Testing (Part 3/3)

Martin Kellogg

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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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B. Valgrind
C. Clang Static Analyzer
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Ways to think about test suite quality

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- 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 Statistics

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Key advantages:

- confidence that tests are indicative of the real world
- can use statistical techniques to estimate the chance that our tests don't cover some important behavior

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- Testing gives confidence the same way sampling (or polling) gives confidence.

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  - Suppose you are conducting a poll to see who will win the next election, but you only ask the current governor's staffers
  - Suppose you are creating tests to see if your program will crash, but you only poll nice, small, inputs

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  - Unfortunately, they often require knowing something about the **distribution** of the full population from which you want to sample a subpopulation
- The basic problem in SE is that the underlying distribution of real user inputs is **not known**

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- in contrast to ***alpha testing***, which is usually performed by developers or a quality assurance team
- Beta testing can be viewed as directly sampling the space of user inputs

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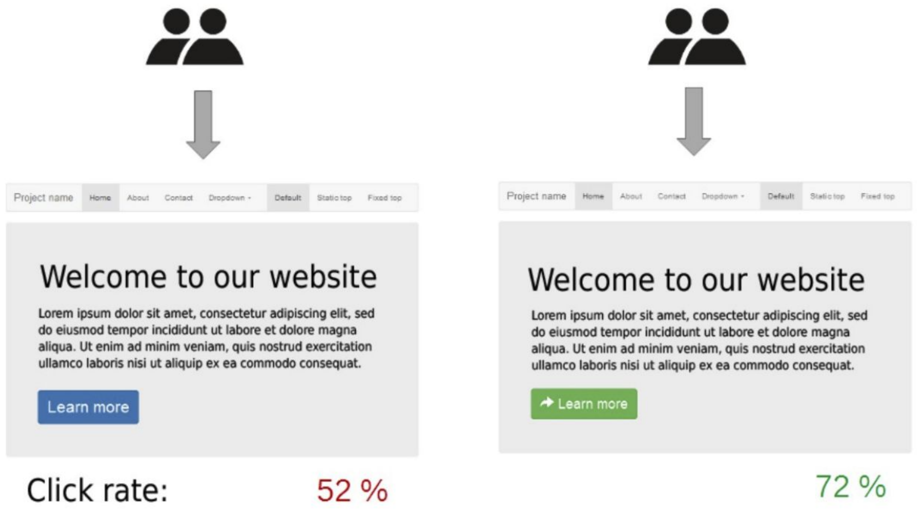

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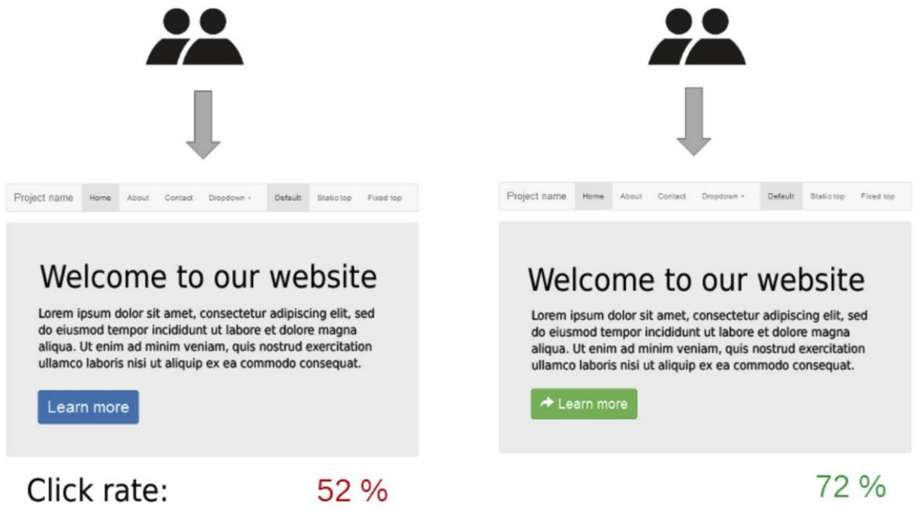
Definition: ***A/B testing*** involves two variants of your software, A and B, which differ only in one feature. Different users are shown different variants and responses are recorded.

- A/B testing is an instance of two-sample hypothesis testing, like you'd encounter in a statistics class.



