Practical Program Analysis: Symbolic and Concolic Testing

Prof. Dr. Michael Pradel

Software Lab, University of Stuttgart

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Plan for Today

1. **Classical Symbolic Execution**
2. **Concolic Testing**
3. **Course Project**

Papers with more details:

- *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
- *Automated Whitebox Fuzz Testing*, Godefroid et al., NDSS'08

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);
}
```

```
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

true

false

z = 2

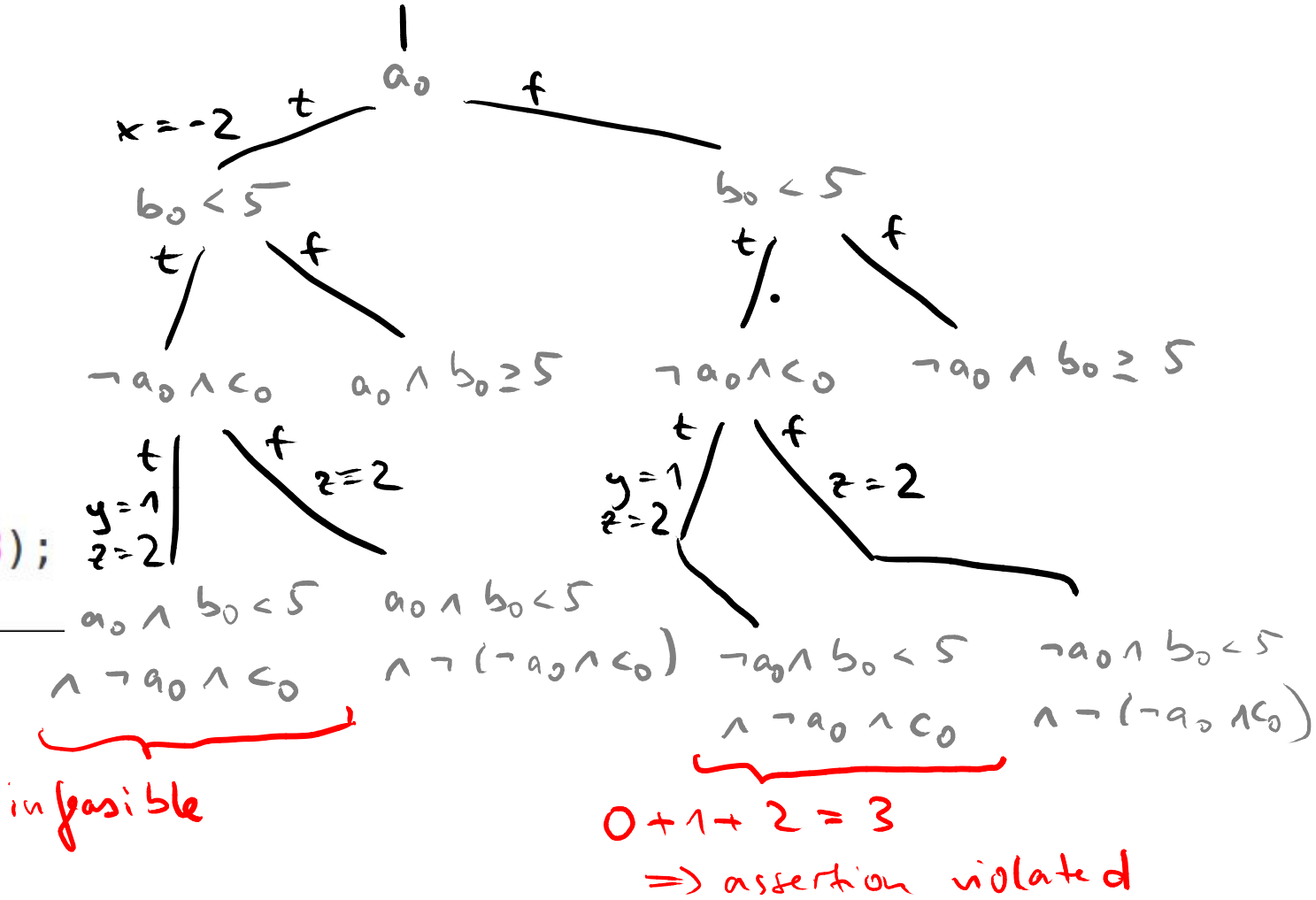
✓

```
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);
}
```

