CS 4530: Fundamentals of Software Engineering

Module 11: What makes a good test suite?

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Learning Objectives for this Lesson

By the end of this lesson, you should be able to

- Explain what makes a good test, and give examples and counter examples
- Explain goals for a test suite, and sketch how how to judge whether it does

What makes for a good test suite?

Desirable properties of a test suite:

- Find bugs
- Run automatically
- Are relatively cheap to run

Desirable properties of one individual test:

- Understandable and debuggable
- No false alarms

Related Terminology: "test smells"

Good Tests are Hermetic

Contain all information necessary to set up, execute, and tear down environment

Leaves no trace of its execution

Important to reduce test failures

```
describe('Create student', () => {
  it('should return an ID', async () => {
    const student = await client.addStudent('Avery');
    expect(student.studentID).toBeGreaterThan(4);
  });
})
```

This test is not hermetic: assumes starting ID 4, leaves an extra Avery in the application

"Software Engineering at Google: Lessons Learned from Programming Over Time," Wright, Winters and Manshreck, 2020 (O'Reilly) 4

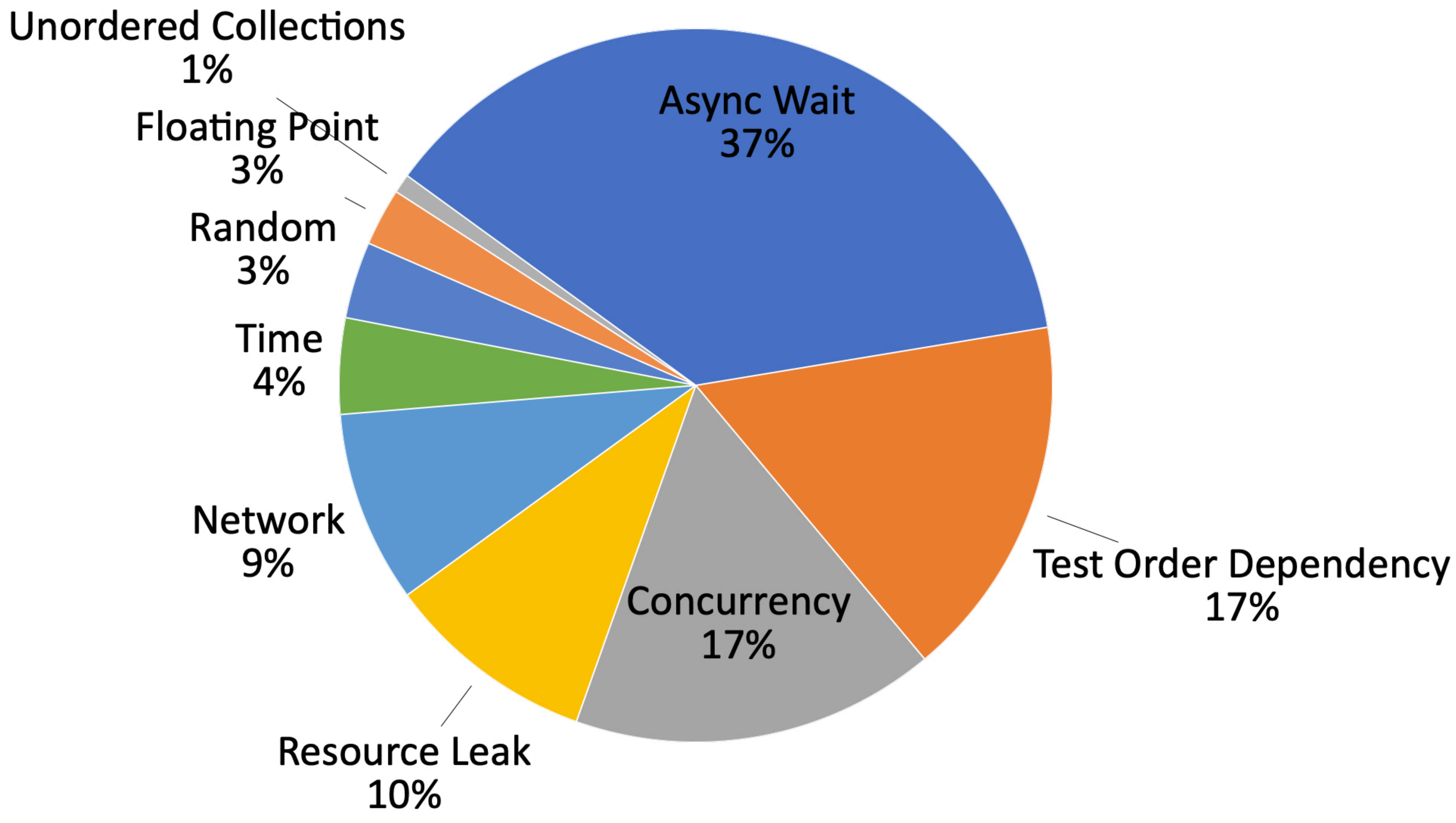
Good Tests Aren't Flaky

Flaky test failures are false alarms

Hermetic tests are robust to *order dependency*, failures when tests run out of order

Most common cause of flaky tests: *async wait*, tests that expect some async action within a timeout

Good tests don't rely on timing



[Luo et al, FSE 2014 "An empirical analysis of flaky tests"]

Good Tests Aren’t *Brittle*

Brittle tests make *invalid assumptions* about the spec

Specs often leave room for undefined behaviors: details subject to change

Brittle tests fail unexpectedly if undefined behavior changes

```
it('Throws if no layer called "objects"', async () => {
  expect(() => town.initializeFromMap(testingMaps.noObjects))
      .toThrowError(‘No layer called "objects"');
});
```