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- **Damage** can also be in other forms
  - e.g., for Amazon, “damage” might be “customer doesn’t complete the purchase”

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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 security bug** to my source code and see if your test suite finds it!”

Mutation testing: verisimilitude

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  - **Implication**: mutation testing requires us to know what real bugs look like

Mutation testing: defect seeding

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This is **exactly** how our "fault injection" system for testing your IP1 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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  - T … **tificial r … n but r …**

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

[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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  - A test suite with a **higher score is better**.
  - (Sorry for all of the vocabulary!)

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- **Difficult** to do well:
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  - 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!

Mutation testing: equivalent mutant problem

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

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    - 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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    - Many programs (especially student programs) read from a file or stdin …
    - 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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  - Lens of **Statistics**: choose inputs "at random"
  - Lens of **Adversity**: choose inputs that kill mutants

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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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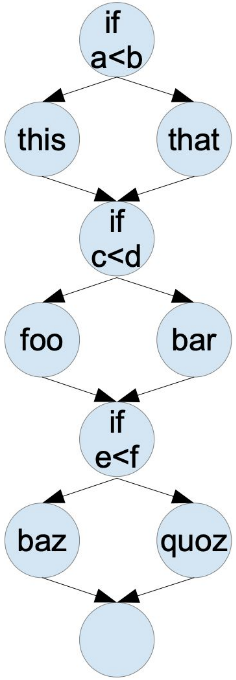

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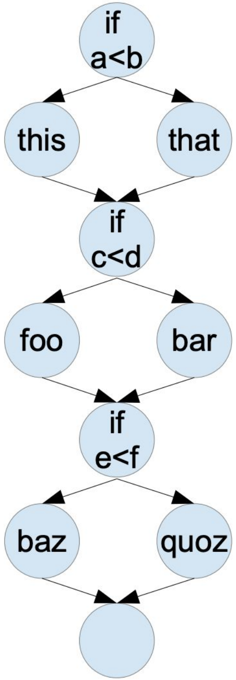

How would you choose inputs that **maximize**:

- line coverage?

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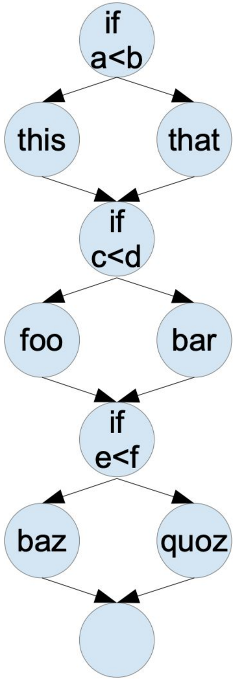

How would you choose inputs that **maximize**:

- **line** coverage?
- **branch** coverage?

Lens of Logic: maximize coverage

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foo(a,b,c,d,e,f):
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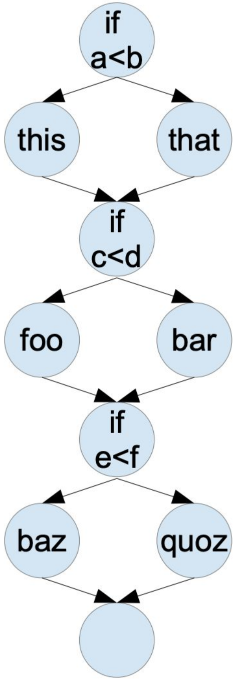

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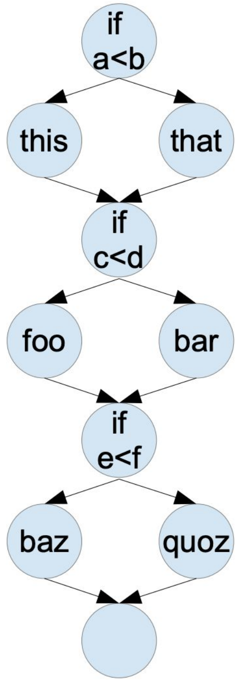

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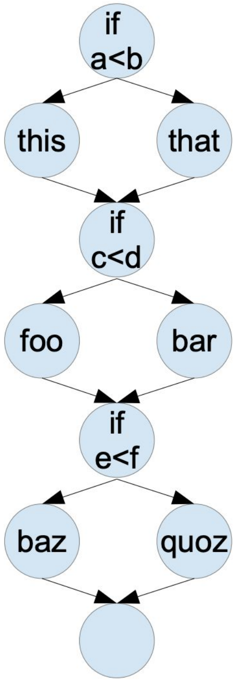

