CS 453/698: Software and Systems Security

Module: Bug Finding Tools and Practices
Lecture: Fuzz testing (a.k.a., fuzzing)

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Outline

1. Introduction
2. Program state coverage: "natural selection" in the fuzzing world
3. Conclusion

Program assurance

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In 80’s, someone remotely logged into a unix system over a dial-up network link during a storm.

The rain caused a lot of random noise on the dial-up link.

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

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

Evolution: from the rain-fuzzer to modern fuzzing

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The key is **genetic algorithm**.

Training a program to play the snake game with genetic algorithm

A classical example

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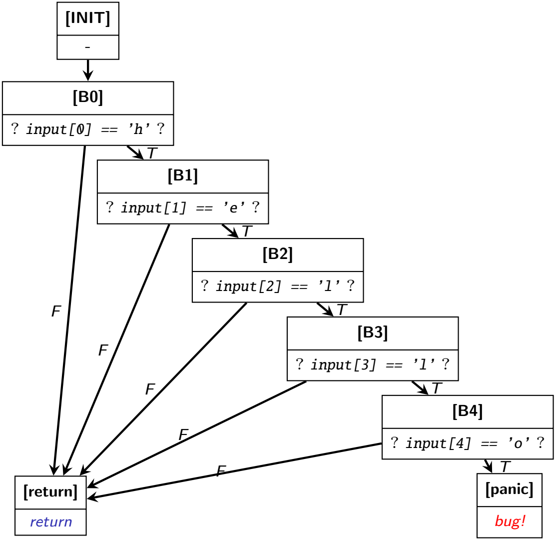
```
pub fn hello_fuzzer(input: Vec<u8>) {
    /* h */
    if input[0] == 0x48 {
        /* e */
        if input[1] == 0x65 {
            /* l */
            if input[2] == 0x6c {
                /* l */
                if input[3] == 0x6c {
                    /* o */
                    if input[4] == 0x6f {
                        panic!("found the bug!");
                    }
                }
            }
        }
    }
}
```

Control-flow graph (CFG)



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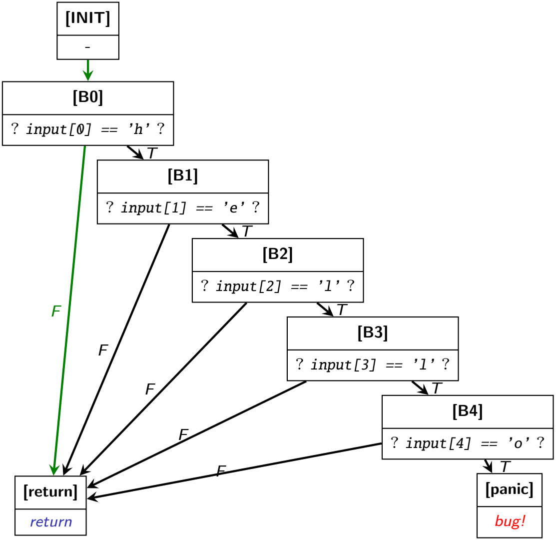

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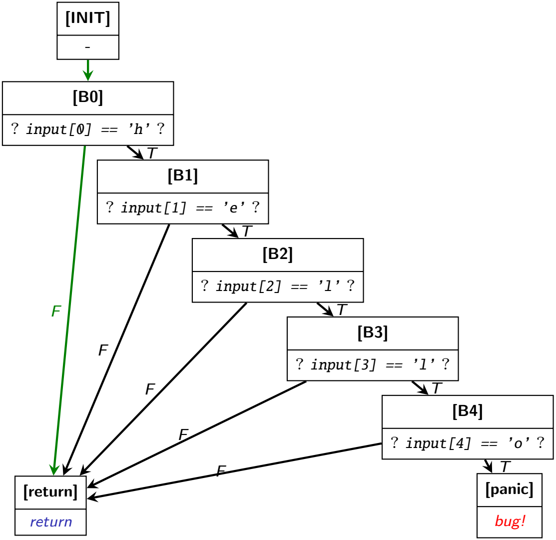