Unless the specification states that this is the exact error message that should be thrown, this test is brittle

Good Tests are Clear

Test failures indicate:

- There is a bug in the system under test, and/or
- There is a bug in the test

Clear tests help engineers diagnose actual problem

```
it('remove only removes one',()=>{
    const tree = makeBST();
    for (let i=0; i<1000; ++i) {
      tree.add(i);
    }
    for (let j=0; j<1000; ++j) {
      for (let i=0; i<1000; ++i) {
        if (i!=j) tree.remove(i);
      }
      expect(tree.contains(j)).
        toBe(true);
    }
  }
```

This test is not clear: if it fails, why?

Good Tests Invoke Public APIs Only

Tests should only invoke public methods of SUT (system under test)

Interact with SUT as a client of the SUT would:

- Public methods within classes
- Exported members of modules

```
public initializeFromMap(map: ITiledMap) {
    ...
  this._validateInteractables();
}

private _validateInteractables() {
  // Test Me!
}
```

It might be tempting to make _validateInteractables public and test it directly: but it's not how clients would call it!

What makes a Test Suite good?

Depends on goals of the test suite

Test Driven Development

- Does the SUT satisfy its spec? (“functional testing”)
- Good test suites exercise and validate entire spec

Regression Test

- Did something change since some previous version?
- Prevent bugs from re-entering during maintenance
- Good test suites detects bugs we introduce in code (“structural testing”)

Acceptance Test

- Does the SUT satisfy the customer (“requirement testing”)
- Good test suites answer: Are we building the right thing?

Does the SUT satisfy its spec?

Test behavior without regard to implementation ("black-box" or "functional testing")

What's a specification?

Not often seen in the wild

- A precise definition of all acceptable behaviors of SUT (outputs, state, effects) in all situations
- A specification may be formal (math), informal (natural language) or implicit ("I know it when I see it").