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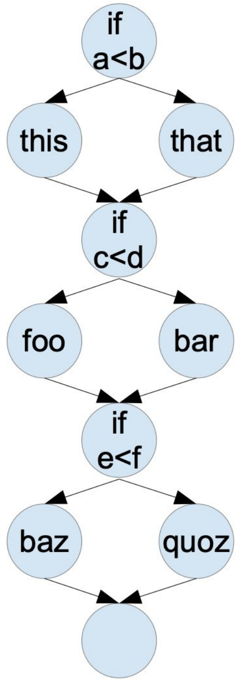

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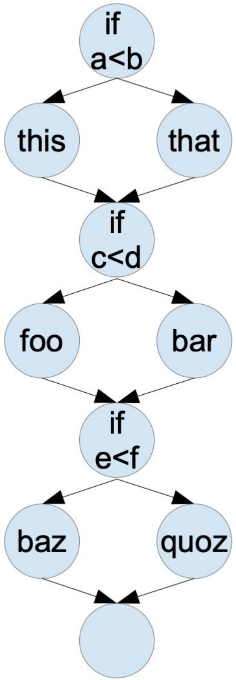

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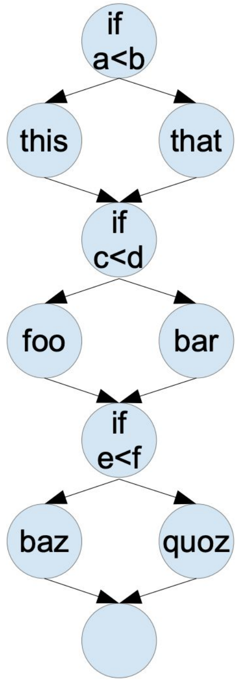

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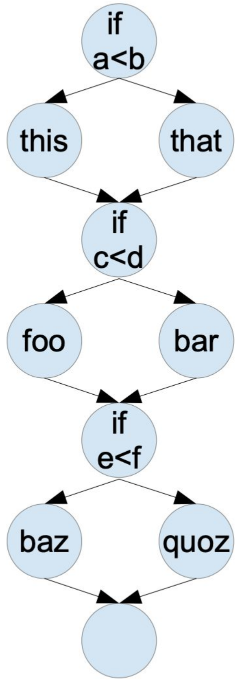

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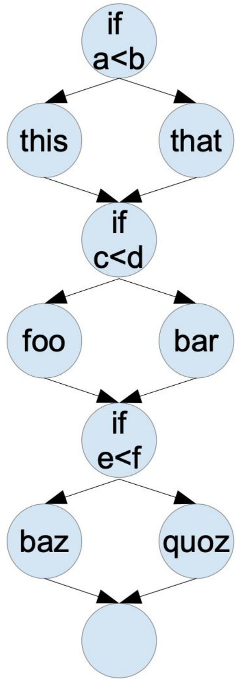
- Path coverage **subsumes** branch coverage



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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

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    - i.e., “false, false, true”
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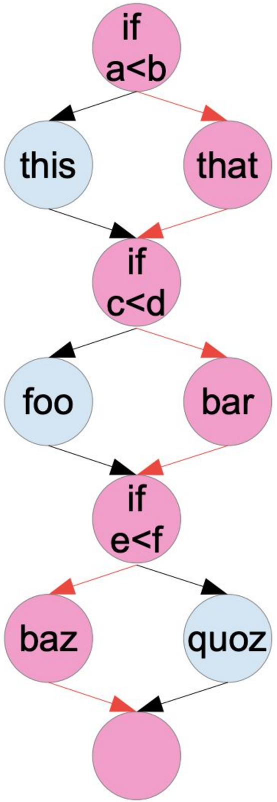

