Testing (Part 3/3)

Martin Kellogg

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- Finish up slides from last lecture
- Test input generation (fuzzing)
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Ways to think about test suite quality

Today we're going to consider three ways to think about test suite quality:

- test suite quality through the lens of **logic**
- test suite quality through the lens of **statistics**
- test suite quality through the lens of **adversity**

The Lens of Adversity: finding bugs

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- Suppose you wanted to evaluate the quality of two bug-finding test suites …

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- Informally: "You claim your test suite is really great at finding security bugs? Well, I'll just **intentionally add a bug** to my source code and see if your test suite finds it!"

Mutation testing: verisimilitude

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- Similarly, if I add a bunch of defects to my software that are not the sort of defects real humans would make, then mutation testing is **uninformative**
  - **Implication**: mutation testing requires us to know what real bugs look like

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This is **exactly** how our "fault injection" system for testing your IP1&2 tests works.

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- Example mutations:
  - `if (a < b)` → `if (a <= b)`
  - `if (a == b)` → `if (a != b)`
  - `a = b + c` → `a = b - c`
  - `f(); g();` → `g(); f();`
  - `x = y` → `x = z`

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```
// original
if (a < b):
x = a + b
print(x)
```

→

```
    // 2nd-order mutant
if (a <= b):
    x = a - b
print(x)
```

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    - Programmers write programs that are largely correct. Thus the mutants simulate the likely effect of real faults.
    - Therefore, **if the test suite is good at catching the artificial mutants, it will also be good at catching the unknown but real faults** in the program.

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Is the competent programmer hypothesis true?

- Yes and no.
- It is true that humans often make simple typos (e.g., + vs -).
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- Is this true?
  - Tests that detect simple mutants were **also** able to detect over 99% of second- and third-order mutants historically

[A. J. Offutt. Investigations of the software testing coupling effect. ACM Trans. Softw. Eng. Methodol., 1(1):5–20, Jan. 1992.]

Mutation testing: putting it all together

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- (Sorry for all of the vocabulary!)

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- **Difficult** to do well:
  - Which mutation operators do you use?
  - Where do you apply them? How often do you apply them?
    - Typically done at random, but how?
- It is **very expensive**. If you make 1,000 mutants, you must now run your test suite 1,000 times!
  - We started by saying testing (1x) was expensive!

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Remember when I mentioned **reductions** earlier? Now is a good time to do one!

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- It is **undecidable**! (= there is no algorithm for it that can always give the correct answer)
  - by direct reduction to the **Halting Problem** (or by **Rice's theorem**)

