# Program Testing and Analysis: Random and Fuzz Testing (Part 2)

**Dr. Michael Pradel**

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# Warm-up Quiz

**What does the following code print?**

```
function f(a,b) {
  var x;
  for (var i = 0; i < arguments.length; i++) {
    x += arguments[i];
  }
  console.log(x);
}
f(1,2,3);
```

**3** **6** **NaN** **Nothing**

# Warm-up Quiz

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  }
  console.log(x);
}
f(1,2,3);
```

**Array-like object that contains all three arguments**

**3** **6** **NaN** **Nothing**

# Warm-up Quiz

**What does the following code print?**

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function f(a,b) {
  var x;
  for (var i = 0; i < arguments.length; i++) {
    x += arguments[i];
  }
  console.log(x);
}
f(1,2,3);
```

**Initialized to `undefined`**

**`undefined` + some number yields `NaN`**

**3** **6** **NaN** **Nothing**

# Outline

- **Feedback-directed random test generation**

  Based on *Feedback-Directed Random Test Generation*, Pacheco et al., ICSE 2007

- **Adaptive random testing**

  Based on *ARTOO: Adaptive Random Testing for Object-oriented Software*, Ciupa et al., ICSE 2008

- **Fuzz testing** 

  Based on *Fuzzing with Code Fragments*, Holler et al., USENIX Security 2012

# Fuzz Testing

## Generate random inputs

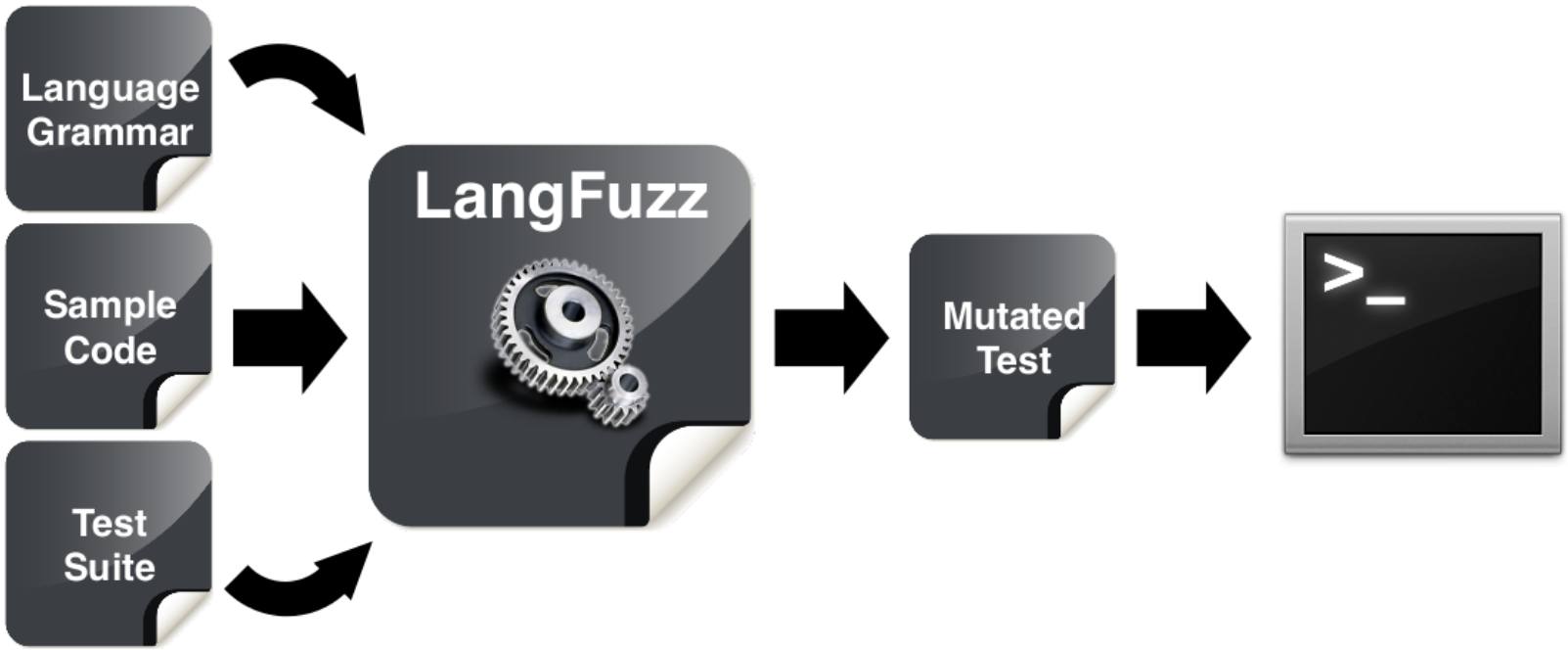
- Generative: Create new random input, possibly based on constraints and rules
- Mutative: Derive new inputs from existing input by randomly modifying it