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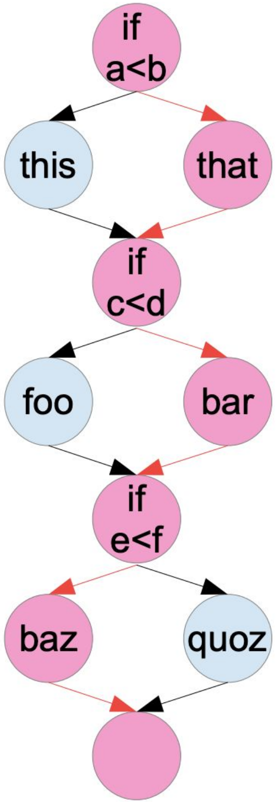

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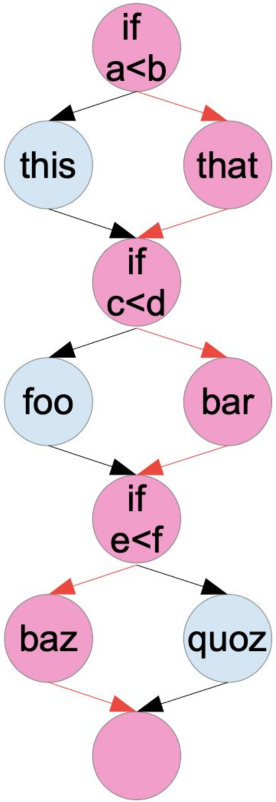

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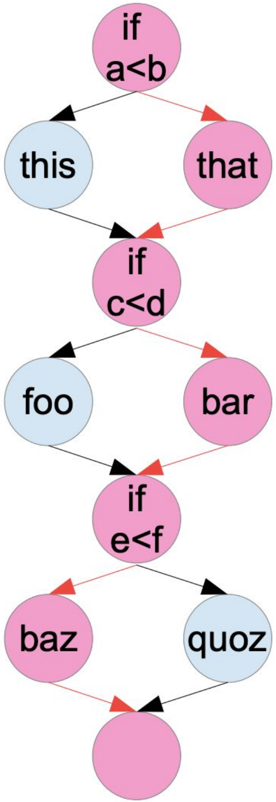
- So, given a path predicate, how do we choose a test input that covers the path?



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- What is a satisfying assignment for
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    - `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:
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return a
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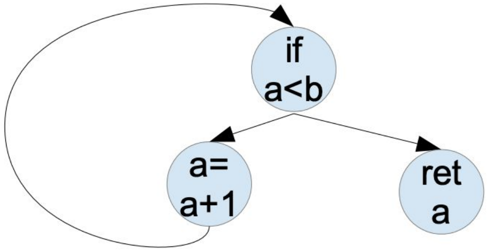

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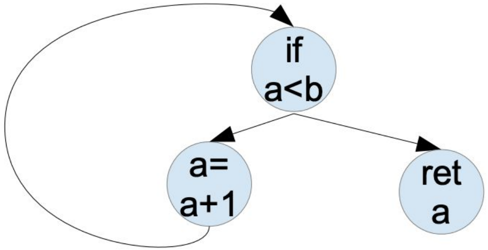

- One path corresponds to executing the loop once, another to twice, another to three times, etc.

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

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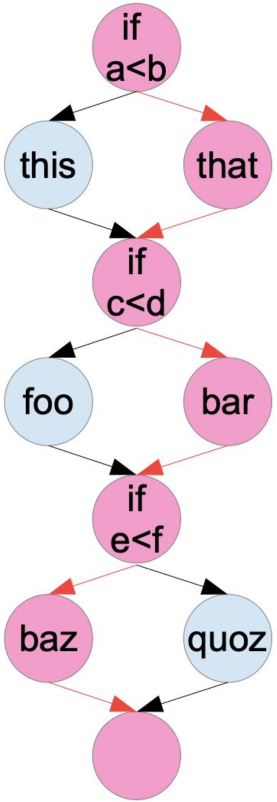

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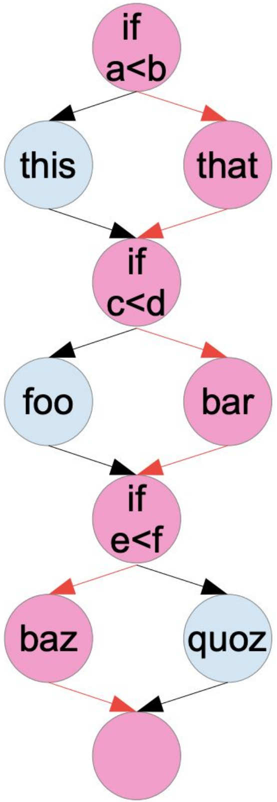