```
def foo():              # foo halts if and only if
if p1() == p2():        # p1 is equivalent to p2
    return 0
foo()
```

Takeaways

- Individual tests should be hermetic and focused
  - avoid flaky and brittle tests
- Three lenses for test suite quality: logic, statistics, and adversity
- Lens of **Logic**: “no visit X → no find bug in X”
  - leads to statement and branch coverage.
- Lens of **Statistics**: “sample the inputs the users will make”
  - leads to beta testing, A/B testing.
- Lens of **Adversity**: “poke realistic holes in the program and see if you find them”
  - leads to mutation testing.

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  - But what **else** is "read in" by a program and may influence its behavior?

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- What are **all** the inputs to a test?
  - Many programs (especially student programs) read from a file

What else besides “input” can **influence** program behavior?

- User Input (e.g., GUI)
- Environment Variables, Command-Line Args
- Scheduler Interleavings
- Data from the Filesystem
  - User configuration, data files
- Data from the Network
  - Server and service responses

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2. We want fully hermetic tests
3. 1 & 2 imply test input generation must also **control the environment**

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  - Lens of **Statistics**: choose inputs "at random"
  - Lens of **Adversity**: choose inputs that kill mutants

Lens of Logic: maximize coverage

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foo(a,b,c,d,e,f):
   if a < b: this
   else: that
   if c < d: foo
   else: bar
   if e < f: baz
   else: quoz
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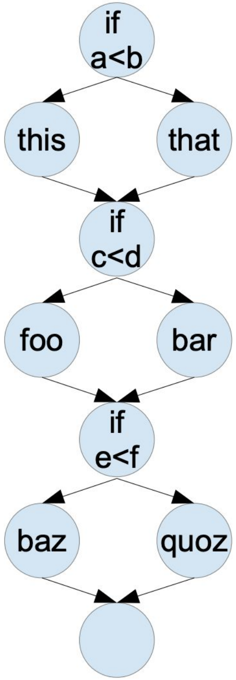

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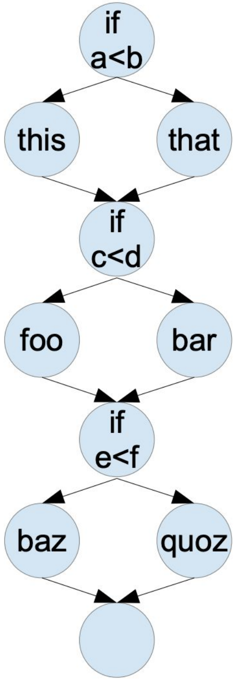

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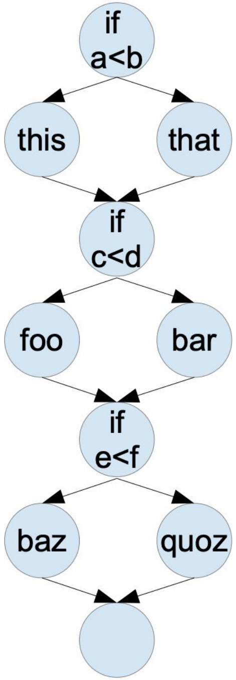