# Grammar-based Language Fuzzing

**Idea: Combine generative and mutative approach to test JavaScript interpreter**

- Create random JavaScript programs based on language grammar
- Use and re-combine fragments of code from existing corpus of programs
  - Corpus: Programs that have exposed bugs before

# Overview of LangFuzz




**Phase I**

Learning code fragments from sample code and test suite

**Phase II**

LangFuzz generated (mutated) test cases

**Phase III**

Feed test case into interpreter, check for crashes and assertions

# Learning Code Fragments

- **Parse existing programs into ASTs**
- **Extract code fragments**
  - Examples for non-terminals of grammar

# Learning Code Fragments: Example

$\langle P \rangle$ ::= $\langle C \rangle$ | $\langle E \rangle$ | $\langle B \rangle$

$\langle C \rangle$ ::= l:=$\langle E \rangle$ | $\langle C \rangle$;$\langle C \rangle$ | if $\langle B \rangle$ then $\langle C \rangle$ else $\langle C \rangle$ | while $\langle B \rangle$ do $\langle C \rangle$ | skip

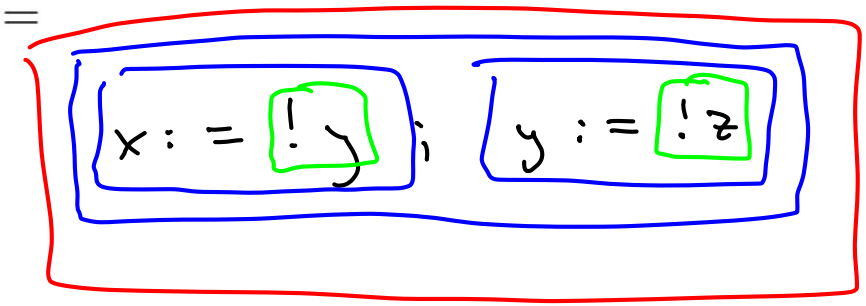
$\langle E \rangle$ ::= !l | n | $\langle E \rangle$ $\langle op \rangle$ $\langle E \rangle$

$\langle op \rangle$ ::= + | - | * | /

$\langle B \rangle$ ::= True | False | $\langle E \rangle$ $\langle bop \rangle$ $\langle E \rangle$ | $\neg\langle B \rangle$ | $\langle B \rangle \wedge \langle B \rangle$

$\langle bop \rangle$ ::= < | > | =

Corpus:




E

C

P

# Mutation of Code

- Randomly pick and parse an existing program
- Randomly pick some fragments and replace with learned fragments of same type

# Mutation of Code: Example

if !x > 4 then y := !z else skip

if !x > 4 then y := !z else x := !y

command from corpus

# Generation of Code

**Breadth-first application of grammar rules**

- Set current expansion $e_{cur}$ to start symbol $P$
- Loop $k$ iterations:
  - Choose a random non-terminal $n$ in $e_{cur}$
  - Pick one of the rules, $r$, that can be applied to $n$
  - Replace occurrence of $n$ in $e_{cur}$ by $r(n)$

