Program Testing
Symbolic Execution

Yue Duan

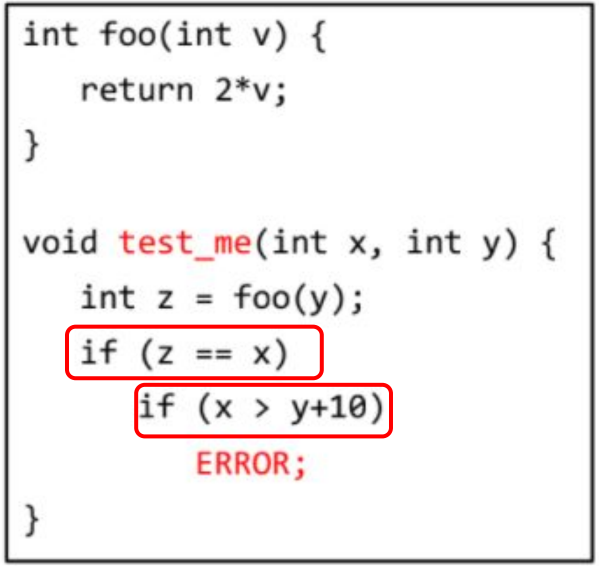
Outline

- Introduction to symbolic execution
- Research paper:
  - KLEE: Unassisted and Automatic Generation of High-Coverage Tests for Complex Systems Programs
  - Automated Whitebox Fuzz Testing

Introduction to Symbolic Execution

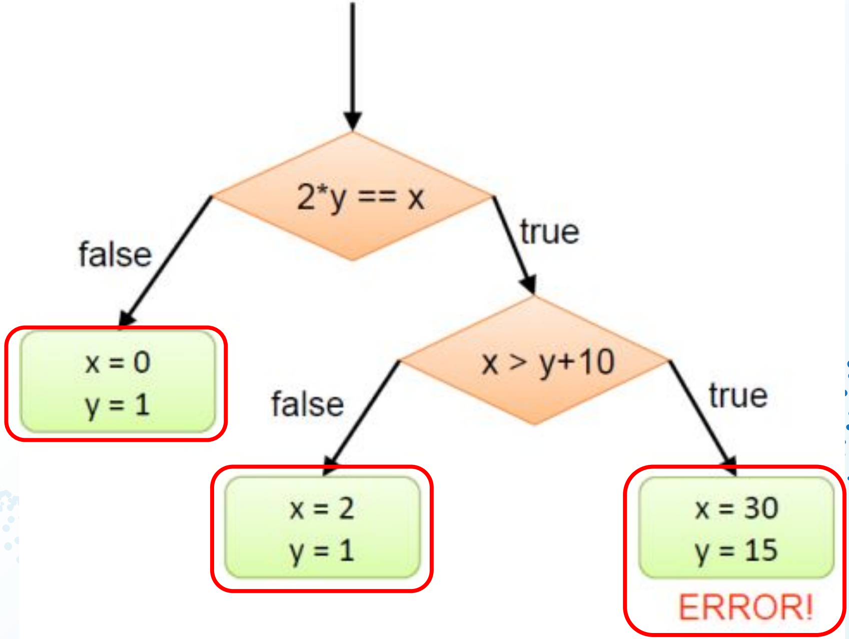
- Symbolic Execution
  - assumes **symbolic values** for inputs rather than obtaining **actual inputs** as normal execution of the program would
  - arrives **expressions** in terms of those symbols for expressions and variables in the program
  - collects **constraints** in terms of those symbols for the possible outcomes of each conditional branch
  - aims to **explore all paths** in the program by generating specific inputs

Introduction to Symbolic Execution



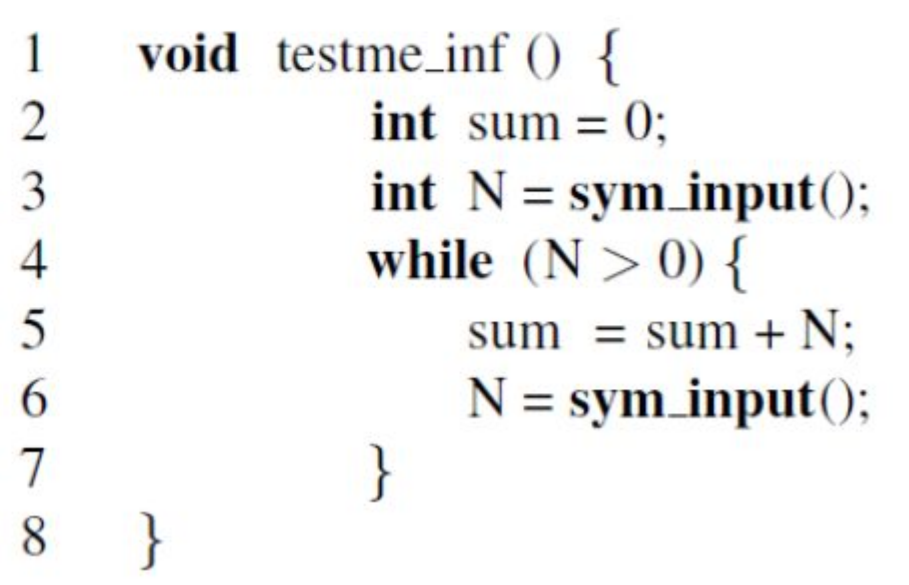
```
int foo(int v) {
    return 2*v;
}

void test_me(int x, int y) {
    int z = foo(y);
    if (z == x)
        if (x > y+10)
            ERROR;
}
```



Problems

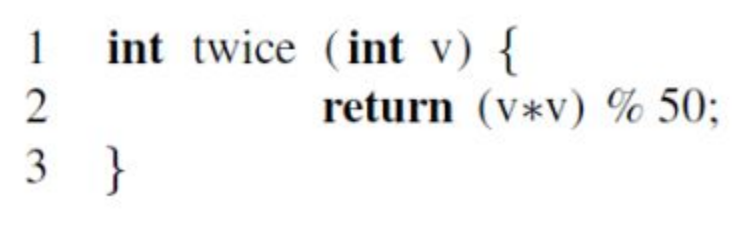
- Problem 1: Path explosion
  - states grow exponentially
  - unbounded loop iterations



```
void testme_inf () {
        int sum = 0;
        int N = sym_input();
        while (N > 0) {
            sum = sum + N;
            N = sym_input();
        }
}
```

Problems

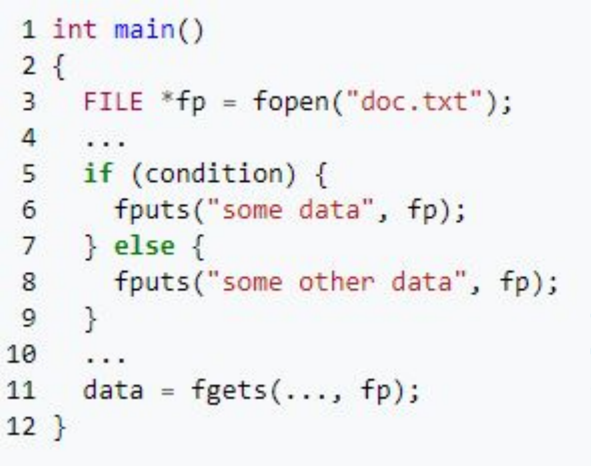
- Problem 2: Unsolvable formulas
    - non-linear computation is general hard to solve
    - solver could take too long



```
int twice (int v) {
            return (v*v) % 50;
}
```

Problems

- Problem 3: Environment interactions
  - External function calls and system calls are hard to model
  - Fo efficiency, symbolic execution system usually model
    - file system related calls
    - string operations

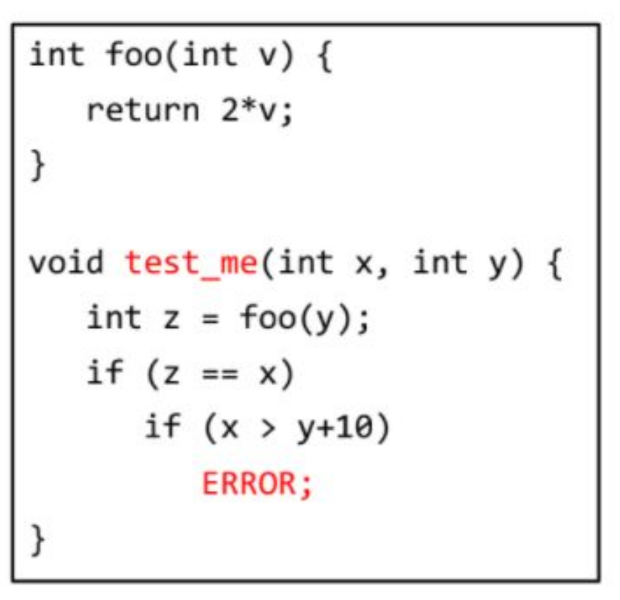


```
int main()
{
  FILE *fp = fopen("doc.txt");
  ...
  if (condition) {
    fputs("some data", fp);
  } else {
    fputs("some other data", fp);
  }
  ...
  data = fgets(..., fp);
}
```

Concolic Testing

- Symbolic + concrete execution
  - run symbolic execution dynamically
  - execute the program on some concrete input values

- Example
  - generate random input: x=22, y=7
  - execute the program both concretely and symbolically

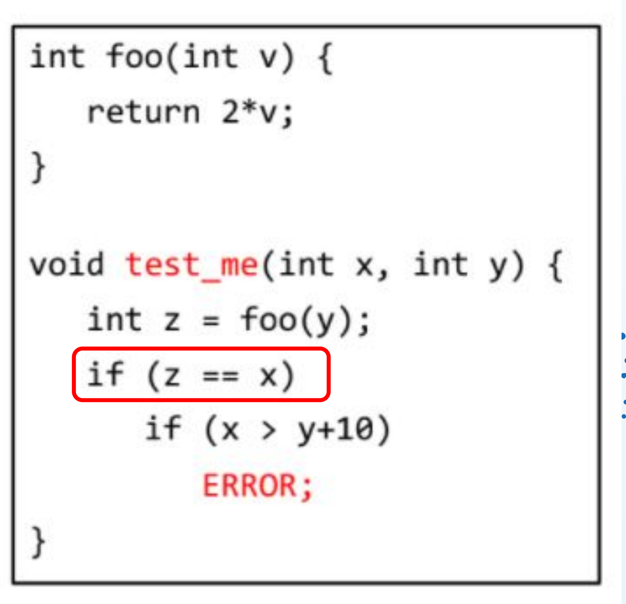


```
int foo(int v) {
   return 2*v;
}

void test_me(int x, int y) {
   int z = foo(y);
   if (z == x)
      if (x > y+10)
         ERROR;
}
```

