Testing (Part 3/3)

Martin Kellogg

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- Finish up mutation testing from part 2
- Reading Quiz
- Test input generation (fuzzing)
- Test oracle generation
- Test prioritization & test suite minimization

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- Detecting these "***equivalent mutants***" is a big deal. How hard is it?
- 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: test & test suite quality

- 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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Reading quiz

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Q2: Which of the following testing strategies do the SQLite developers put the most effort into (in terms of CPU cycles):

A. fuzz testing
B. branch coverage
C. regression testing
D. differential testing

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Announcements:

- preliminary project plan due today
- IP2 due in one week (TODO: number of submissions as of tomorrow AM)

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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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  - 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
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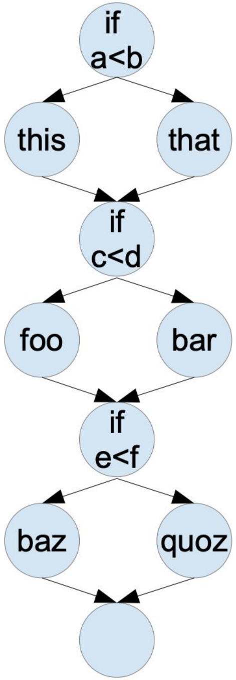

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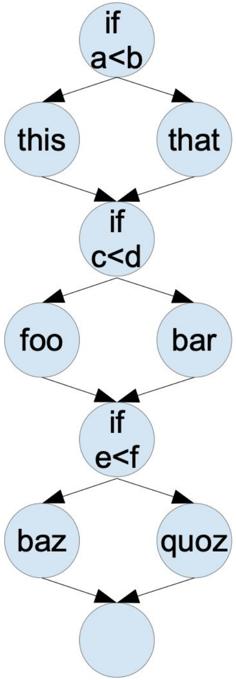

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  - branch coverage?
  - path coverage?

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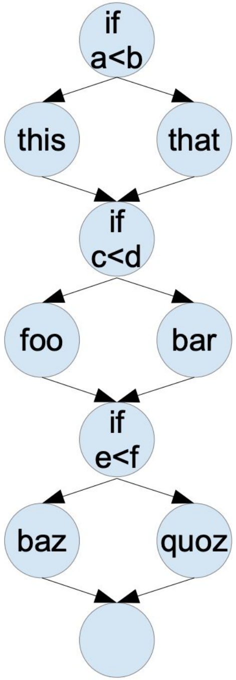

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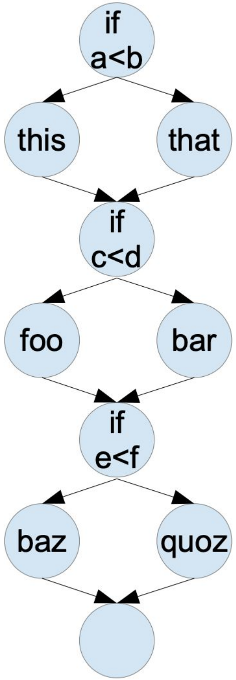

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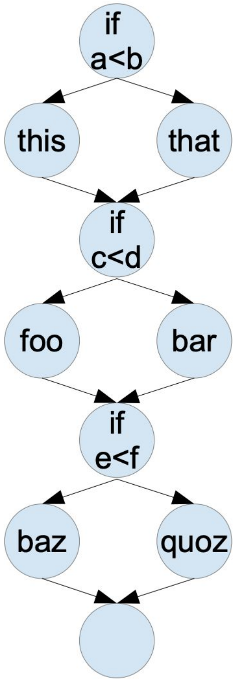

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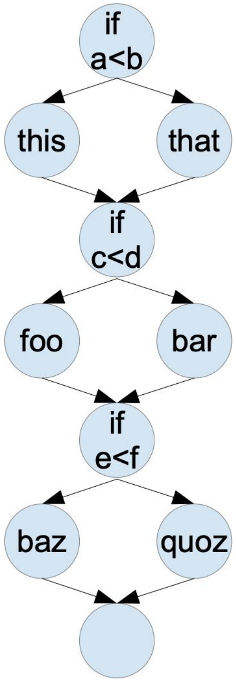

