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

Program assurance

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- Latest development: **concolic execution**
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  x: u64, y: u64, n: u64
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```rust
// use the `calc` function
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  // use the results
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We know how to use calc (as shown in the main function).

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More importantly, we know when calc is wrong (by the assertion the `main` function).

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Real-world software is of course more complicated than this simple example.

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Q: Now we have the source code of the calc function, how do we know it is correct?

A: Just try it with some concrete inputs and see if the results match with our expectations.

Outline

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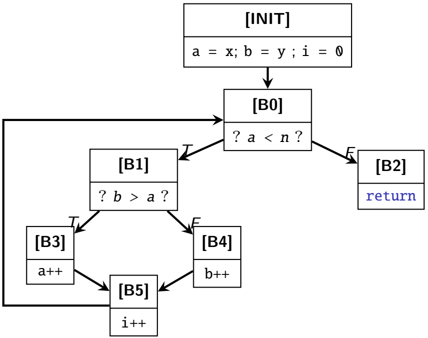
Figure: the control-flow graph (CFG) of function `calc(..)`



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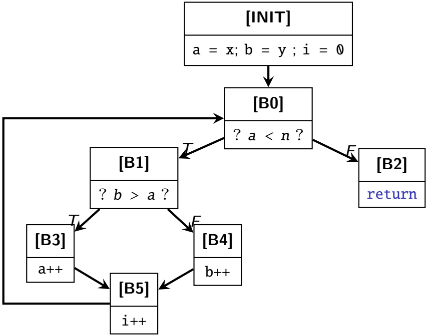

100% code coverage usually means:

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

100% coverage does not imply a worry-free program

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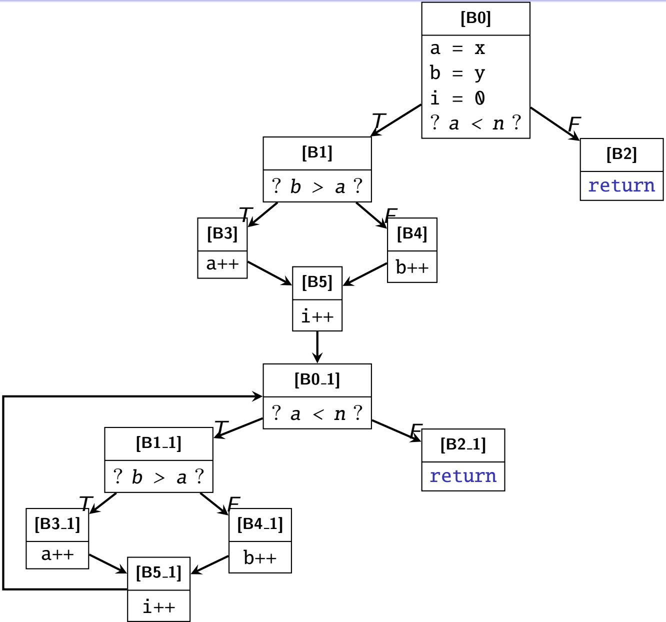
Reason: loop unrolling yields new components in CFG



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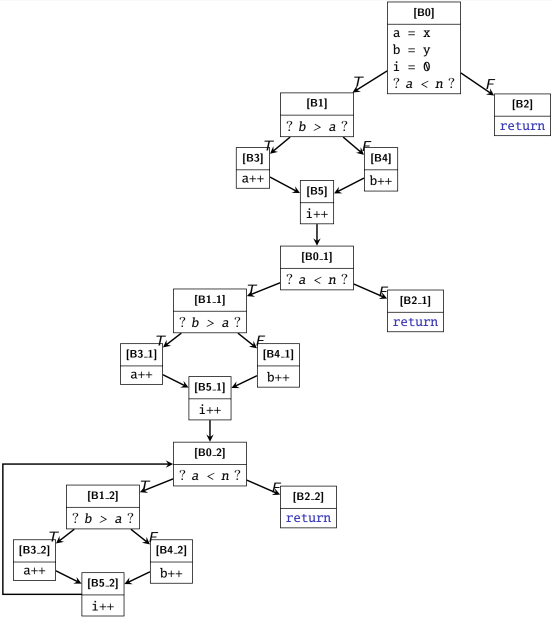

