Coverage

Martin Kellogg

Quiz!

Not just about the reading! Other questions about last week's lecture.

You may use any **hand-written** notes that you took during last week's class. No other aids are permitted.

- you must turn in hand-written notes that you use along with your quiz

Three ways to think about test suite quality

Consider three ways to think about test suite quality:

- test suite quality through the lens of logic
  - intuition: if we don't test it, we can't find bugs
  - leads to ***coverage*** (main subject of today's lecture)
- test suite quality through the lens of **statistics**
  - intuition: test what happens to real users
- test suite quality through the lens of adversity
  - intuition: inject bugs and see if the test suite catches them
  - leads to ***mutation testing***, which we'll cover later this semester

The Lens of Logic

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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 you were writing a sqrt program and one of the requirements was that it should abort gracefully on negative inputs.
- 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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- We desire all of the requirements to be covered (“checked”) by the test suite.
- 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?

Coverage: statement 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”

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- 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; }
- test: foo(6,2) does not throw DivideByZeroException

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?
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  - Instrument “print” with a call to “print”?

Good news: coverage instrumentation is a “solved” problem:

- e.g., `gcov`, Python’s `coverage`, etc.

Background: control flow graphs

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- a ***path*** in a program is a possible execution trace
- the CFG is the internal representation used by many program analysis tools
- brief CFG example on the whiteboard

Example: computing statement coverage

```
public double avgAbs(double... numbers) {
  // We expect the array to be non-null and non-empty
  if (numbers == null || numbers.length == 0) {
     throw new IllegalArgumentException("numbers is null or empty!");
  }
  double sum = 0;
  for (int i = 0; i < numbers.length; ++i) {
    double d = numbers[i];
    if (d < 0) { sum -= d; }
    else { sum += d; }
 }
 return sum / numbers.length;
}
```

Example: computing stat

What does this method do?

It averages the absolute values of an array of doubles.