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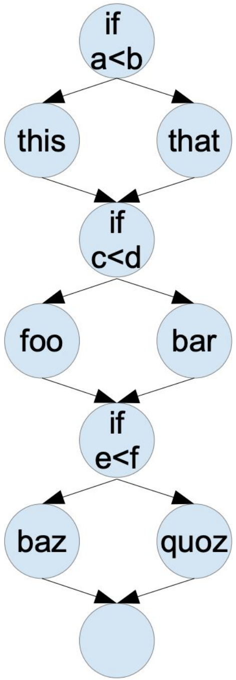

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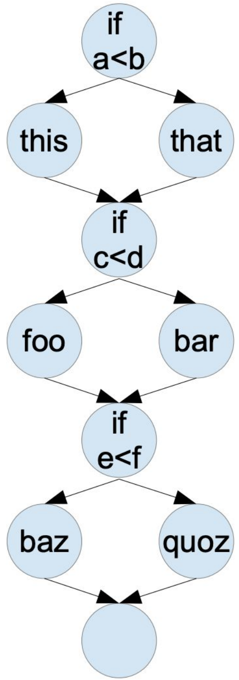

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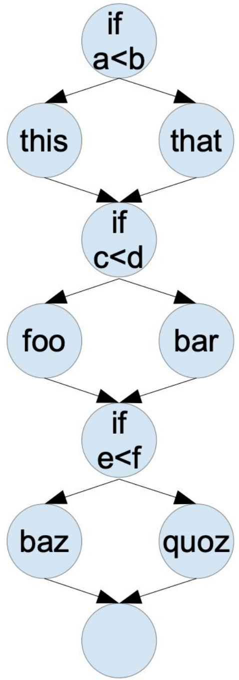

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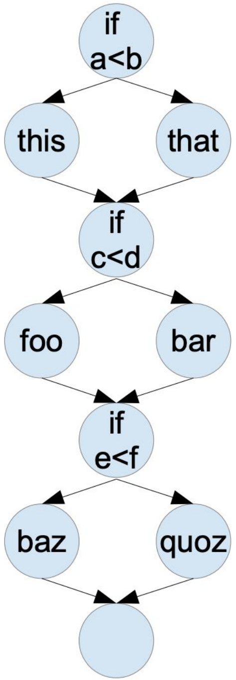

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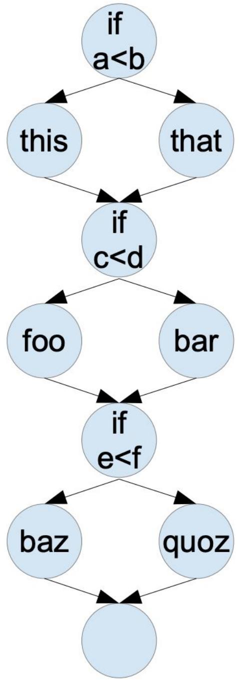
- Path coverage **subsumes** branch coverage



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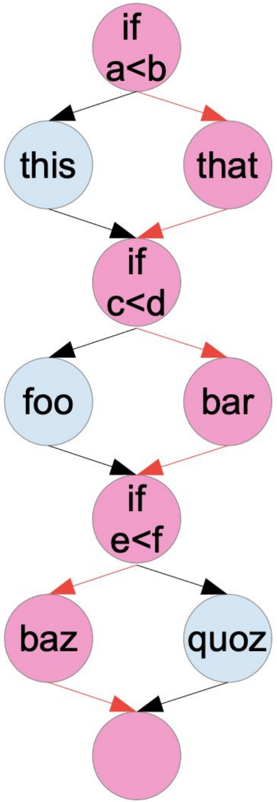
Definition: a ***path predicate*** (or ***path condition***, or ***path constraint***) is a boolean formula over program variables that is true when the program executes the given path

Lens of Logic: path predicate example

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



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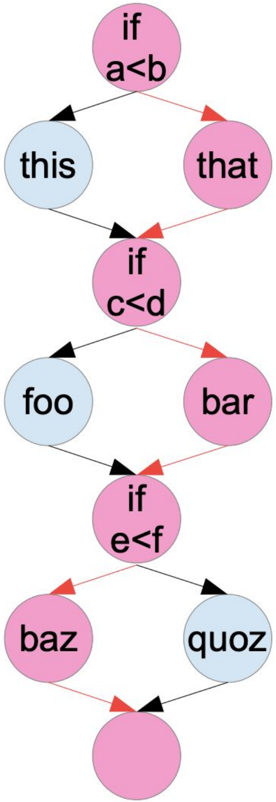