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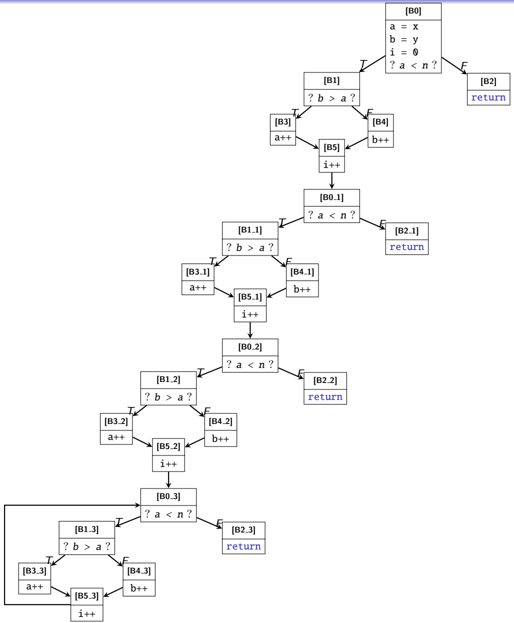

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A genetic programming solution: coverage-guided fuzzing.

1. Randomly selects a seed s from a pool of test cases (seed pool)
   - e.g., seed test case $s = \{\ \mathtt{x}{=}0,\ \mathtt{y}{=}1,\ \mathtt{n}{=}2\ \}$
2. Mutate seed s to produce a new test case t
   - e.g., test case $t = \{\ \mathtt{x}{=}0,\ \mathtt{y}{=}42,\ \mathtt{n}{=}2\ \}$
3. Execute t and collect coverage on the CFG during execution
   - if t yields new coverage, save t to the seed pool
   - otherwise, discard t
4. Go back to step 1 — completing one round of evolution

Outline

1. Introduction
2. Testing with concrete inputs
3. Fuzzing overview
4. Program state coverage: “natural selection” in the fuzzing world
5. Conclusion

History: why do we call it “fuzzing”?

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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.

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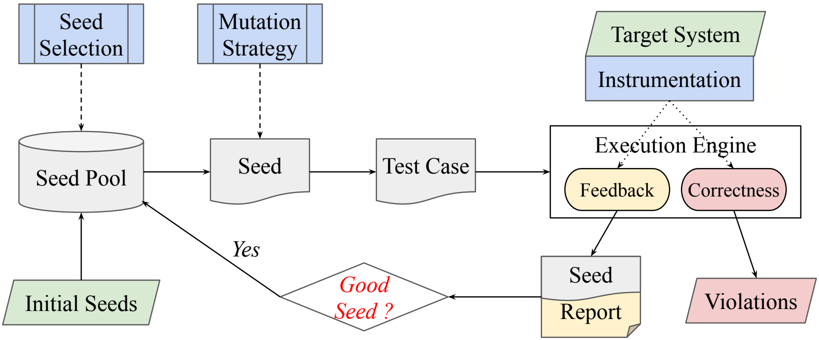
The key is **genetic algorithm**.

Training a program to play the snake game with genetic algorithm

Feedback-guided evolution process



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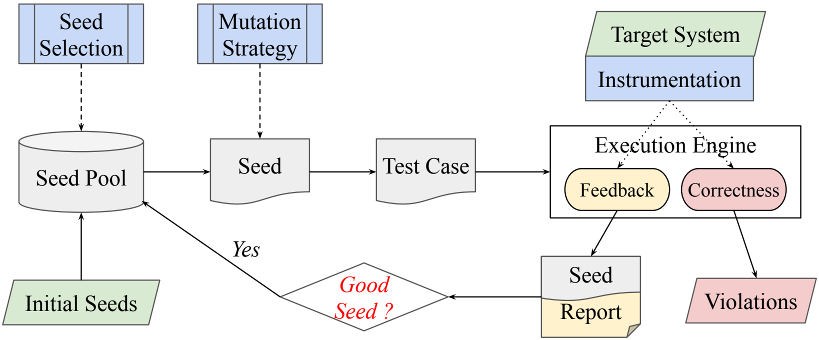