symbolic execution

$a = a_0, \quad b = b_0, \quad c = c_0$

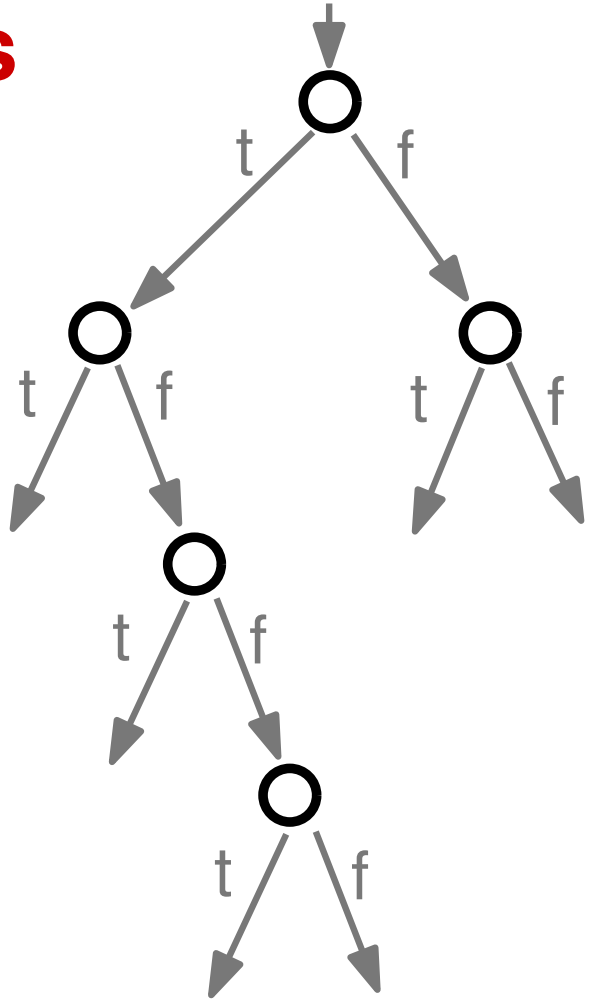
$x = y = z = 0$



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

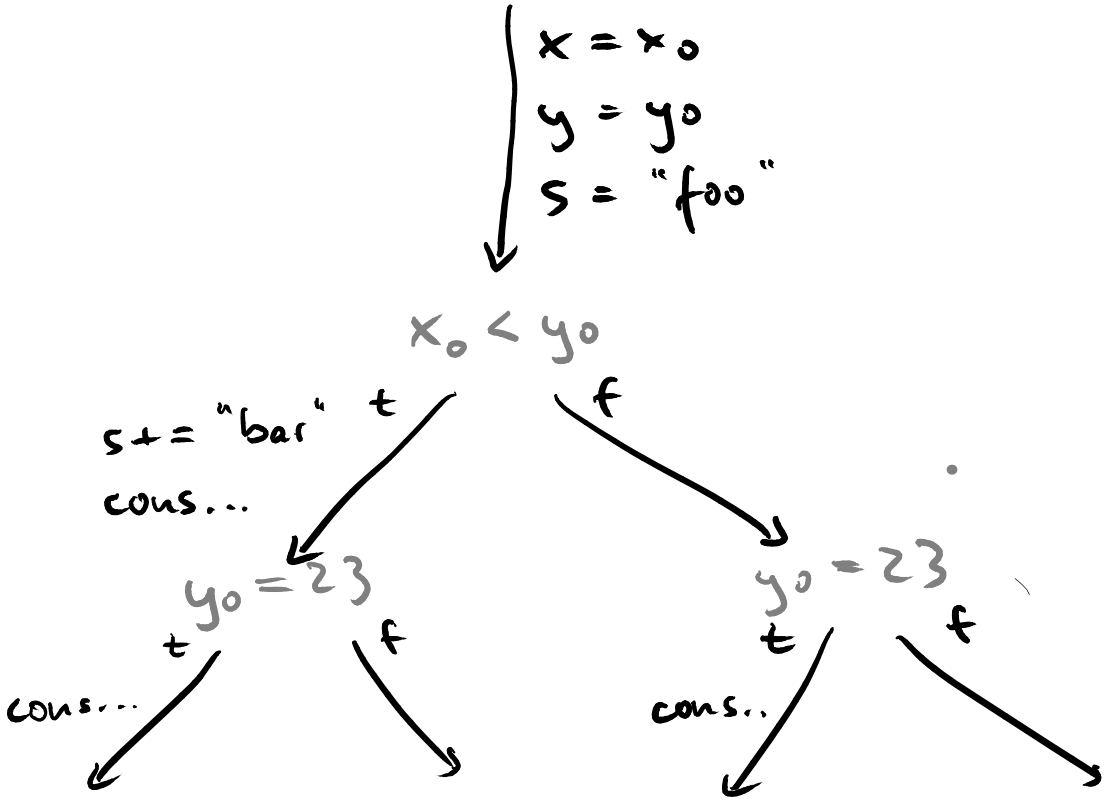


Quiz

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

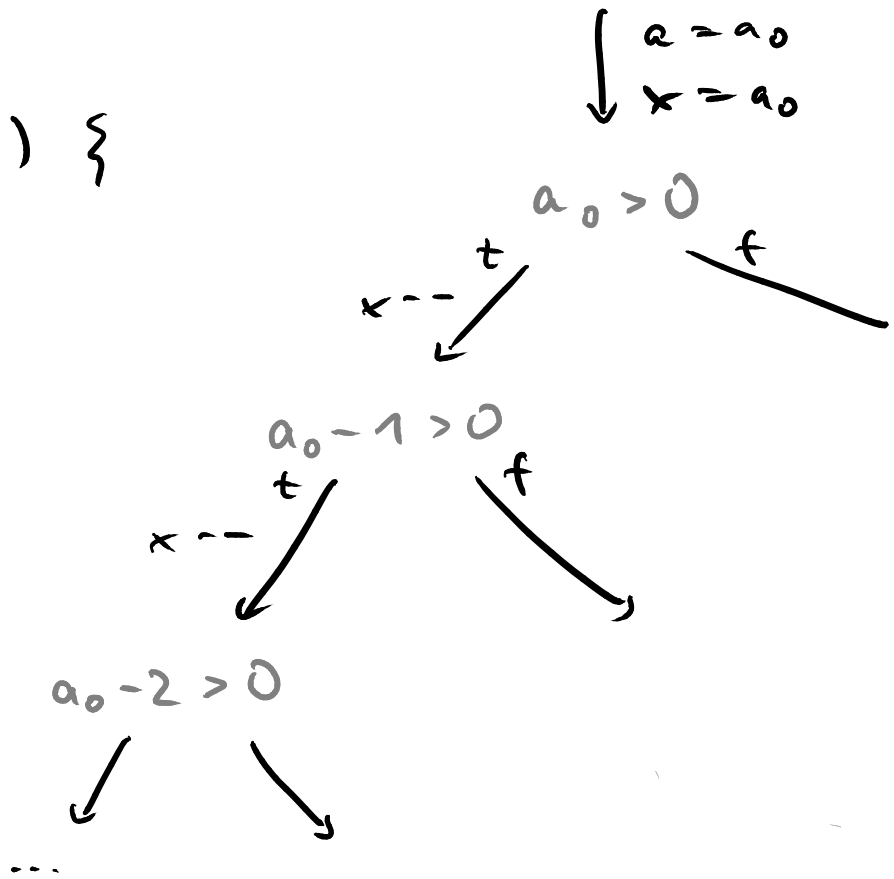
```
function f(x,y) {
  var s = "foo";
  if (x < y) {
    s += "bar";
    console.log(s);
  }
  if (y === 23) {
    console.log(s);
  }
}
```

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



→ 3 nodes, 7 edges

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



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) {
    ...
  }
}
```

Symbolic Values and Symbolic State

- Unknown values, e.g., user inputs, are kept symbolically
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```
function f(x, y) {
  var z = x + y;
  if (z > 0) {
    ...
  }
}
```

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, e.g., 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

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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Concolic Testing