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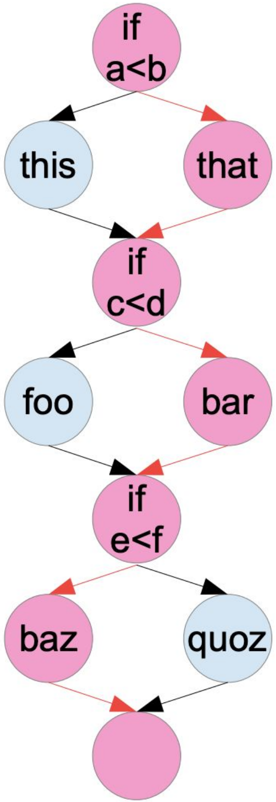

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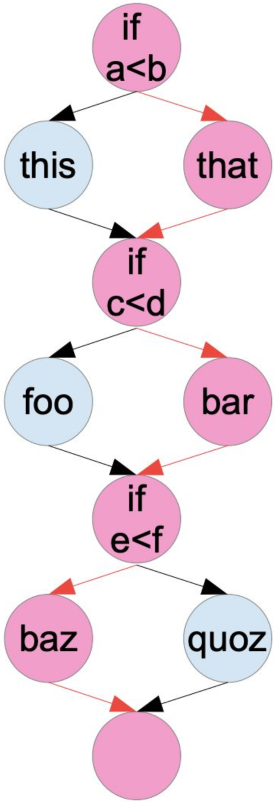
- So, given a path predicate, how do we choose a test input that covers the path?



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- What is a satisfying assignment for
  - `a >= b && c >= d && e < f` ?
    - `a=5, b=4, c=3, d=2, e=1, f=2`
    - `a=0, b=0, c=0, d=0, e=0, f=1`
    - … many more

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  - Option 1: **ask humans**
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  - Option 2: repeatedly **guess randomly**
    - works surprisingly well (when answers are **not sparse**)
  - Option 3: use an ***automated theorem prover***
    - cf. Wolfram Alpha, MatLab, Mathematica, Z3, etc.
    - works very well for a **restricted class of equations** (e.g., linear but not arbitrary polynomials, etc.)

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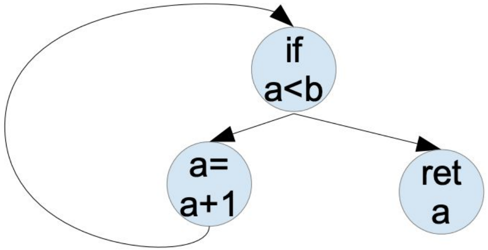

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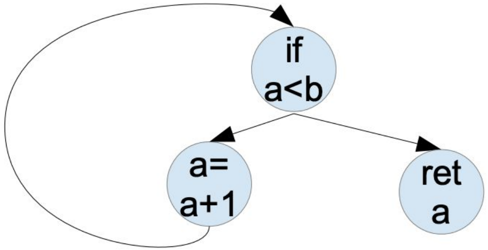

- One path corresponds to executing the loop once, another to twice, another to three times, etc.

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

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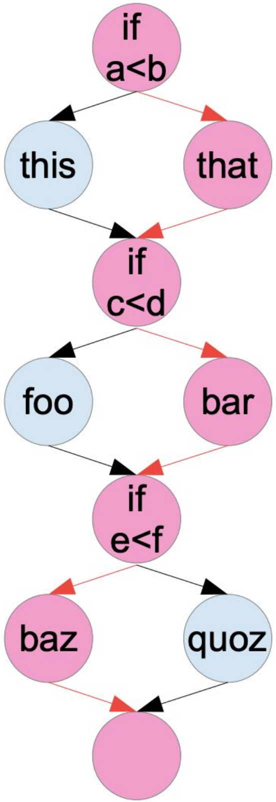

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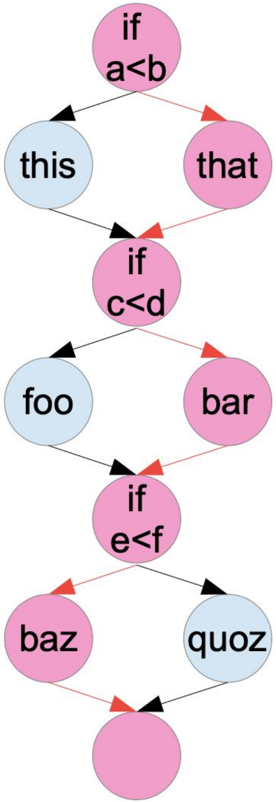