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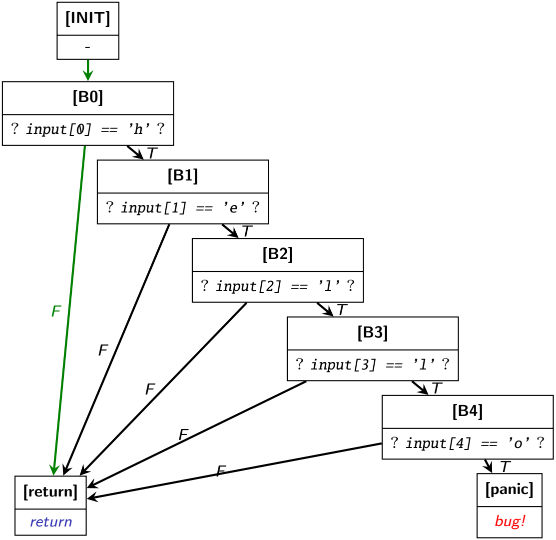

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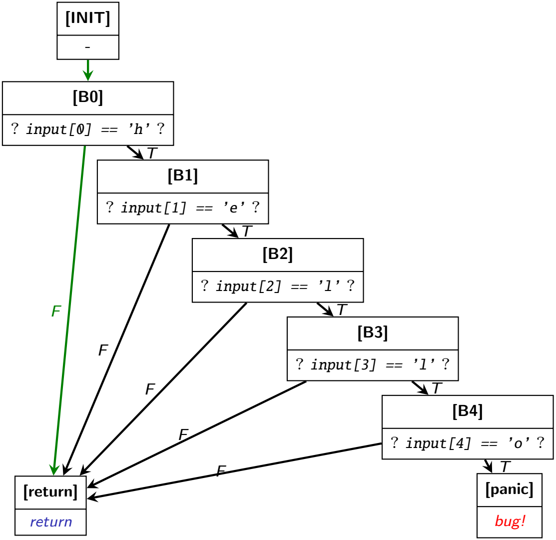

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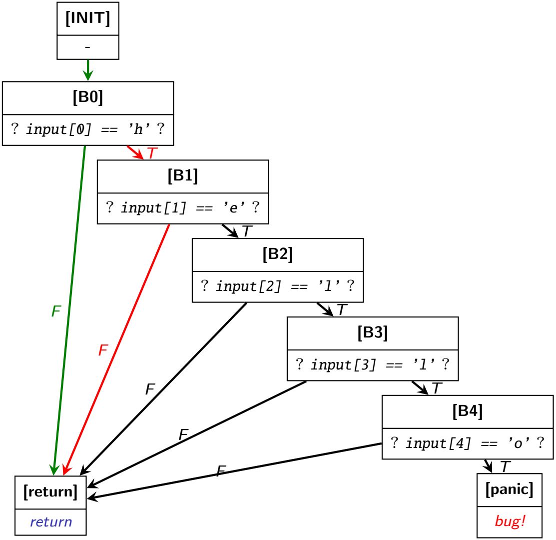

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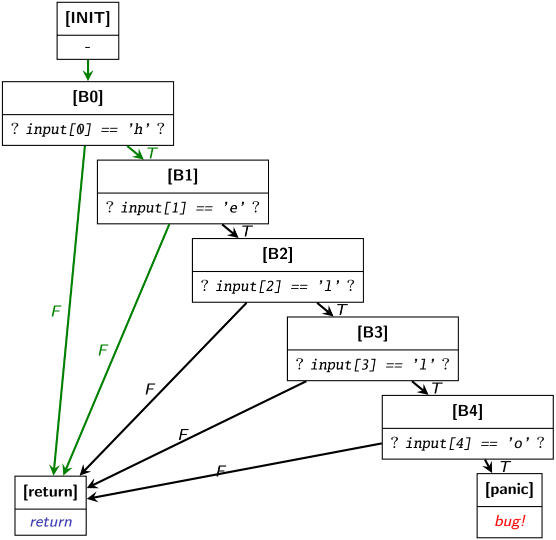