Concolic Testing

- Example (Cont.)
  - concrete execution takes the ‘else’ branch on Ln.7
  - symbolic execution generates the path constraint: x != 2*y
  - a negation will make the path constraint: x == 2*y
  - solve the path constraint and get a new test input: x=2, y=1
  - test the program with the new input



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}

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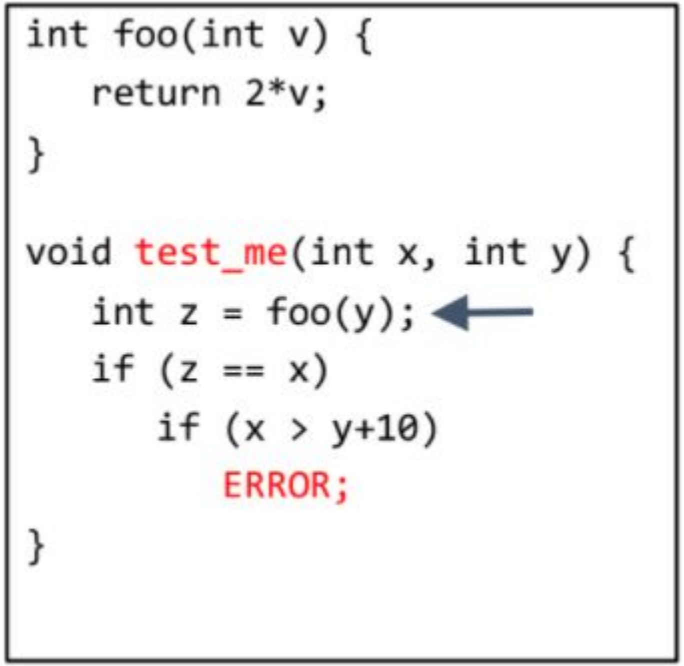
Concolic Testing



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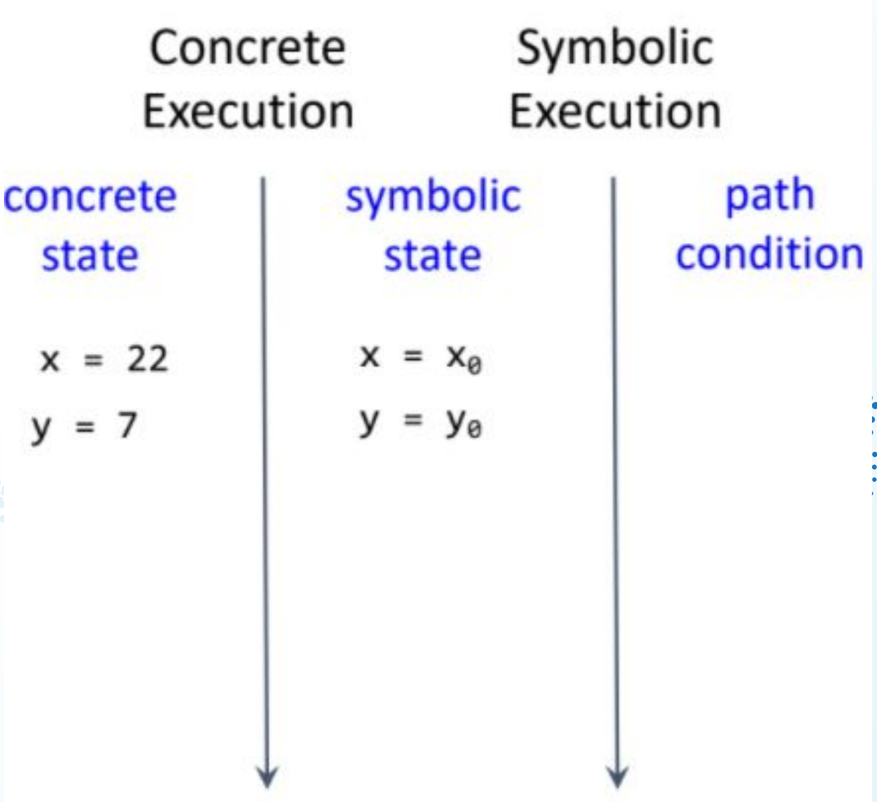
         ERROR;
}
```



Concrete Execution

Symbolic Execution

concrete state

symbolic state

path condition

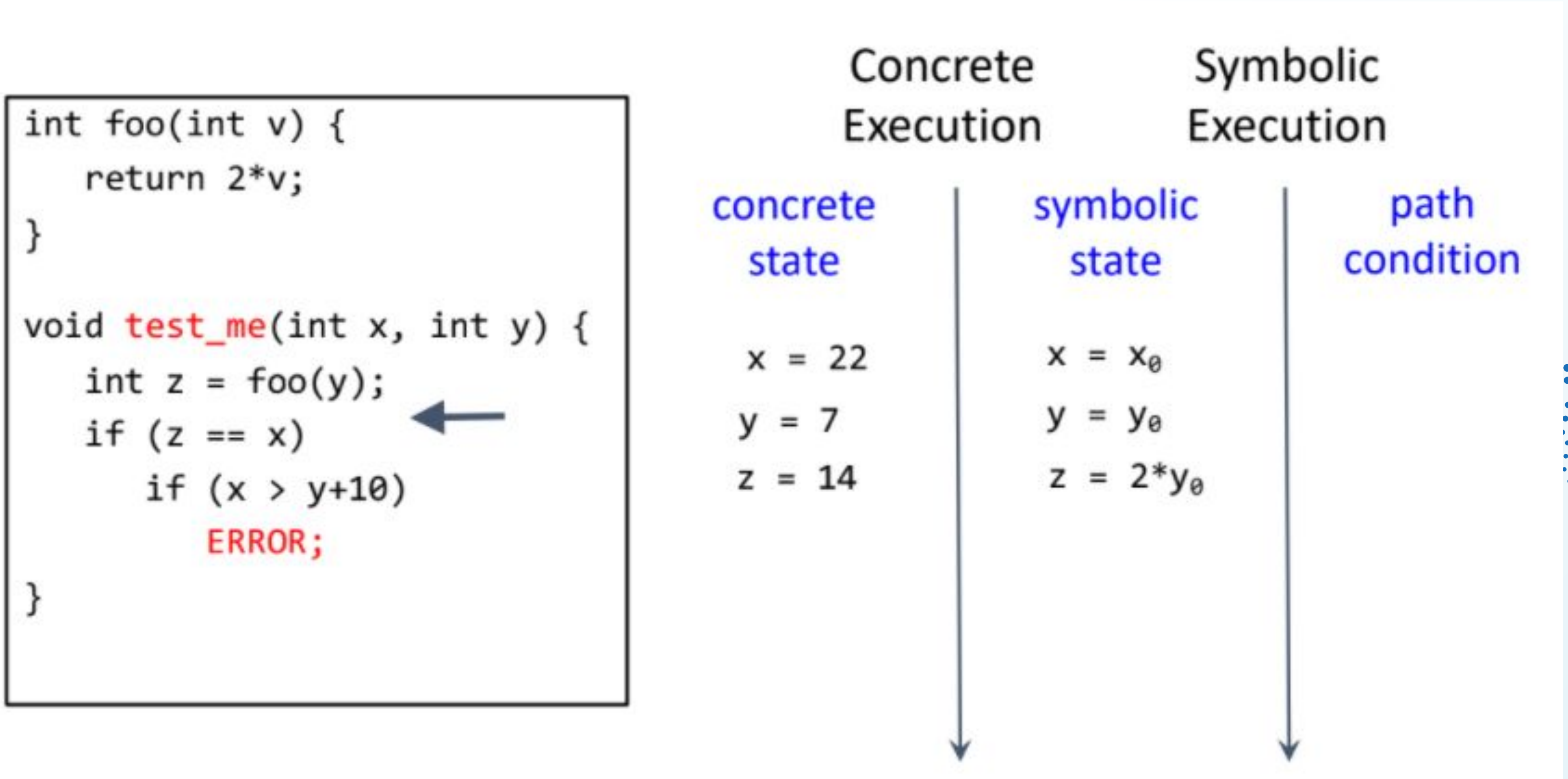
x = 22

y = 7

$x = x_0$

$y = y_0$

Concolic Testing



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}

void test_me(int x, int y) {
   int z = foo(y);
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      if (x > y+10)
         ERROR;
}
```