A test suite is an approximation to an unwritten specification

- That's the "T" in TDD
- Adequacy of test suite is likelihood that an implementation passing all tests actually fulfills the spec

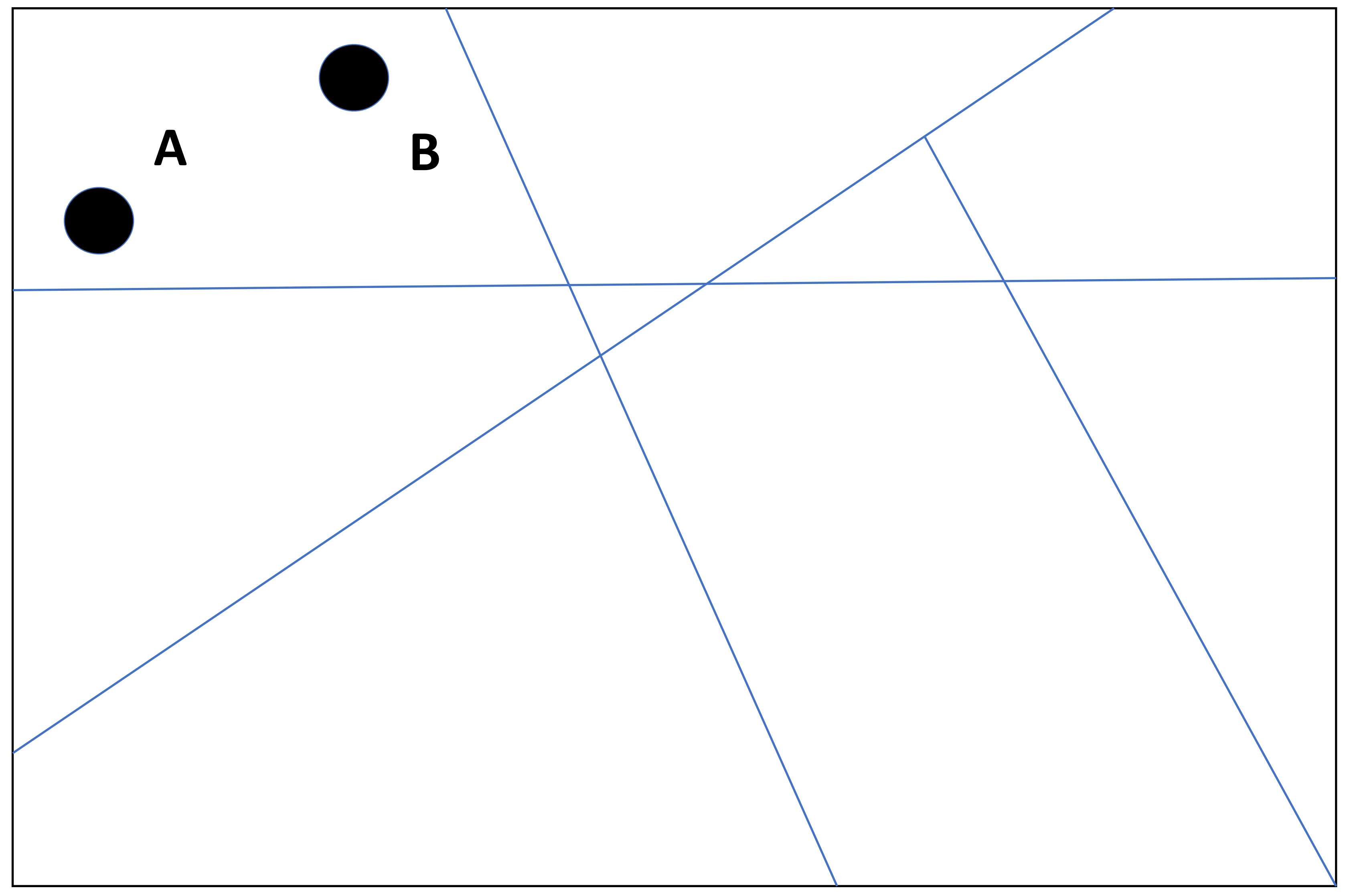
Building Test Suites From Specifications

Enumerate equivalence classes of inputs to SUT, and expected behavior of that class

Identify boundary cases (near misses between input classes)

Evaluate adequacy of a suite by comparing tested behaviors with specified behaviors