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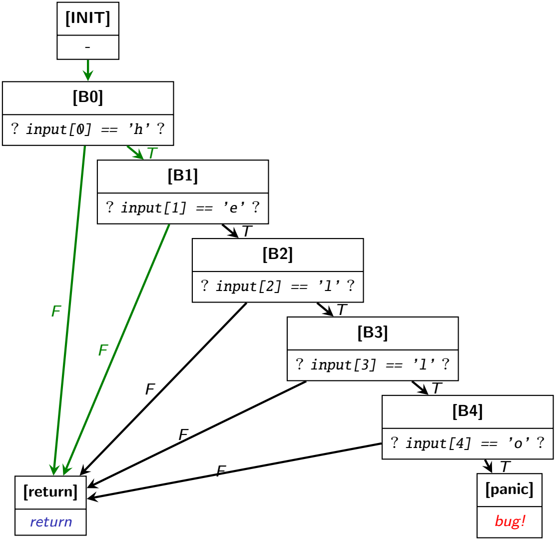

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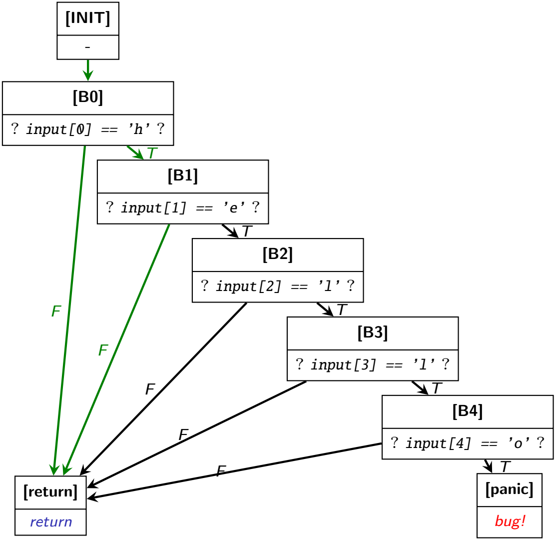


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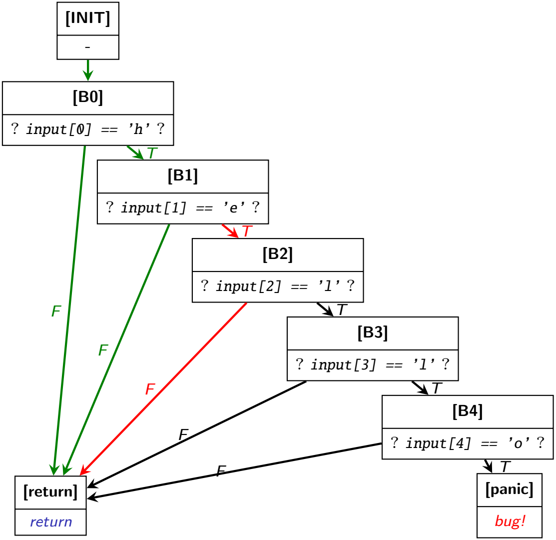

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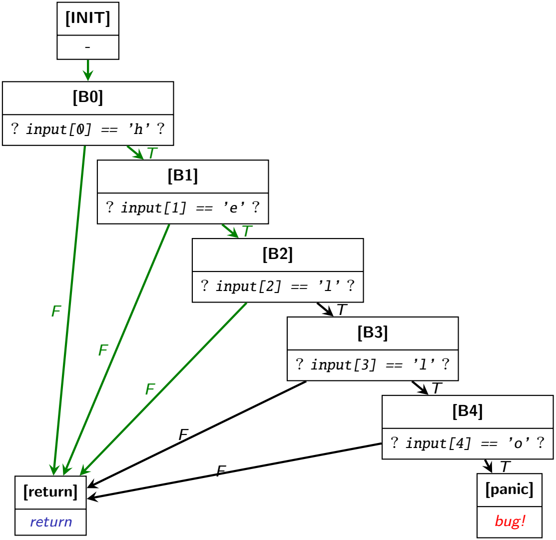