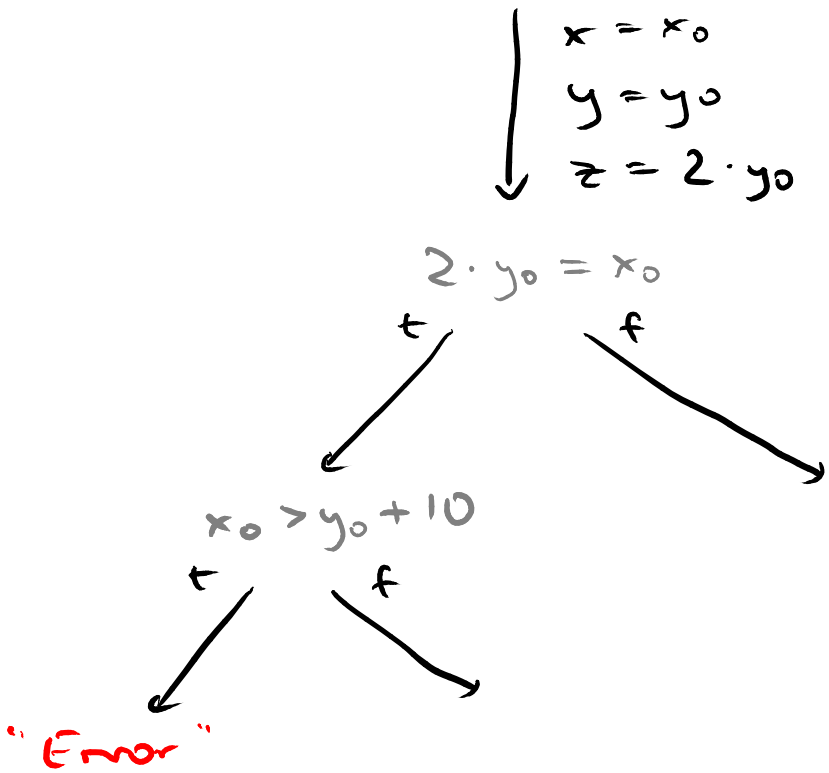
Mix concrete and symbolic execution = "concolic"