Sometimes referred to as “black box” testing



If the program works for input A, it will probably work for input B

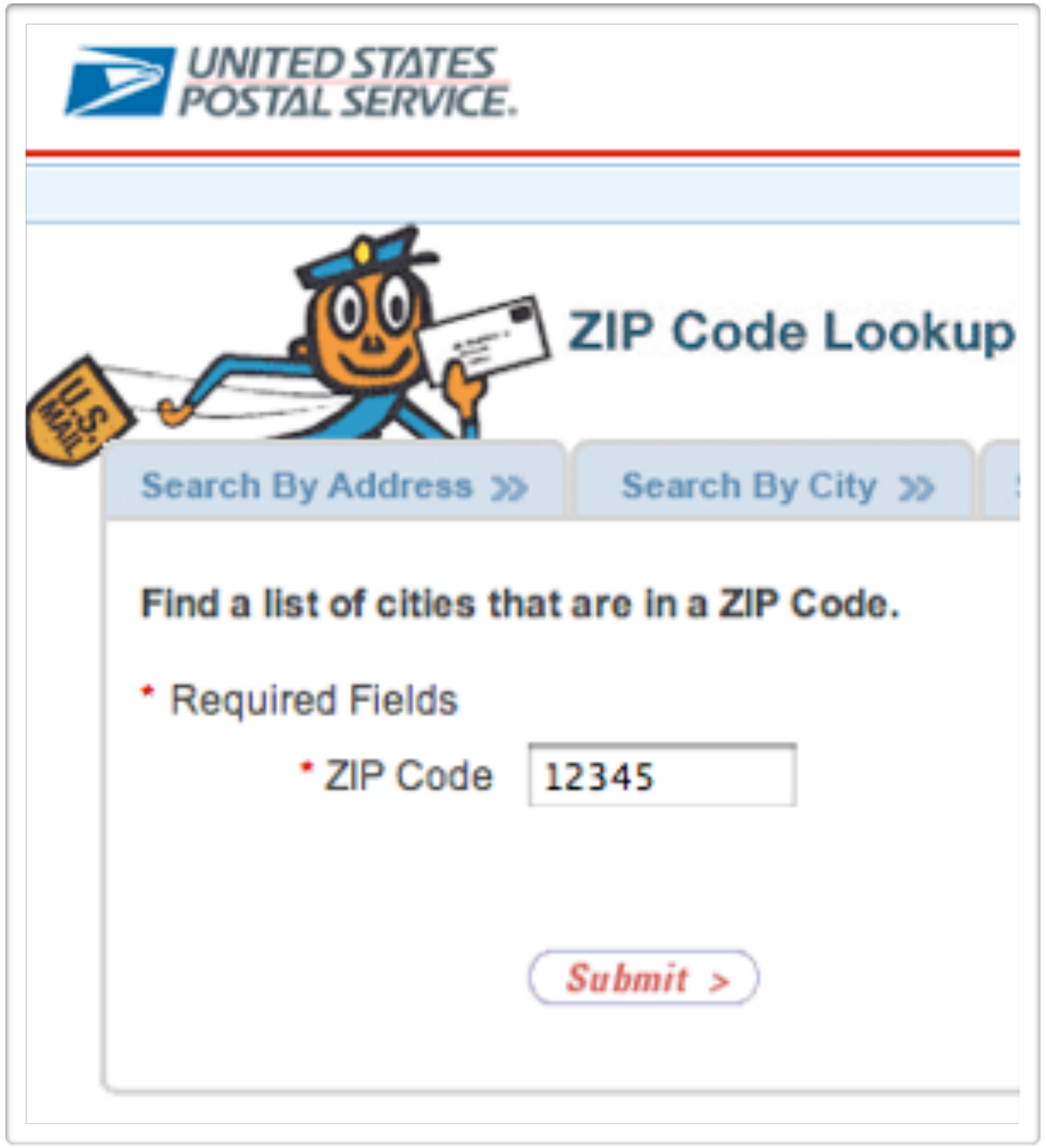
Building Test Suites From Specs: Zip Code Lookup

USPS ZIP code lookup tool accepts a zip code as input, and outputs:

- The "place names" that correspond to that ZIP code, or
- "Invalid zip code"

Strategy:

- Determine the input equivalence classes, boundary conditions
- Write tests for those inputs



Find a list of cities that are in a ZIP Code.