Concrete Execution

Symbolic Execution

concrete state

symbolic state

path condition

x = 22

y = 7

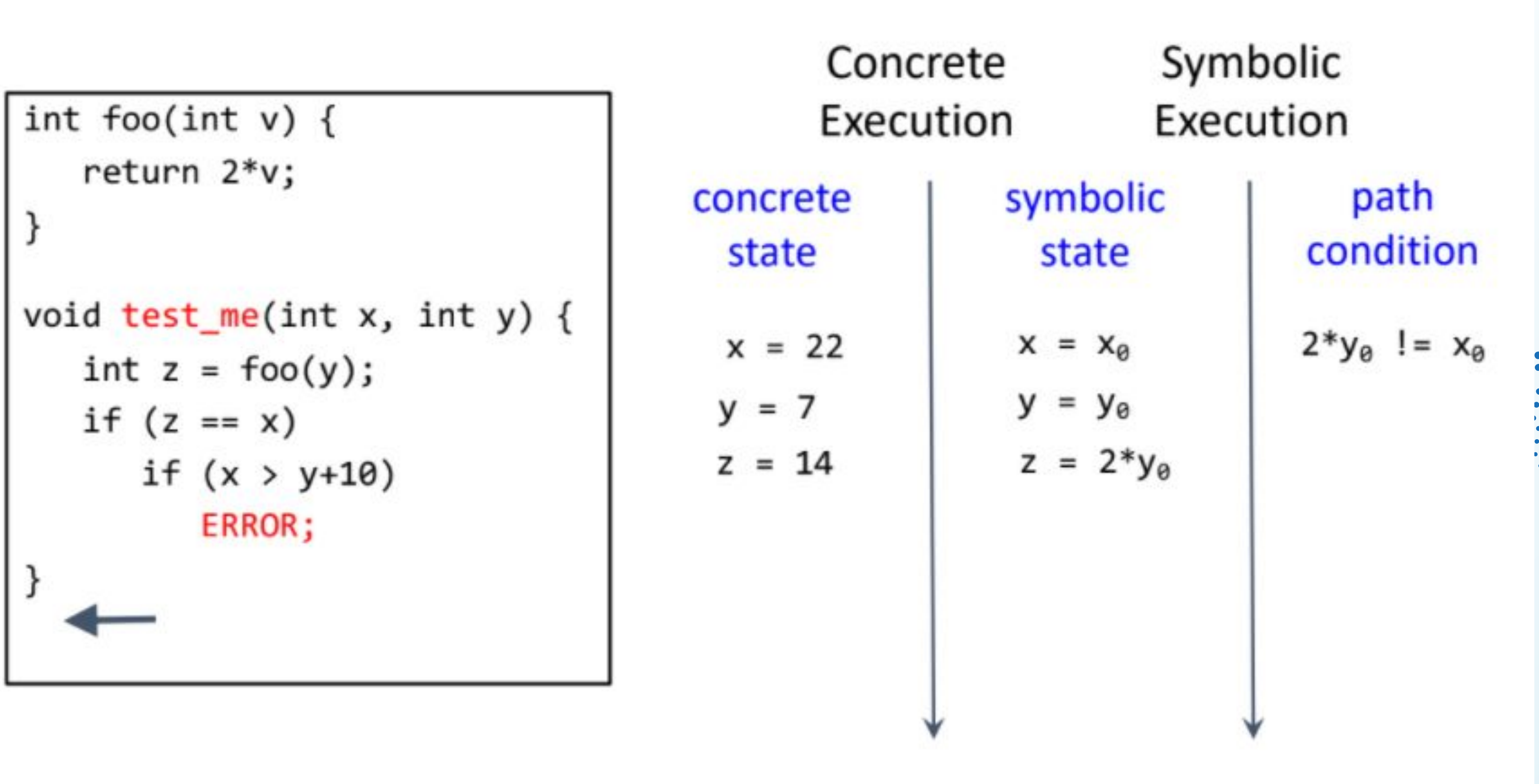
z = 14

$x = x_0$

$y = y_0$

$z = 2*y_0$

Concolic Testing



```
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   return 2*v;
}

void test_me(int x, int y) {
   int z = foo(y);
   if (z == x)
      if (x > y+10)
         ERROR;
}
```
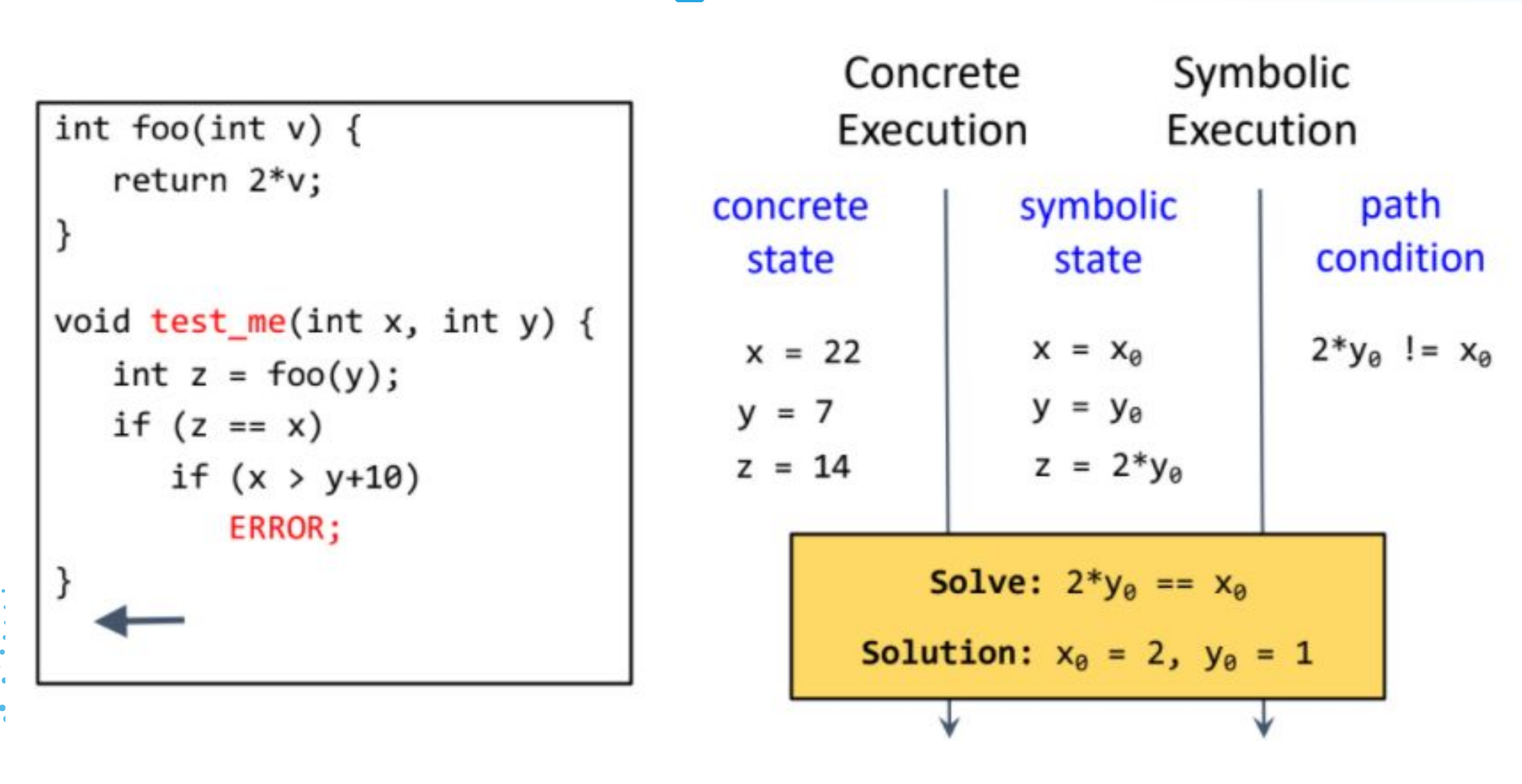

Concrete Execution

Symbolic Execution

concrete state	symbolic state	path condition
x = 22	x = x_0	2*y_0 != x_0
y = 7	y = y_0	
z = 14	z = 2*y_0	

Concolic Testing



```
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   return 2*v;
}

void test_me(int x, int y) {
   int z = foo(y);
   if (z == x)
      if (x > y+10)
         ERROR;
}
```

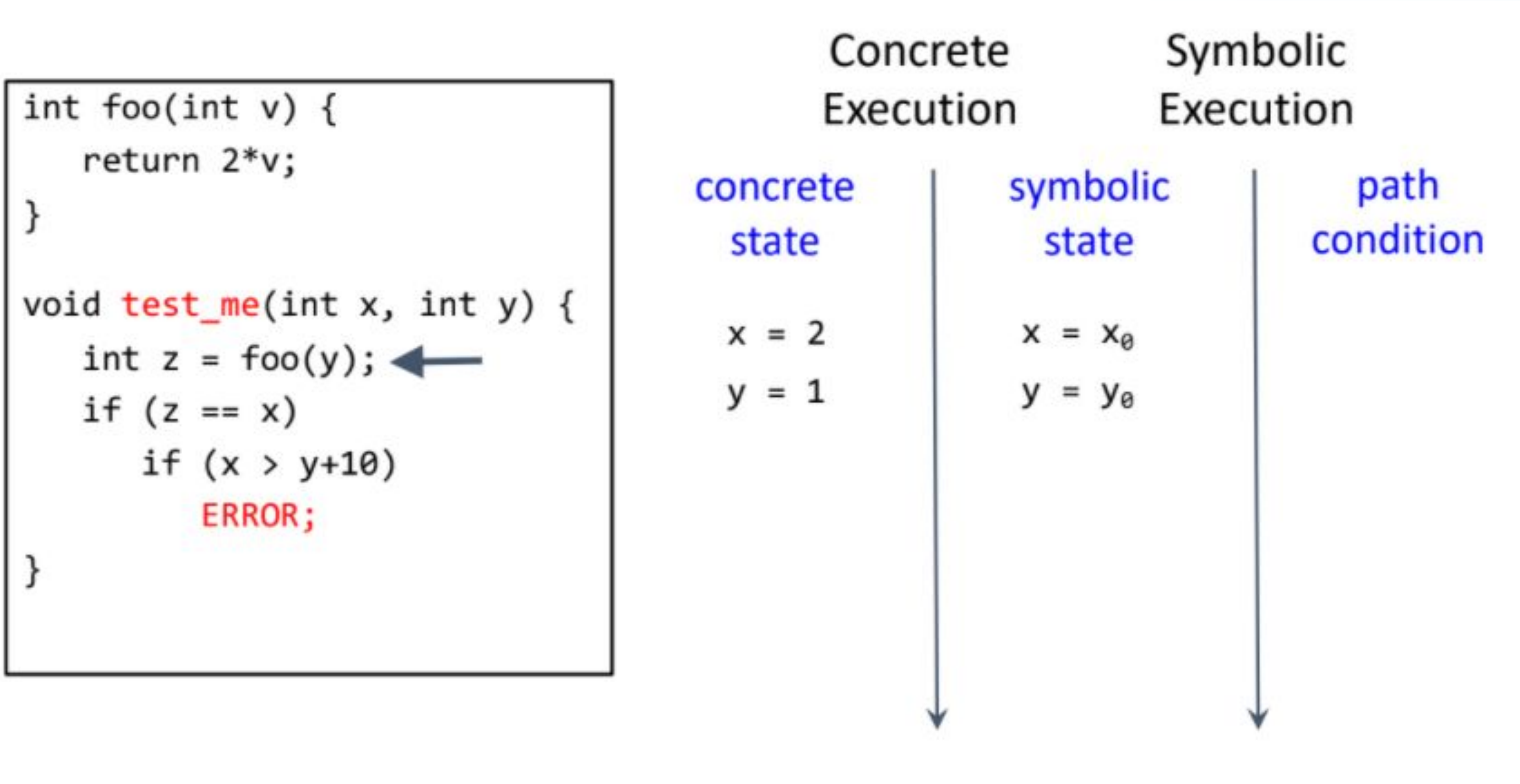
Concrete Execution	Symbolic Execution	
concrete state	symbolic state	path condition