**After $k$ iterations: Replace remaining non-terminals with fragments**

# Code Generation: Example

$k = 3$

$e_{cur} = P$ $\quad P ::= C \mid \ldots$

$e_{cur} = C$ $\quad C ::= \ldots \mid \text{while } B \text{ do } C \mid \ldots$

$e_{cur} = \text{while } B \text{ do } C$ $\quad C ::= \ldots \mid C_i\ C \mid \ldots$

$e_{cur} = \text{while } B \text{ do } C_i\ C$

Replace with fragments learned from corpus

# Quiz

**Which of the following SIMP programs could have been generated by LangFuzz?**

```
if B then C; C
```

```
if !x > 3 then skip else skip; y := 1
```

```
if !x > 3 then while; while
```

# Quiz

**Which of the following SIMP programs could have been generated by LangFuzz?**

```
if B then C; C
```

**(has unexpanded non-terminals)**

```
if !x > 3 then skip else skip; y := 1
```

```
if !x > 3 then while; while
```

**(syntactically incorrect)**

# Results

- **Used to test Mozilla's and Chrome's JavaScript engines**
- **Found various bugs**
  Mostly crashes of engine due to memory issues
- **Rewarded with bug bounties summing up to $50,000**
- **First author now works at Mozilla**

# Summary

## Random and fuzz testing

- Fully automated and unbiased
- Non-naive approaches can be very effective
- Trade-off: Cost of generating inputs vs. effectiveness in exposing bugs
  - Quickly generated, less effective tests may be better than slowly generated, more effective tests

