Program Analysis – Lecture 7

Symbolic and Concolic Execution (Part 1)

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Warm-up Quiz

What does the following code print?

```
var sum = 0;
var array = [11, 22, 33];
for (x in array) {
  sum += x;
}
console.log(sum);
```

112233 **0012** **66** **Something else**

Warm-up Quiz

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Some JS engines

Warm-up Quiz

What does the following code print?

```
var sum = 0;
var array = [11, 22, 33];
for (x in array) {
  sum += x;
}
console.log(sum);
```

Arrays are objects

For-in iterates over object property names (not property values)

112233 | **0012** | **66** | Some JS engines **Something else**

Warm-up Quiz

What does the following code print?

```
var sum = 0;
var array = [11, 22, 33];
for (x in array) {
  sum += x;
}
console.log(sum);
```

For arrays, use traditional for loop:

```
for (var i=0;
     i < array.length;
     i++) ...
```

112233 | **0012** | 66 | Some JS engines: **Something else**

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);
}
```

Concrete execution

```
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);
}
```

a = b = c = 1

x = y = z = 0

true

x = -2

true

false

z = 2

-2 + 0 + 2 ≠ 3 ✓

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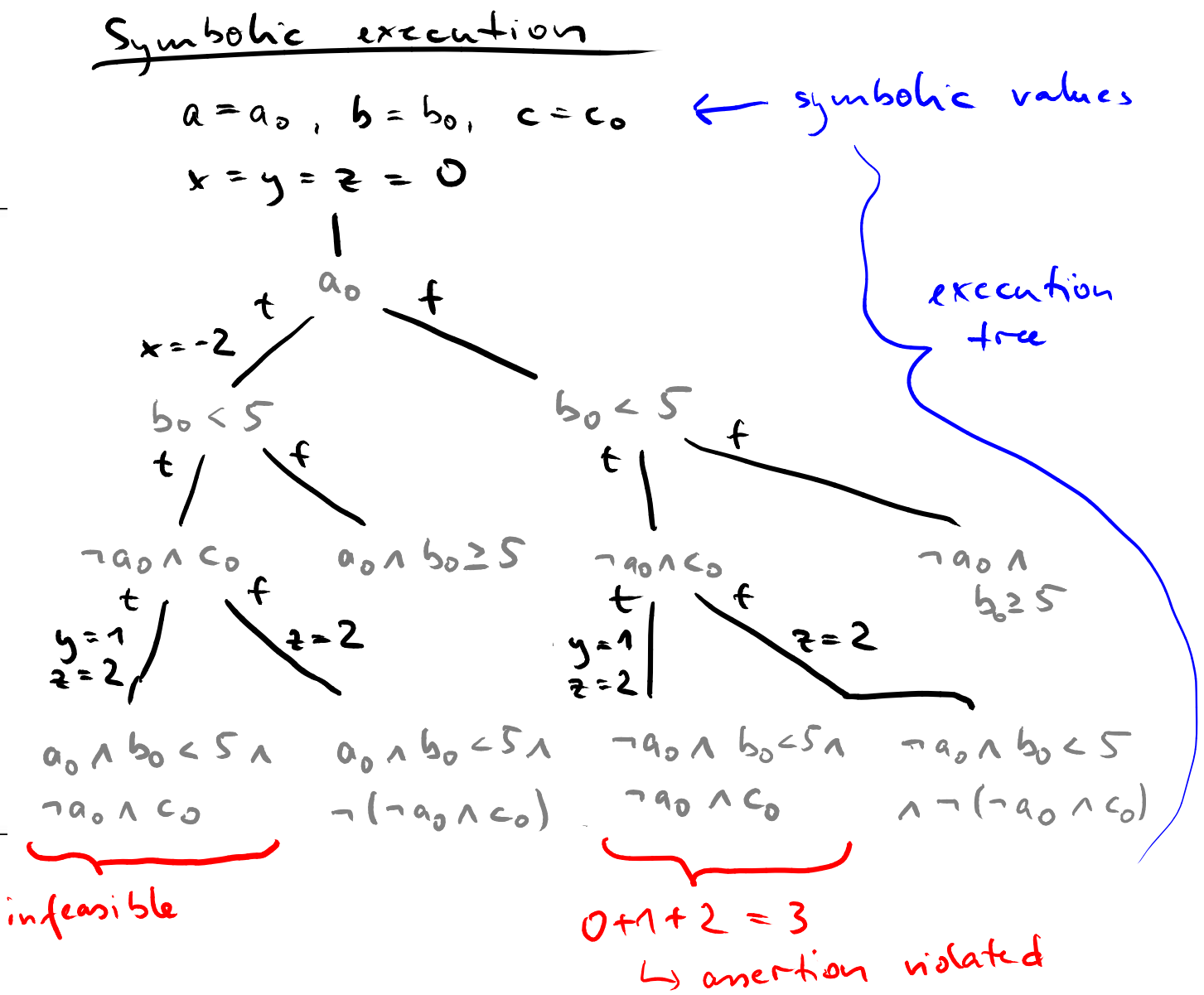
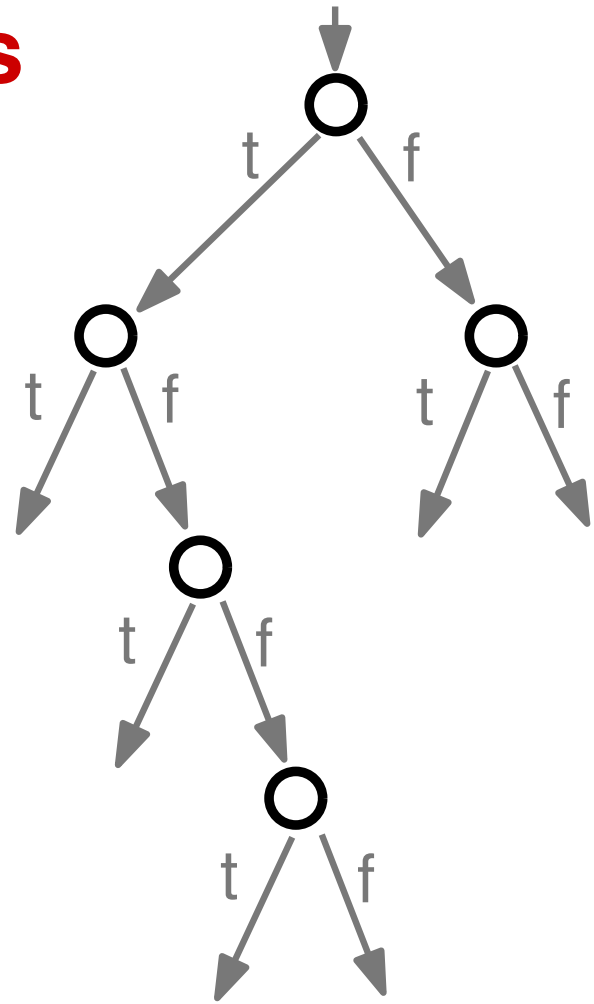



Execution Tree

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

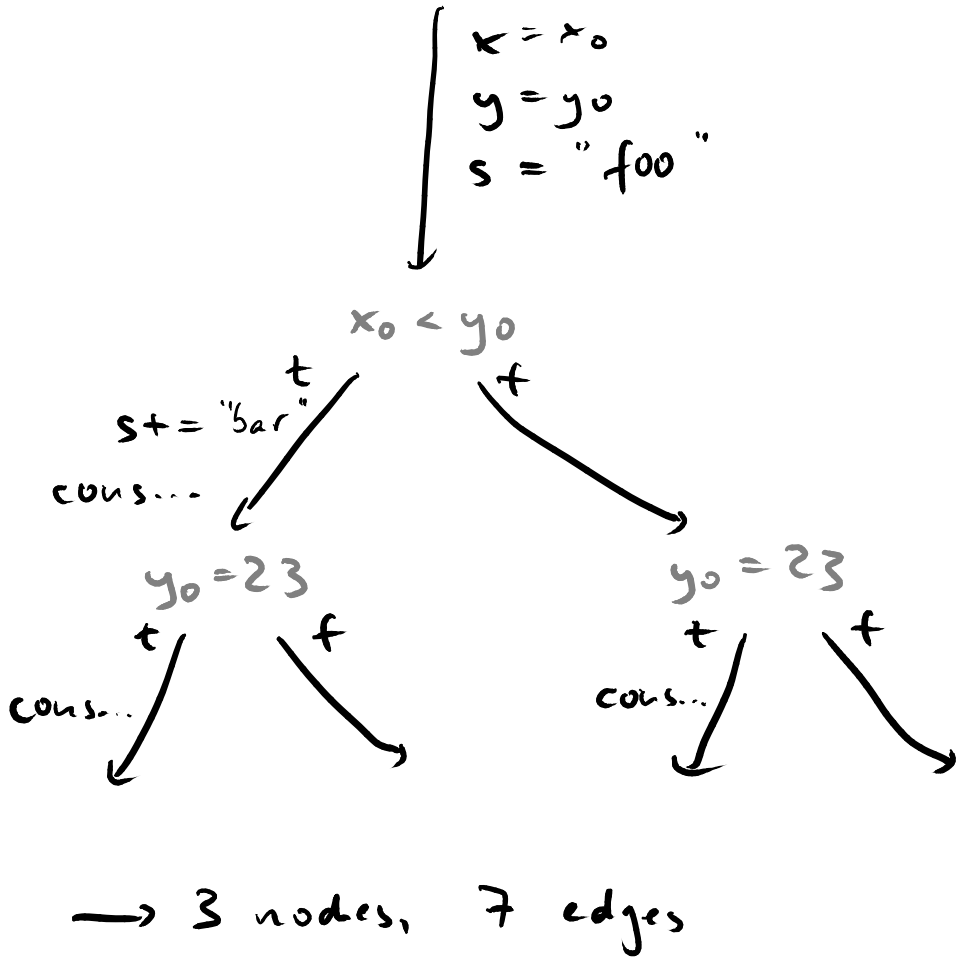


Quiz

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

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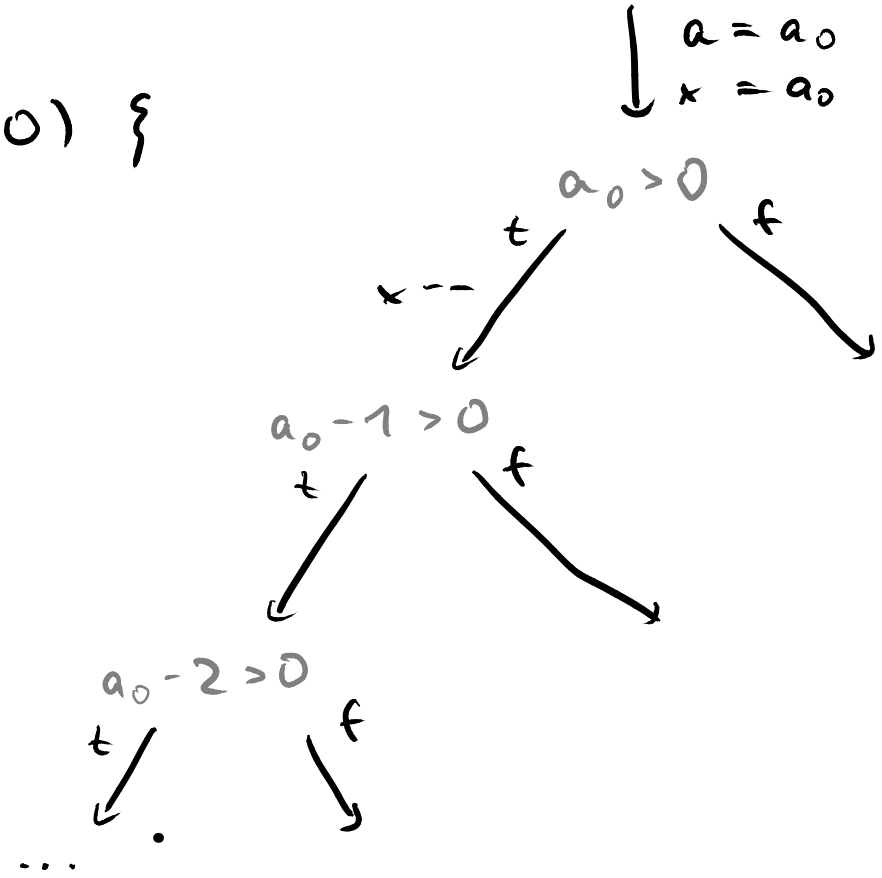
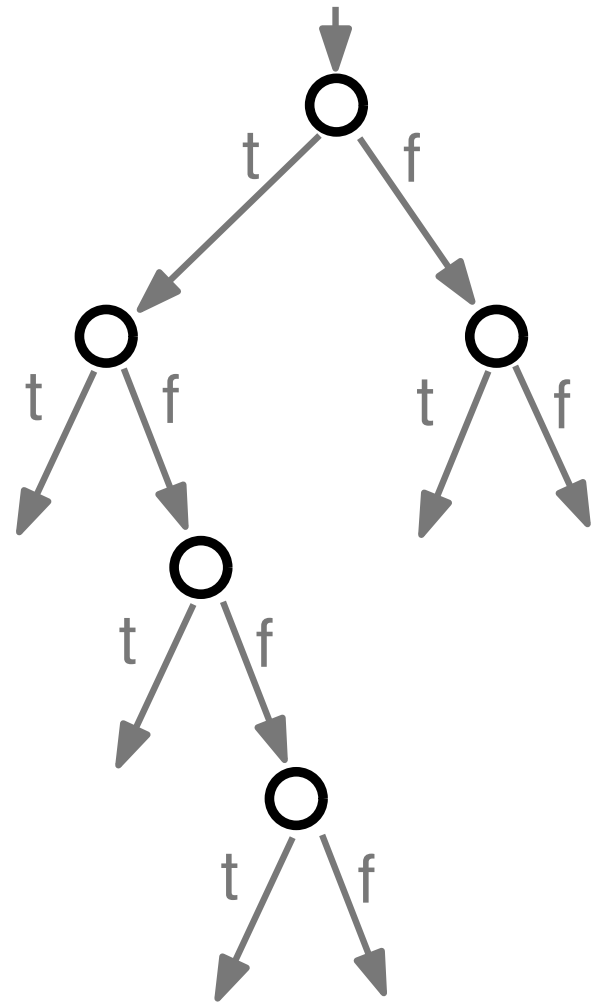
```
function f(a) {
    var x = a;
    while (x > 0) {
        x--;
    }
}
```



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