x = 22
y = 7
z = 14
	$x = x_0$
	$y = y_0$
	$z = 2*y_0$
		$2*y_0 \ != x_0$

Solve: $2*y_0 == x_0$

Solution: $x_0 = 2,\ y_0 = 1$

Concolic Testing

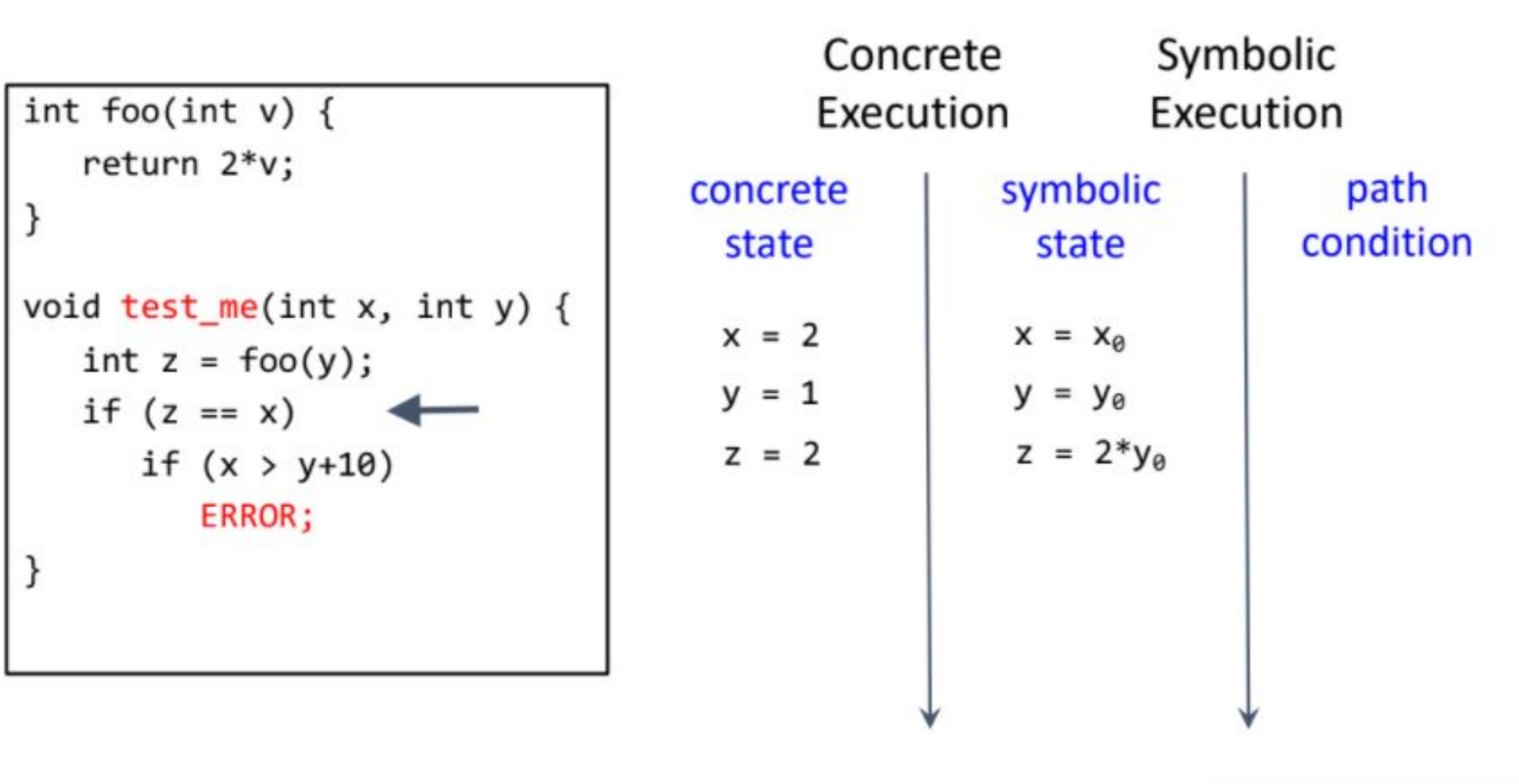


```
int foo(int v) {
   return 2*v;
}

void test_me(int x, int y) {
   int z = foo(y); ←
   if (z == x)
      if (x > y+10)
         ERROR;
}
```

	Concrete Execution		Symbolic Execution	
concrete state		symbolic state		path condition
$x = 2$ $y = 1$		$x = x_0$ $y = y_0$		

Concolic Testing

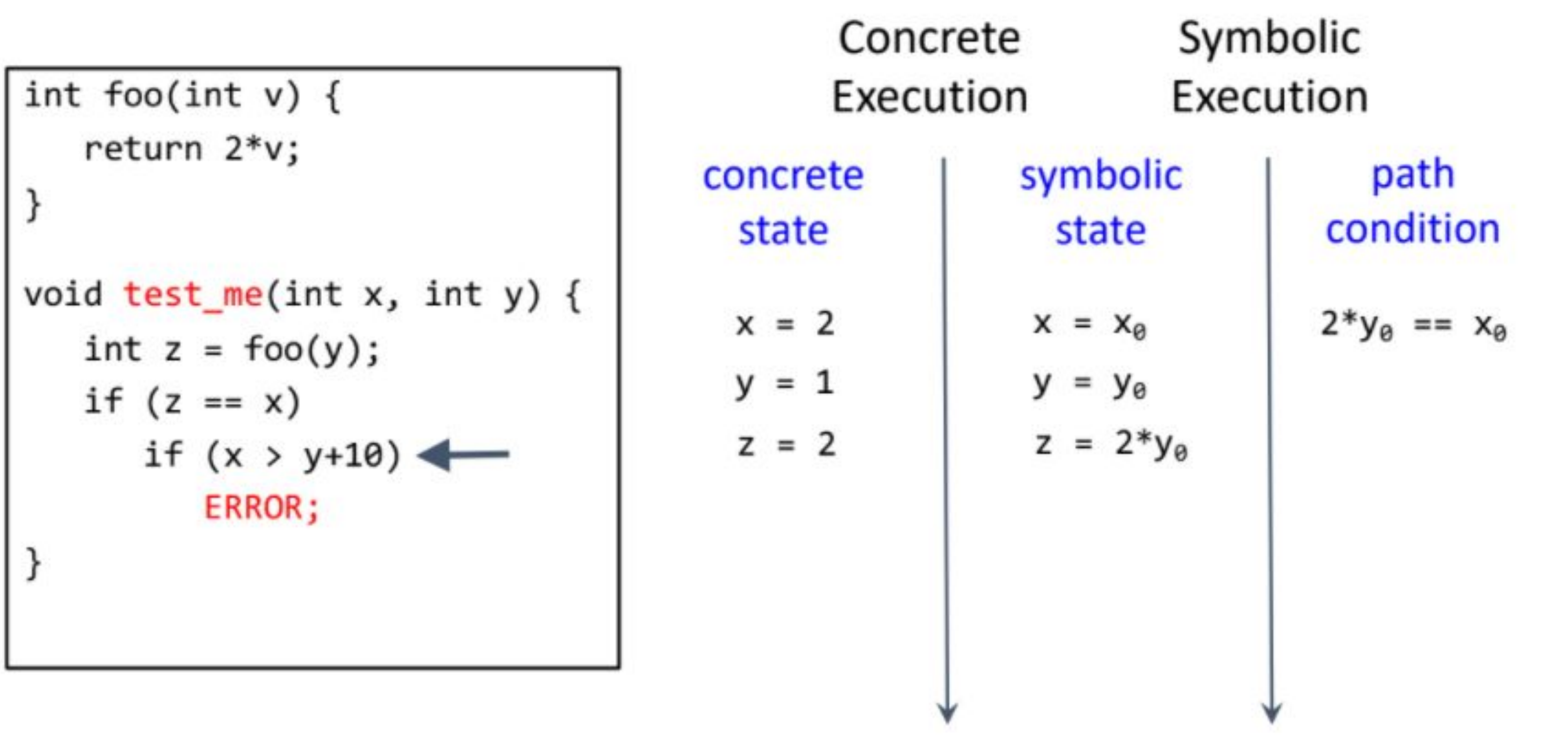


```
int foo(int v) {
   return 2*v;
}

void test_me(int x, int y) {
   int z = foo(y);
   if (z == x)
      if (x > y+10)
         ERROR;
}
```

Concrete Execution		Symbolic Execution
concrete state	symbolic state	path condition
x = 2	$x = x_0$	
y = 1	$y = y_0$	
z = 2	$z = 2*y_0$	

Concolic Testing



```
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   return 2*v;
}

void test_me(int x, int y) {
   int z = foo(y);
   if (z == x)
      if (x > y+10)
         ERROR;
}
```