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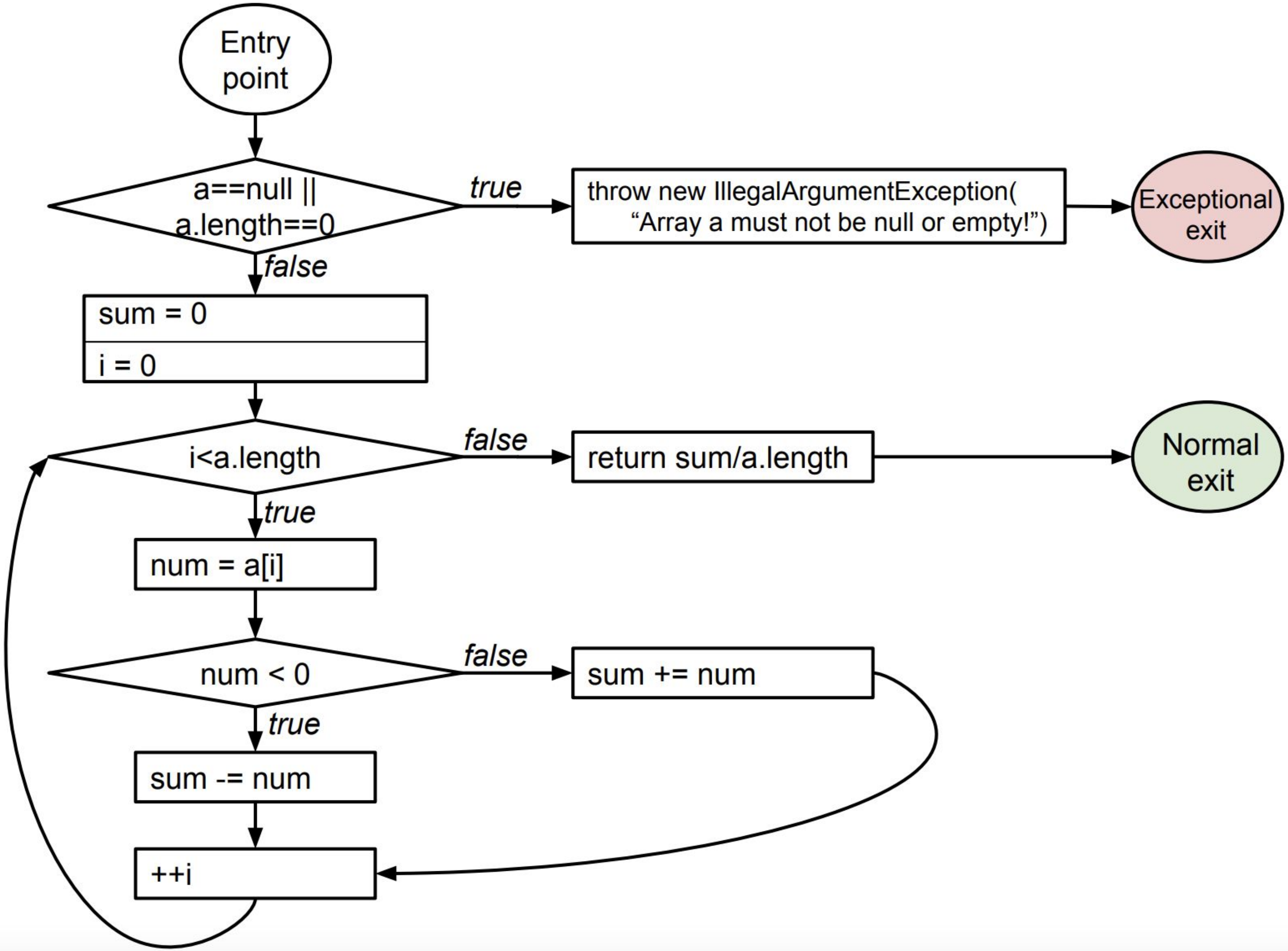
With a partner, draw the control flow graph for this method. (3 min)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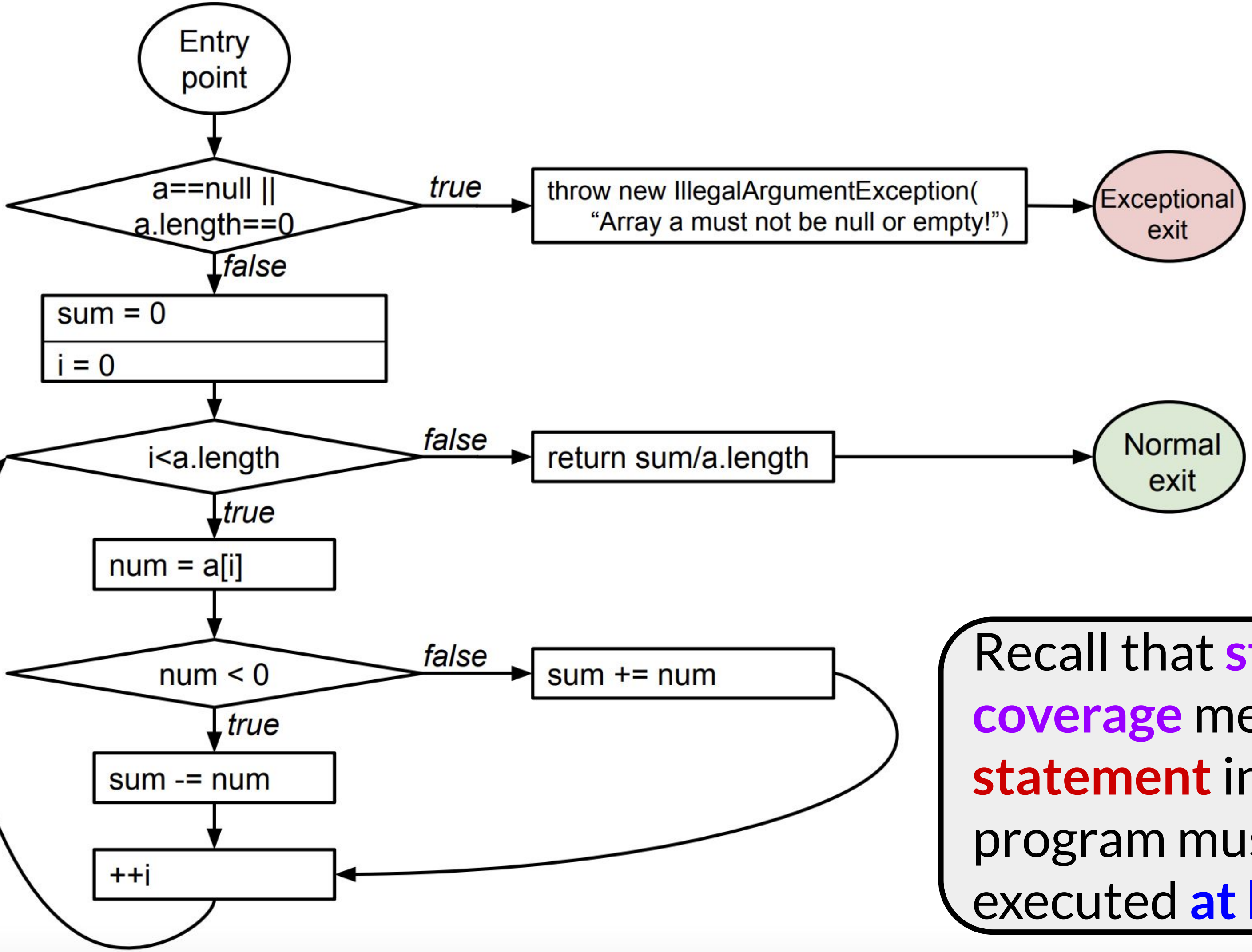
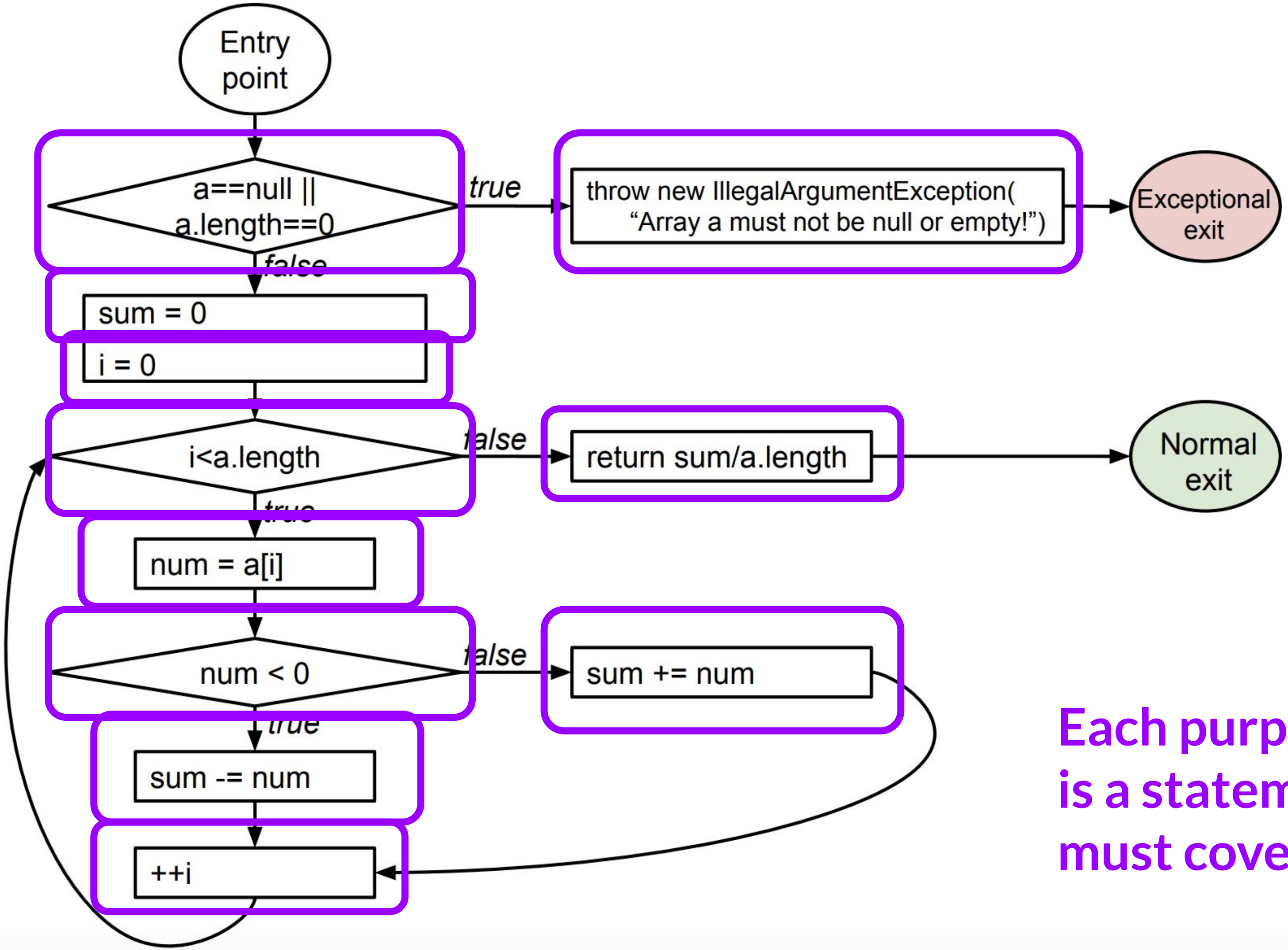


Recall that **statement coverage** means "**every statement** in the program must be executed **at least once**."



Each purple box is a statement we must cover!

