Testing (Part 2/3)

Martin Kellogg

Testing (part 2)

Today's agenda:

- **Reading Quiz**
- Test quality
- Test suite quality
  - lens of logic: coverage
  - lens of statistics: testing on real users
  - lens of adversity: mutation testing

Reading Quiz: testing (part 2)

Q1: **TRUE** or **FALSE**: The author considers it unproductive to mutate the condition of an if statement if the statement's the body is arid (e.g., a logging statement).

Q2: When does the author's mutation testing tool surface unkilled mutants to the developer?

- **A.** whenever the tests run
- **B.** at code review time
- **C.** in the developer's IDE

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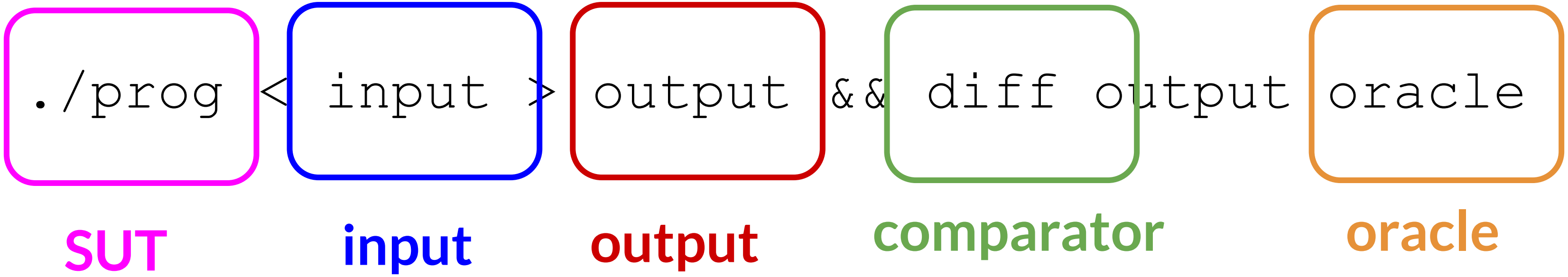
Review: parts of a test

Definition: a *test* executes a **given input** on a program (the *system under test* or *SUT*) and **compares** the SUT's **output** to a given **oracle**



```
./prog < input > output && diff output oracle
```

SUT

input

output

comparator

oracle

Test quality: what makes a test good or bad?

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Good	Bad

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Good	**Bad**
isolated (only tests one thing)	brittle
runs quickly	slow
strong oracle	weak oracle
hermetic	redundant
easy to understand	hard to understand (“mystery”)
deterministic	non-deterministic (“flaky”)
etc.	etc.

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- avoid dependencies on the environment (e.g., software installed on the machine, environment variables, contents of other files, operating system behaviors, etc.)
- being hermetic is also important for builds generally (we’ll discuss more in our lecture on build systems later this semester)

Brittle tests

Definition: a ***brittle*** test fails for reasons unrelated to what it ostensibly tests

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- common causes:
  - not being hermetic
  - testing too much at once
  - comparator or oracle is too specific

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- commonly **co-occurs with brittleness**: test is brittle because it is too complicated, and when it fails it's not clear why
    - especially common for very large, end-to-end tests
- **best practice**: tests should give as much information as possible when they fail
    - **implication**: when writing tests, think about why they might fail in the future and document that in the test itself

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- sometimes caused by **non-determinism in the program** itself
    - e.g., relying on randomness, iteration order of hashtables, etc.
- are a **major problem in practice**
    - difficult to debug, so waste a lot of developer time
    - detecting them is an active research area

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Question: what makes one test suite **better or worse** than another?

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Question: what makes one test suite **better or worse** than another?

- not just the sum of the “goodness” of all the individual tests!

Test suite quality: who cares?

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- sometimes, we may not even have enough resources to run all tests
  - we'll discuss test suite minimization next time

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 Logic

Informally, we want the following property:

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- The program passes the tests if and only if it does **all the right things** and **none of the wrong things**.
    - Pass all tests → program adheres to requirements
    - Each failing test → program behaves incorrectly

The Lens of Logic: intuition

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- Suppose further that your test suite does not include any negative inputs.
- Can we conclude that passing all of the tests implies adhering to all of the requirements?

