COMP 587: AFL and KLEE

Kyle Dewey

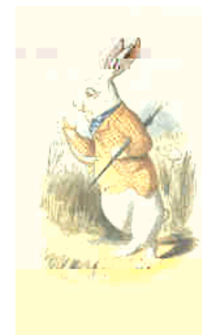
Fuzzing Approaches

- Generation-based: generate whole test inputs from scratch (what we've been doing)
- Mutation-based: generate new test inputs by modifying old ones
- Can do both, even simultaneously

AFL

- Very popular fully-automated fuzzer
- Mutation-based: make new tests by tweaking existing tests
- Tell it where the input is, and it does the rest

AFL - Basic Idea



-Flip bits
-Rearrange bits / bytes
-Randomly inject bits
-Look at code coverage information while this is happening to see if tests are getting into new areas - tests that hit new areas are selected more frequently for mutation

AFL Demo

AFL Highlights

- Fast
- Easy to use
- Needs a *seed corpus* (starting set of tests) to start mutations from
  - Has major impact on performance
- Good, but tends to plateau quickly compared to specialized fuzzers

Symbolic Execution
(Towards KLEE)

Symbolic Execution

- Basic idea: remember the conditions that led you to your current place in the code
  - This is called the *path condition*

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Example

Path Condition

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

`x > 0`

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

```
x > 0 &&
 y > 10
```

-So to print "a", x must be > 0 and y must be > 10

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

`x > 0`

-if, however, we went down the false branch...

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

```
x > 0 &&
!(y > 10)
```

–...then to print "b", it must be that x > 10 and NOT y > 10

Example

Path Condition

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

-Going back to the beginning, if the condition was false...

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

```
!(x > 0)
```

–...then it must be the case that x is not > 0

Concolic Execution

- Combines *concrete* (normal) execution and symbolic execution
- Basic idea: use the path condition to discover test inputs which explore different program paths

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

Tests

`x = 1, y = 1`

–Randomly choose inputs of x = 1 and y = 1

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

Tests

`x = 1, y = 1`

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

Tests

`x = 1, y = 1`

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

`x > 0`

Tests

`x = 1, y = 1`

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

`x > 0`

`x > 0` goes down this path, so `!(x > 0)` goes down another path

Tests

`x = 1, y = 1`

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

`x > 0`

`x > 0` goes down this path, so `!(x > 0)` goes down another path

Tests

`x = 1, y = 1`

`x = 0, y = 1`

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

```
x > 0 &&
!(y > 10)
```

Tests

```
x = 1, y = 1
x = 0, y = 1
```

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

`x > 0 && !(y > 10)`

To go down another path, need

`x > 0 && y > 10`

Tests

`x = 1, y = 1`

`x = 0, y = 1`

Example

```
def foo(x, y):
  if x > 0:
    if y > 10:
      print("a")
    else:
      print("b")
  else:
    print("c")
```

Path Condition

```
x > 0 &&
!(y > 10)
```

To go down another path, need

```
x > 0 && y > 10
```

Tests

```
x = 1, y = 1
x = 0, y = 1
x = 1, y = 11
```

Basic Idea

- Negate parts of the path condition to discover different program paths
- Find inputs which satisfy these negated paths to generate new test inputs
- Keep running generated test inputs and continue this process until all paths are explored

Finding Inputs Satisfying Constraints

- This is what SMT solvers do
- Best-case NP-Complete, worst-case undecidable
- Usually surprisingly fast in practice

`x > 0 && y > 10` → `x = 1, y = 11`

KLEE

- Tool which performs concolic execution
- Has a custom SMT solver internally for doing this quickly (STP)
- Been used to find bugs in tons of systems, including the Linux kernel

KLEE Demo

Concolic Execution Downside

Explores all program paths...whether you want to or not.

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Explores all program paths...whether you want to or not.

```
def bar(x):
  while x > 10:
    x = x - 1
```

Path Condition

Concolic Execution Downside

Explores all program paths...whether you want to or not.

```
def bar(x):
  while x > 10:
    x = x - 1
```

Path Condition

`!(x > 10)`

Tests

`x > 10; x = 11`

Concolic Execution Downside

Explores all program paths...whether you want to or not.

```
def bar(x):
  while x > 10:
    x = x - 1
```

Path Condition

Tests

`x > 10; x = 11`

Concolic Execution Downside

Explores all program paths...whether you want to or not.

```
def bar(x):
  while x > 10:
    x = x - 1
```

Path Condition

`x0 > 10`

Tests

`x > 10; x = 11`

Concolic Execution Downside

Explores all program paths...whether you want to or not.

```
def bar(x):
  while x > 10:
    x = x - 1
```

Path Condition

`x0 > 10`

Tests

`x > 10; x = 11`

Concolic Execution Downside

Explores all program paths...whether you want to or not.

```
def bar(x):
  while x > 10:
    x = x - 1
```

Path Condition

`x0 > 10 &&`
`!(x1 > 10)`

Tests

`x > 10; x = 11`

-Key point: each iteration introduces a new variable into the path constraint
-There are ways around this in specific cases, but loops can trip up symbolic execution systems

Concolic Execution Overall

- Great for code dealing with specific conditions which are unlikely to hit otherwise
- Can get tripped up on loops