Program Analysis

Symbolic and Concolic Execution

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Warm-up Quiz

How many lines does this Python code print?

```
print("\n")
print("\\n")
print(r"\\n")
print(r"\\\n")
```

4 **5** **6** **None**

Warm-up Quiz

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4 | **5** | **6** | **None**

Warm-up Quiz

How many lines does this Python code print?

Normal string: Backslash is an escape character

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```

Raw string: Backslash is kept as-is

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Warm-up Quiz

How many lines does this Python code print?

Normal string: Backslash is an escape character

```
print("\n")
print("\\n")
print(r"\\n")
print(r"\\\n")
```

Raw string: Backslash is kept as-is

Output:

```


\n
\\n
\\\n
```

4   **[5]**   6   None

Overview

1. Classical Symbolic Execution ←
2. Challenges of Symbolic Execution
3. Concolic Testing
4. Large-Scale Application in Practice

Mostly based on these papers:

- *DART: directed automated random testing*, Godefroid et al., PLDI'05
- *KLEE: Unassisted and Automatic Generation of High-Coverage Tests for Complex Systems Programs*, Cadar et al., OSDI'08
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Symbolic Execution

- Reason about behavior of program by ”executing” it with symbolic values
- Originally proposed by James King (1976, CACM) and Lori Clarke (1976, IEEE TSE)
- Became practical around 2005 because of advances in constraint solving (SMT solvers)

Example

```
function f(a, b, c) {
  var x = y = z = 0;
  if (a) {
    x = -2;
  }
  if (b > 5) {
    if (!a && c) {
      y = 1;
    }
    z = 2;
  }
  assert(x + y + z != 3);
}
```