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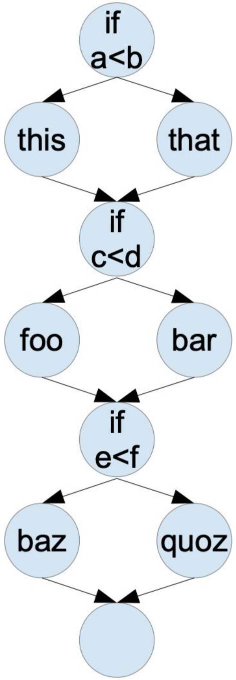

How would you choose inputs that **maximize**:

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- **branch** coverage?
- **path** coverage?

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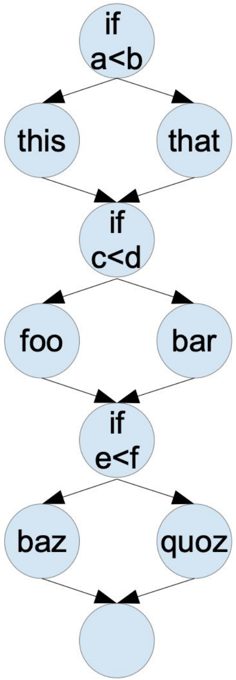

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- If you have **N** sequential (or serial) if statements …
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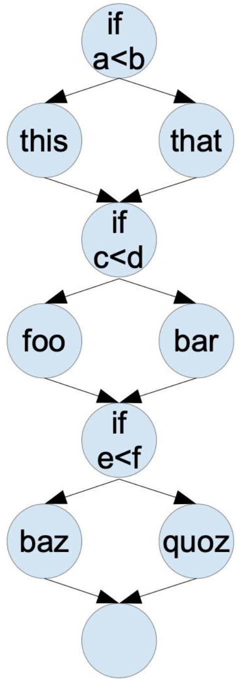

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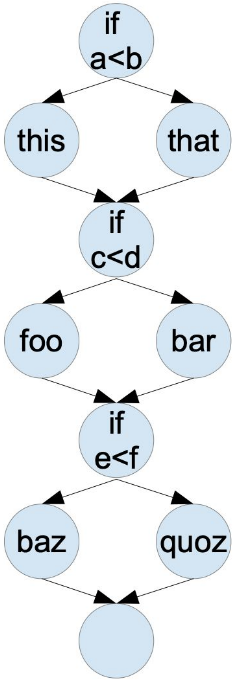
  - Which you could cover in 2 tests!



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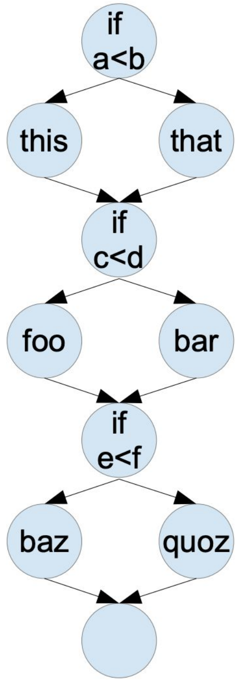

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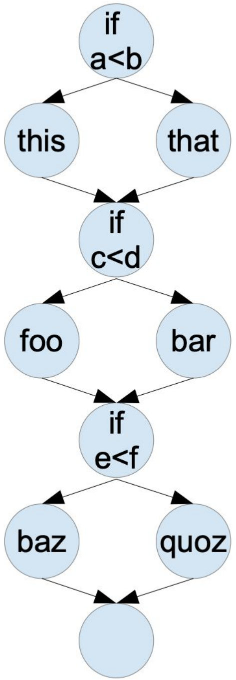

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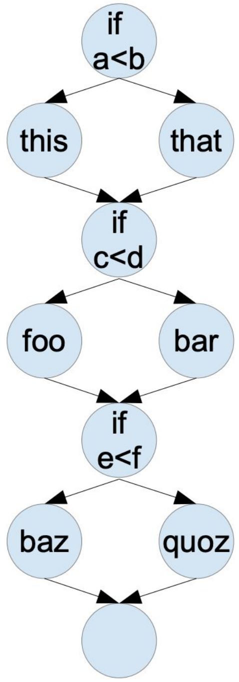

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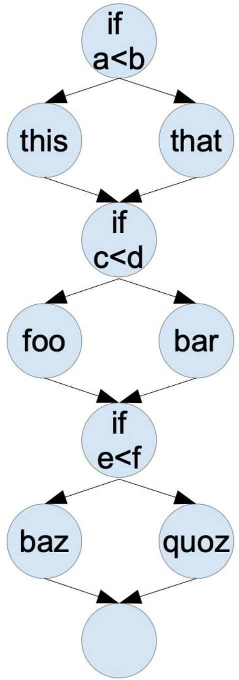
- Path coverage **subsumes** branch coverage



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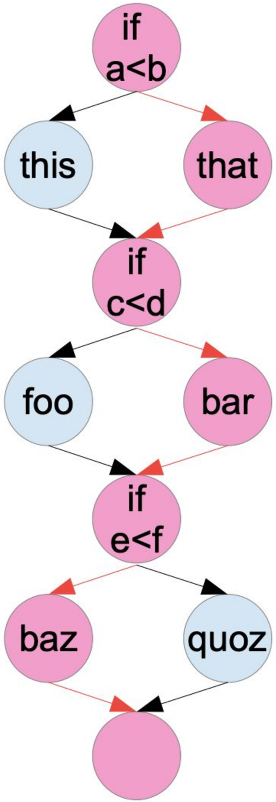
Definition: a ***path predicate*** (or ***path condition***, or ***path constraint***) is a boolean formula over program variables that is true when the program executes the given path

Lens of Logic: path predicate example

- Consider the highlighted (in **pink**) path
  - i.e., “false, false, true”
- What is its path predicate?



Lens of Logic: path predicate example

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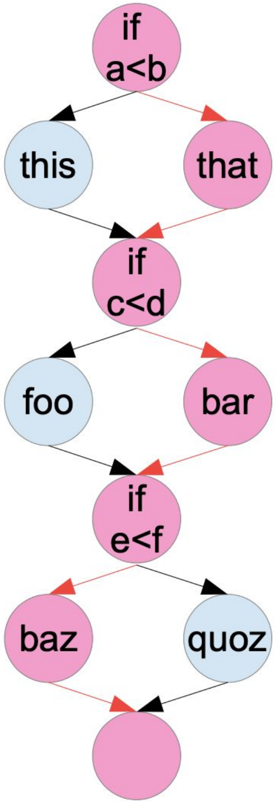
  - `a >= b && c >= d && e < f`



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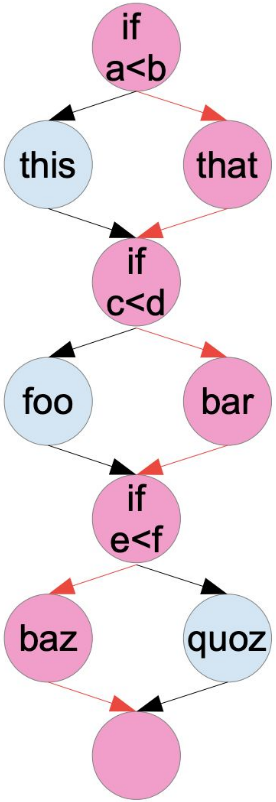

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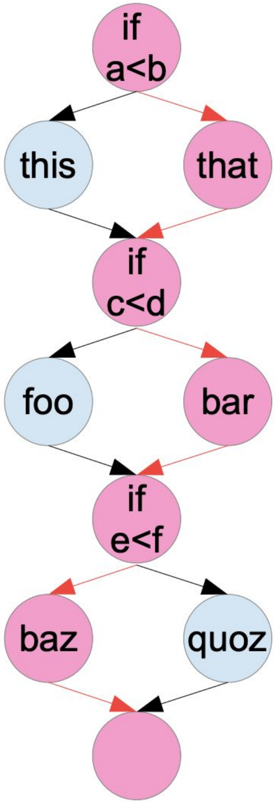

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- What is a satisfying assignment for
  - `a >= b && c >= d && e < f` ?
    - `a=5, b=4, c=3, d=2, e=1, f=2`
