CS 489 / 698: Software and Systems Security

Module 2: Program Security (Defenses)
fuzz testing

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Spring 2023

Outline

1. Introduction
2. Evolution: from the rain-fuzzer to modern fuzzing
3. Program state coverage: “natural selection” in the fuzzing world
4. Loops: another trouble maker for branch coverage
5. Concolic execution: forced path exploration
6. Conclusion

History: why we call it “fuzzing”?

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And these noise caused applications that were using data off the dial-up network line to crash.

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And these noise caused applications that were using data off the dial-up network line to crash.

Gist of the story? — The rain tests the program way better than human beings.

The goal of fuzzing

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A: To drive the execution of a system into desired states.

Elaborating the definition

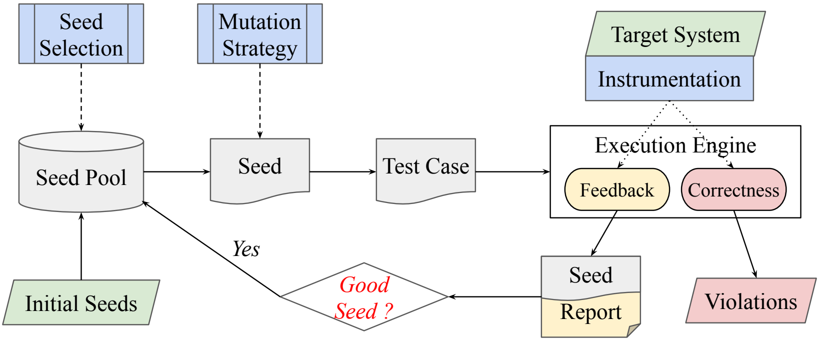
- What is special about the target system?
  - Do we know the source code?
  - Do we know the input format?
  - What are the challenges when executing the "system"?
- What do we mean by a state?
  - How can we tell that one state is different from another?
- What do we mean by desired?
  - New/unseen behavior?
  - Closeness to targeted execution points?
- What do we mean by driving the execution?
  - What can possibly be one mutation?
  - How do you select the next mutation?

Outline

Genetic algorithm

Training a program to play the snake game with genetic algorithm

Feedback-guided evolution process



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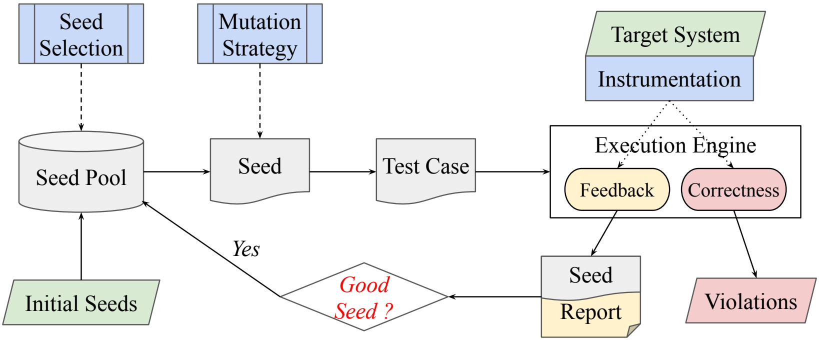

Natural selection — survival of the fittest

Demo with AFL++

Acknowledgement: this demo is based on one of the examples used in the "Fuzzing with AFL" workshop by Michael Macnair.

Outline

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pub fn foo(a: num, b: num) {
    let c = if (a >= 0) {
        1
    } else {
        2
    };

    // irrelevant operations

    let d = if (b >= 0) {
        2
    } else {
        3
    };