# 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);
}
```

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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  assert(x + y + z != 3);
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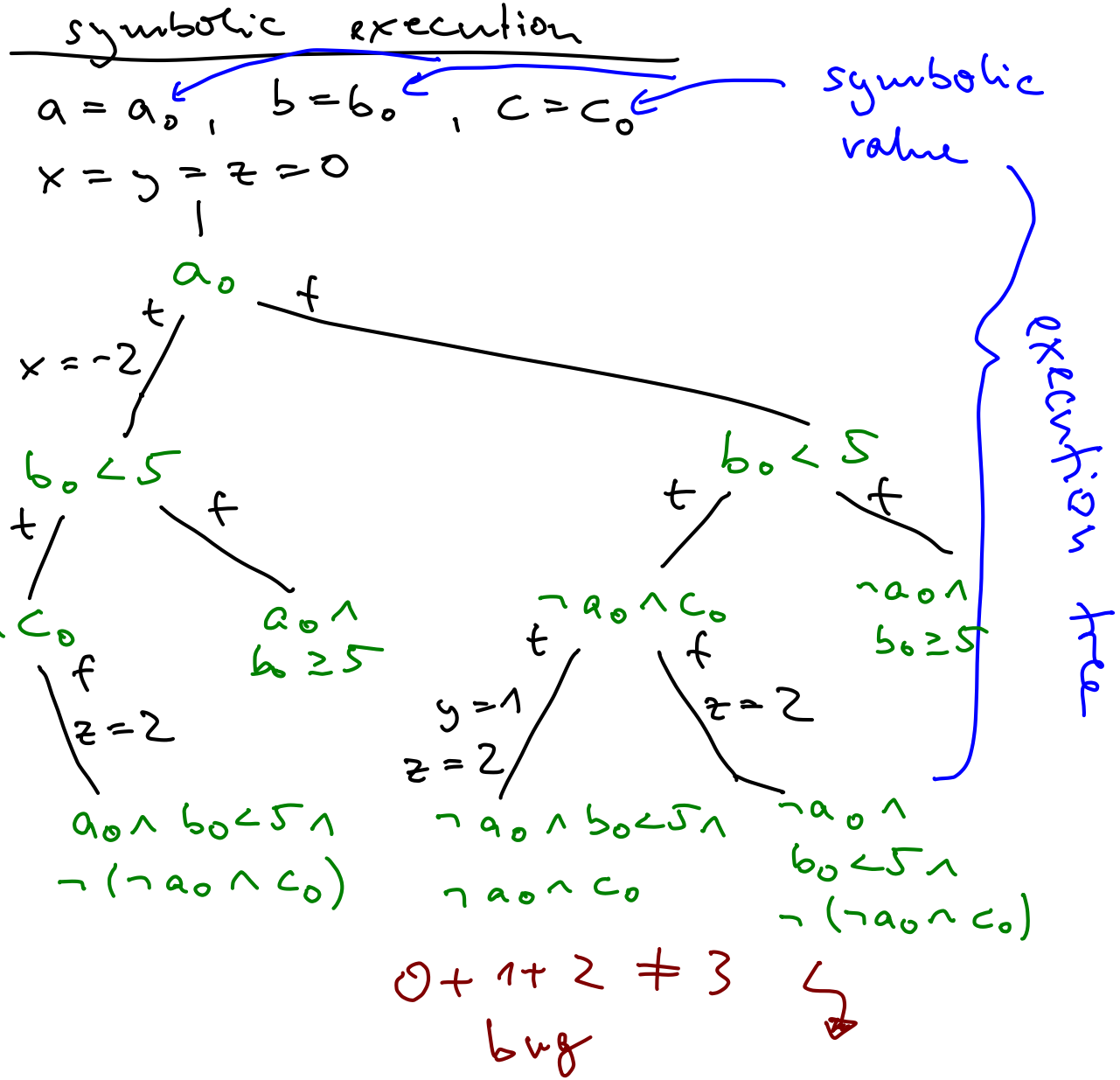