Natural selection — survival of the fittest

Demo with AFL++

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

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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 {
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    // irrelevant operations

    let d = if (b >= 0) {
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    assert!(c != d);
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$\implies$ 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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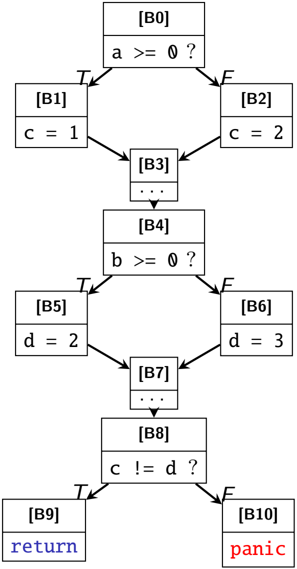

Illustration of different coverage metrics

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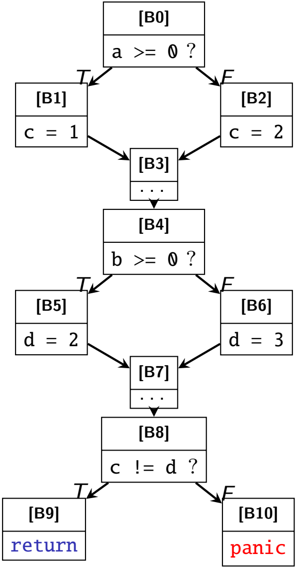
  - Path coverage



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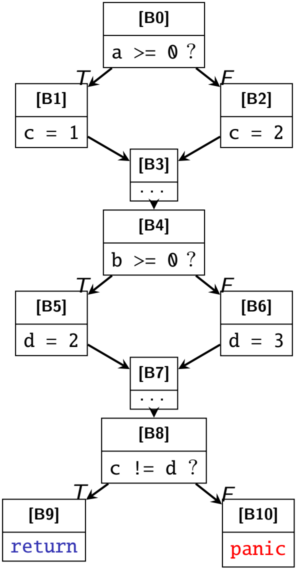
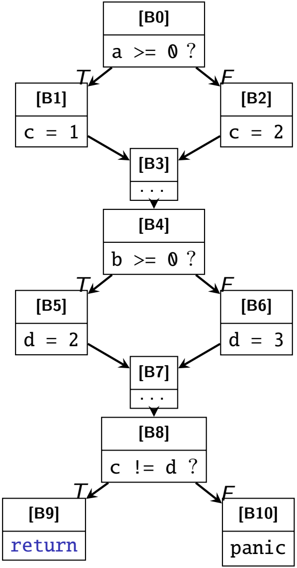


Path coverage: a theoretical optimum

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

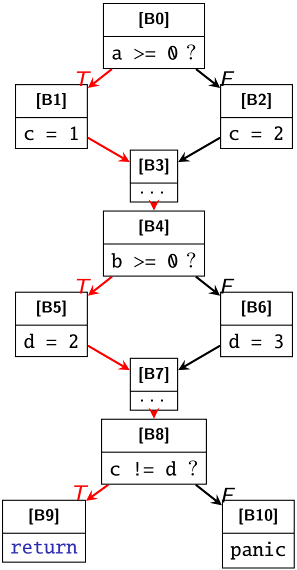
NOTE: feasible paths include paths that leads to explicit and implicit panics.

Path coverage demo



Path coverage demo

- `a = 1, b = 1`



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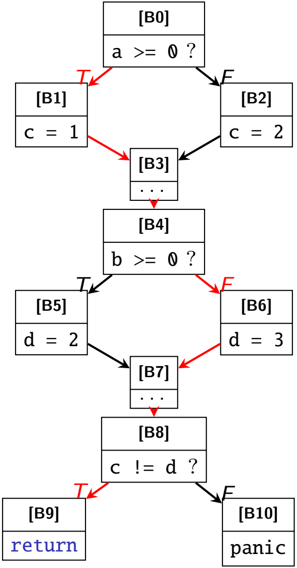

Path coverage demo

- a = 1, b = 1
- a = 1, b = -1
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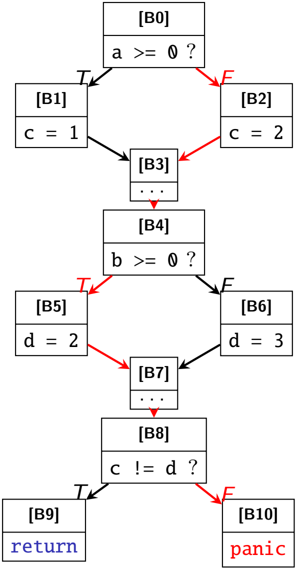