Concrete execution

$a = b = c = 1$

$x = y = z = 0$

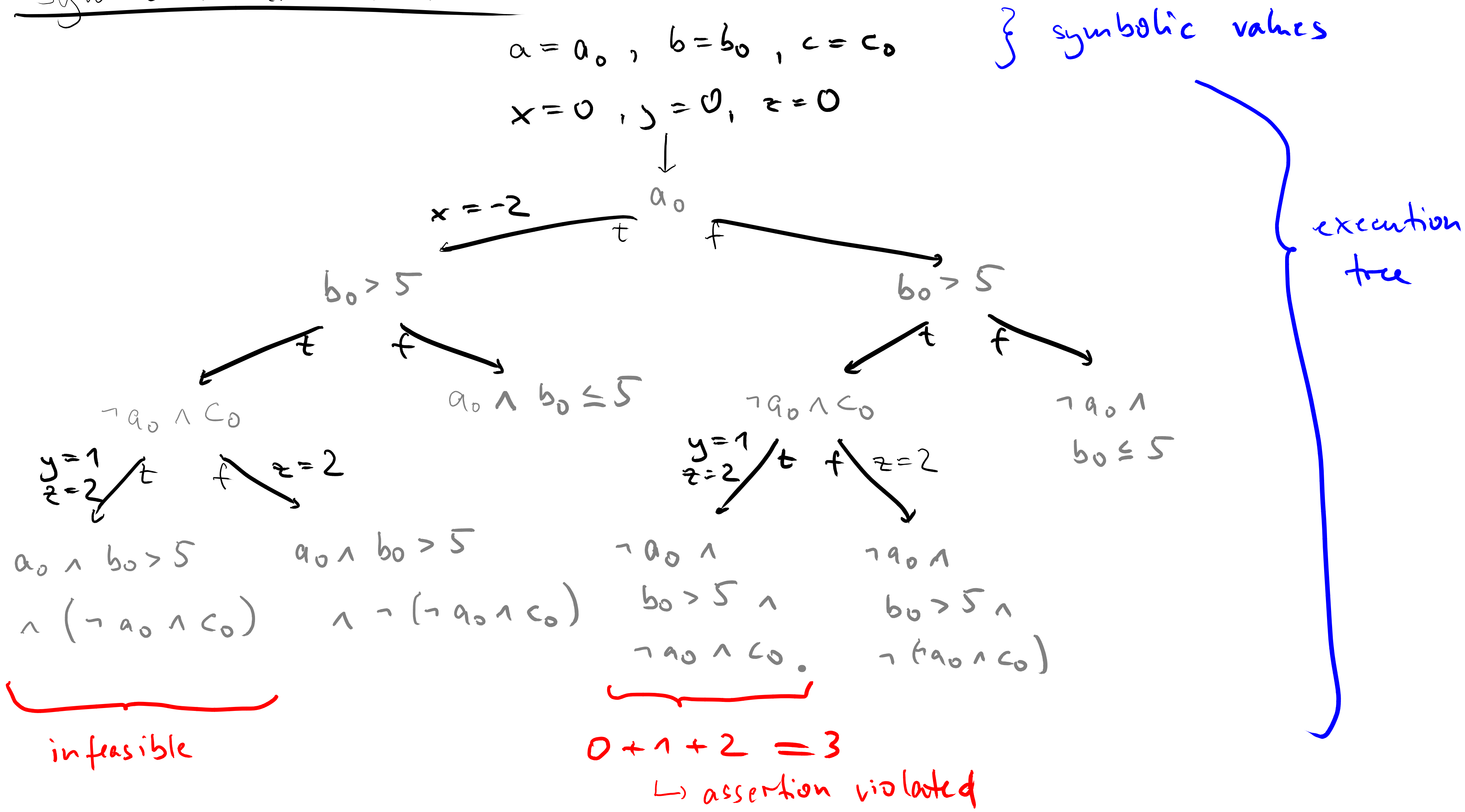
true

$x = -2$

false

$-2 + 0 + 0 \neq 3$ ✓

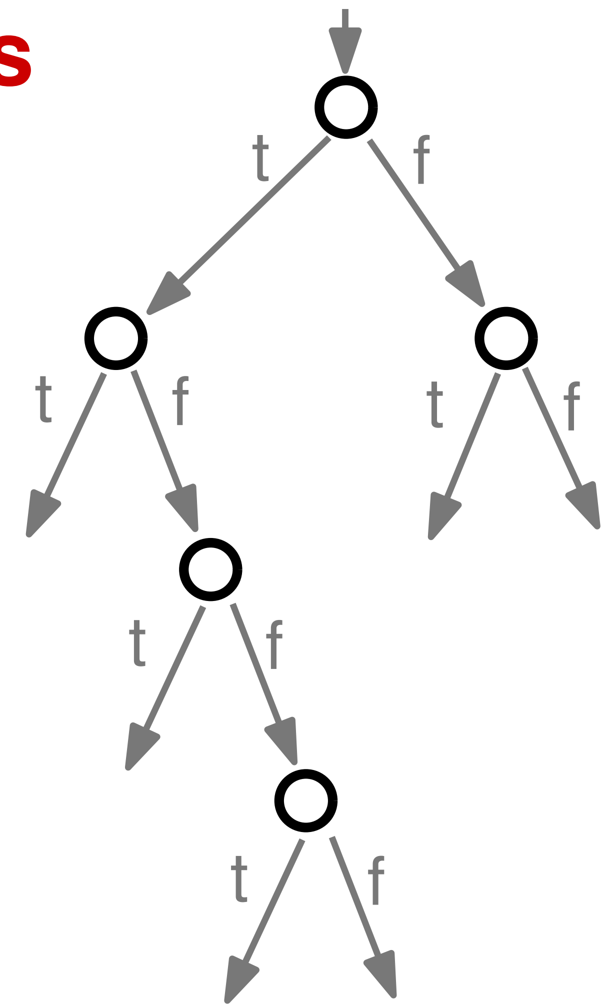
Symbolic execution



Execution Tree

All possible execution paths

- Binary tree
- Nodes: Conditional statements
- Edges: Execution of sequence on non-conditional statements
- Each path in the tree represents an equivalence class of inputs