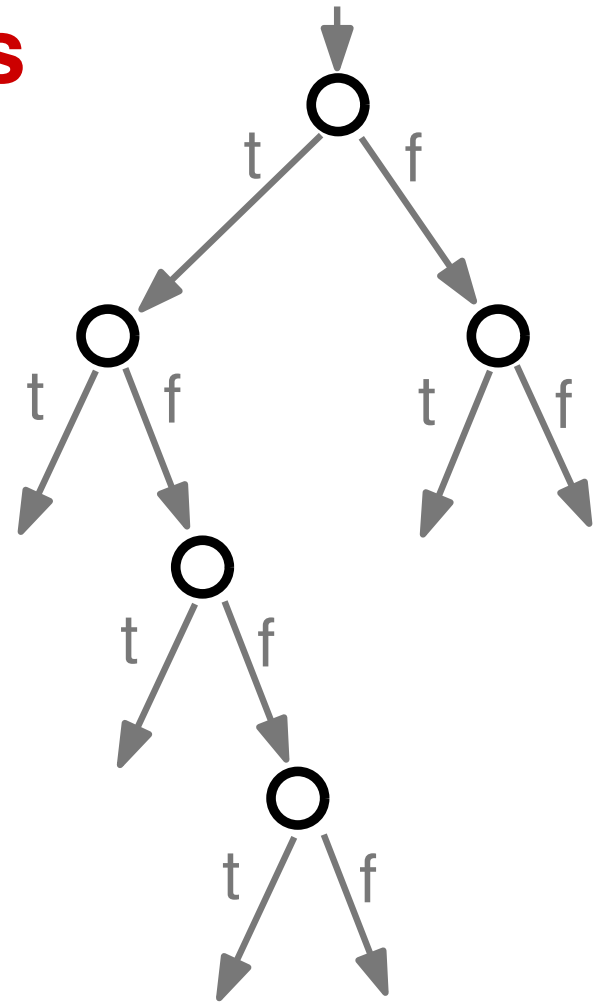


# Execution Tree

## 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



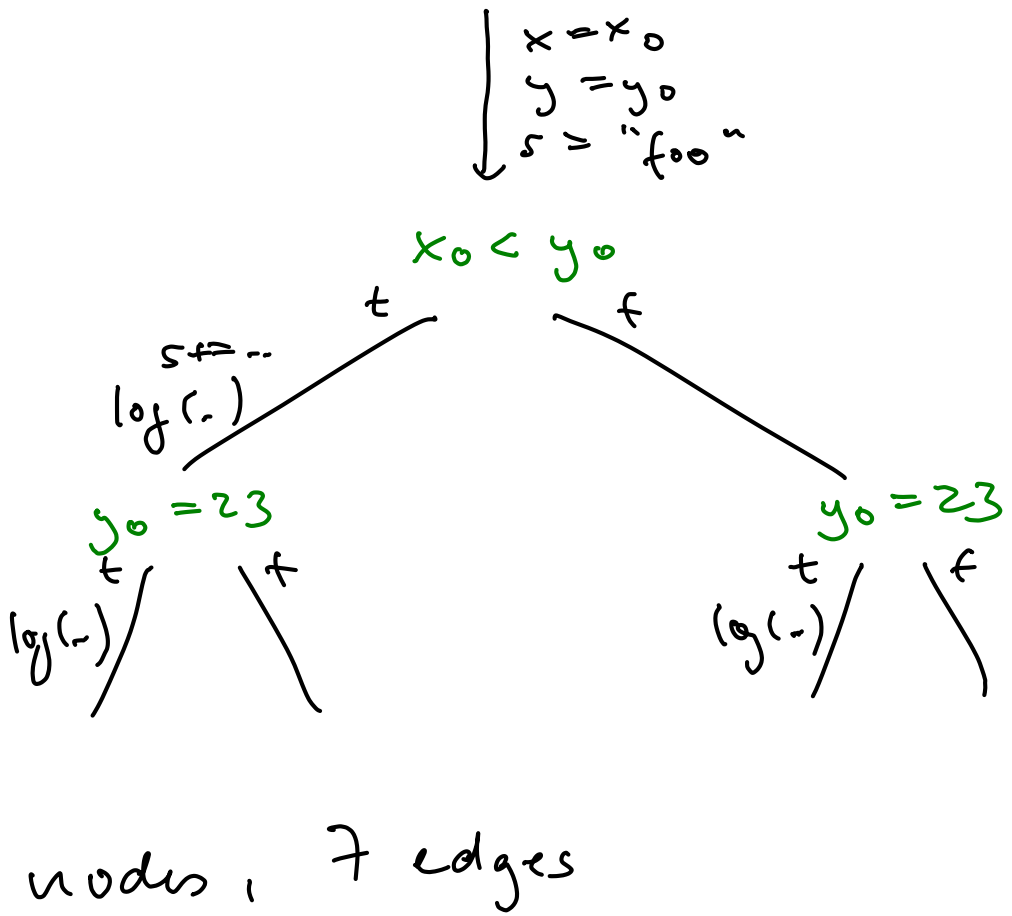
# Quiz

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);
  }
}
```