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    - … many more

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Ask me about how an **SMT solver** works in office hours if you want to know more!

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while a < b:
  a = a + 1
return a
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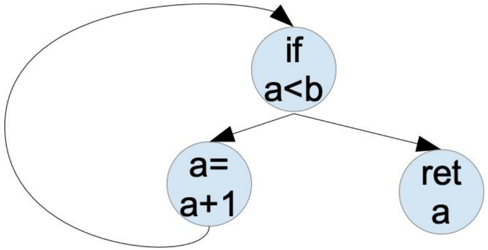

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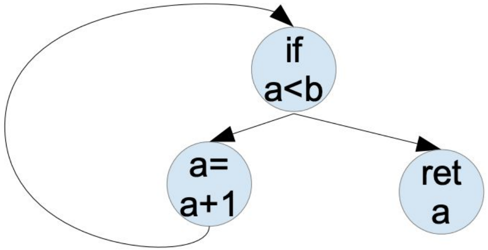

- One path corresponds to executing the loop once, another to twice, another to three times, etc.

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- For more on this topic, take a graduate-level course on program analysis or compilers

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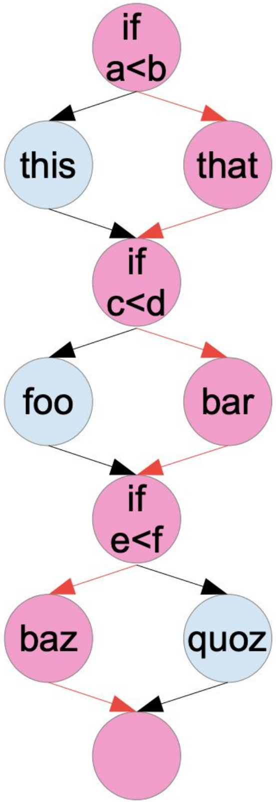

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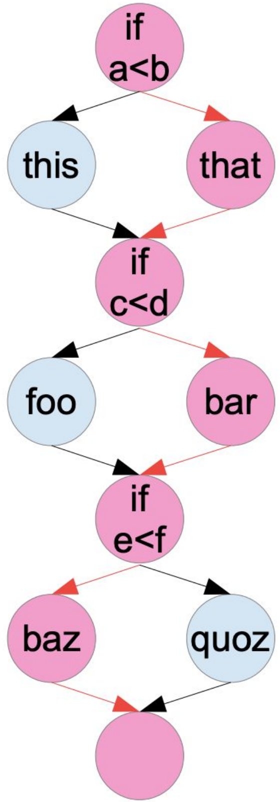

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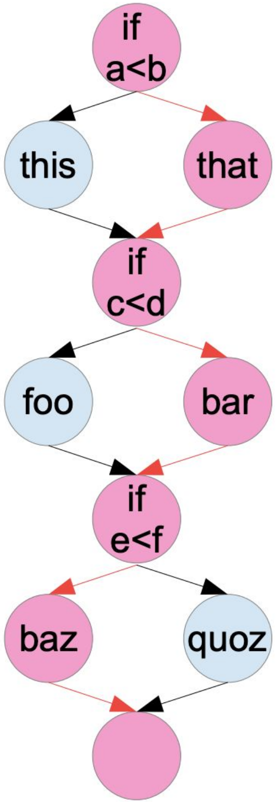

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Suppose we want to exercise the path that calls `bar`. One predicate is `str1==str2`. What do you assign to `a` and `b`?

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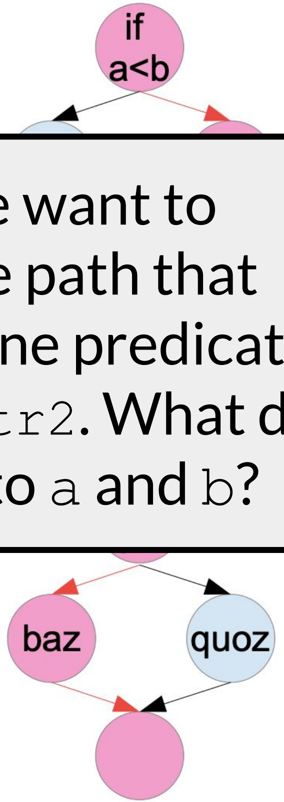

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  - If it can't (because the math is too hard, we don't control the input, etc.), we give up

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  - Oracles!

Testing (part 3)

Today's agenda:

- Reading Quiz
- Finish up slides from last lecture
- Test input generation (fuzzing)
- **Test oracle generation**
- Test prioritization & test suite minimization

Oracle generation

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- **Key question**: if we generate an input for a given path, **how do we tell** if the program behaved correctly?

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    - and, for machines, sometimes impossible!

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Implicit oracles like these are used by **most test generation tools** in the real world.