Concrete Execution

Symbolic Execution

concrete state

x = 2

y = 1

z = 2

symbolic state

$x = x_0$

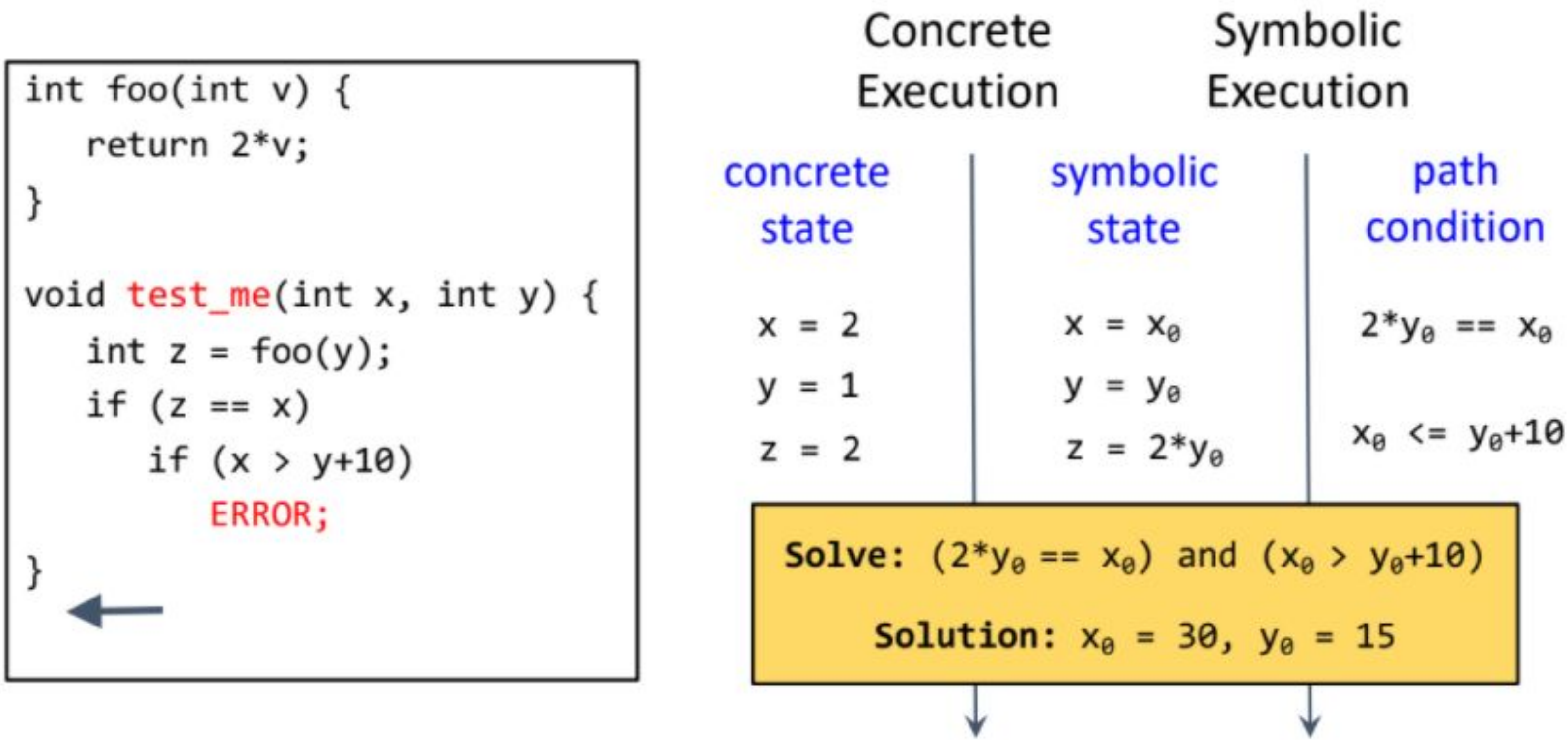
$y = y_0$

$z = 2*y_0$

path condition

$2*y_0 == x_0$

Concolic Testing



```
int foo(int v) {
   return 2*v;
}

void test_me(int x, int y) {
   int z = foo(y);
   if (z == x)
      if (x > y+10)
         ERROR;
}
```

Concrete Execution

Symbolic Execution

concrete state	symbolic state	path condition
$x = 2$	$x = x_0$	$2*y_0 == x_0$
$y = 1$	$y = y_0$	
$z = 2$	$z = 2*y_0$	$x_0 <= y_0+10$

Solve: $(2*y_0 == x_0)$ and $(x_0 > y_0+10)$

Solution: $x_0 = 30$, $y_0 = 15$

Concolic Testing

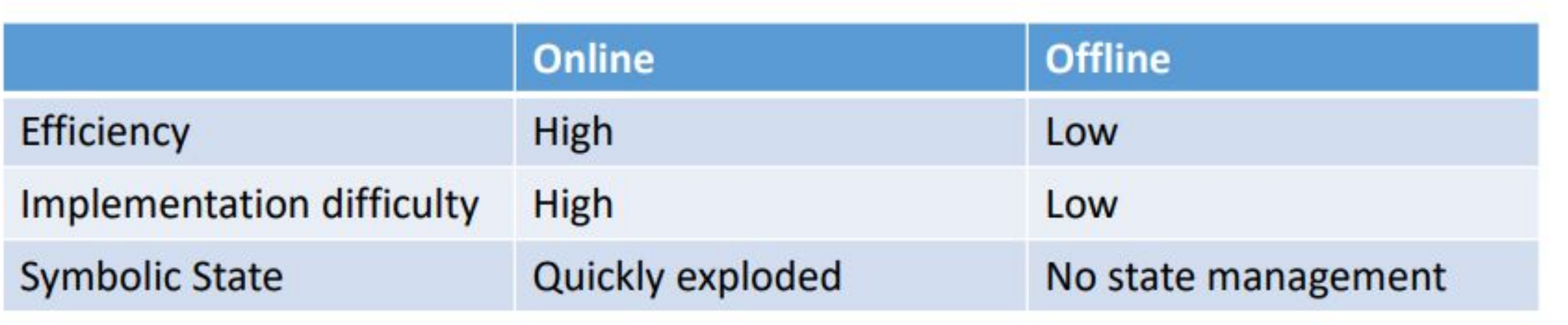
- Benefits:
  - solve complex formulas
    - x == (y*y) mod 50, unsolvable if x and y are both symbolic
    - if some value is concretized, then it becomes solvable
  - External library call and system call
    - e.g., fd = open(filename)
    - set filename to its concrete value "/tmp/abc.txt"
    - execute the system call concretely
    - set fd to be concrete after the system call return

Online V.S Offline Approaches

- Online
  - encounter a new symbolic branch
  - solve path constraints for both ‘true’ and ‘false’
  - if both feasible, fork the execution states
- Offline
  - trace-based approach
  - choose an input, execute the program and collect execution trace
  - compute path contracts from the trace
  - negate each conjunct, solve the new path constraint and generate new inputs
  - start again

Online V.S Offline Approaches

- Pros and Cons



	Online	Offline
Efficiency	High	Low
Implementation difficulty	High	Low
Symbolic State	Quickly exploded	No state management

Implementations

- Dynamic Instrumentation
  - source code needed:
    - compile C/C++ into LLVM bytecode
    - add instrumentation during compilation
  - binary:
    - run in QEMU with two machines (concrete and symbolic)
    - convert TCG IR to LLVM bytecode
- Trace-based
  - collect execution trace using tools such as Pintrace and tracecap
  - convert trace into IR
  - perform analysis on IR

Implementations

- Pure Interpretation or Simulation
  - interpret binary execution and add symbolic execution logic
  - Pros:
    - full control
    - easy to implement
  - Cons:
    - low efficiency (all instructions must be interpreted)

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

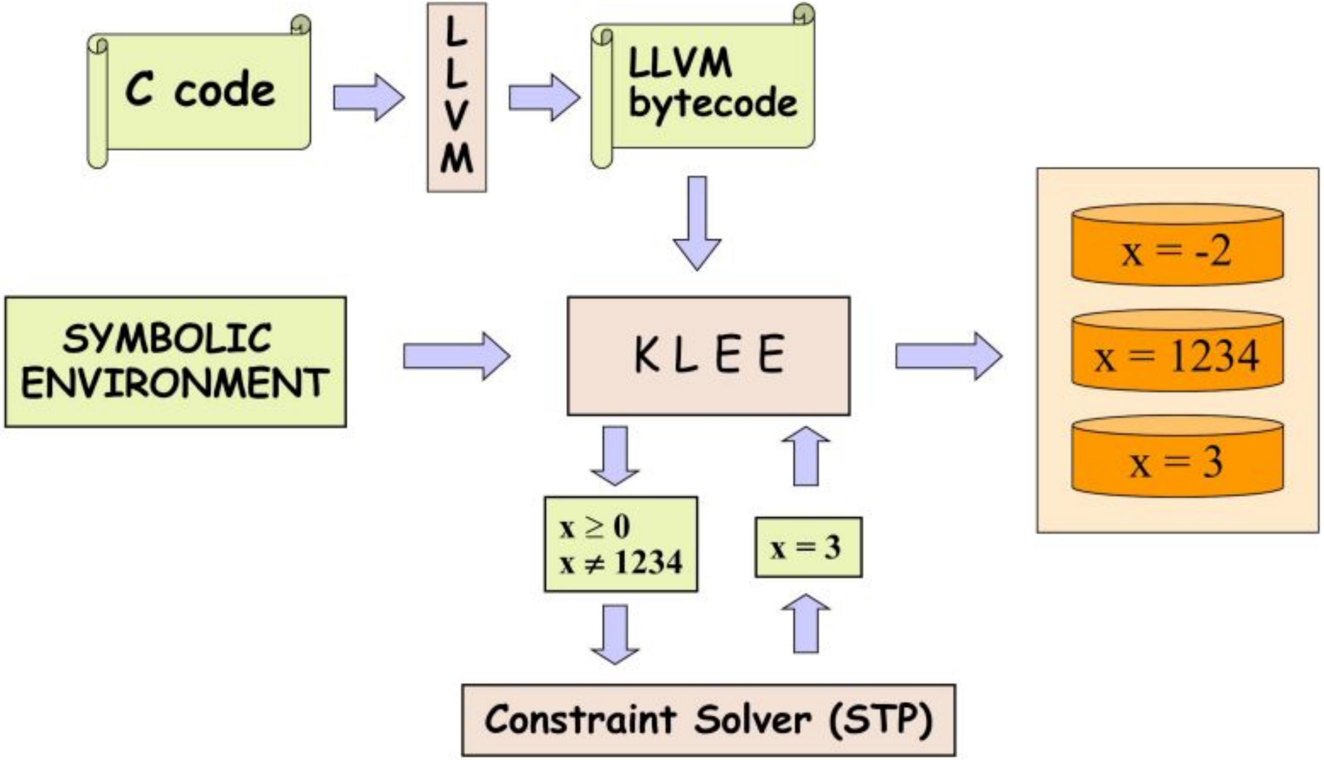
Cristian Cadar, Daniel Dunbar, Dawson Engler