Quiz:

```
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) {
    ...
  }
}
```

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- 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 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

# Examples

**hand-written notes**

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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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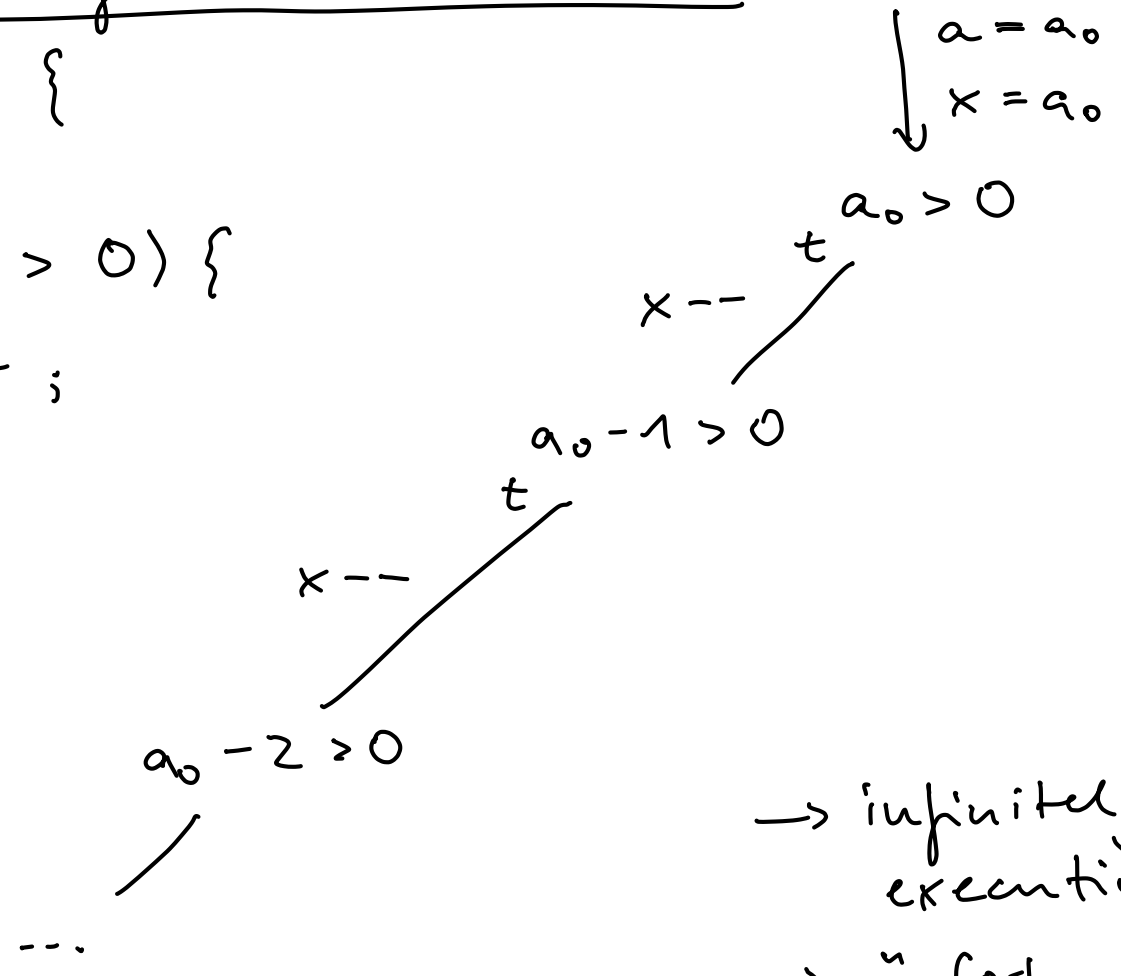
# Dealing with Large Execution Trees

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



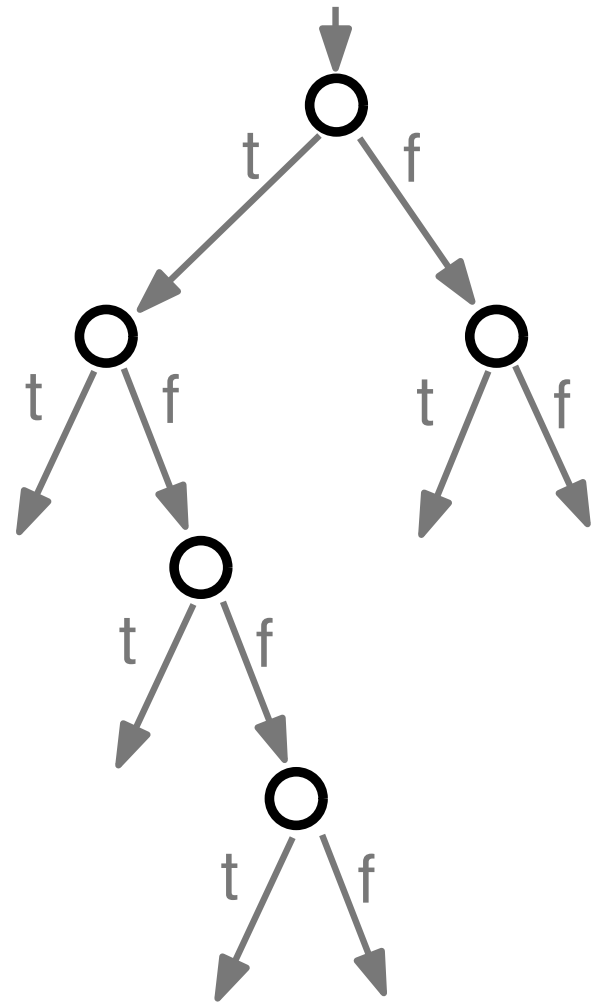

→ infinitely large execution tree

→ "fork bomb"