The CFG is useful for computing coverage

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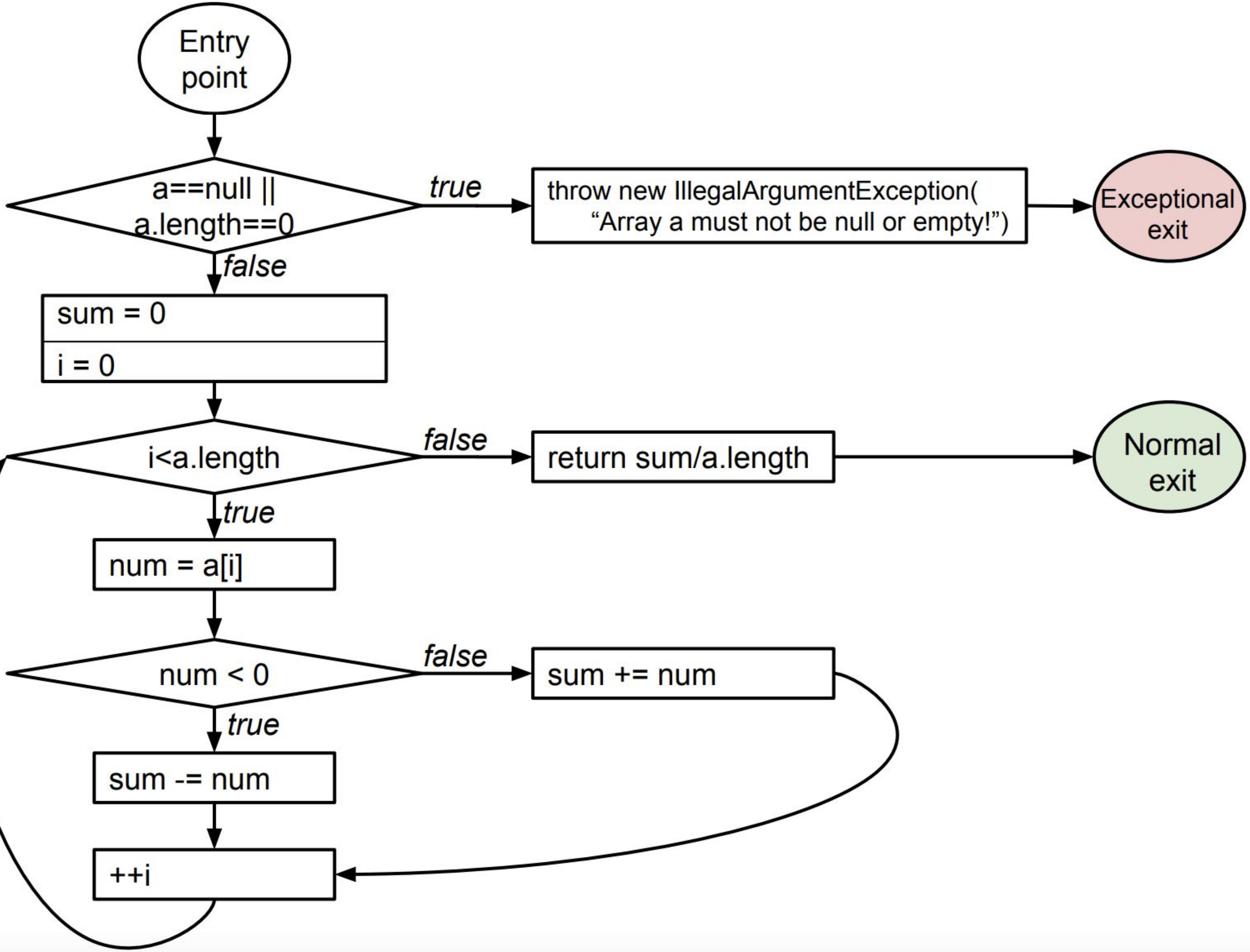
  - that is, if we have a test that causes every CFG node to be executed, we are guaranteed to have 100% statement coverage
- In practice, this means that a tool for computing coverage will instrument each CFG node rather than each statement
  - where does this cause a difference in our example?