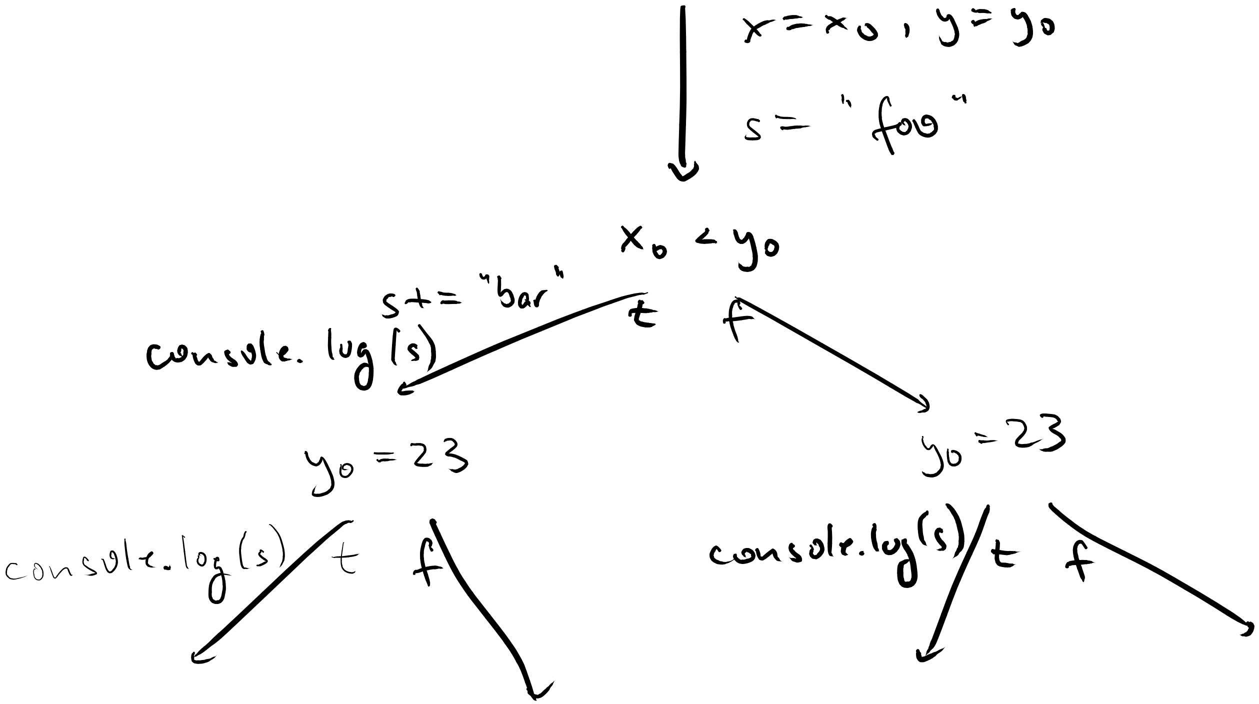


Quiz

Draw the execution tree for this function. How many nodes and edges does it have?

```
function f(x,y) {
  var s = "foo";
  if (x < y) {
    s += "bar";
    console.log(s);
  }
  if (y === 23) {
    console.log(s);
  }
}
```

Quiz



→ 3 nodes (root & leaves not counted)

→ 7 edges

Symbolic Values and Symbolic State

- Unknown values, e.g., user inputs, are kept symbolically
- Symbolic state maps variables to symbolic values

```
function f(x, y) {
  var z = x + y;
  if (z > 0) {
    ...
  }
}
```

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function f(x, y) {
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    ...
  }
}
```

Symbolic input values: x_0, y_0

Symbolic state: $z = x_0 + y_0$

Path Conditions

Quantifier-free formula over the symbolic inputs that encodes all branch decisions taken so far

```
function f(x, y) {
  var z = x + y;
  if (z > 0) {
    ...
  }
}
```

Path Conditions

Quantifier-free formula over the symbolic inputs that encodes all **branch decisions** taken so far