# 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 names
  }
}
```

# Problems of Symbolic Execution

- Loops and recursion: Infinite execution trees
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**One approach: Mix symbolic with concrete execution**

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# Concolic Testing

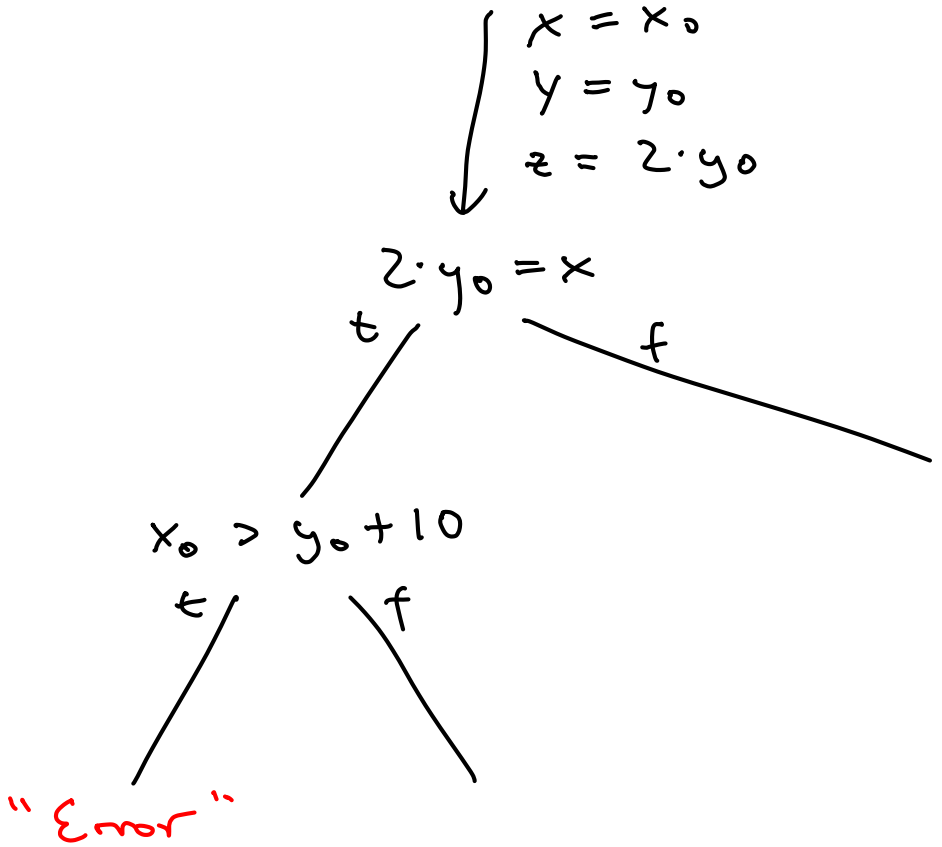
**Mix concrete and symbolic execution = ”concolic”**

- 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

# Concolic Execution: Example

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

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



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 exec. | Path condition |
|---|---|---|
| $x = 22, y = 7$ | $x = x_0, y = y_0$ | |
| $x = 22, y = 7,$ $z = 14$ | $x = x_0, y = y_0,$ $z = 2 \cdot y_0$ | |
| $x = 22, y = 7,$ $z = 14$ | $x = x_0, y = y_0$ $z = 2 \cdot y_0$ | $2 \cdot y_0 \neq x_0$ |

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

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";
    }
  }
}
```