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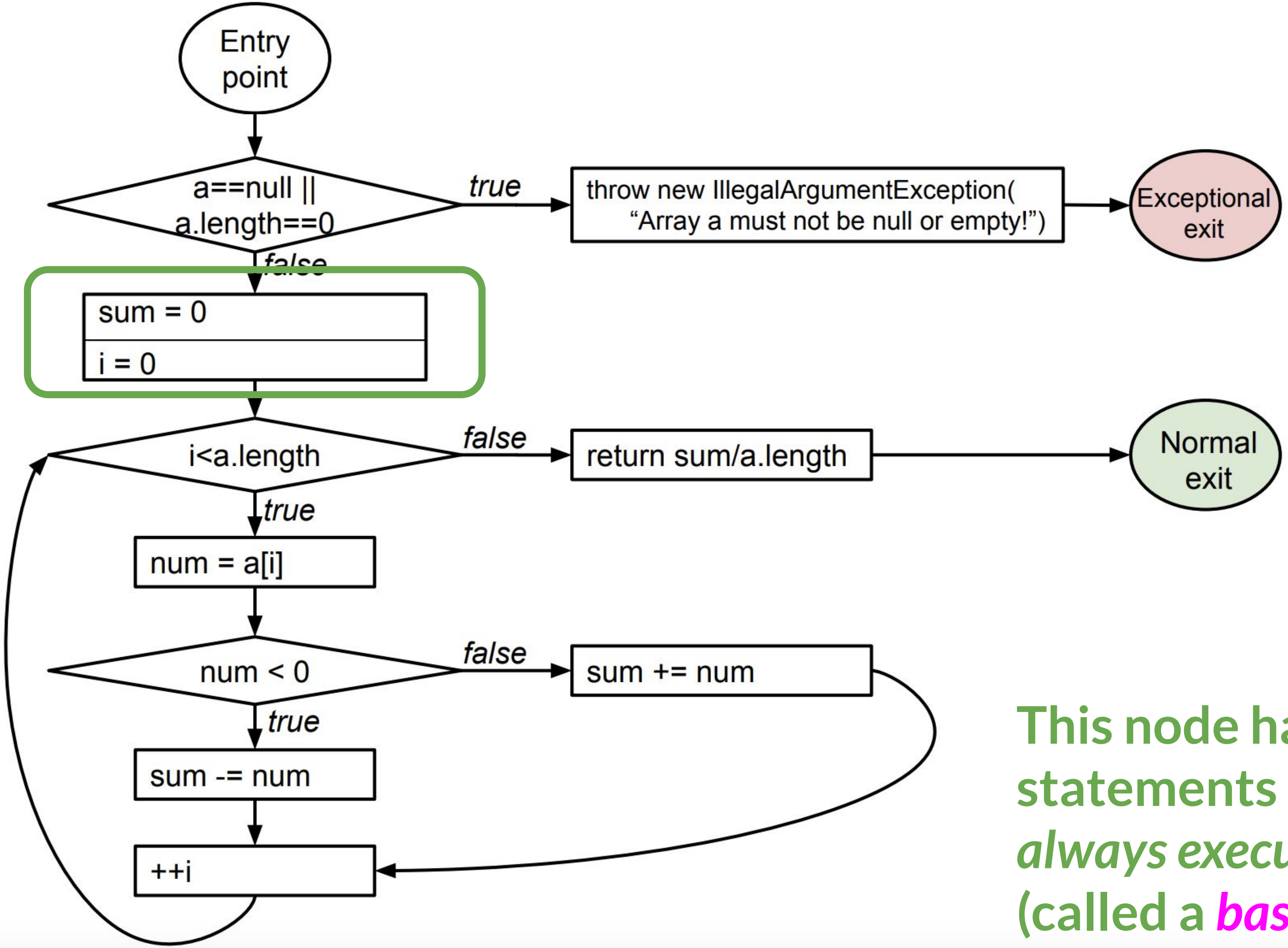
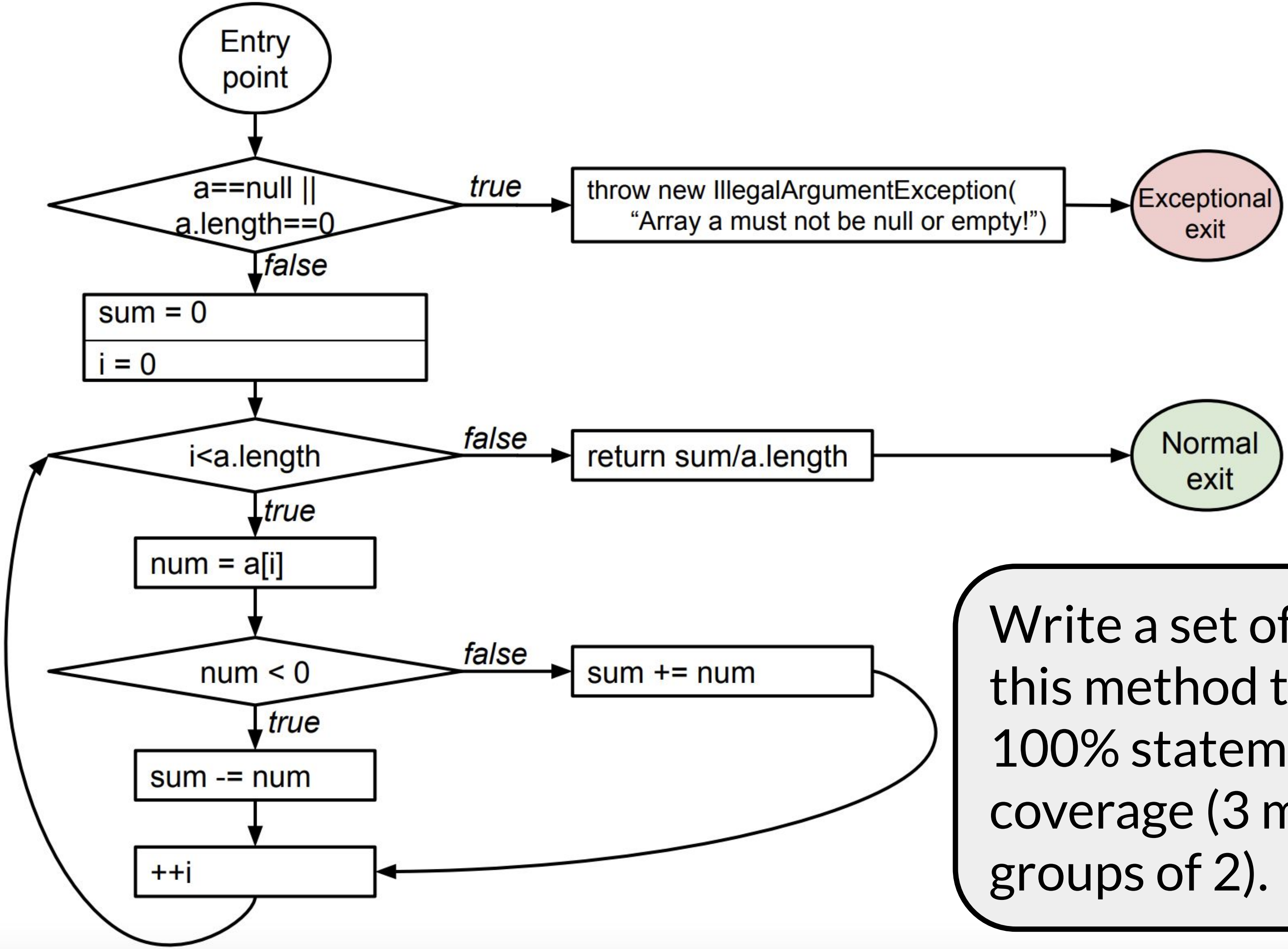


This node has two statements that are *always executed together* (called a *basic block*)



Write a set of tests for this method that achieves 100% statement (= node) coverage (3 minutes, groups of 2).

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- Executing every line doesn't guarantee no bugs
- 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

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- should be covered in a theory of computation class (likely near the end of the semester)

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- examples: reducing something to the halting problem to show that it is not computable; redu[...] show that it is NP-hard
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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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Test Suite { `foo(7)` } has 100% line coverage but 50% branch coverage.

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- Branch coverage typically gives us **more confidence** than line coverage
  - Typically, 100% branch coverage **implies** 100% line coverage
- 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. It is ***being correct*** that is expensive.

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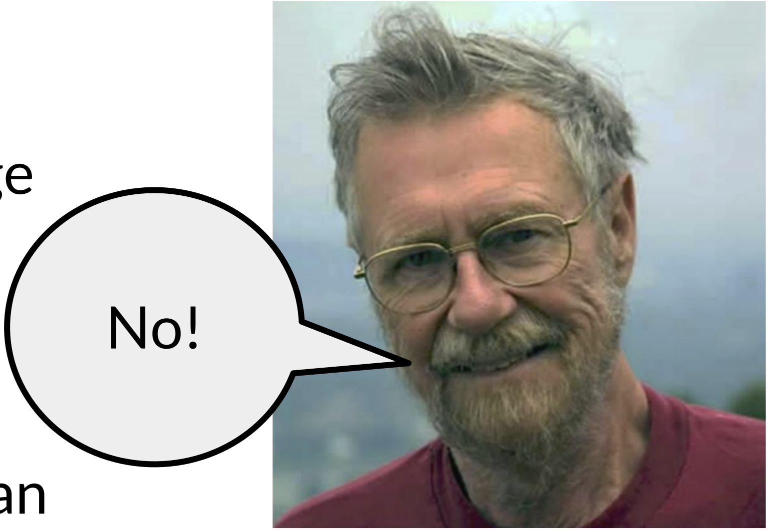