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- a = 1, b = -1
- a = -1, b = 1
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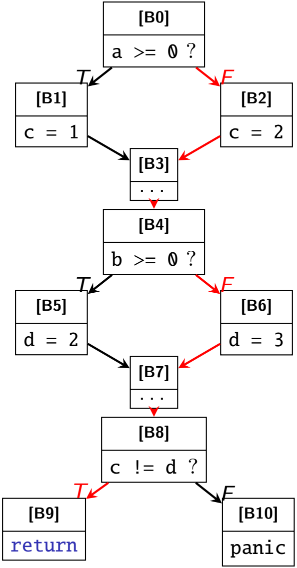

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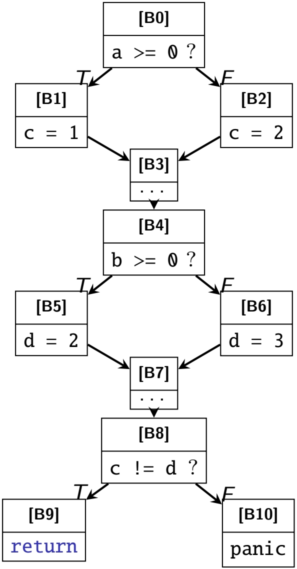
No new program behaviors can be discovered $\implies$ the program is saturately tested



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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.
- 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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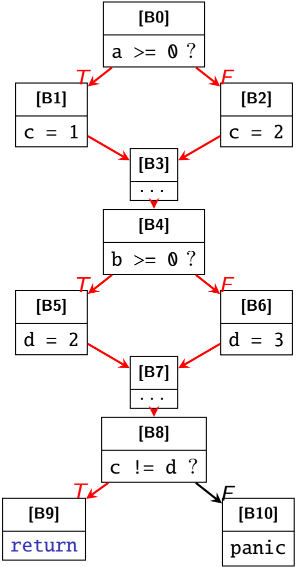

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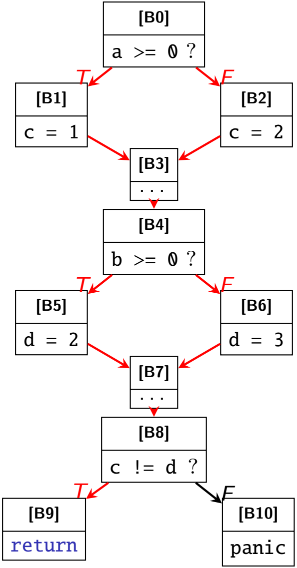

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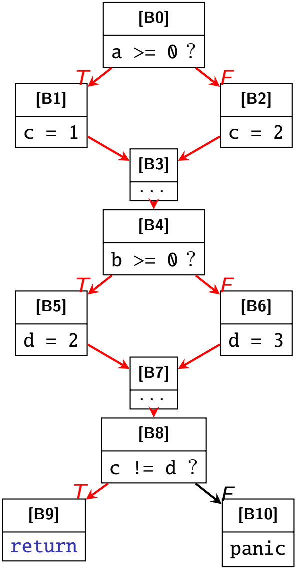

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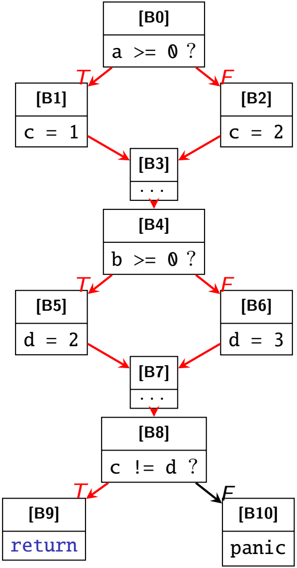
$\Longrightarrow$ fuzzer is not rewarded by mutating `a` and `b`, hence, lowering their priorities and the panic case may never be found, especially when fuzzing complex CFGs



Outline

1. Introduction
2. Testing with concrete inputs
3. Fuzzing overview
4. Program state coverage: “natural selection” in the fuzzing world
5. Conclusion

The goal of fuzzing

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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 ⟩