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

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Reading quiz: mutation testing

Q1: **TRUE** or **FALSE**: the author found that in over 90% of cases, a new test case that kills one mutant on a particular line of code does not kill all the other mutants on that line of code

Q2: How does the mutation testing system detect arid nodes?

A. heuristic patterns over the AST
B. machine learning from historical data
C. dataflow analysis
D. this reading didn't mention something called "arid nodes"

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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?

Good	Bad

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In-class exercise: with a partner, spend ~2 minutes making a list of factors that make a test "good" or "bad". Then, we'll make a list on the whiteboard.

Test quality: what makes a test good or bad?

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

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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
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- 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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Definition: a ***test suite*** is a collection of tests for the same program

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

- not just the sum of the "goodness" of all the individual tests!

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  - ideal world: all tests pass = software is 100% correct

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- we want to know how much **confidence** our tests give us
  - ideal world: all tests pass = software is 100% correct
- 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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- e.g., foo(a,b) { return a/b; }
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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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  - 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

Your CS education is incomplete until you have **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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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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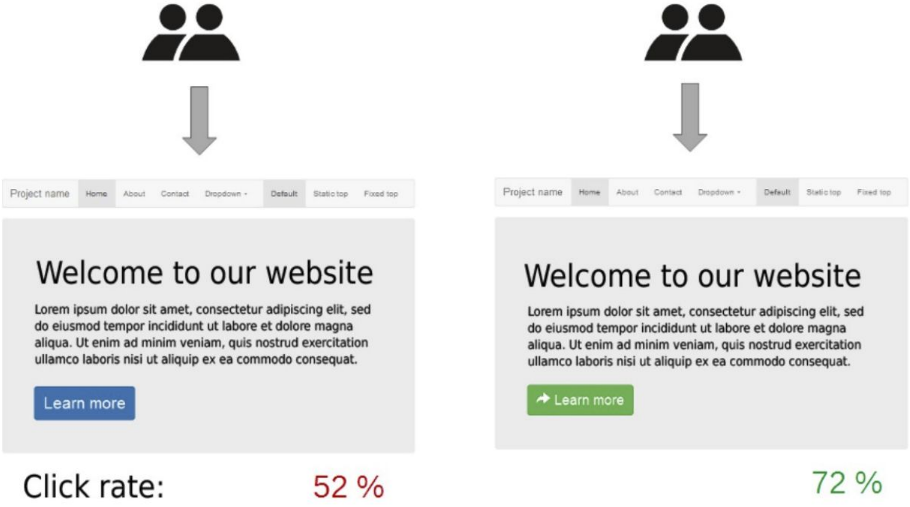

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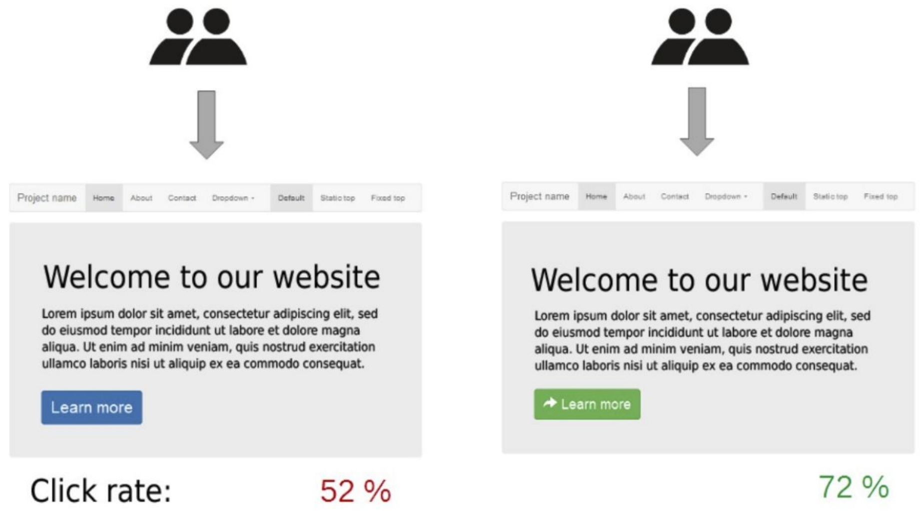
Definition: ***A/B testing*** involves two variants of your software, A and B, which differ only in one feature. Different users are shown different variants and responses are recorded.

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



The Lens of Statistics: practical options

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- The latter often relates to **computer security**
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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

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

Mutation testing: competent programmers

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  - F… . Thus t…
  - T… **…ificial r… …n but r…**

Is the competent programmer hypothesis true?

- Yes and no.
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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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  - A test suite with a **higher score is better**.
- (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.