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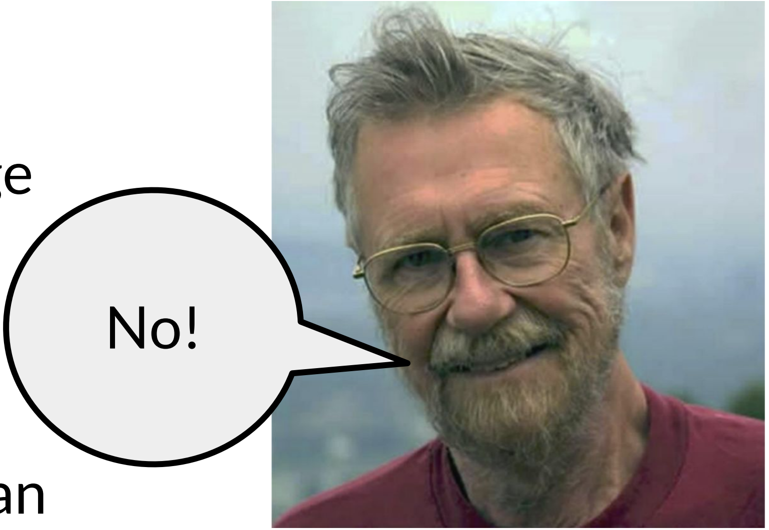

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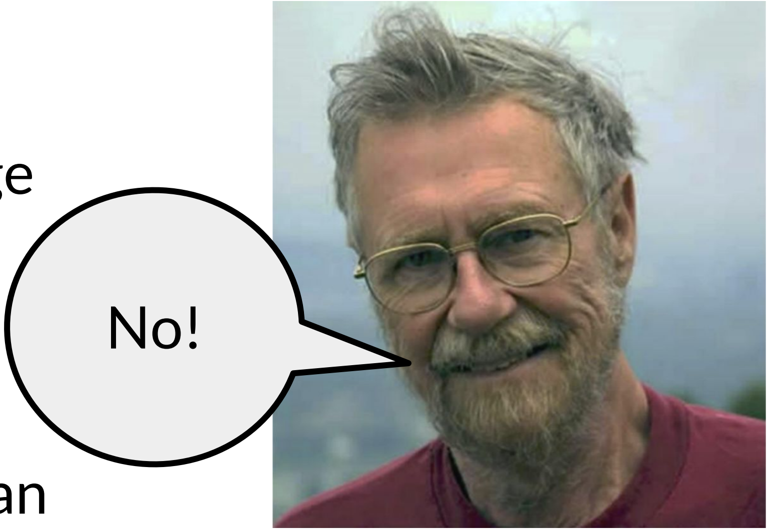
- Recall: “tests can only show the presence of bugs, not their absence”
- More coverage = more confidence, but **no guarantees**!



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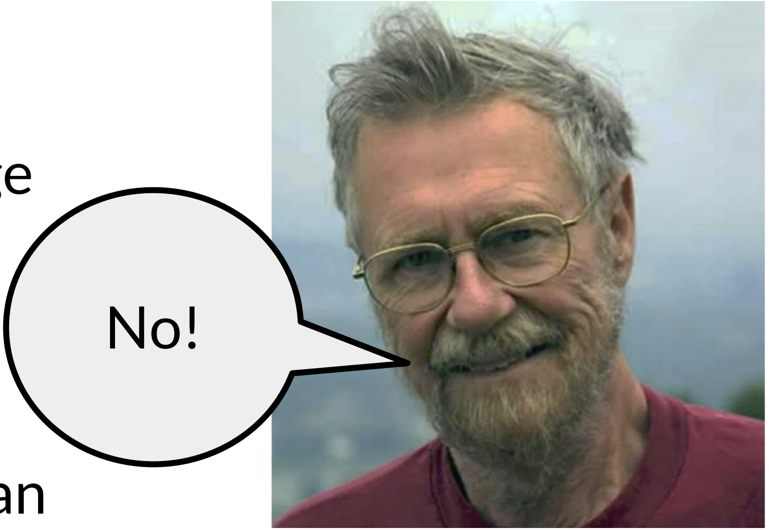

- Recall: "tests can only show the presence of bugs, not their absence"
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- Can we get **finer-grained** than branch coverage?

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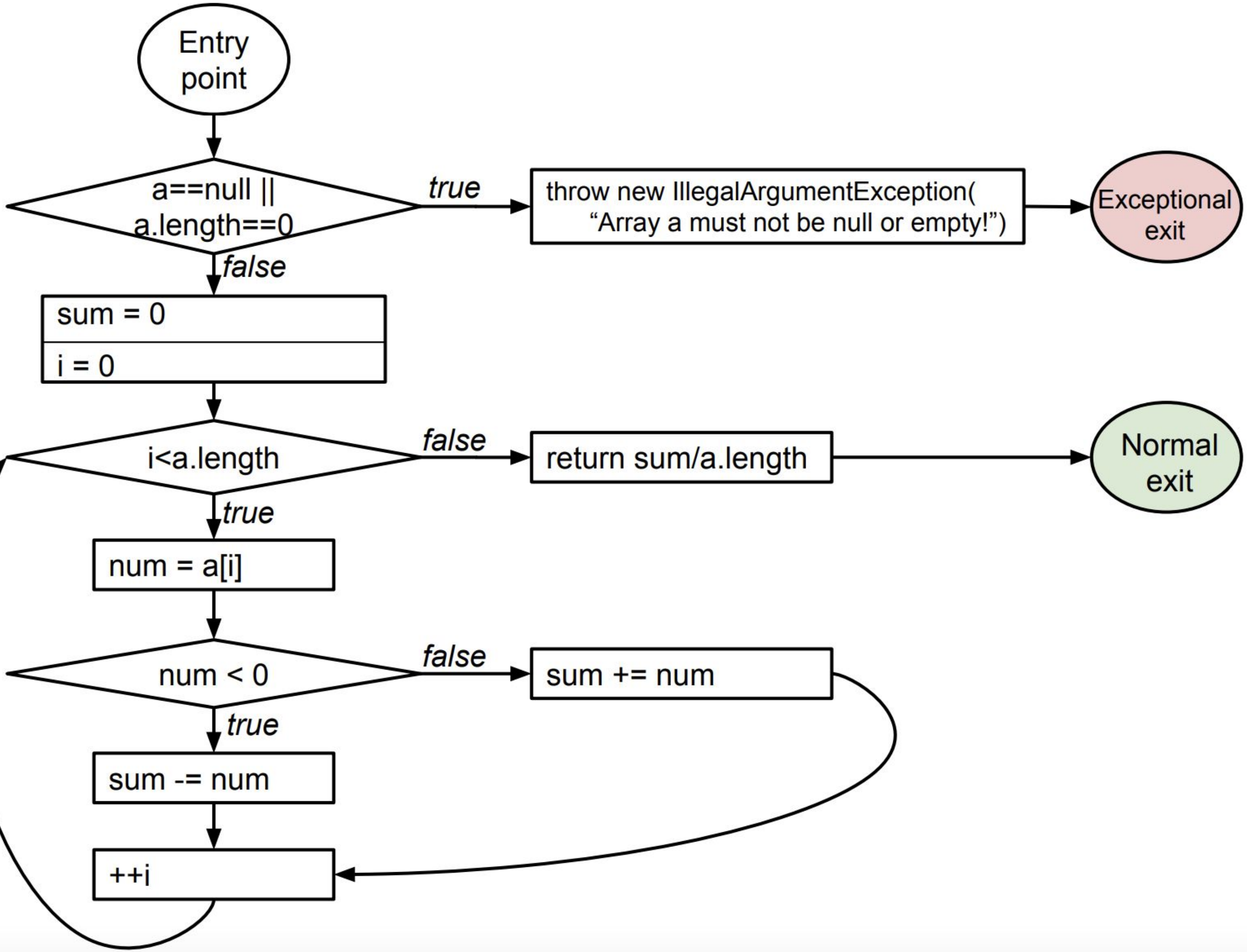
- Example: `if (a | b) {...}`
    - *a* and *b* are **conditions**
    - the boolean expression *a* | *b* is a **decision**