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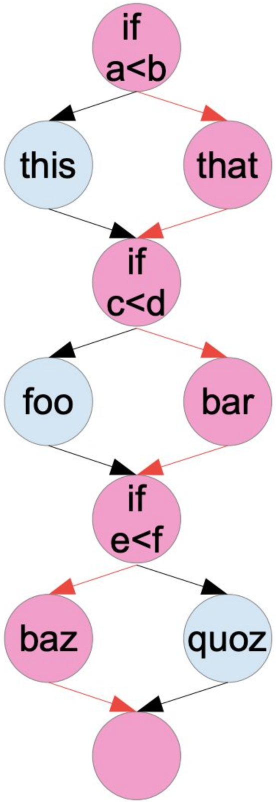

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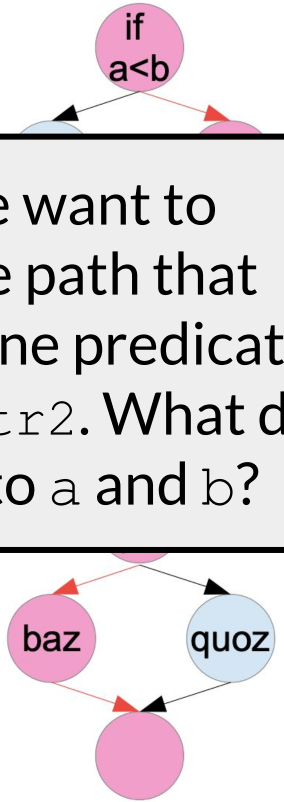

Suppose we want to exercise the path that calls `bar`. One predicate is `str1==str2`. What do you assign to `a` and `b`?

Lens of Logic: path predicate woes

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- So, we make a **best effort**:

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  - Ask the solver to find a solution in terms of the input variables
  - If it can't (because the math is too hard, we don't control the input, etc.), we give up

Lens of Logic: test input generation plan

- Consider generating high-branch-coverage tests for a method:
- **Enumerate** "all" paths in the method
- For each path, **collect** the path predicate
- For each path predicate, **solve** it
  - A solution is a satisfying assignment of values to input variables → those are your test input
  - None found? Dead code, tough predicate, etc.

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  - Oracles!

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- Reading Quiz
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- **Test 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?

Oracle generation: difficulty

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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

Oracle generation: dynamic invariant detection

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    - report any violation to a human
  - For more information (e.g., how to build one) take a class on program analysis or read the Daikon paper (Feb 7 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

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Test input generation

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- 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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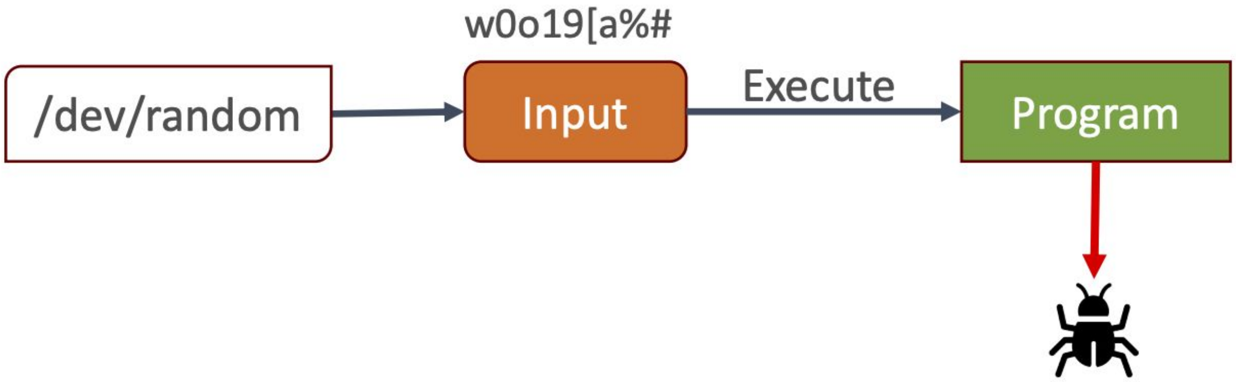

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- totally random input rarely works well
  - most programs have **structured input**
  - so modern fuzzers use some kind of **semi-random, directed search**

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- Fuzzing is **machine-intensive**
  - most inputs aren't useful
- 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

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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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  - 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