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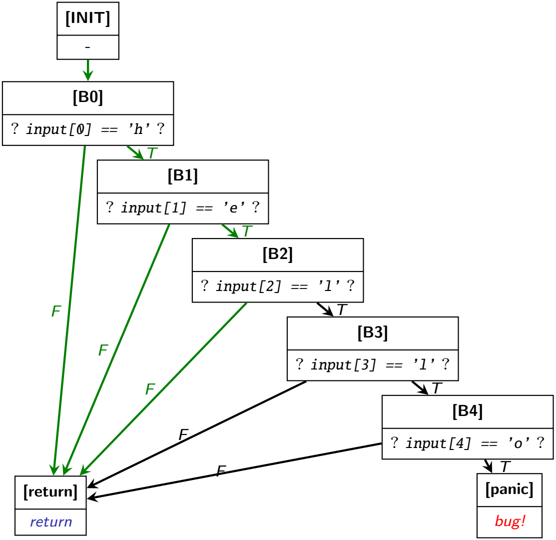

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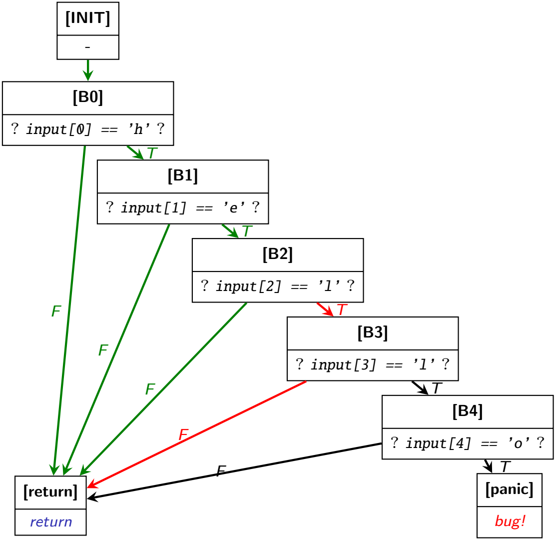

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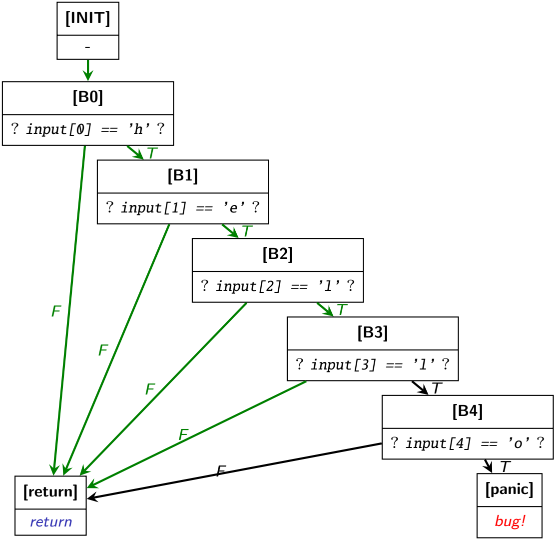

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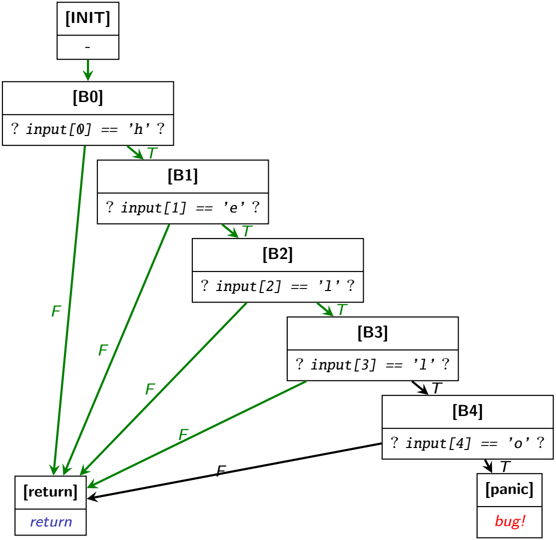

