if (b) ... else ...;
4. if (c) ... else ...;
```

- Ex: 3 variables, 8 program paths

- Loops on symbolic variables even worse

```
1. int a =  $\alpha$ ; // symbolic
2. while (a) do ...;
3.
```

- Potentially 2^{31} paths through loop!

Search Strategies: Naive Approach

DFS (depth first search), BFS (breadth first search)

The two approaches purely are based on the structure of the code

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- ▶ DFS: search can stuck at somewhere in a loop

Search Strategies: Naive Approach

DFS (depth first search), BFS (breadth first search)

The two approaches purely are based on the structure of the code

- ▶ You cannot enumerate all the paths
- ▶ DFS: search can stuck at somewhere in a loop
- ▶ BFS: very slow to determine properties for a path if there are many branches

Search Strategies: Random Search

How to perform a random search?

- ▶ Idea 1: pick next path to explore uniformly at random
- ▶ 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
- ▶ ...

Drawback: reproducibility, probably good to use psuedo-randomness based on seed, and then record which seed is picked

Search Strategies: Coverage Guided Search

Goal: Try to visit statements we haven't seen before

Approach:

- ▶ Select paths likely to hit the new statements
- ▶ Favor paths on recently covering new statements: unblock a new area of code
- ▶ Score of statement = $\#$ times it's been seen and how often; Pick next statement to explore that has lowest score

Pros and cons:

- ▶ Good: Errors are often in hard-to-reach parts of the program, this strategy tries to reach everywhere.
- ▶ Bad: Maybe never be able to get to a statement

Search Strategies: Generational Search

- ▶ Hybrid of BFS and coverage-guided search
- ▶ Generation 0: pick one path 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
- ▶ ...
- ▶ Generation n : similar, but branching off gen $n-1$ (also uses a coverage heuristic to pick priority)

Search Strategies: Combined Search

- ▶ Run multiple searches at the same time and alternate between them
- ▶ Depends on conditions needed to exhibit bug; so will be as good as *best* solution, with a constant factor for wasting time with other algorithms
- ▶ Could potentially use different algorithms to reach different parts of the program

Challenge 2: Complex Code and Environment Dependencies

- ▶ System calls: `open(file)`
- ▶ Library calls: `sin(x)`, `glibc`
- ▶ Pointers and heap: `linklist`, `tree`
- ▶ Loops and recursive calls: how many times it should iterate and unfold?
- ▶ ...

Solutions

- ▶ Simulate system calls
- ▶ Build simple versions of library calls
- ▶ Assign random values after library calls
- ▶ Run library and system calls with a concrete value
- ▶ Summarize the loops
- ▶ ...

An Example

```
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

Program was initiated with a symbolic file system with up to N files.
Open all N files + one open() failure.

Solutions: Concretization

[2005:PLDI:Godefroid],[2005:FSE:Sen]

- ▶ Concolic (concrete/symbolic) testing: run on concrete random inputs. In parallel, execute symbolically and solve constraints. Generate inputs to other paths than the concrete one along the way.
- ▶ Replace symbolic variables with concrete values that satisfy the path condition
- ▶ So, could actually do system calls
- ▶ And can handle cases when conditions too complex for SMT solver

Challenge 3: Constraint Solving - SAT

SAT: find an assignment to a set of Boolean variables that makes the Boolean formula true

Complexity: NP-Complete



Constraint Solving - SMT [2011:ACM:DeMoura]

SMT (Satisfiability Modulo Theories) = SAT++

$$\sin(x)^3 = \cos(\log(y) \cdot x) \vee b \vee -x^2 \geq 2.3y$$

- ▶ An SMT formula is a Boolean combination of formulas over first-order theories
- ▶ Example of SMT theories include bit-vectors, arrays, integer and real arithmetic, strings, ...
- ▶ The satisfiability problem for these theories is typically hard in general (NP-complete, PSPACE-complete, ...)
- ▶ Program semantics are easily expressed over these theories
- ▶ Many software engineering problems can be easily reduced to the SAT problem over first-order theories

Constraint Solving - SMT

The State of the Art: Handle linear integer constraints

Challenges:

- ▶ Constraints that contain non-linear operands, e.g., $\sin()$, $\cos()$
- ▶ Float-point constraints: no theory support yet, convert to bit-vector computation
- ▶ String constraints: $a = b.\text{replace}('x', 'y')$
- ▶ Quantifies: \exists, \forall
- ▶ Disjunction

Tool Design KLEE - Path Explosion

- ▶ Random, coverage-optimize search
- ▶ Compute state weight using:
 - ▶ Minimum distance to an uncovered instruction
 - ▶ Call stack of the state
 - ▶ Whether the state recently covered new code
- ▶ Timeout: one hour per utility when experimenting with *coreutils*

Tool Design KLEE - Tracking Symbolic States

Trees of symbolic expressions:

- ▶ Instruction pointer
- ▶ Path condition
- ▶ Registers, heap and stack objects
- ▶ Expressions are of C language: arithmetic, shift, dereference, assignment. . .
- ▶ Checks inserted at dangerous operations: division, dereferencing

Modeling environment:

- ▶ 2500 lines of modeling code to customize system calls (e.g. open, read, write, stat, lseek, ftruncate, ioctl)
- ▶ How to generate tests after using symbolic env: supply an description of symbolic env for each test path; a special driver creates real OS objects from the description

Tool Design KLEE - Constraint Solving

- ▶ STP: a decision procedure for Bit-Vectors and Arrays
- ▶ “Decision procedures are programs which determine the satisfiability of logical formulas that can express constraints relevant to software and hardware”
- ▶ STP uses new efficient SAT solvers
- ▶ Treat everything as bit vectors: arithmetic, bitwise operations, relational operations.

Tool Usage KLEE

- ▶ Using LLVM to compile to bytecode
- ▶ Run KLEE with bytecode

Discussions

- ▶ Symbolic environment interaction - how reliable can the customized modeling really be? think about concurrent programs, inter-process programs.
- ▶ What is more commonly needed - functional testing or security/completeness/crash testing?

Further Learning

Test Input Generation in practice, Talk by Patrice Godefroid @ Microsoft