OSDI 2008

Introduction

- Operates on LLVM bytecode
- A **symbolic process** (or **state**) is the state of a symbolically executing process
  - register file, stack, heap, program counter, path condition
  - storage locations(stack, heap, registers) contain **symbolic expressions**
- when symbolic execution encounters a branch
  - state is cloned
  - update instruction pointer and path condition accordingly

KLEE Architecture



State Exploration

- Problem:
  - The number of states grow exponentially
- Solution
  - use compact state representation:
    - copy-on-write at the object level
    - heap as an immutable map can be shared among states
    - heap can be cloned in constant time

Path Selection

- Multiple concurrent states, representing different program executions
- Aim:
  - good code coverage
- Problem:
  - which state to run at each step?
- Solution
  - two strategies
    - random path selection
    - coverage-optimized search

Environment Modeling

- Problem:
  - interactions with the environment are complex
- Solution:
  - model semantics and redirects library calls to these models
- Example: symbolic file system
  - single directory with N symbolic files
  - co-exist with real file system
    - when called with concrete file name, will open real file
      - int fd = open(“/etc/fstab”, O_RDNLY);
    - when called with symbolic file name, will form and match each of the N symbolic files
      - int fd = open(argv[1], O_RDNLY);

Evaluation

- Metrics: Line coverage
- Dataset:
  - Coreutils, Busybox, HiStar
- Results:
  - in much shorter time, better coverage than tests manually developed for over 15 years

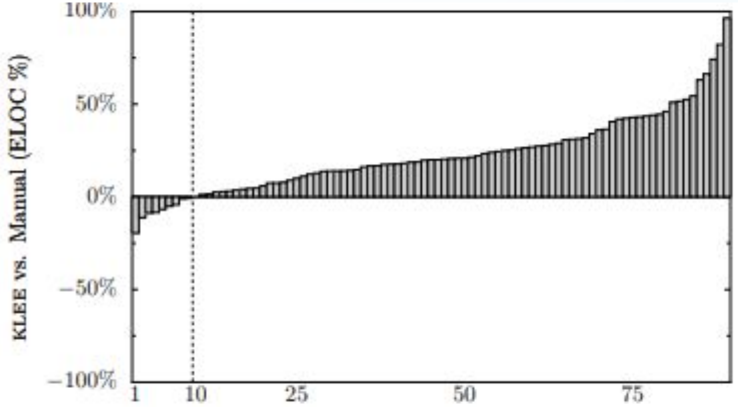
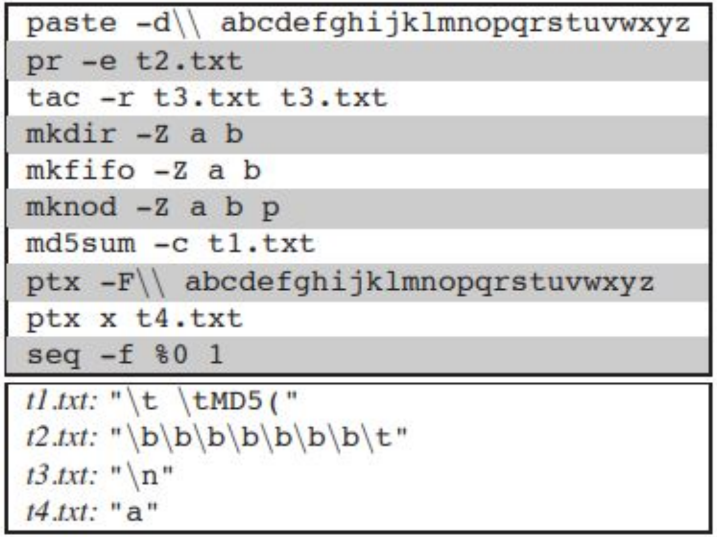


Figure 6: Relative coverage difference between KLEE and the COREUTILS manual test suite, computed by subtracting the executable lines of code covered by manual tests (L_{man}) from KLEE tests (L_{klee}) and dividing by the total possible: $(L_{klee} - L_{man})/L_{total}$. Higher bars are better for KLEE,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

Evaluation

- Found 10 unique bugs in Coreutils
- Found 21 bugs in Busybox
- Found 21 bugs in Minix
- All memory errors



```
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"
```

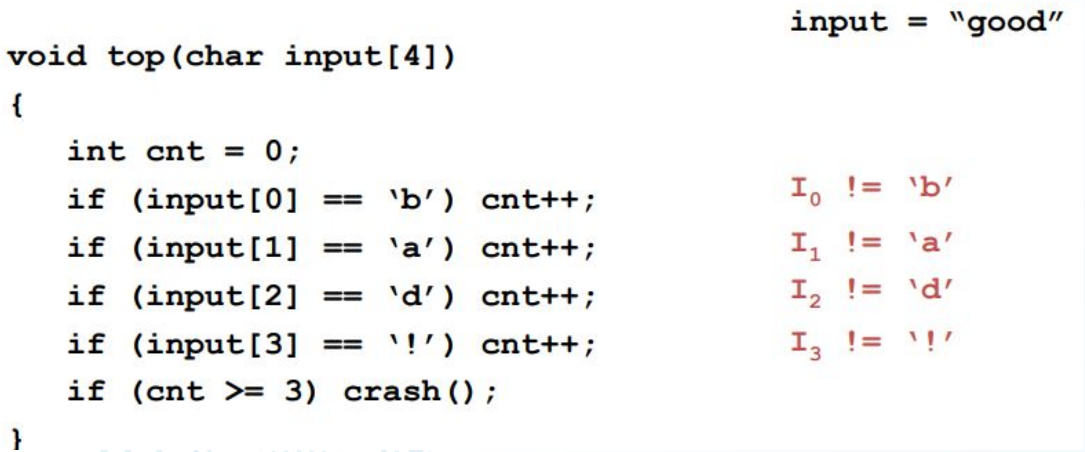
Figure 7: KLEE-generated command lines and inputs (modified for readability) that cause program crashes in COREUTILS version 6.10 when run on Fedora Core 7 with SELinux on a Pentium machine.

Automated Whitebox Fuzz Testing

Patrice Godefroid, Michael Y. Levin, David Molnar

NDSS 2008

Motivation



input = “good”

```
void top(char input[4])
{
    int cnt = 0;
    if (input[0] == ‘b’) cnt++;
    if (input[1] == ‘a’) cnt++;
    if (input[2] == ‘d’) cnt++;
    if (input[3] == ‘!’) cnt++;
    if (cnt >= 3) crash();
}
```

I_0 != ‘b’

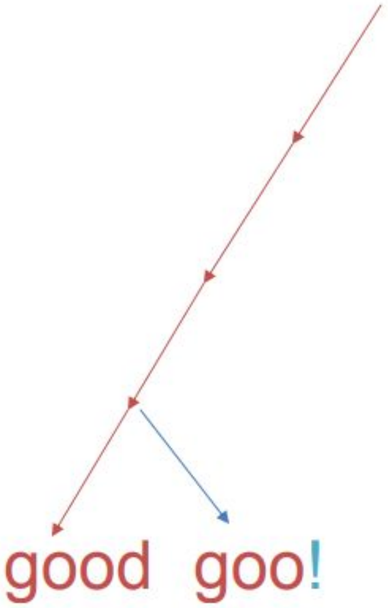
I_1 != ‘a’

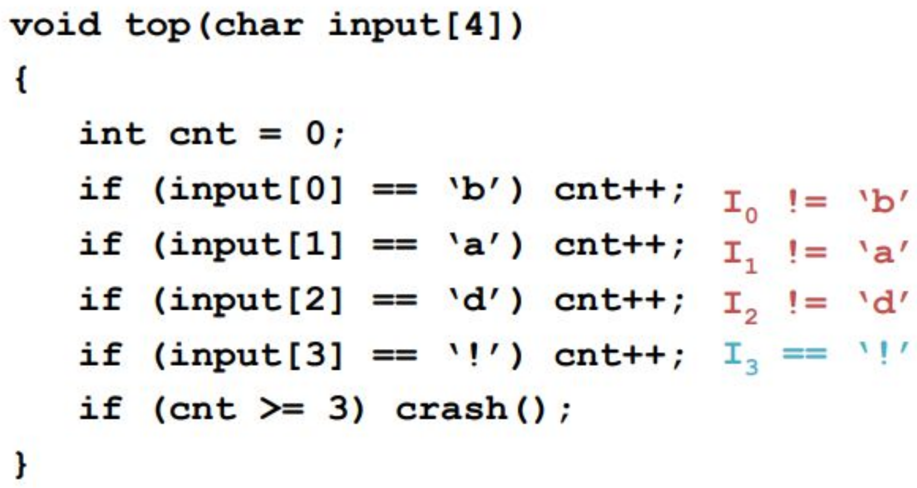
I_2 != ‘d’

I_3 != ‘!’

