Program Testing and Analysis: Symbolic and Concolic Testing

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Outline

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
- *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);
}
```

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function f(a, b, c) {
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```

concrete execution

$a = b = c = 1$
$x = y = z = 0$
true
$x = -2$

true
false

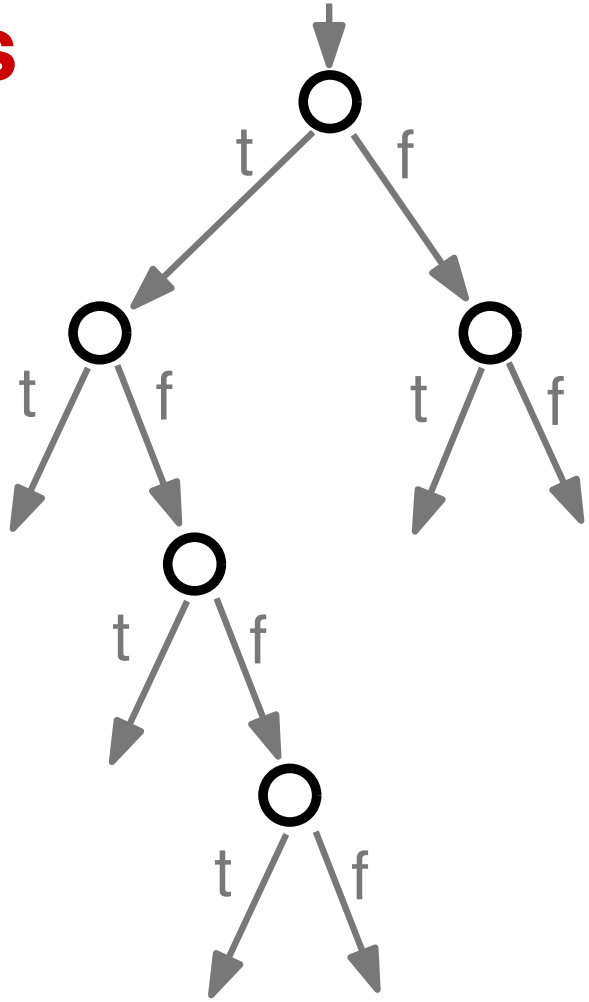
$z = 2$

$-2 + 0 + 2 \neq 3$ ✓

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



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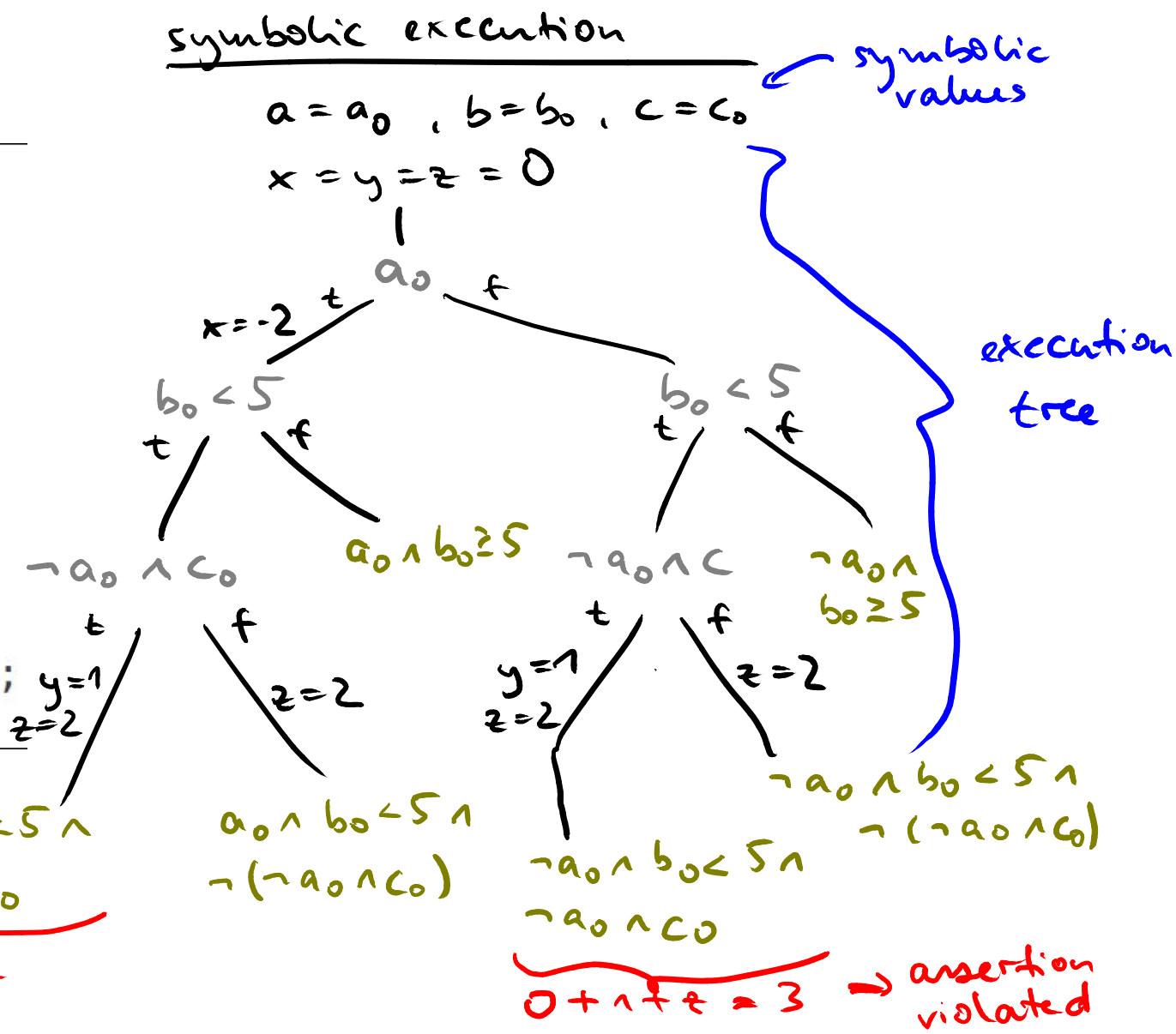

Quiz

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);
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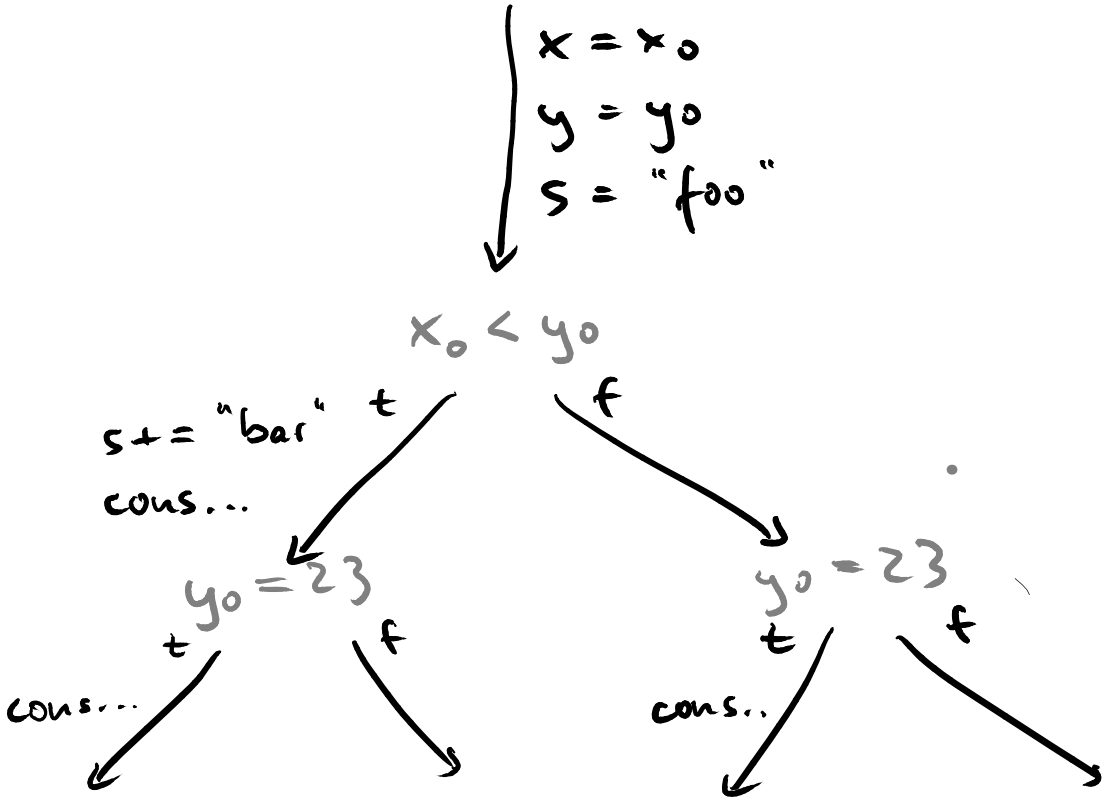
}
```



→ 3 nodes, 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