- 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

Symbolic execution (again)

```
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 1:

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

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

Concrete execution	Symbolic execution	Path conditions
$x = 22,\ y = 7$	$x = x_0,\ y = y_0$	
$x = 22,\ y = 7,$ $z = 14$	$x = x_0,\ y = y_0,$ $z = 2 \cdot y_0$	
$x = 22,\ y = 7,$ $z = 14$	$x = x_0,\ y = y_0,$ $z = 2 \cdot y_0$	$2 \cdot y_0 \neq x_0$

Solve: $2 \cdot y_0 = x_0$

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

Concolic execution

Execution 2:

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

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

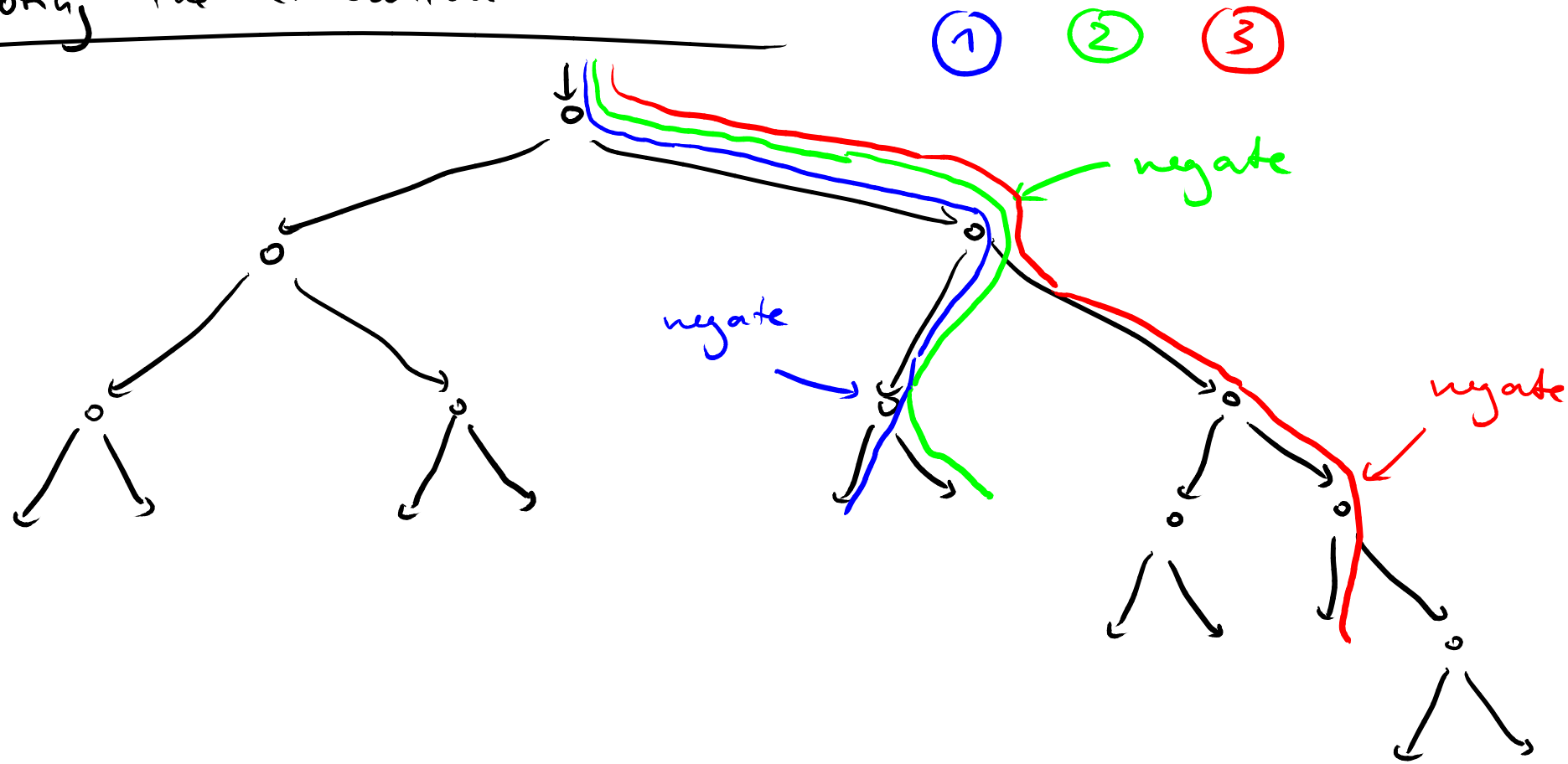
Concrete execution	Symbolic execution	Path conditions
$x = 2,\ y = 1$	$x = x_0,\ y = y_0$	
$x = 2,\ y = 1,$ $z = 2$	$x = x_0,\ y = y_0,$ $z = 2 \cdot y_0$	
$x = 2,\ y = 1,$ $z = 2$	$x = x_0,\ y = y_0,$ $z = 2 \cdot y_0$	$2 \cdot y_0 = x_0$
"	"	$2 \cdot y_0 = x_0$ $\wedge\ x_0 \leq y_0 + 10$

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

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

Will hit "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”

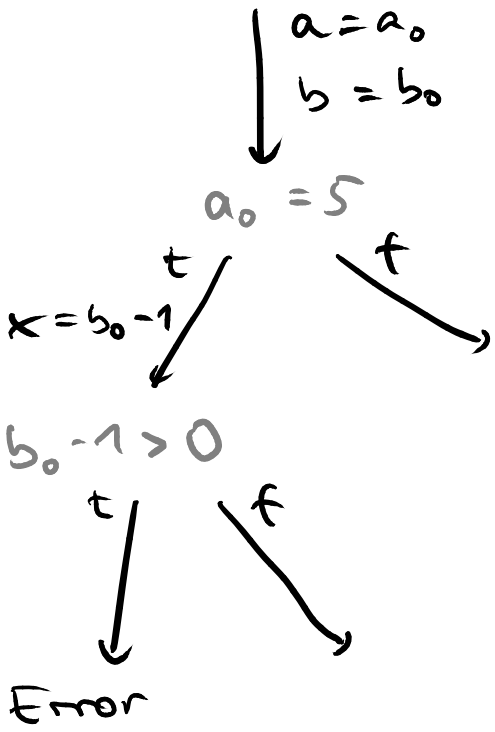
Quiz

After how many executions and how many queries to the solver does concolic testing find the error?

Initial input: `a=0, b=0`

```
function concolicQuiz(a, b) {
  if (a === 5) {
    var x = b - 1;
    if (x > 0) {
      console.log("Error");
    }
  }
}
```

Quiz:



Exec. 1

$a_0 = 0$, $b_0 = 0$

Solve : $a_0 = 5$ $\rightarrow$ $a_0 = 5$

Exec. 2

$a_0 = 5$, $b_0 = 0$

Solve : $a_0 = 5 \wedge b_0 - 1 > 0$

$\rightarrow$ $a_0 = 5$, $b_0 = 2$

Exec 3

$\rightarrow$ reach error

$\Rightarrow$ 3 executions, 2 queries

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)

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 Windows 7

Details: Bounimova et al., ICSE 2013

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