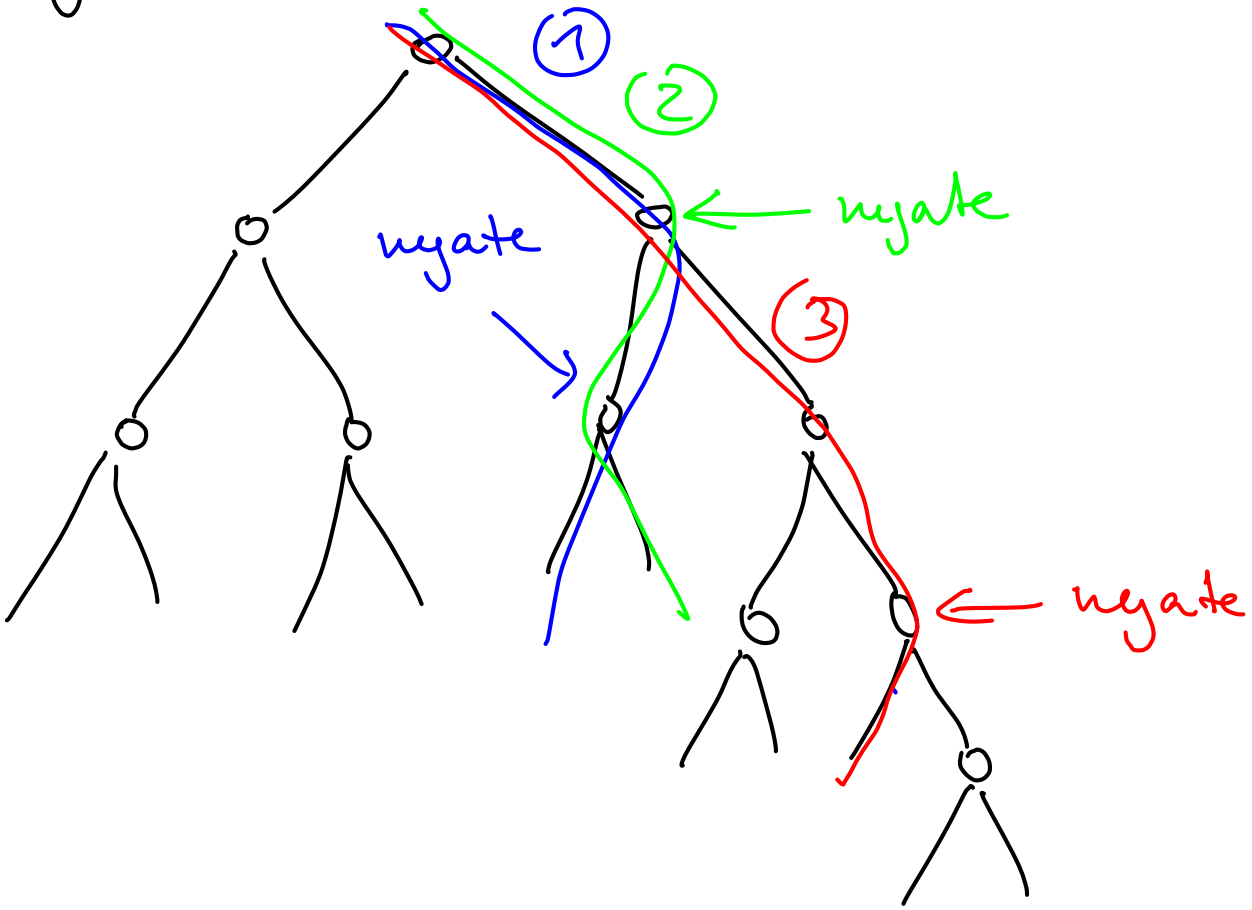
| Concrete exec. | Symb. exec. | Path constraint |
|---|---|---|
| $x = 2, y = 1$ | $x = x_0, y = y_0$ | |
| $x = 2, y = 1, z = 2$ | $x = x_0, y = y_0, z = 2 \cdot y_0$ | |
| — " — | | $2 \cdot y_0 = x_0$ |
| — " — | | $2 \cdot y_0 = x_0 \wedge x_0 \leq y_0 + 10$ |

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

Solution: $x_0 = 30, y_0 = 15$

↪ Will hit error!

# Exploring the execution tree




etc.