```
function f(x, y) {
  var z = x + y;
  if (z > 0) {
    ...
  }
}
```

Path condition:

$x_0 + y_0 > 0$

Satisfiability of Formulas

Determine whether a path is feasible:
Check if its path condition is satisfiable

- Done by powerful SMT/SAT solvers
  - SAT = satisfiability,
    SMT = satisfiability modulo theory
  - E.g., Z3, Yices, STP
- For a satisfiable formula, solvers also provide a concrete solution
- Examples:
  - $a_0 + b_0 > 1$: Satisfiable, one solution: $a_0 = 1, b_0 = 1$
  - $(a_0 + b_0 < 0) \wedge (a_0 - 1 > 5) \wedge (b_0 > 0)$: Unsatisfiable

Applications of Symbolic Execution

- General goal: Reason about behavior of program
- Basic applications
  - Detect infeasible paths
  - Generate test inputs
  - Find bugs and vulnerabilies
- Advanced applications
  - Generating program invariants
  - Prove that two pieces of code are equivalent
  - Debugging
  - Automated program repair

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Problems of Symbolic Execution

- Loops and recursion: Infinite execution trees
- Path explosion: Number of paths is exponential in the number of conditionals
- Environment modeling: Dealing with native/system/library calls
- Solver limitations: Dealing with complex path conditions
- Heap modeling: Symbolic representation of data structures and pointers

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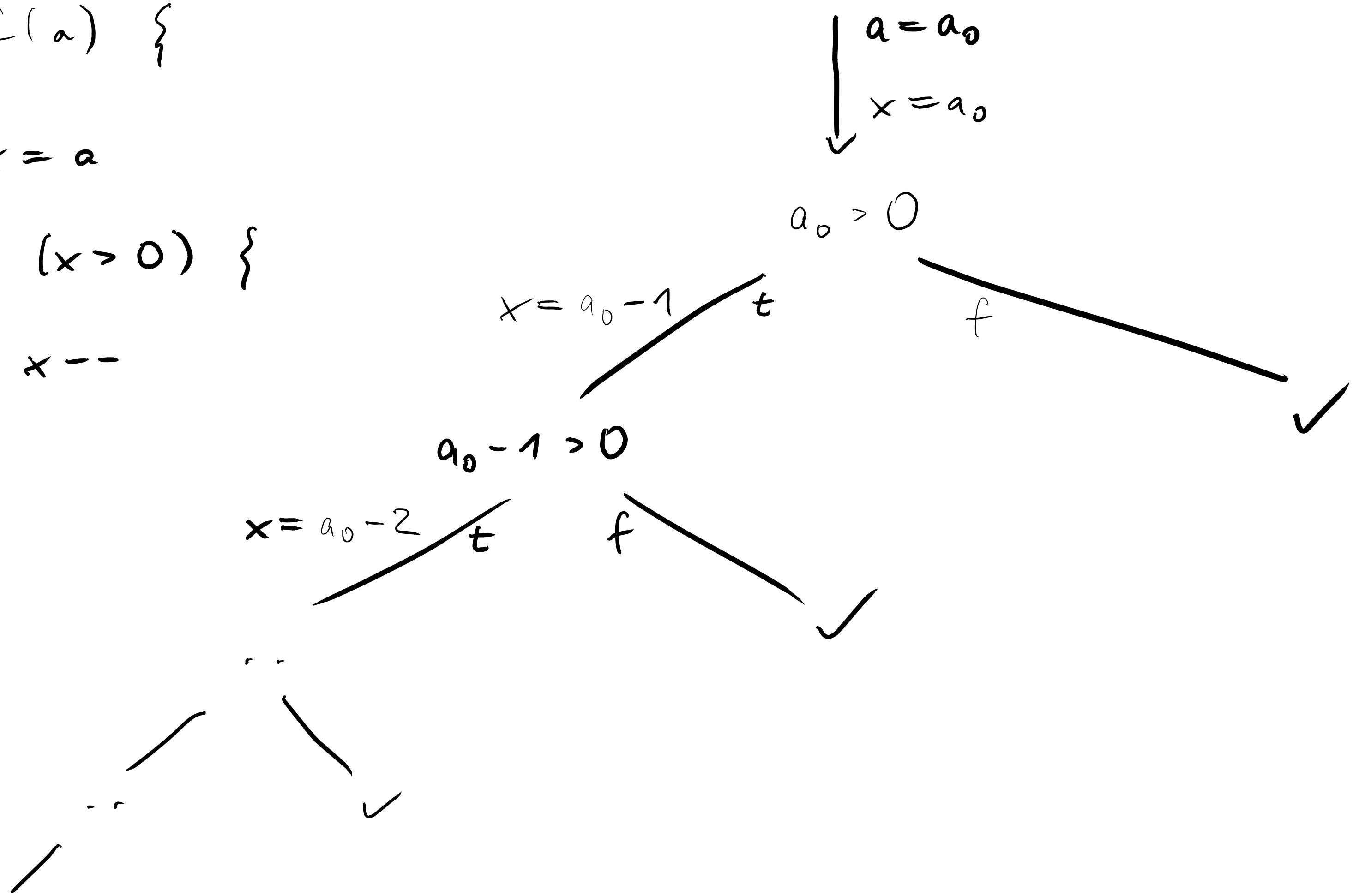
Path Explosion

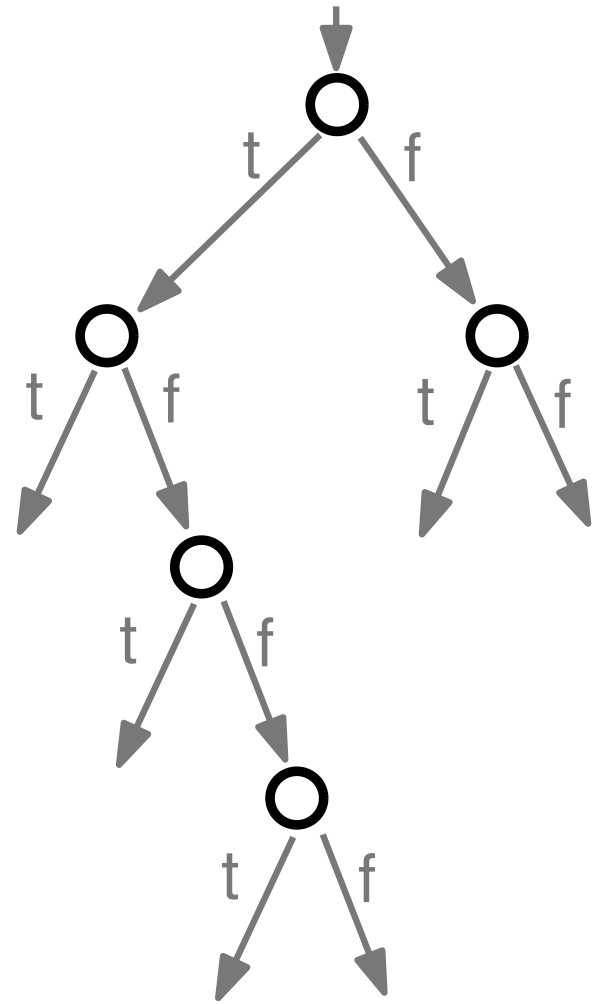
```
function f(a) {
    var x = a
    while (x > 0) {
        x--
    }
}
```



Dealing with Large Execution Trees

Heuristically select which branch to explore next

- Select at random
- Select based on coverage
- Prioritize based on distance to ”interesting” program locations
- Interleaving symbolic execution with random testing



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Modeling the Environment

- Program behavior may depend on parts of system not analyzed by symbolic execution
- E.g., native APIs, interaction with network, file system accesses