Decision coverage

- ***Decision coverage*** is the percentage of decisions that are true on at least one execution and false on at least one execution
  - i.e., 100% decision coverage = "**every decision** in the program must take on **all possible outcomes** (true/false) **at least once**"



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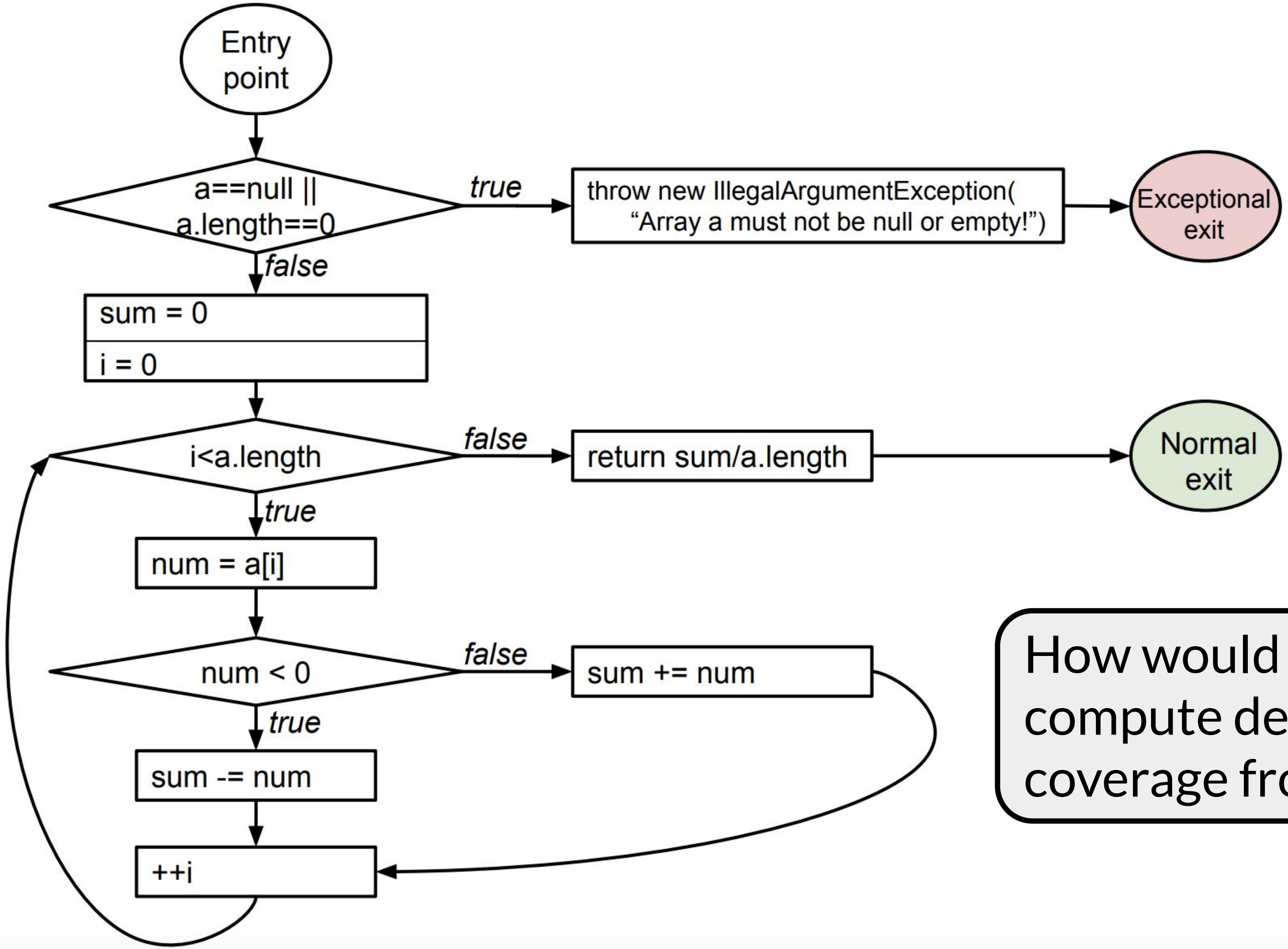

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  - this is straightforward to instrument