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- For our purposes, ***X* coverage** is the degree to which ***X*** is executed/exercised by the test suite.
- **Code coverage** is the degree to which the source code is executed by the test suite.
    - How do we actually **measure** code coverage?

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- **Key Logical Observation**: If we **never test** line X then testing **cannot rule out** the presence of a bug on line X
- Example: if our test executes lines 1 and 2, but there is a bug on line 3, there is **no way** that our test will find the bug!

Aside: “don’t do bad things”

- We can test that programs **do not do certain bad things**
    - e.g., “don't segfault”, “don't send my password to Microsoft”, “on this one particular input, don't get the wrong answer”
- Note that “I never do bad things” is not the same as “I always/eventually do good things”
    - For more information, take a class on *Modal Logic* or read about *Liveness* vs. *Safety properties*

Coverage: statement coverage

Implication for statement coverage: you could test line X and still have a bug on line X

- e.g., foo(a,b) { return a/b; }
- test: foo(6,2) does not throw DivideByZeroException

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But testing line X gives us some **small but non-zero confidence** in the correctness of line X

Coverage: statement coverage: assumptions

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- We gain the same amount of confidence (or information) for each visited line
- The amount of confidence (or information) we gain per visited line is positive
- …

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  - Run all the tests, collect all the printed information, remove duplicates, count
- Practical concern: the **observer effect** (from physics) is the fact that simply observing a situation or phenomenon necessarily changes that phenomenon.
  - Implication for computing statement coverage: program might depend on timing info, amount of I/O, etc.

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- This can be done at the source or binary level.
- Don't actually print to stdout/stderr
- Don't slow things down too much
    - Pre-check before printing a duplicate?
- Don't introduce infinite loops
    - Instrument "print" with a call to "print"?

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Good news: coverage instrumentation is a "solved" problem:

- e.g., Jest does it automatically

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- Not only that, but executing every line doesn't even guarantee that we cover all of the program's **behaviors**
    - many behaviors are dependent on data that causes particular **control flows**: that is, that cause different branches of conditionals to be executed
- Informally, the problem of ensuring that we cover interesting data values may **reduce** to the problem of ensuring that we **cover all branches** of conditionals

Aside: reductions

Quick poll: raise your hand if you have ever **reduced** one problem to another

- examples: reducing something to the halting problem to show that it is not computable; reducing something to satisfiability to show that it is NP-hard
- should be covered in a theory of computation class (likely near the end of the semester)

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the end of the semester)

Reduction is a **powerful tool** for thinking about problems: it lets you solve difficult problems indirectly by re-using solutions for other, related problems.

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- However, branch coverage is “**more expensive**” in the sense that it is harder for a test suite to have high branch coverage than to have high line coverage
    - Note: quality isn't really “more expensive”, you were just fooling yourself before by thinking line coverage was OK. Being correct is expensive.

Coverage: other kinds of coverage

- **Function Coverage**: what fraction of functions have been called?
- **Condition Coverage**: what fraction of boolean subexpressions have been evaluated to both true and also (e.g., on another run) to false?
  - Comparing this to branch coverage is a not-uncommon test question …
- **Modified Condition / Decision Coverage** (MC/DC): function coverage + branch coverage (this is a simplification)
  - Used in mission critical (e.g., avionics) software

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- Compare:
    - Risk = (Probability of Event) * (Damage if Event Occurs)

Example: limited input domain

- Suppose you are writing a point-of-sale cashier application that makes change for a dollar. Given any price between 1 and 100 cents, you must indicate the coins to give out as change.
    - e.g., 23 → return 3 quarters and 2 pennies

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    - e.g., 23 → return 3 quarters and 2 pennies
- In this scenario, you can **exhaustively test** all 100 inputs that will occur to real users in the real world
    - In some sense, it does not matter if that is 100% statement or code coverage (e.g., dead code): your testing is still exhaustive of the inputs that will matter in the real world