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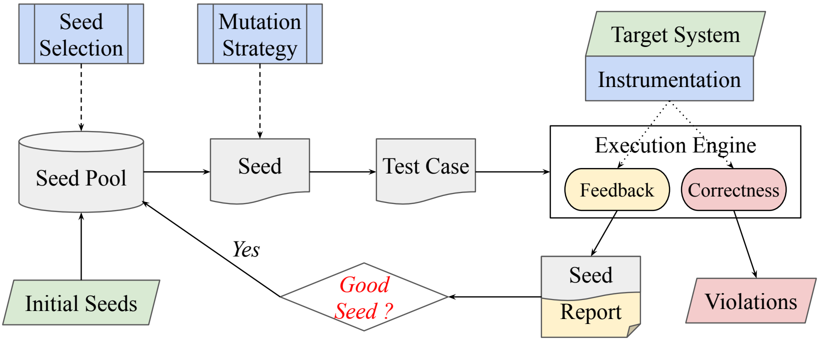
Test cases that yield new coverage are called **seeds**.

Feedback-guided evolution process



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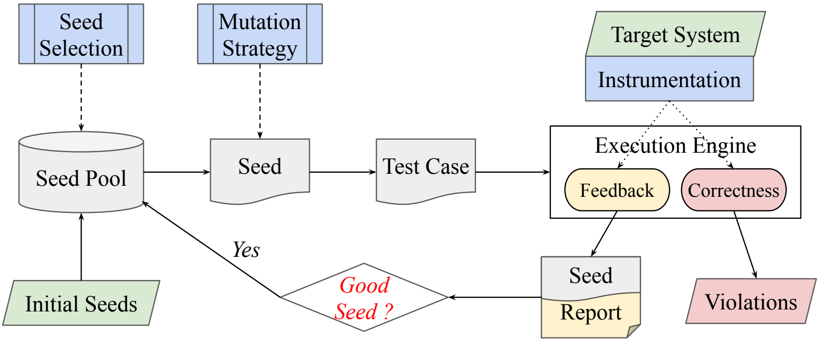

Natural selection — survival of the fittest

Demo with AFL++

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

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Intuition: what makes a high-quality seed?

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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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```

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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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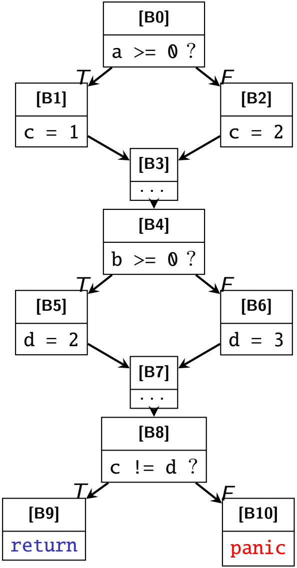

Illustration of different coverage metrics

- Cover every line?
  - Block coverage
- Cover every if-else branch?
  - Branch coverage
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  - Return coverage
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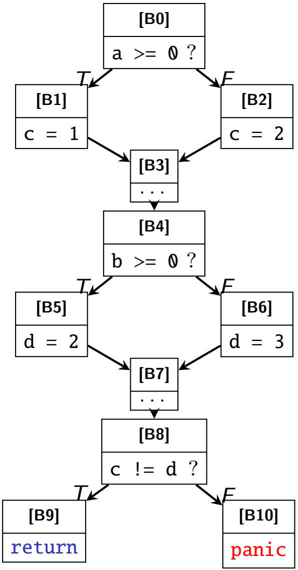

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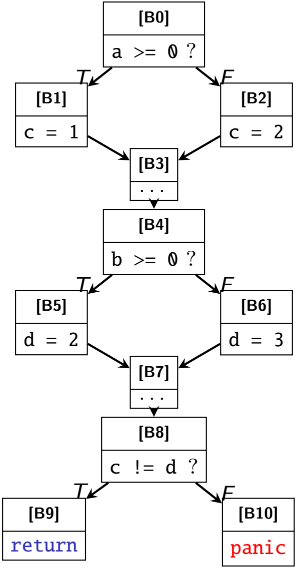
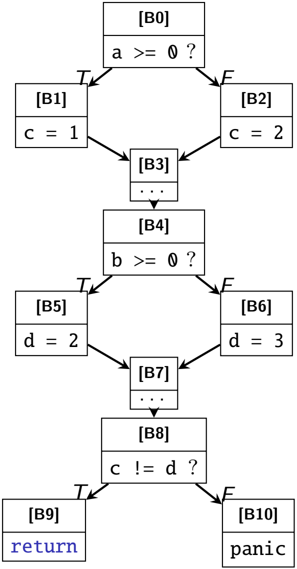