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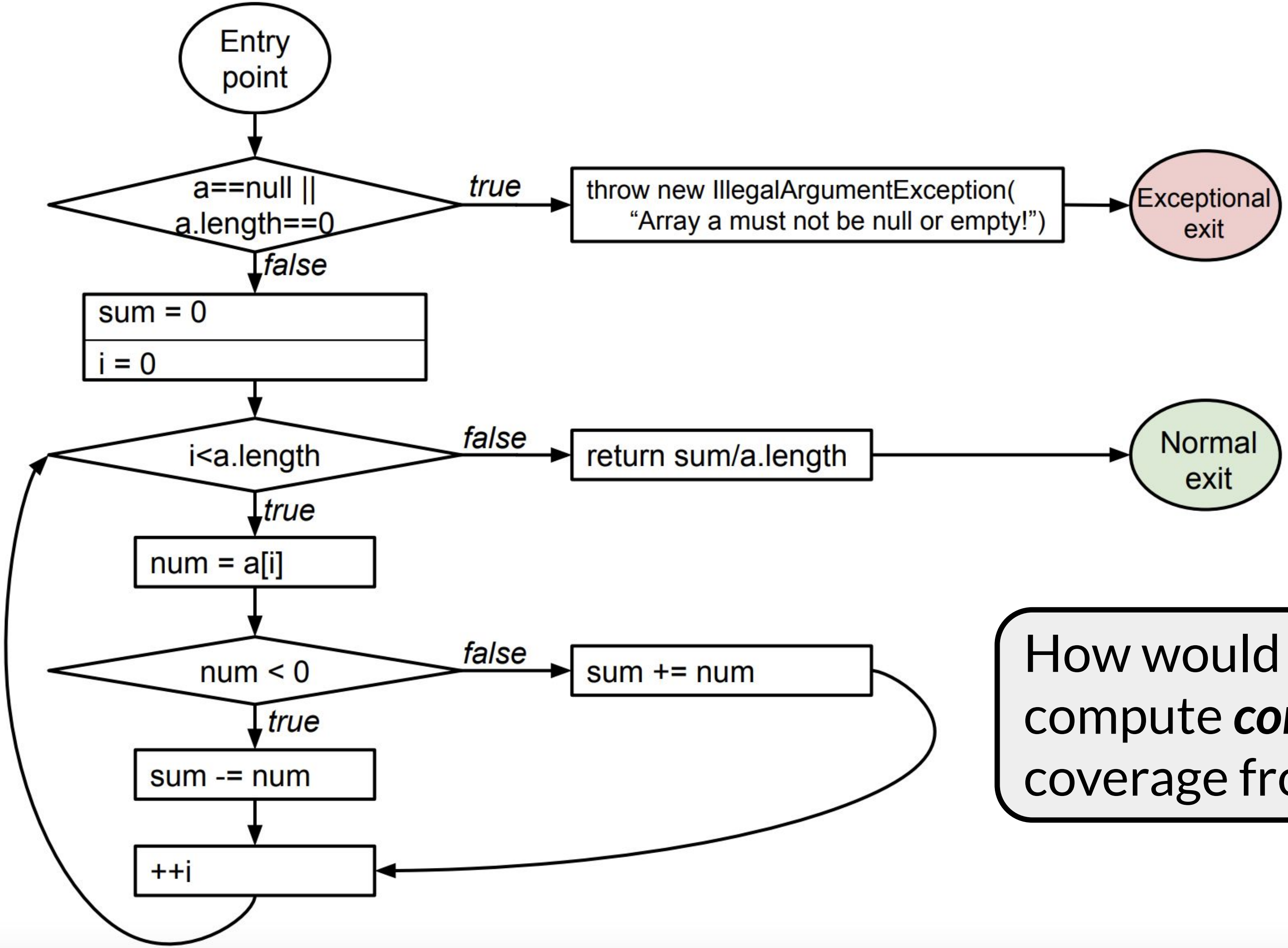

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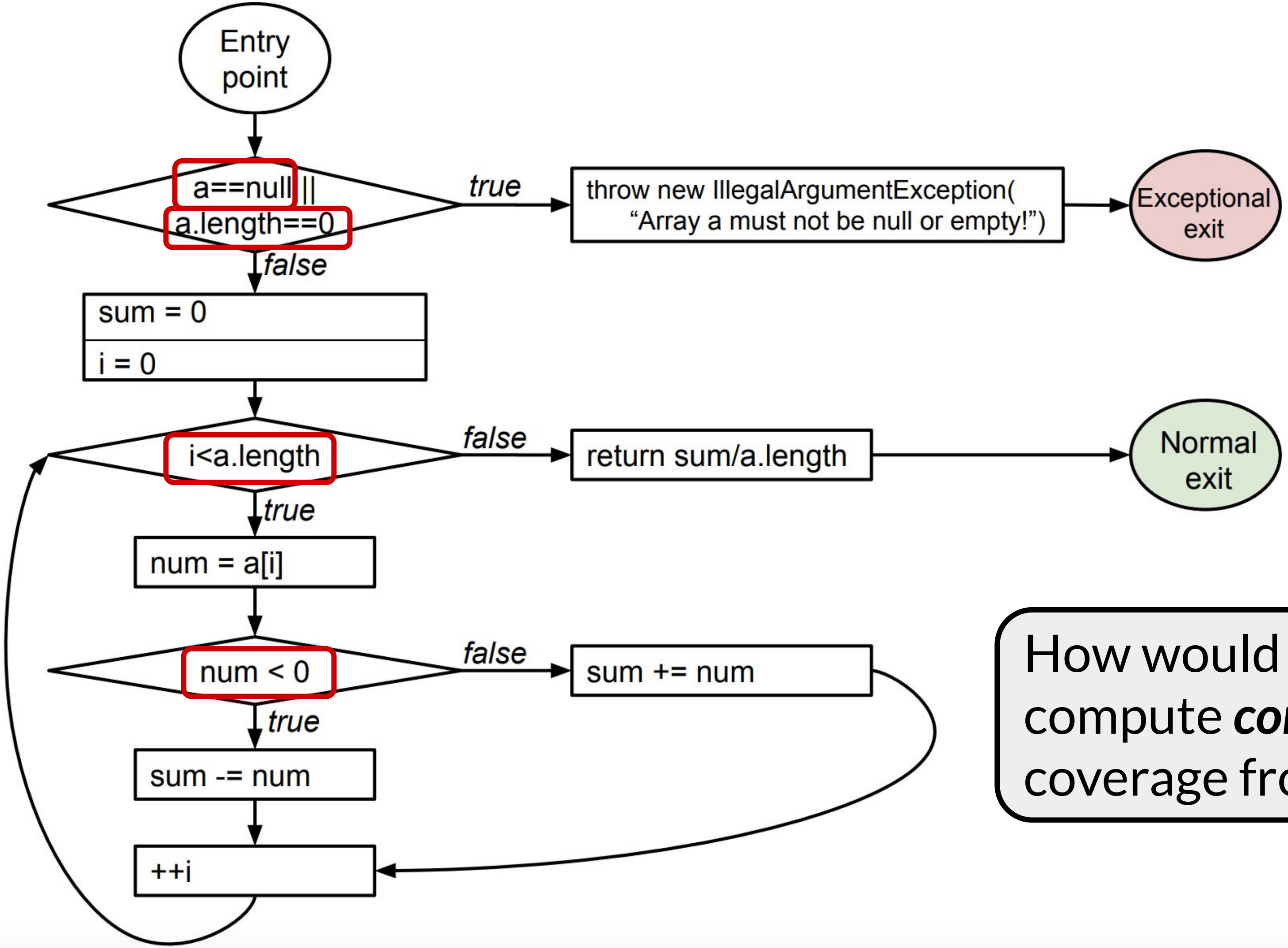

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Subsumption

- We said earlier that branch coverage **subsumes** statement coverage
  - **Definition**: given two coverage criteria *A* and *B*, *A* **subsumes** *B* iff satisfying *A* implies satisfying *B*
- What about other kinds of coverage?
  - Does statement coverage subsume decision coverage?
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Subsumption: decisions vs conditions

- There are 4 possible tests for the decision $a \mid b$:
  - $a = 0, b = 0$ $\quad\quad a \mid b = 0$
  - $a = 0, b = 1$ $\quad\quad a \mid b = 1$
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Subsumption: decisions vs conditions

- There are 4 possible tests for the decision $a \mid b$:
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  - $a = 1, b = 1$ — $a \mid b = 1$
- Implication: **neither** decision coverage **nor** condition coverage subsumes the other!

