Program Analysis – Lecture 8

Symbolic and Concolic Execution (Part 2)

Prof. Dr. Michael Pradel

Software Lab, University of Stuttgart

Winter 2019/2020

Warm-up Quiz

What does the following code print?

```
var x = 23;
function f() { console.log(this.x); }
var obj = Object.create({ f: f });
obj.x = 42;
f();
obj.f();
```

23	42	23	42
23	42	42	23

https://ilias3.uni-stuttgart.de/vote/KN2I

Warm-up Quiz

What does the following code print?

```
var x = 23;
function f() { console.log(this.x); }
var obj = Object.create({ f: f });
obj.x = 42;
f();
obj.f();
```

`obj`'s prototype has method `f`

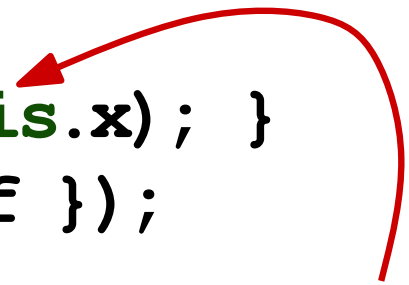
23	42	23	42
23	42	42	23

https://ilias3.uni-stuttgart.de/vote/KN2I

Warm-up Quiz

What does the following code print?

```
var x = 23;
function f() { console.log(this.x); }
var obj = Object.create({ f: f });
obj.x = 42;
f();
obj.f();
```



`this` is determined at call site:

- Simple call: `global`
- Object method: base object

23	42	23	42
23	42	42	23

https://ilias3.uni-stuttgart.de/vote/KN2I

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

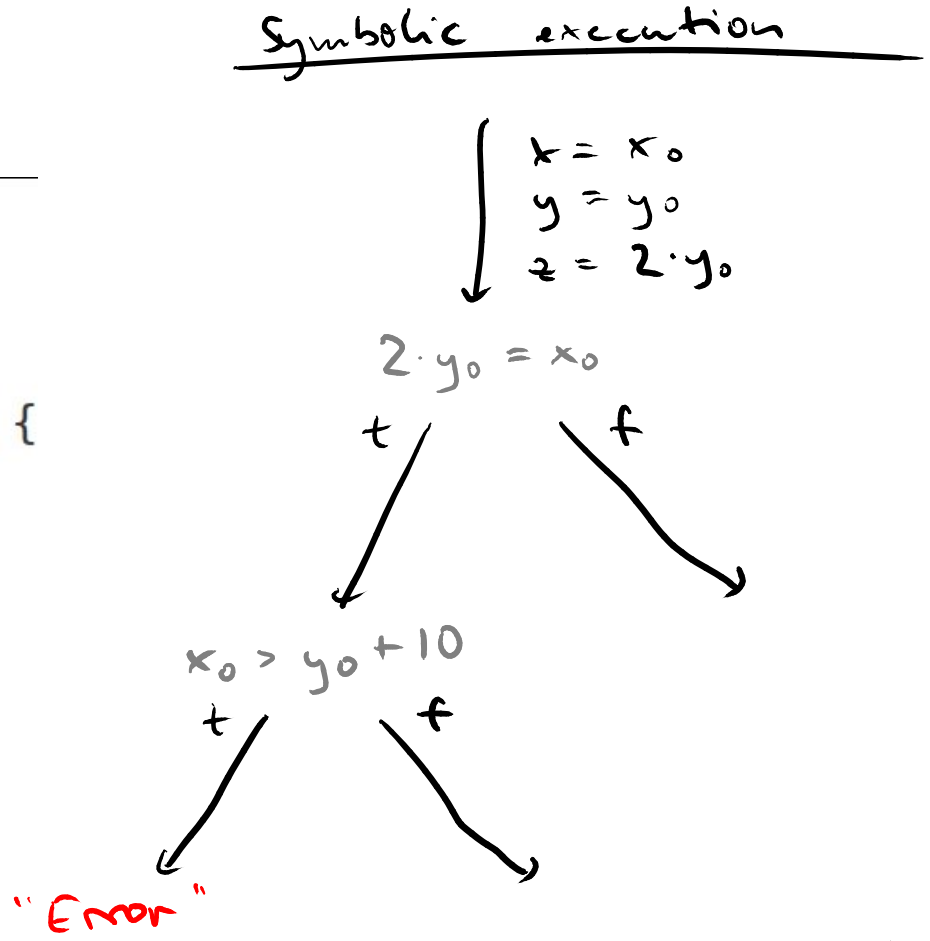
Concolic Testing

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

```
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:

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

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

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

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";
    }
  }
}
```