- Traditional trace-based approach
  - Collect constraints from trace
  - create new constraints by negating
  - solve ⇒ new input
  - start again with new input

Motivation





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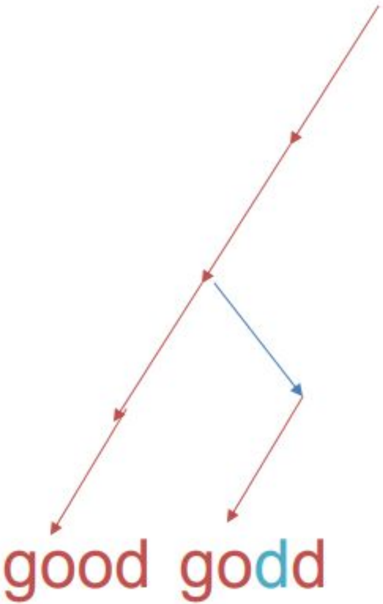
I_0 != ‘b’

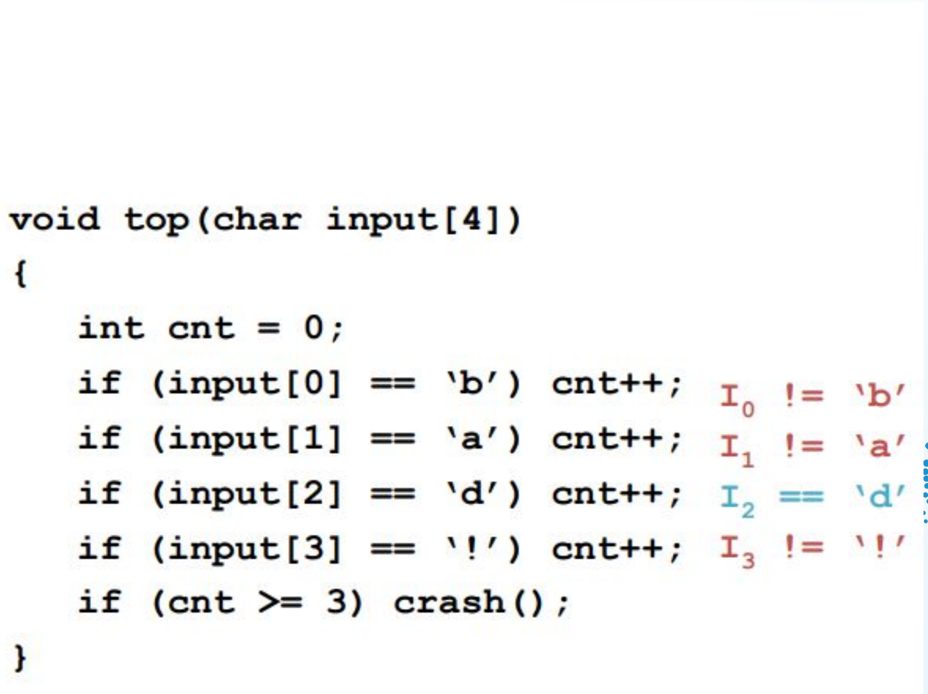
I_1 != ‘a’

I_2 != ‘d’

I_3 == ‘!’

Motivation





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void top(char input[4])
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}
```

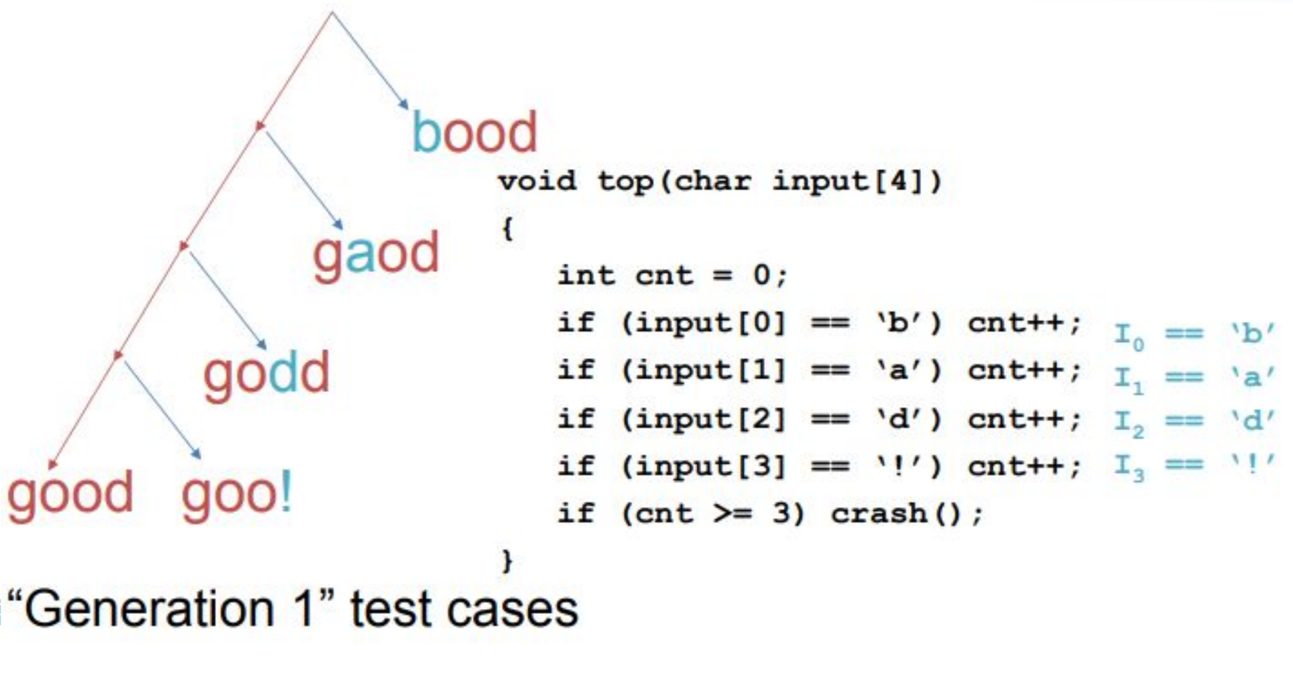
I_0 != ‘b’

I_1 != ‘a’

I_2 == ‘d’

I_3 != ‘!’

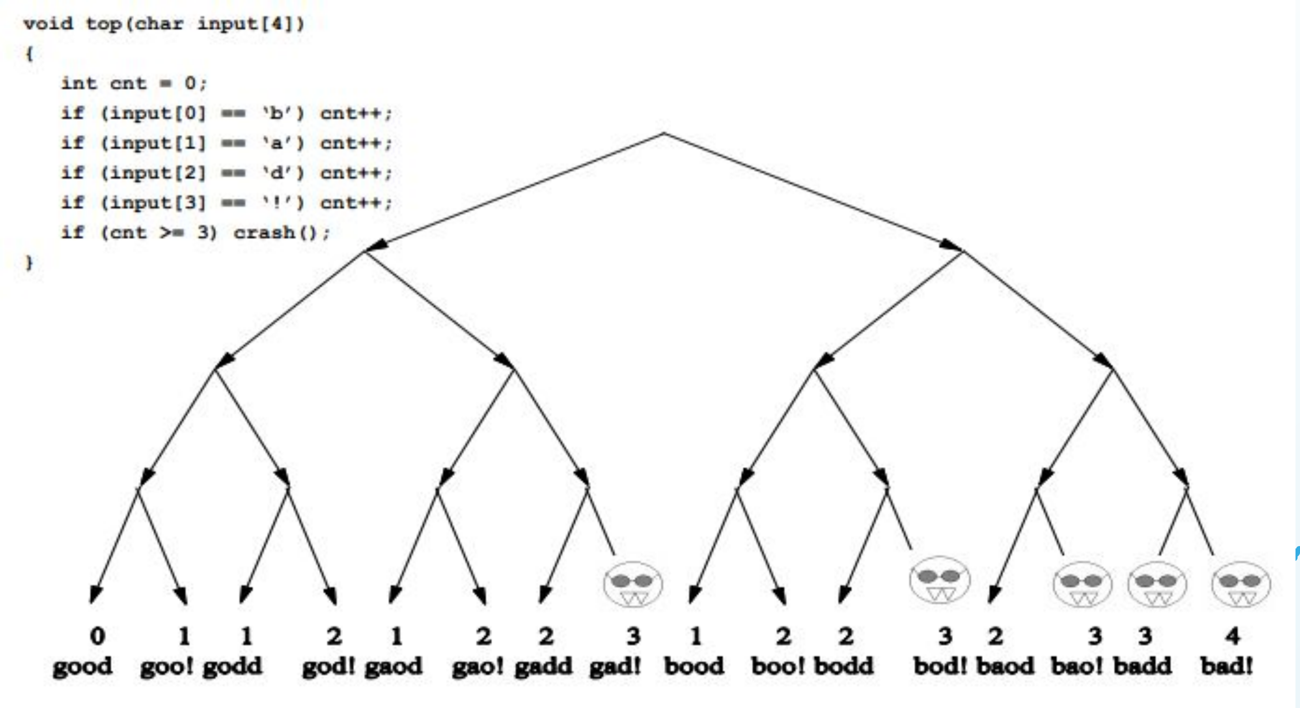
Key Idea: One Trace Many Tests