```
var fs = require("fs");
var content = fs.readFileSync("/tmp/foo.txt");
if (content === "bar") {
  ...
}
```

Modeling the Environment (2)

Solution implemented by KLEE

- If all arguments are concrete, forward to OS
- Otherwise, provide models that can handle symbolic files
  - Goal: Explore all possible legal interactions with the environment

```
var fs = {
  readFileSync: function(file) {
    // doesn't read actual file system, but
    // models its effects for symbolic file nam
  }
}
```

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One approach: Mix symbolic with concrete execution

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Concolic Testing

Mix concrete and symbolic execution = ”concolic”

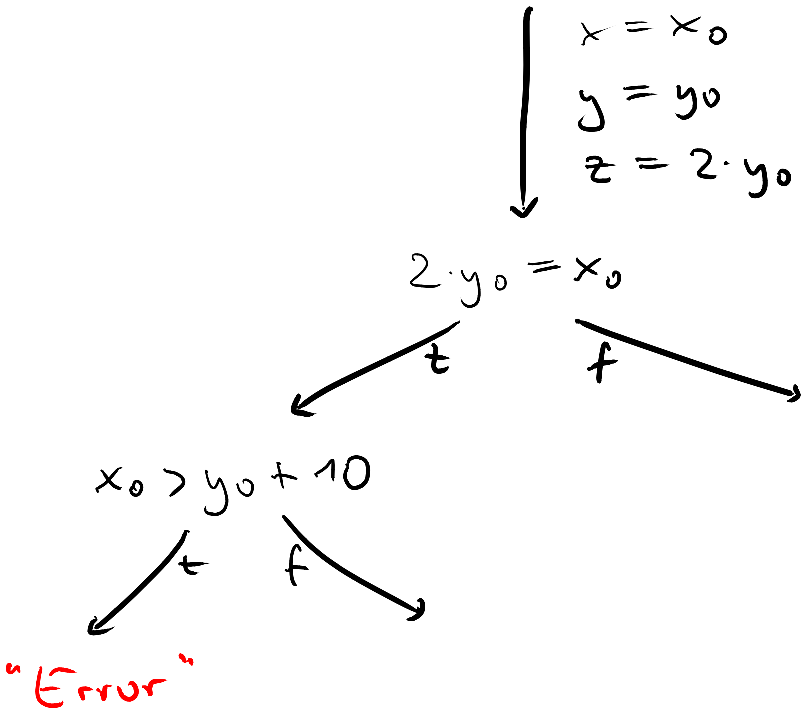
- Perform concrete and symbolic execution side-by-side
- Gather path constraints while program executes
- After one execution, negate one decision, and re-execute with new input that triggers another path

Example

```
function double(n) {
  return 2 * n;
}

function testMe(x, y) {
  var z = double(y);
  if (z === x) {
    if (x > y + 10) {
      throw "Error";
    }
  }
}
```

Concolic execution: Execution tree



Execution 1