MC/DC coverage

- ***modified condition and decision coverage*** (***MC/DC coverage***) is a coverage criterion that requires:

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100% MC/DC coverage is **required** for safety critical systems (DO-178B/C)!

MC/DC coverage example

```
if (a | b)
```

a	b	outcome
0	0	0
0	1	1
1	0	1
1	1	1

MC/DC =

- 100% decision coverage
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Which tests (combinations of a and b) satisfy MC/DC?

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Which tests (combinations of a and b) satisfy MC/DC?

MC/DC is still cheaper than testing all possible combinations!

MC/DC: another example

```
if (a || b)
```

a	b	outcome
0	0	0
0	1	1
1	-	1
1	-	1

MC/DC =
- 100% decision coverage
- 100% condition coverage
- each condition shown to independently affect outcome

Why is this example different? Short-circuiting operators may not evaluate all conditions.

MC/DC: a third example

`if (!a) … if (a || b)`

a	b	outcome
0	0	0
0	1	1
1	0	1
1	1	1

MC/DC =

- 100% decision coverage
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What about this example?

MC/DC: a third example

`if (!a) … if (a || b)`

a	b	outcome
0	0	0
0	1	1
X	X	X
X	X	X

MC/DC =
- 100% decision coverage
- 100% condition coverage
- each condition shown to independently affect outcome

What about this example?

Not all combinations of conditions may be possible!

MC/DC coverage: complex expressions

- With a partner, take a few minutes to provide an MC/DC-adequate test suite for:
  - `a | b | c`
  - `a & b & c`

MC/DC =
- 100% decision coverage
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Coverage: other kinds of coverage

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    - e.g., what do you think **function coverage** is?

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- You can define coverage over any kind of program structure
  - e.g., what do you think **function coverage** is?
- You can also define coverage over non-programmatic things
  - e.g., **requirements coverage** or **user-story coverage** are sometimes used in industry

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- Coverage is **easy to compute**
- Coverage has an **intuitive interpretation**
- Coverage is **common in industry** (e.g., think about today's reading about Google)
- But coverage on its own is **not sufficient** to guarantee correctness
  - just because you executed a line does not mean that that line did the right thing! (oracles!)

Three ways to think about test suite quality

Consider three ways to think about test suite quality:

- test suite quality through the lens of logic
  - intuition: if we don't test it, we can't find bugs
  - leads to ***coverage*** (main subject of today's lecture)
- test suite quality through the lens of **statistics**
  - intuition: test what happens to real users
- test suite quality through the lens of adversity
  - intuition: inject bugs and see if the test suite catches them
  - leads to ***mutation testing***, which we'll cover later this semester

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Rest of today’s lecture:
a brief discussion of the
lens of statistics

The Lens of Statistics: intuition

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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

Example: limited input domain

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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

Limitations on users in the real world

- Usually, in the real world, your input domain isn't so limited
- But, you might still be able to say:

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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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  - "Our test suite is a sample of inputs that could occur in the real world. Our program behaves well on our test suite." → later → "Our program behaves badly on some other untested real input. Sampling error!"
- 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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- Possible solution: there are a number of **well-established sampling techniques** in the field of statistics to help address such biases
  - 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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But beware of sampling errors! Who signs up to be a beta tester?
Hint: **not the average user**!

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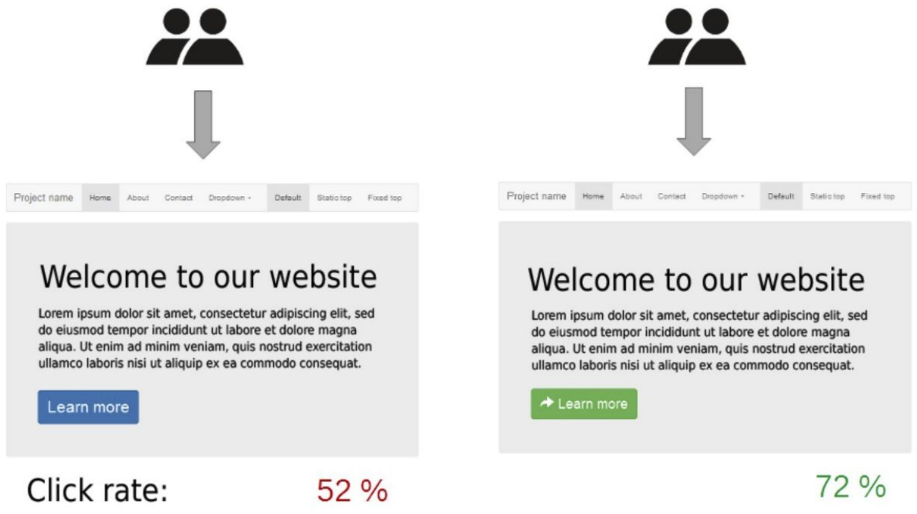
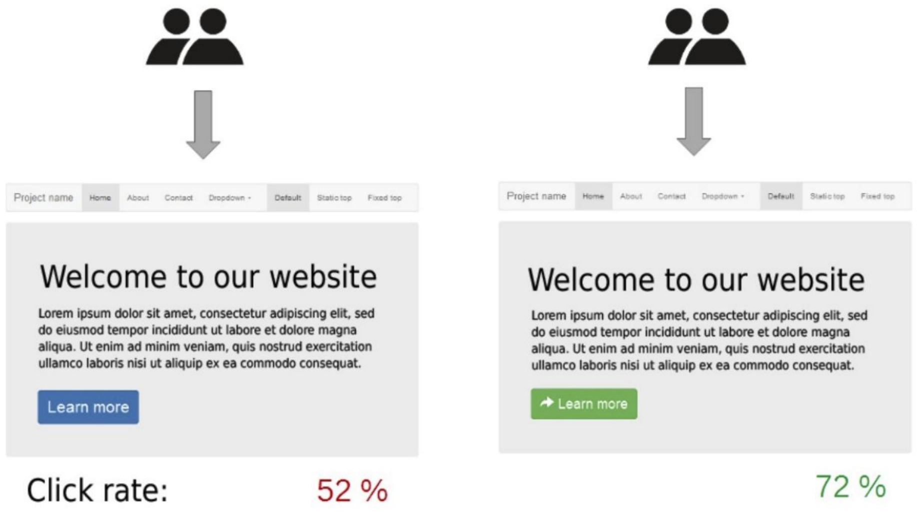


The Lens of Statistics: practical options

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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- The latter often relates to **computer security**
  - E.g., exploit generation, penetration testing, etc.
- **Damage** can also be in other forms
  - e.g., for Amazon, "damage" might be "customer doesn't complete the purchase"

Today’s in-class

- Achieve higher coverage on libpng
  - inputs are image files
- This assignment is supposed to be harder than HW2
  - libpng is ~85k LoC, so I don’t expect you to read it all
  - this is indicative of real-world engineering: you usually don’t have time to read all the relevant code
  - getting started can be tricky, so use us for the rest of class to get around any difficulties collecting coverage locally
  - good luck!