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    - Aside: why do you have line 4?
  - Even if line 4 has a bug, users will **never** encounter it
- Note "will": this either requires a **prediction of the future** or a **finite input domain**

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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 poll republicans.
  - 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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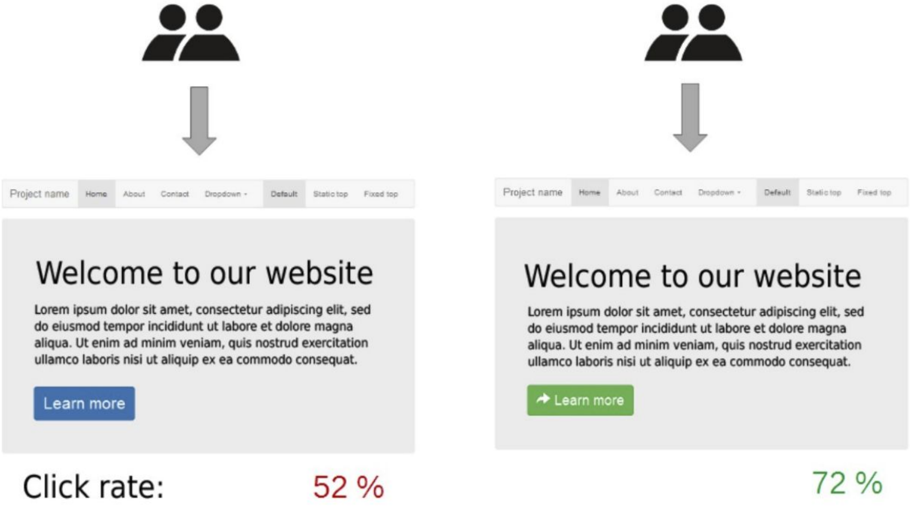

Welcome to our website

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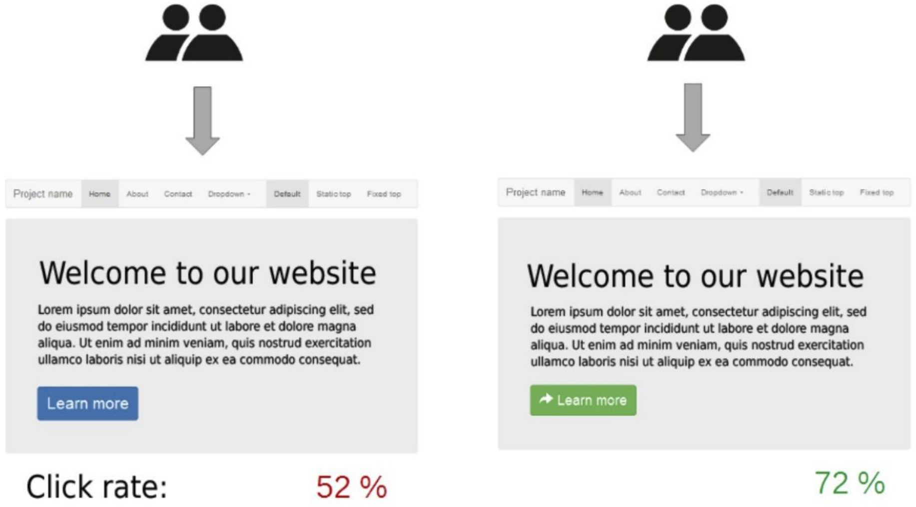
The Lens of Statistics: practical options

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”

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

- Suppose you wanted to evaluate the quality of two truffle-sniffing pigs

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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

- In the truffle-pig example, if every truffle I hide in my backyard is next to a smelly red flower, a pig that finds them all may not actually do well in the real world

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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

Mutation testing: defect seeding

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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)
```

Mutation testing: competent programmers

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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.

Mutation testing: competent programmers

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Is the competent programmer hypothesis true?

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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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    - Typically done at random, but how?

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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!

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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- 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.