Path coverage: a theoretical optimum

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

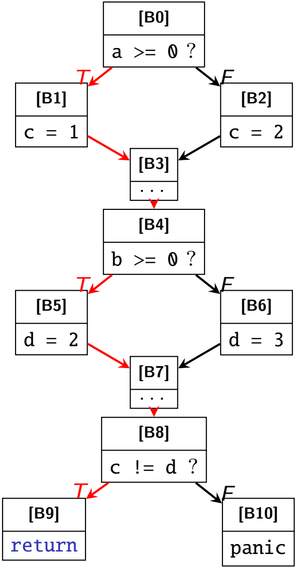
NOTE: feasible paths include paths that leads to explicit and implicit panics.

Path coverage demo



Path coverage demo

- a = 1, b = 1



Path coverage demo

- a = 1, b = 1
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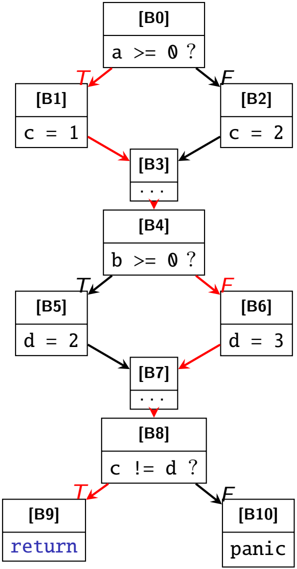

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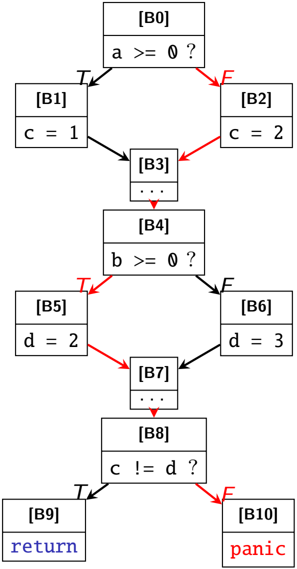

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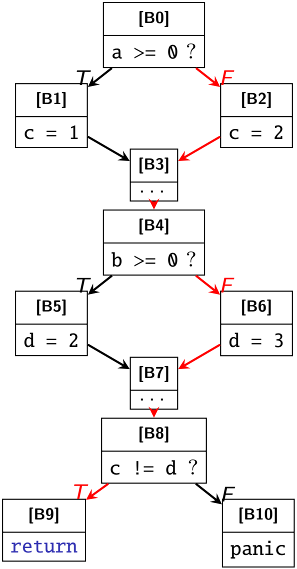

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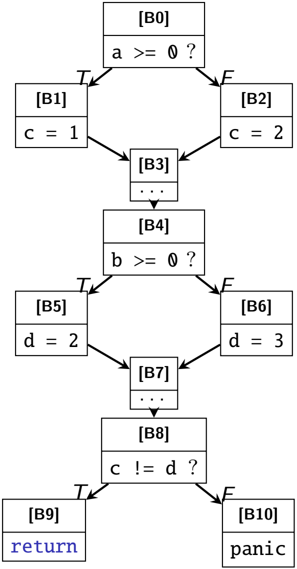
No new program behaviors can be discovered $\implies$ the program is saturately tested



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

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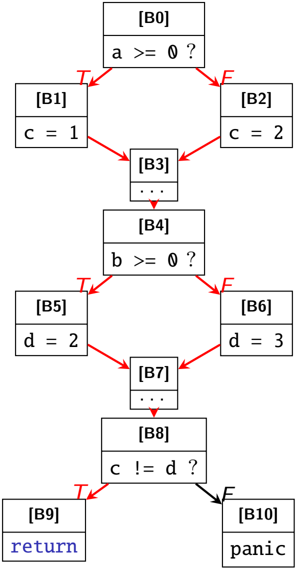