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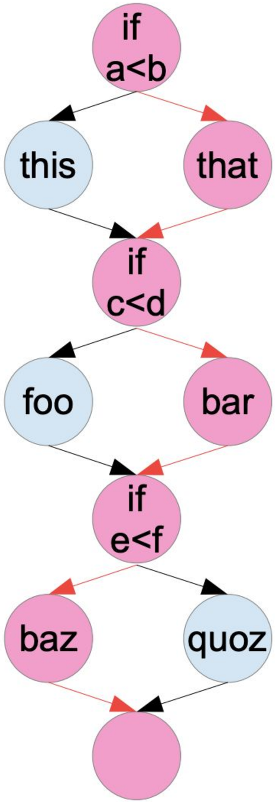

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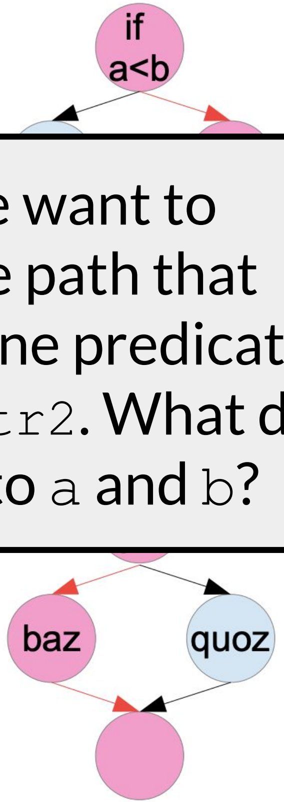

Suppose we want to exercise the path that calls `bar`. One predicate is `str1==str2`. What do you assign to `a` and `b`?

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  - 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 (October 6 optional reading!)

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- only applicable in **limited situations**: need another implementation
  - but **useful more often than you might think** - for example, when writing a “fast” version of a routine, you can compare its output to a “slow” but easy-to-implement version

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  - and sometimes neither is!
- but, differential testing provides a **much stronger oracle** than other automated techniques

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

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

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”
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Lens of Statistics: fuzzing and random testing

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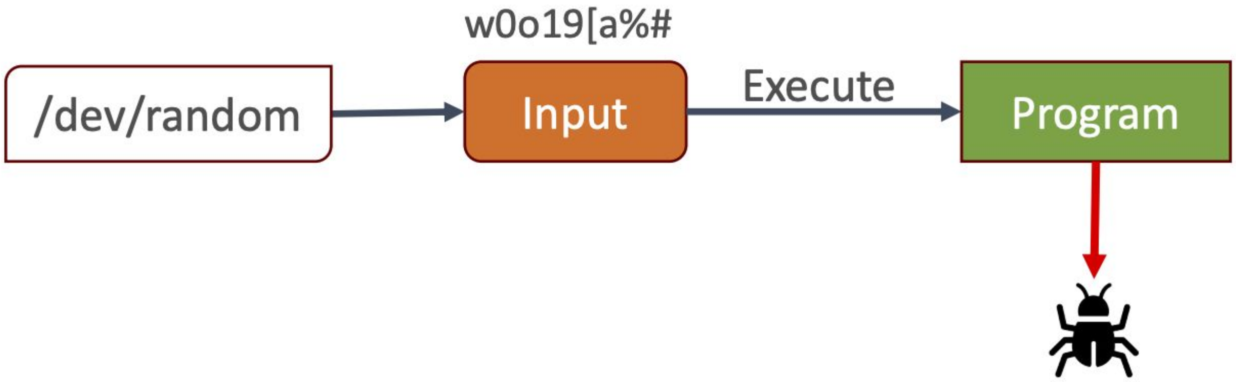

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  - so modern fuzzers use some kind of **semi-random, directed search**

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Lens of Statistics: fuzzing in practice

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- Fuzzing **finds real bugs**
  - especially useful for finding security bugs

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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

Aside: red-bordered slides

- The **red border** on the this slide indicates material that is **not** fair game for exam questions
  - Generally I will only use this border in 490 for slides that get skipped due to time constraints
  - Be warned: red-bordered slides may make another appearance later on in another lecture!

Testing (part 3)

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- Reading Quiz
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- **Test prioritization & test suite minimization**

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  - 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