Concrete execution	Symbolic exec.	Path conditions
$x = 22$, $y = 7$ (After entering the fct.)	$x = x_0$, $y = y_0$	
$x = 22$, $y = 7$ $z = 14$ (After call to double & assignment)	$x = x_0$, $y = y_0$ $z = 2 \cdot y_0$	
$x = 22$, $y = 7$ $z = 14$ (After outer if)	$x = x_0$, $y = y_0$, $z = 2 \cdot y_0$	$2 \cdot y_0 \neq x_0$

Solve: $2 \cdot y_0 = x_0$

Solutions: $x_0 = 2$, $y_0 = 1$

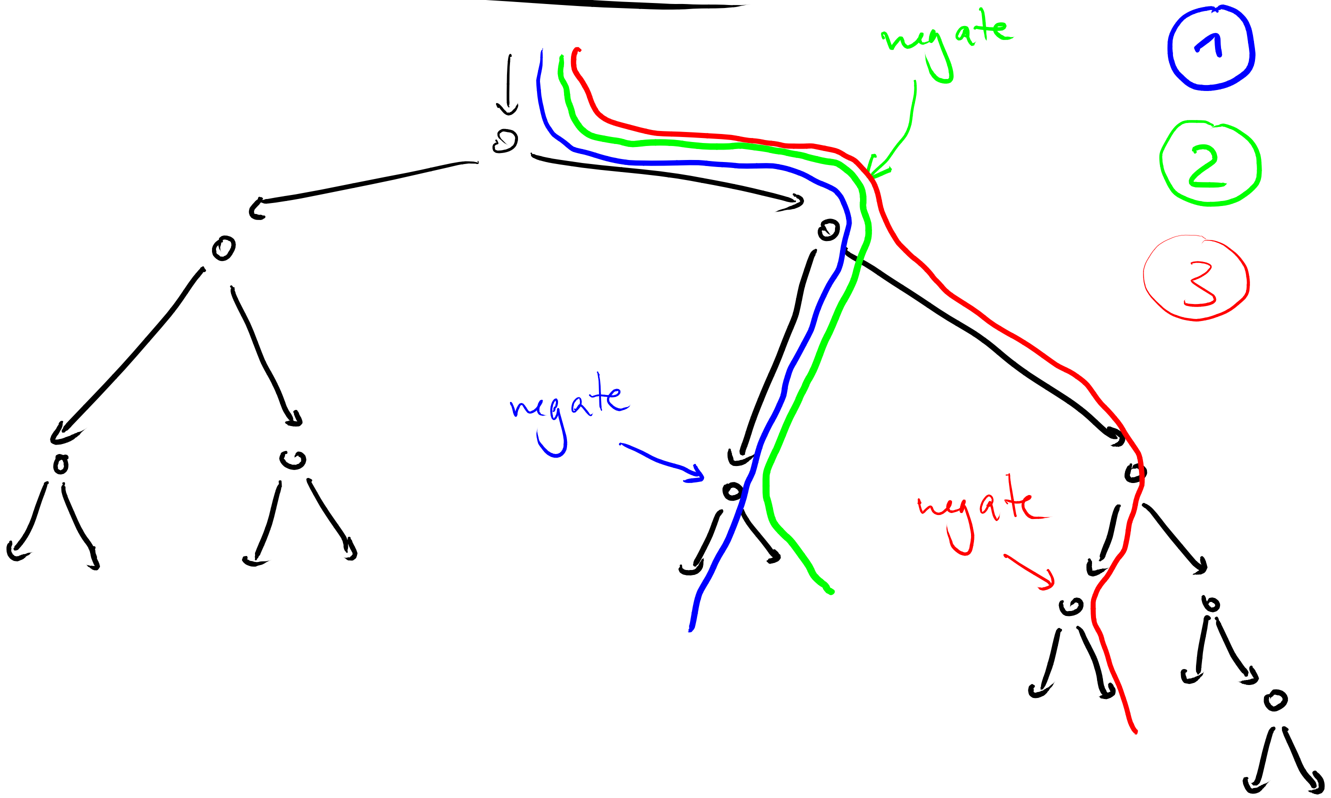
Execution 2

Concrete exec.	Symb. exec.	Path condition
$x=2,\ y=1$	$x=x_0,\ y=y_0$	
$x=2,\ y=1,$ $z=2$	$x=x_0,\ y=y_0,$ $z=2\cdot y_0$	
—"—	—"—	$2\cdot y_0 = x_0$
—"—	—"—	$2\cdot y_0 = x_0\ \wedge$ $x_0 \leq y_0+10$

Solve: $2\cdot y_0 = x_0 \wedge x_0 > y_0 + 10$

Solution: $x_0 = 30,\ y_0 = 15$ } Hits "Error"

Exploring the Execution Tree



Algorithm

Repeat until all paths are covered

- Execute program with concrete input i and collect symbolic constraints at branch points: C
- Negate one constraint to force taking an alternative branch b': Constraints C'
- Call constraint solver to find solution for C': New concrete input i'
- Execute with i' to take branch b'
- Check at runtime that b' is indeed taken
  Otherwise: "divergent execution"

Divergent Execution: Example