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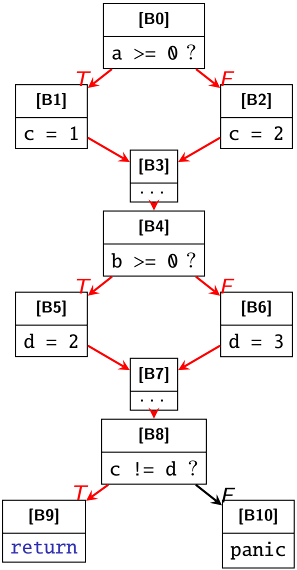
A seed that yields new path but is considered as a bad seed as it yields no new branch coverage.



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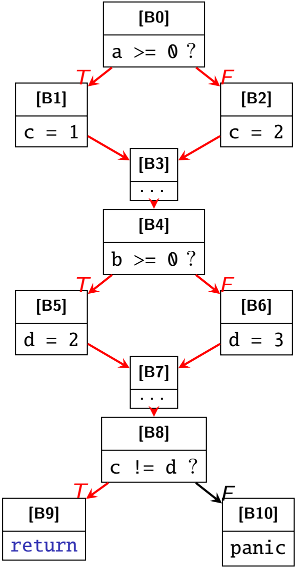

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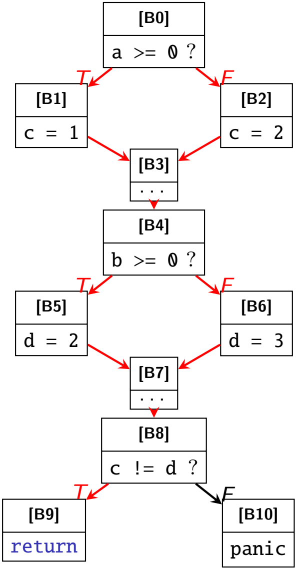
$\Longrightarrow$ fuzzer is not rewarded by mutating `a` and `b`, hence, lowering their priorities and the panic case may never be found, especially when fuzzing complex CFGs