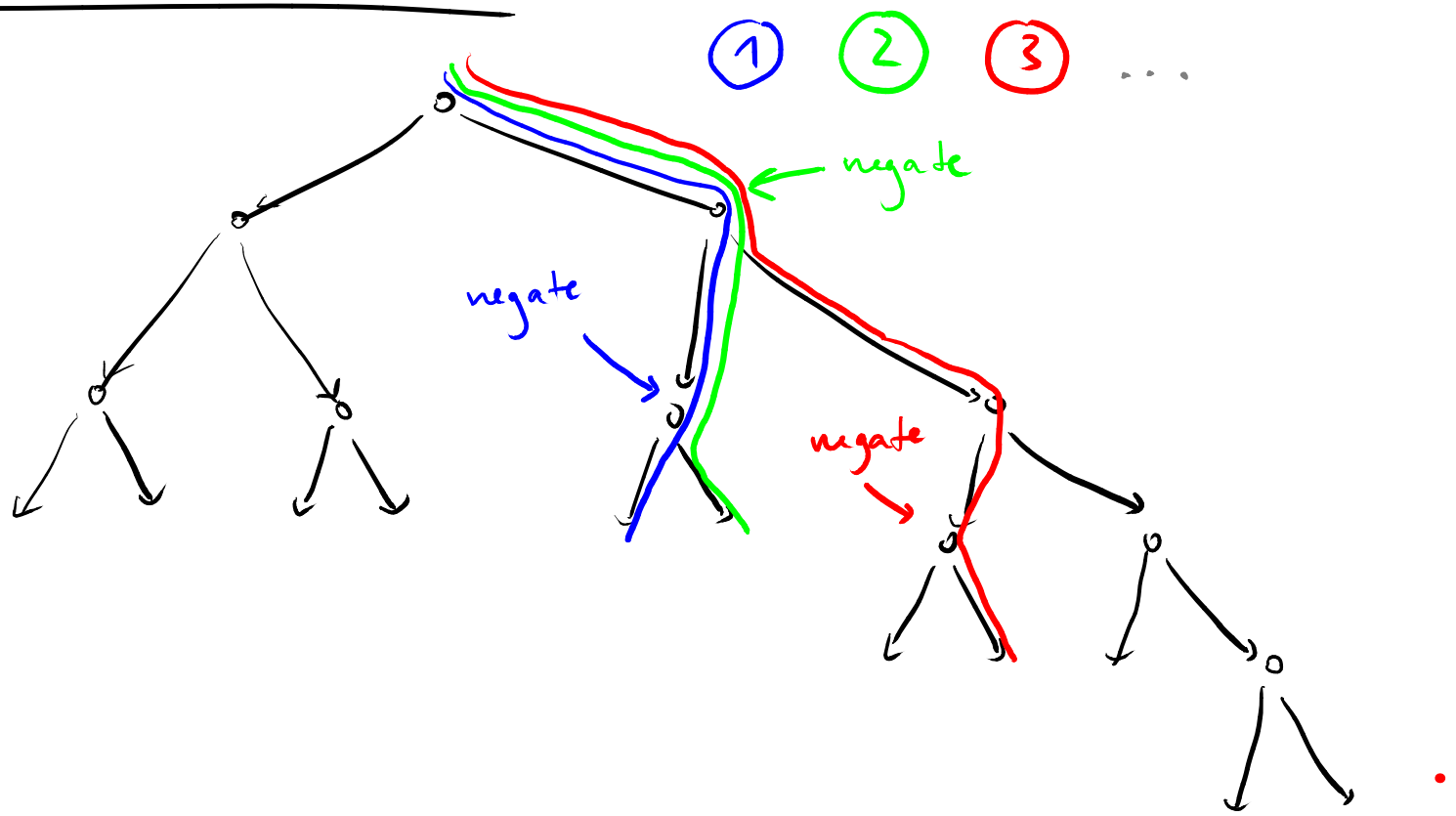
Concrete execution	Symbolic execution	Path conditions
$x = 2, y = 1$	$x = x_0, y = y_0$	
$x = 2, y = 1,$ $z = 2$	$x = x_0, y = y_0,$ $z = 2 \cdot y_0$	
"	"	$2 \cdot y_0 = x_0$
"	"	$2 \cdot y_0 = x_0 \wedge$ $x_0 \leq y_0 + 10$

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("took it");
    }
  }
}
```

First execution

$a = 0$

branch taken

branch not taken

path constraint:

$a_0 \leq 1$

negate & solve:

$a_0 = 2$

Second execution

$a = 2$

branch <u>not</u> taken

→ 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");
    }
  }
}
```

https://ilias3.uni-stuttgart.de/vote/KN2I

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)

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

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