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- high-quality invariants can serve as test oracles

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  - For more information (e.g., how to build one) take a graduate-level class on program analysis or read the Daikon paper (September 27 optional reading!)

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Definition: ***differential testing*** is a technique for testing two related programs by comparing their output on generated test inputs. Any difference indicates non-conformance in one of the two.

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- but, differential testing provides a **much stronger oracle** than other automated techniques

Testing (part 3)

This is how far we got on 9/20/24. This lecture will resume on October 2.

Today's agenda:

- Reading Quiz
- Finish up slides from last lecture
- Test input generation (**fuzzing**)
- Test oracle generation
- Test prioritization & test suite minimization

Test input generation

- As a human, often **choosing good test inputs** is the hardest part of writing a test
- For a computer, that's not true: computers can pick inputs **very fast** (given some policy)
- **Key problem**: which inputs should we pick?
    - Lens of **Logic**: choose inputs that will maximize coverage
    - Lens of **Statistics**: choose inputs "at random"
    - Lens of **Adversity**: choose inputs that kill mutants

Lens of Statistics: fuzzing and random testing

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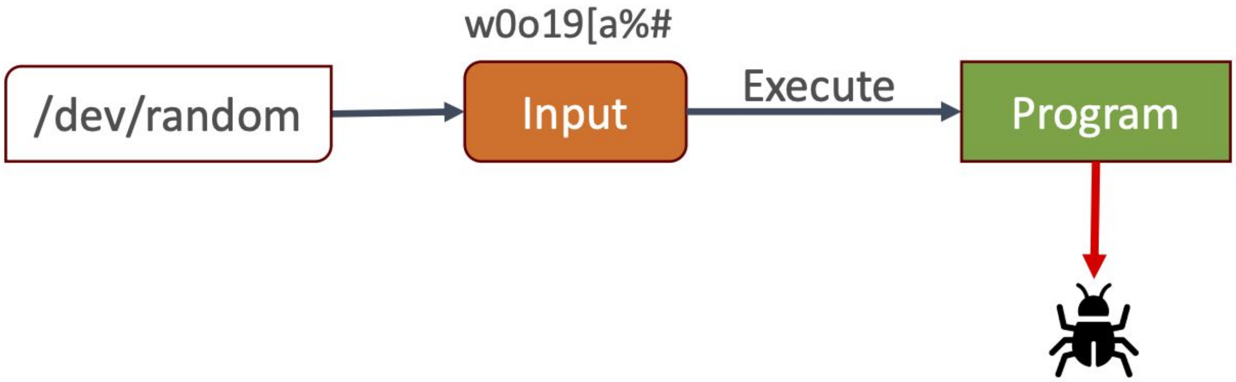

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  - so modern fuzzers use some kind of **semi-random, directed search**

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- **combination with path predicates**:
  - add inputs that are guaranteed to increase coverage to the seed pool

Lens of Statistics: fuzzing in practice

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- Fuzzing is **common in industry**