```
void top(char input[4])
{
    int cnt = 0;
    if (input[0] == ‘b’) cnt++;   I0 == ‘b’
    if (input[1] == ‘a’) cnt++;   I1 == ‘a’
    if (input[2] == ‘d’) cnt++;   I2 == ‘d’
    if (input[3] == ‘!’) cnt++;   I3 == ‘!’
    if (cnt >= 3) crash();
}
```

“Generation 1” test cases

Key Idea: One Trace Many Tests



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```
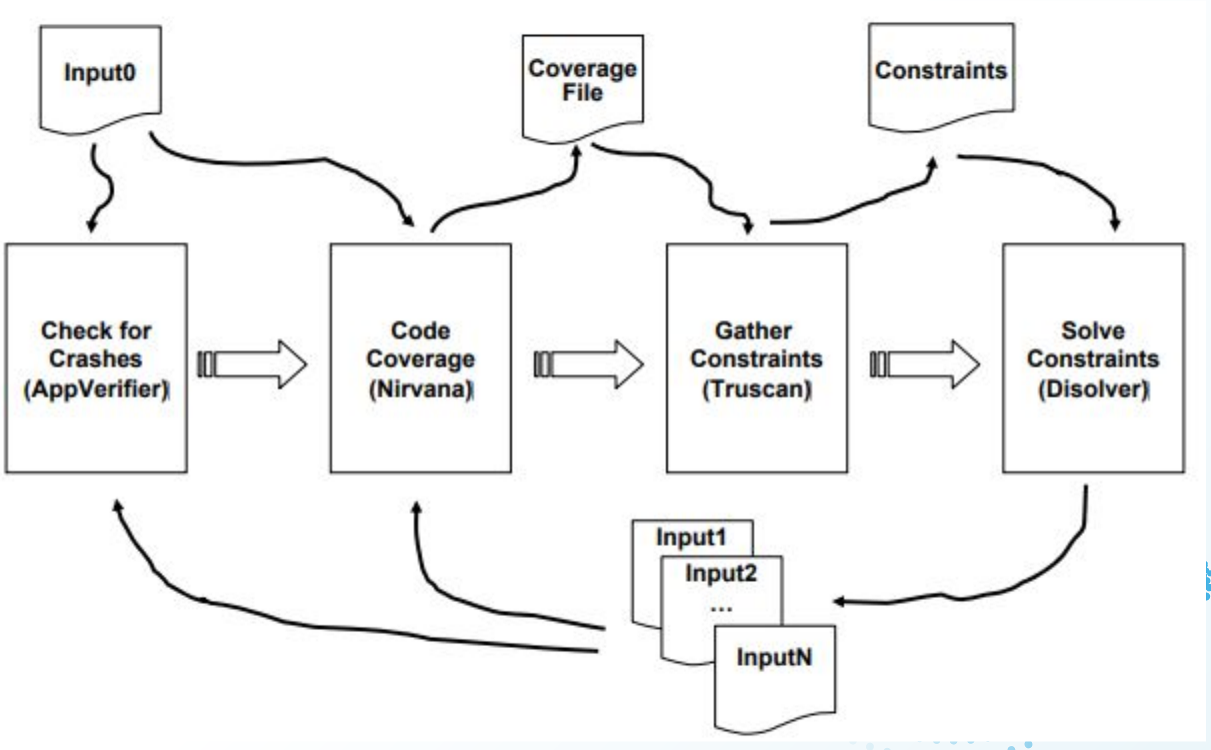
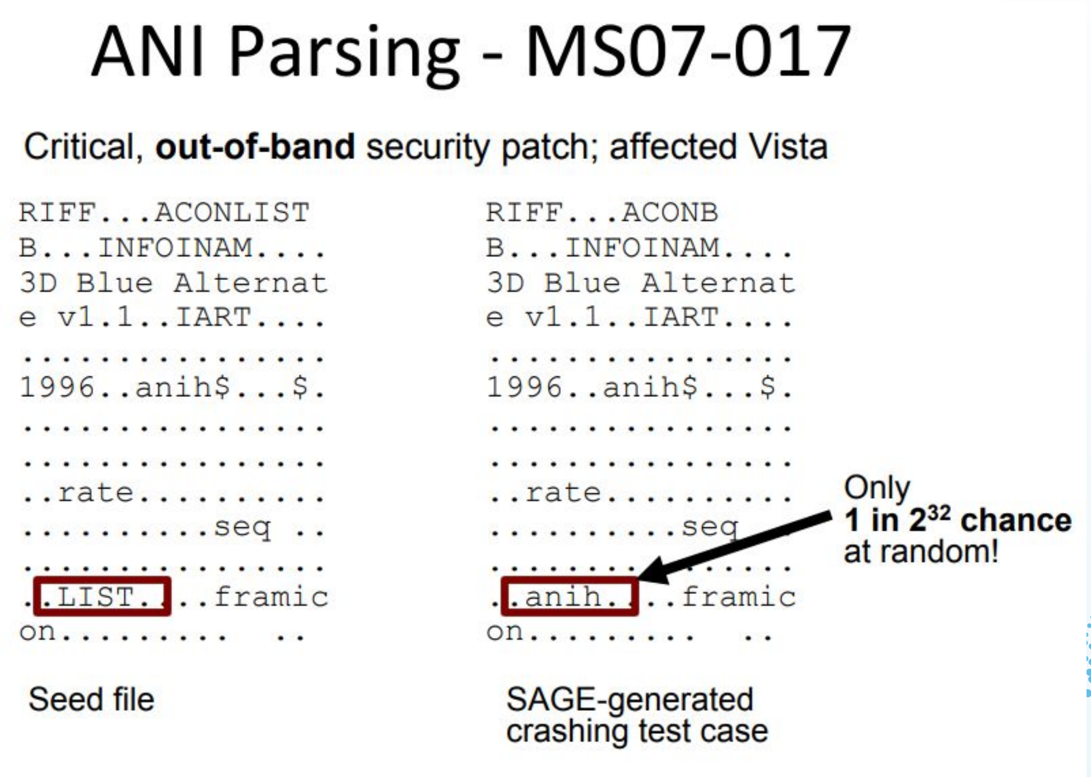

SAGE Architecture


Input0
Coverage File
Constraints
Check for Crashes (AppVerifier)
Code Coverage (Nirvana)
Gather Constraints (Truscan)
Solve Constraints (Disolver)
Input1
Input2
...
InputN

Case Study



ANI Parsing - MS07-017

Critical, **out-of-band** security patch; affected Vista

```
RIFF...ACONLIST          RIFF...ACONB
B...INFOINAM....         B...INFOINAM....
3D Blue Alternat         3D Blue Alternat
e v1.1..IART....         e v1.1..IART....
................         ................
1996..anih$...$.         1996..anih$...$.
................         ................
................         ................
..rate..........         ..rate..........
..........seq ..         ..........seq ..
................         ................
..LIST....framic         ..anih....framic
on.........  ..          on.........  ..
```

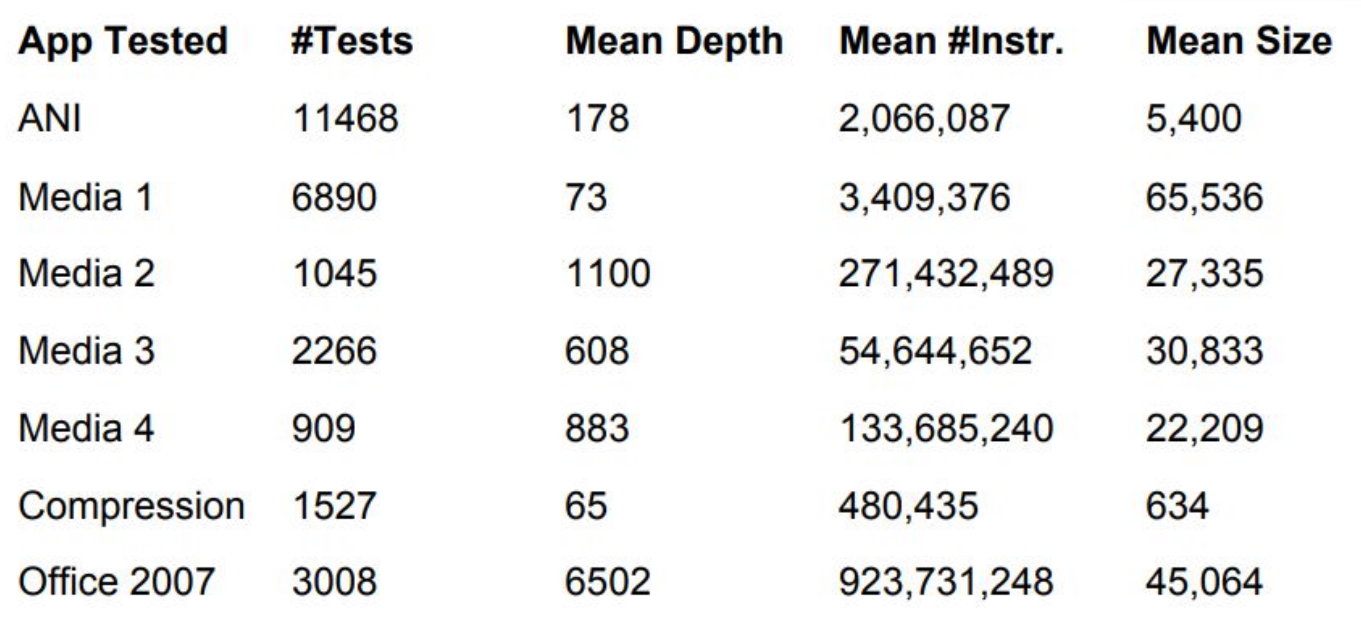
Only **1 in 2^{32} chance** at random!

Seed file

SAGE-generated crashing test case

Evaluation

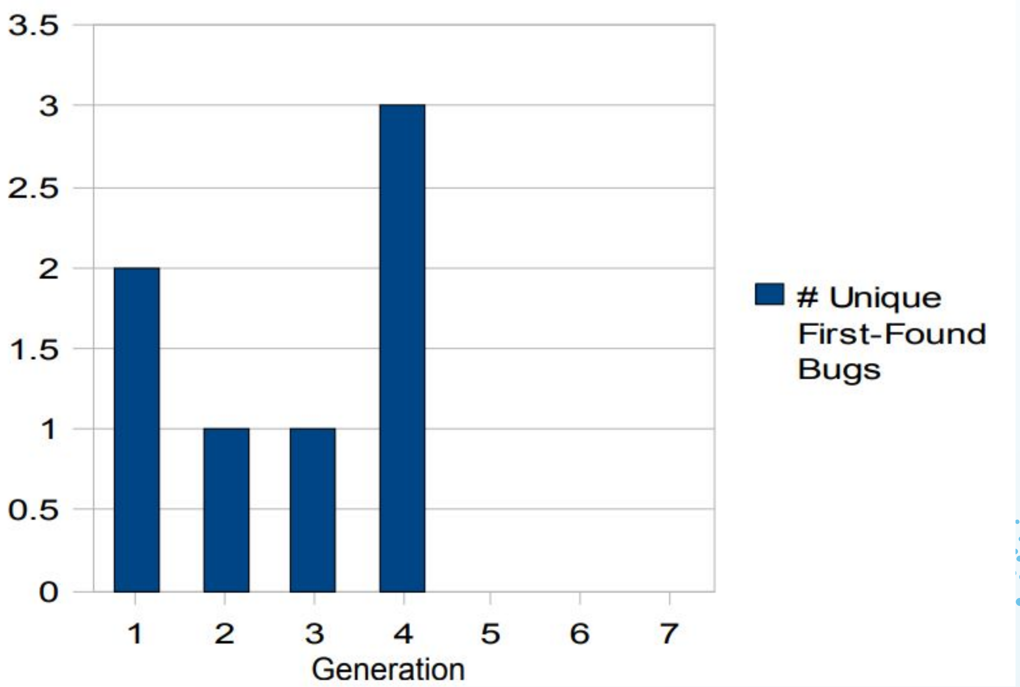
- Very large dataset



App Tested	#Tests	Mean Depth	Mean #Instr.	Mean Size
ANI	11468	178	2,066,087	5,400
Media 1	6890	73	3,409,376	65,536
Media 2	1045	1100	271,432,489	27,335
Media 3	2266	608	54,644,652	30,833
Media 4	909	883	133,685,240	22,209
Compression	1527	65	480,435	634
Office 2007	3008	6502	923,731,248	45,064

Evaluation

- Most bugs found are ‘shallow’



Thank you!

Questions?