Programs with loops: an example

```
// implementation of `calc`
fn calc(
  x: u64, y: u64, n: u64
) -> (u64, u64, u64) {
  let a = x, b = y, i = 0;
  while (a < n) {
    if (b > a) {
      a++;
    } else {
      b++;
    }
    i++;
  }
  return (a, b, i);
}
```

```
// use the `calc` function
pub fn main() {
  let (x, y, n) = /* input */;
  let (a, b, i) = calc(x, y, n);
  assert!(n-a-b+i != 42);

}
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Programs with loops: an example

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  let a = x, b = y, i = 0;
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  return (a, b, i);
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  let (x, y, n) = /* input */;
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Q: When should fuzzing end?

A: The *de facto* answer is: when achieved 100% code coverage.

CFG and code coverage

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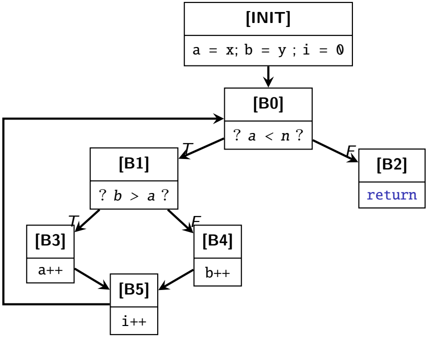
Figure: the control-flow graph (CFG) of function `calc(..)`



CFG and code coverage

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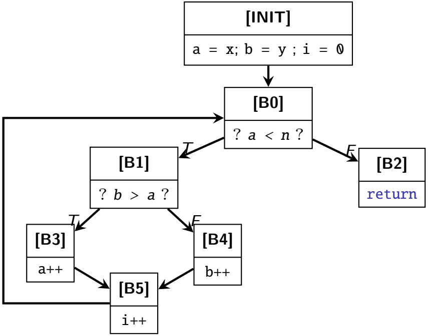

100% code coverage usually means:

- all nodes in the CFG, or
- all edges in the CFG

100% coverage does not imply a worry-free program

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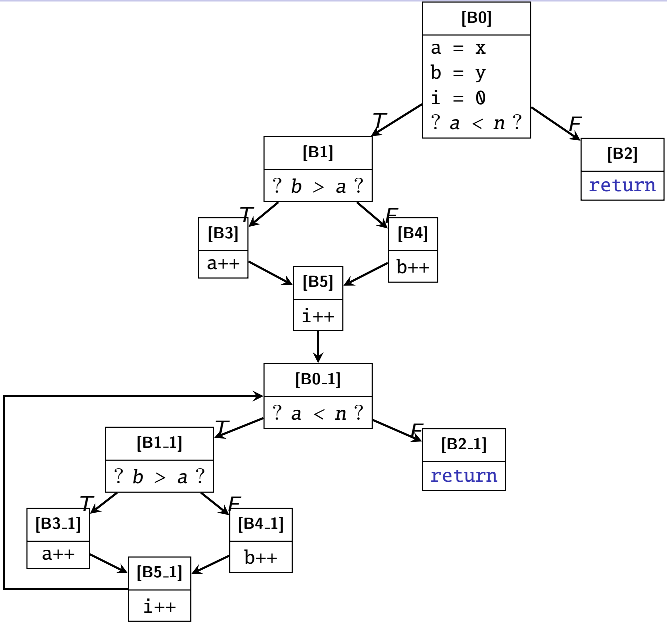

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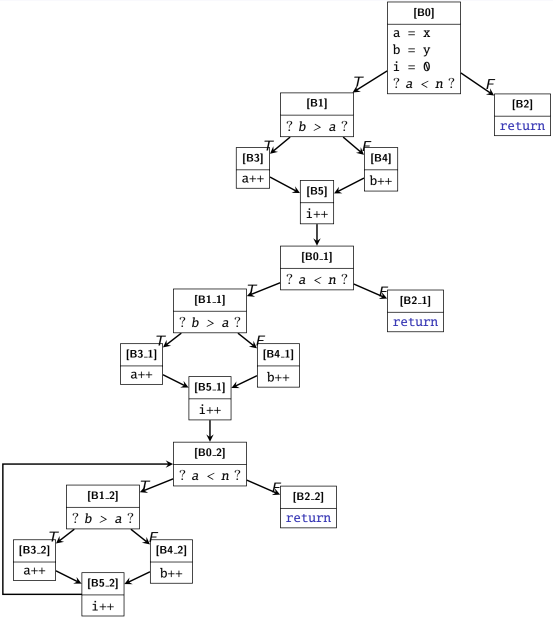

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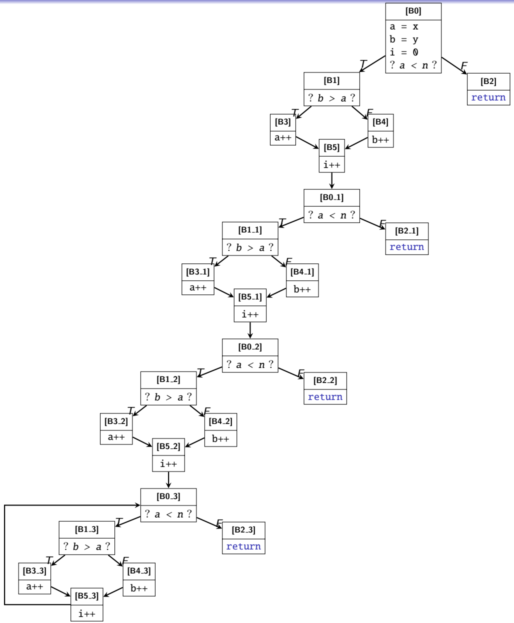

Outline

The goal of fuzzing

Q: What is fuzzing doing essentially? Try to describe it in a way that is as abstract/general as possible.

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

Elaborating on 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?

⟨ **End** ⟩