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    assert!(c != d);
}
```

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$\Longrightarrow$ if the fuzzer generates an input that expands the coverage, that input is a good seed.

Illustration of different coverage metrics

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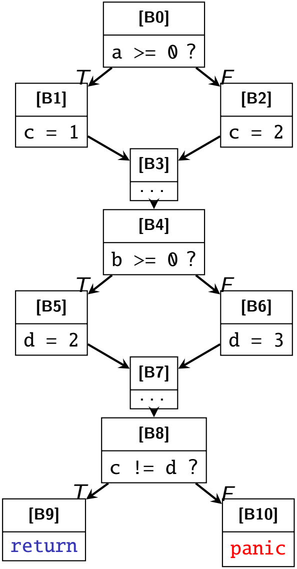

Illustration of different coverage metrics

- Cover every line?
  - Block coverage
- Cover every if-else branch?
  - Branch coverage
- Cover every exit status?
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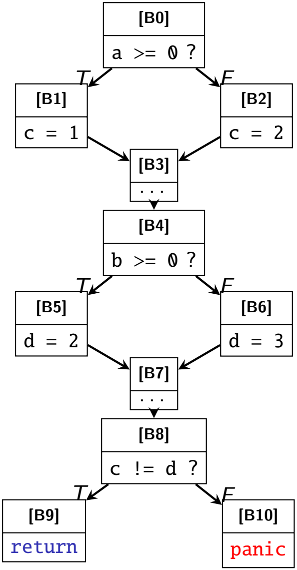

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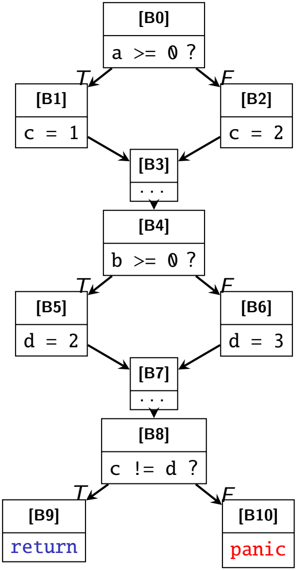
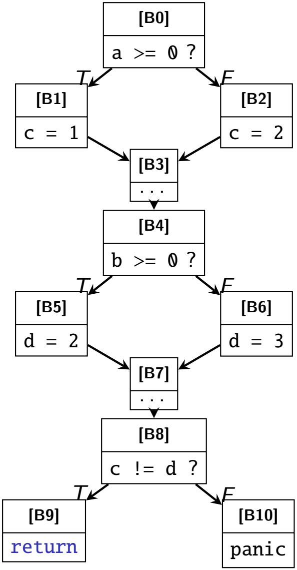


Path coverage: a theoretical optimum

Claim: A program is saturately tested if we obtain a set of inputs that covers every feasible path of the program CFG.

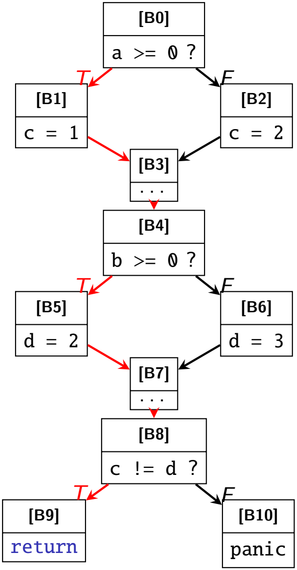
NOTE: feasible paths include paths that leads to explicit and implicit panics.

Path coverage demo



Path coverage demo

- a = 1, b = 1



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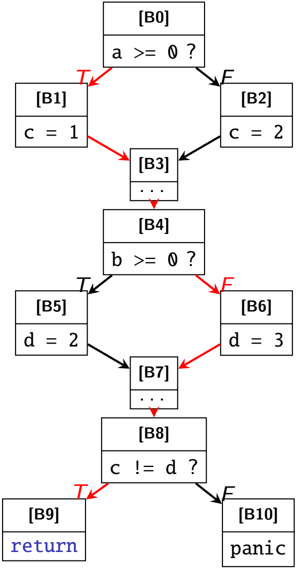

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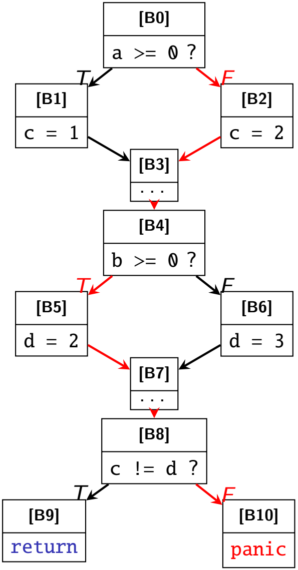

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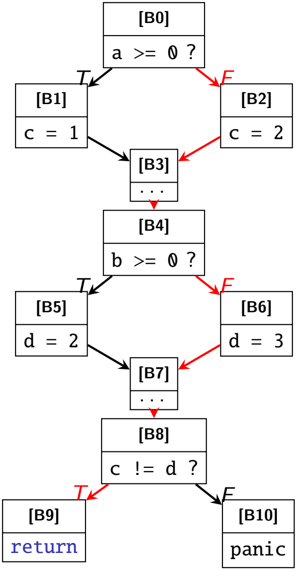

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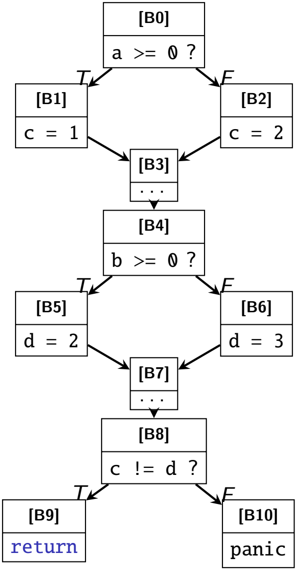