  - AFL (most famous coverage-guided fuzzer) was built at Google
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- Fuzzing **finds real bugs**
  - especially useful for finding security bugs

Test input generation

- As a human, often **choosing good test inputs** is the hardest part of writing a test
- For a computer, that's not true: computers can pick inputs **very fast** (given some policy)
- **Key problem**: which inputs should we pick?
    - Lens of **Logic**: choose inputs that will maximize coverage
    - Lens of **Statistics**: choose inputs "at random"
    - Lens of **Adversity**: choose inputs that kill mutants

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  - still need to use either path predicates or fuzzing to choose inputs

Lens of Adversity: killing mutants

- Actually, **not as useful as it seems** for automatic test generation
  - still need to use either path predicates or fuzzing to choose inputs
- Can be a useful **fitness function** or guide for other automated test input generation approaches

Testing (part 3)

Today's agenda:

- Reading Quiz
- Finish up slides from last lecture
- Test input generation (fuzzing)
- Test oracle generation
- **Test prioritization & test suite minimization**

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  - Which many produce many tests but **lower-quality** ones than humans would produce
  - A **big cost problem**!

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- **question**: how **hard** are these problems?
  - theory strikes again!
  - answer: it's "hard" (similar "traditional" problem that you might consider a reduction to: **knapsack**)

Takeaways

- two typical ways to generate test inputs:
  - solve path constraints
  - “at random” via fuzzing
- both common in practice
- both suffer from the oracle problem
  - implicit oracles are most common solution
  - invariants, differential testing, etc. also options
- in practice, you often have too many tests
  - deciding which to run is a hard problem, too