```
function f(a) {
    if (Math.random() < 0.5) {
        if (a > 1) {
            console.log("yes")
        }
    }
}
```

Exec. 1

a = 0

true

false

path constraint:

$a_0 \leq 1$

negate & solve:

$a_0 = 2$

Exec. 2

a = 2

false

Divergent execution

Benefits of Concolic Approach

When symbolic reasoning is impossible or impractical, fall back to concrete values

- Native/system/API functions
- Operations not handled by solver (e.g., floating point operations)

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Large-Scale Concolic Testing

- SAGE: Concolic testing tool developed at Microsoft Research
- Test robustness against unexpected inputs read from files, e.g.,
  - Audio files read by media player
  - Office documents read by MS Office
- Start with known input files and handle bytes read from files as symbolic input
- Use concolic execution to compute variants of these files

Large-Scale Concolic Testing (2)

- Applied to hundreds of applications
- Over 400 machine years of computation from 2007 to 2012
- Found hundreds of bugs, including many security vulnerabilties
  - One third of all the bugs discovered by file fuzzing during the development of Microsoft's Windows 7

Details: Bounimova et al., ICSE 2013

Summary: Symbolic & Concolic Testing

Solver-supported, whitebox testing

- Reason symbolically about (parts of) inputs
- Create new inputs that cover not yet explored paths
- More systematic but also more expensive than random and fuzz testing
- Open challenges
  - Effective exploration of huge search space
  - Other applications of constraint-based program analysis, e.g., debugging and automated program repair