No new program behaviors can be discovered $\Longrightarrow$ the program is saturately tested



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Short answer: I don't know... AFL (American Fuzzy Lop) didn't adopt path coverage, so everyone follows suite...

Long answer:

- tracking block / branch coverage is stateless while tracking path coverage requires stateful instrumentations.
- different parts of the execution are not necessarily related, i.e., a new path does not necessarily mean interesting findings.
- it is hard to quantitatively measure the completeness of path coverage (because of infeasible paths). But by default, all branches should be somewhat feasible.

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In practice, branch coverage hits a nice balance between effectiveness and easiness of instrumentation.

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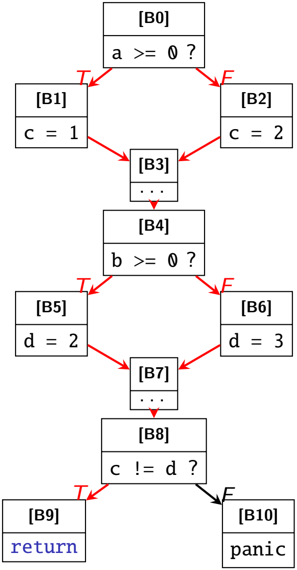

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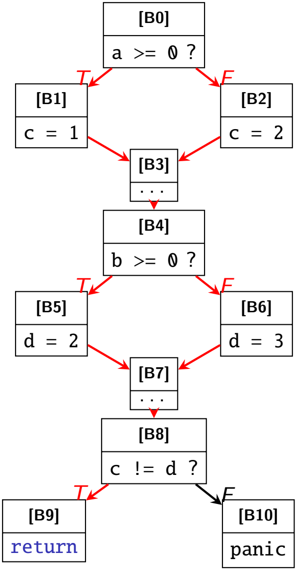

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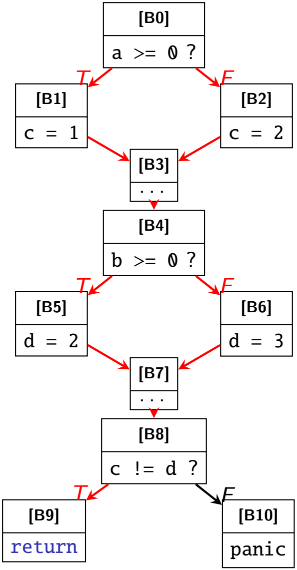

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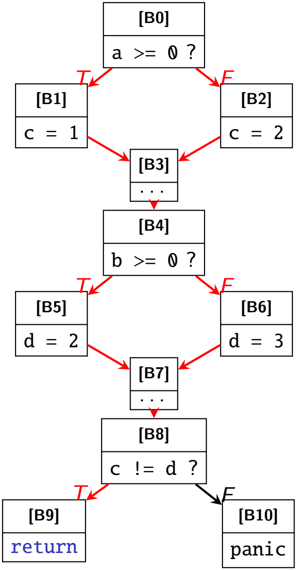
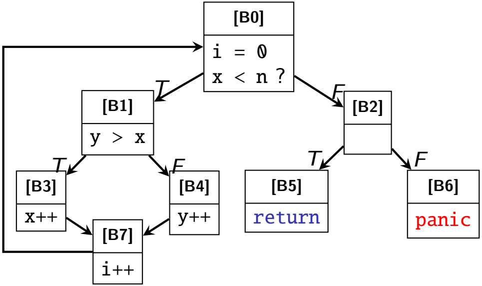
$\Longrightarrow$ fuzzer is not rewarded by mutating `a` and `b`, hence, lowering their priorities and the panic case may never be found, especially when fuzzing complex CFGs



Outline

Looping example

```
pub fn looping(
  x: num,
  y: num,
  n: num
) {
  let i = 0;
  while (x < n) {
    if (y > x) {
      x++;
    }
    else {
      y++;
    }
    i++;
  }
  assert!(i != 7);
}
```



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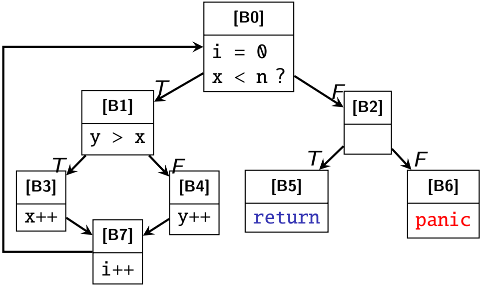

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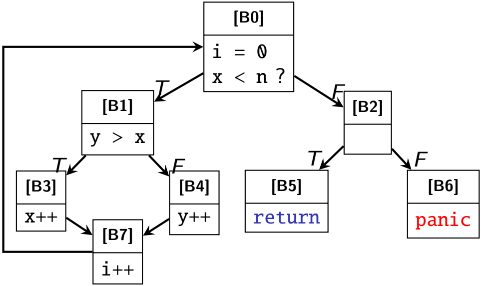

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`x < y <= n`

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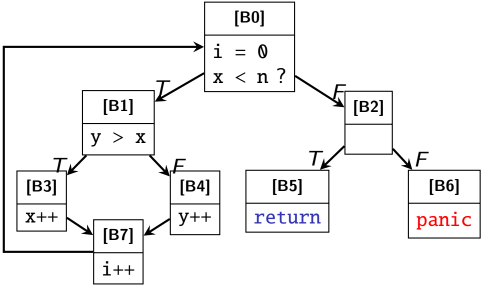
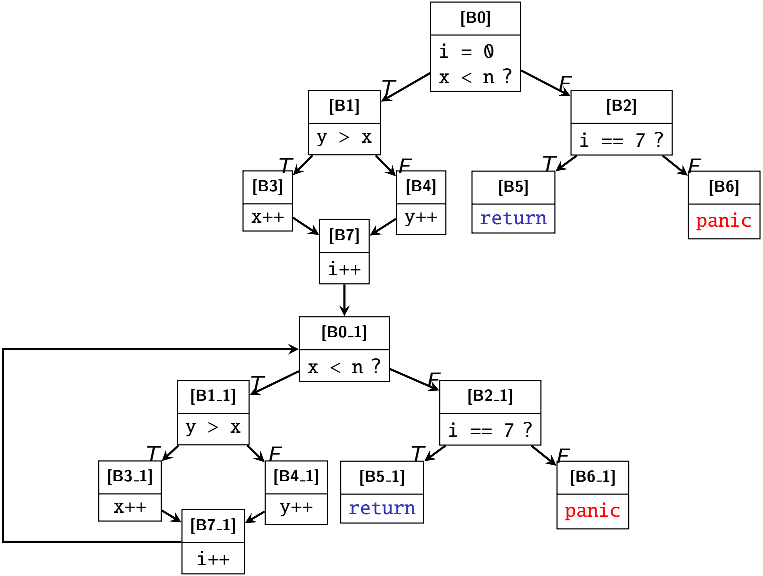


y <= x < n	x < y <= n	x < n <= y
1 y++ until y == x	1 x++ until x == y	1 x++ until x == n
2 y++; x++ until x == n	2 y++; x++ until x == n	

Solution: bounded loop unrolling



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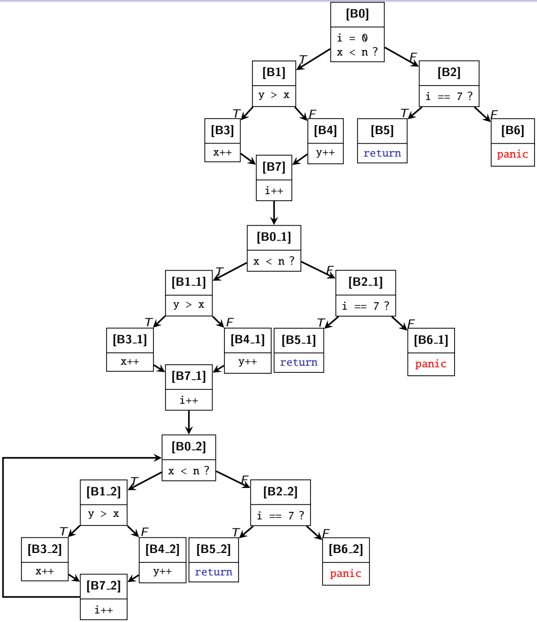

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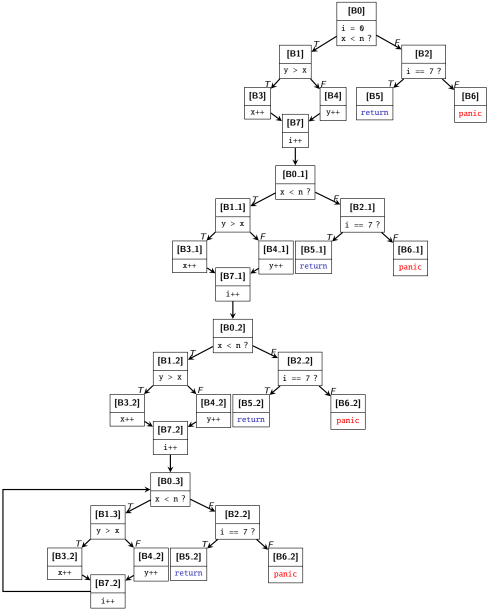

Outline

Narrow-range constraints

Random input generation is not suitable for passing narrow-ranged constraints. For example:

```
fn foo(x: u64, y: u64) {
  if x + y = 42 {
    panic!();
  }
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If x and y are randomly generated u64, the chances that their sum equals 42 is extremely low.

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If `x` and `y` are randomly generated `u64`, the chances that their sum equals 42 is extremely low.

On the other hand, this is much easier for SMT solvers to produce valid values for `x` and `y` that satisfies this constraint.

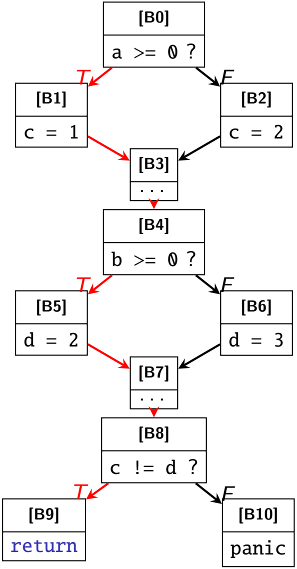
The general intuition behind concolic execution

Let fuzzing do must of the state exploration. If the coverage saturates, i.e., the fuzzer is not able to make progress on finding new coverage, invoke the symbolic reasoning engine to breakthrough.

Concolic execution demo

- a = 1, b = 1

We start with a sample input for the program, and execute the input concretely to obtain an execution trace.



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Query 1: given constraint $a \geq 0 \wedge b \geq 0$ and the program, can we toggle $c \neq d$?
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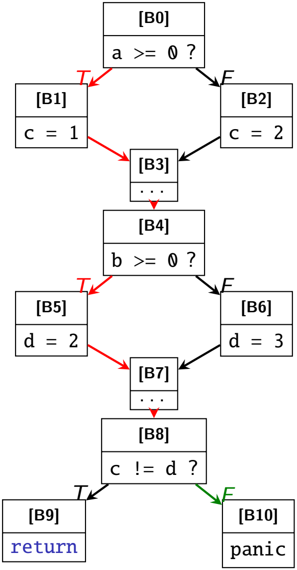

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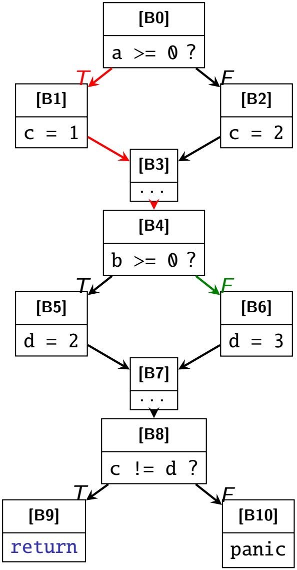

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Query 3: given constraint *true* and the program, can we toggle $a \geq 0$?
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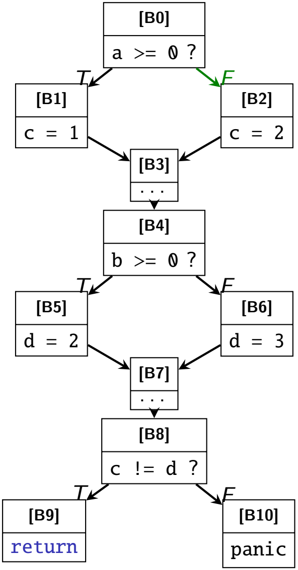

Outline

A comprehensive survey of current works

Fuzzing Family Tree

$\langle$ **End** $\rangle$