* Required Fields

* ZIP Code 12345

Building Test Suites From Specs: Zip Code Lookup

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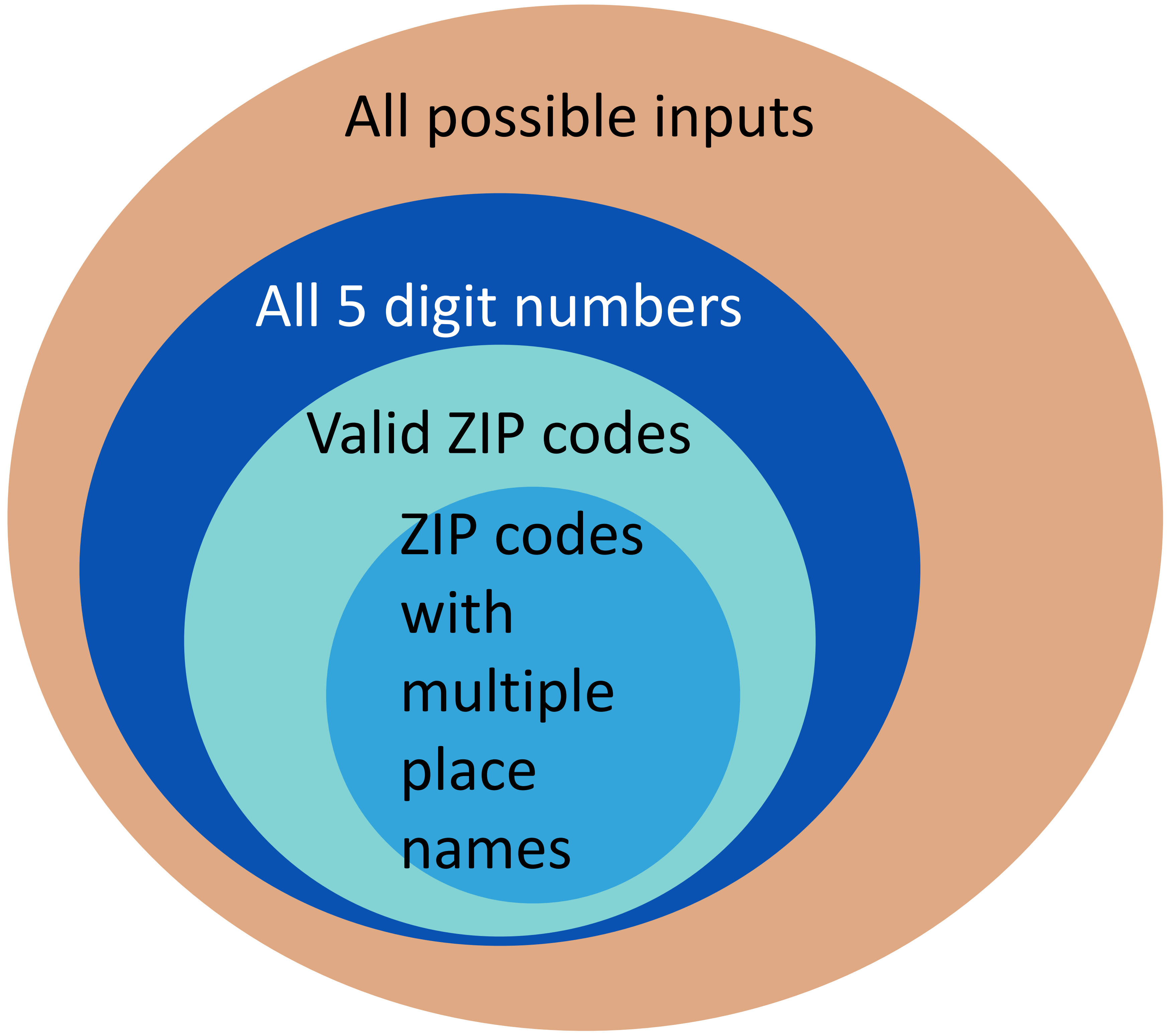
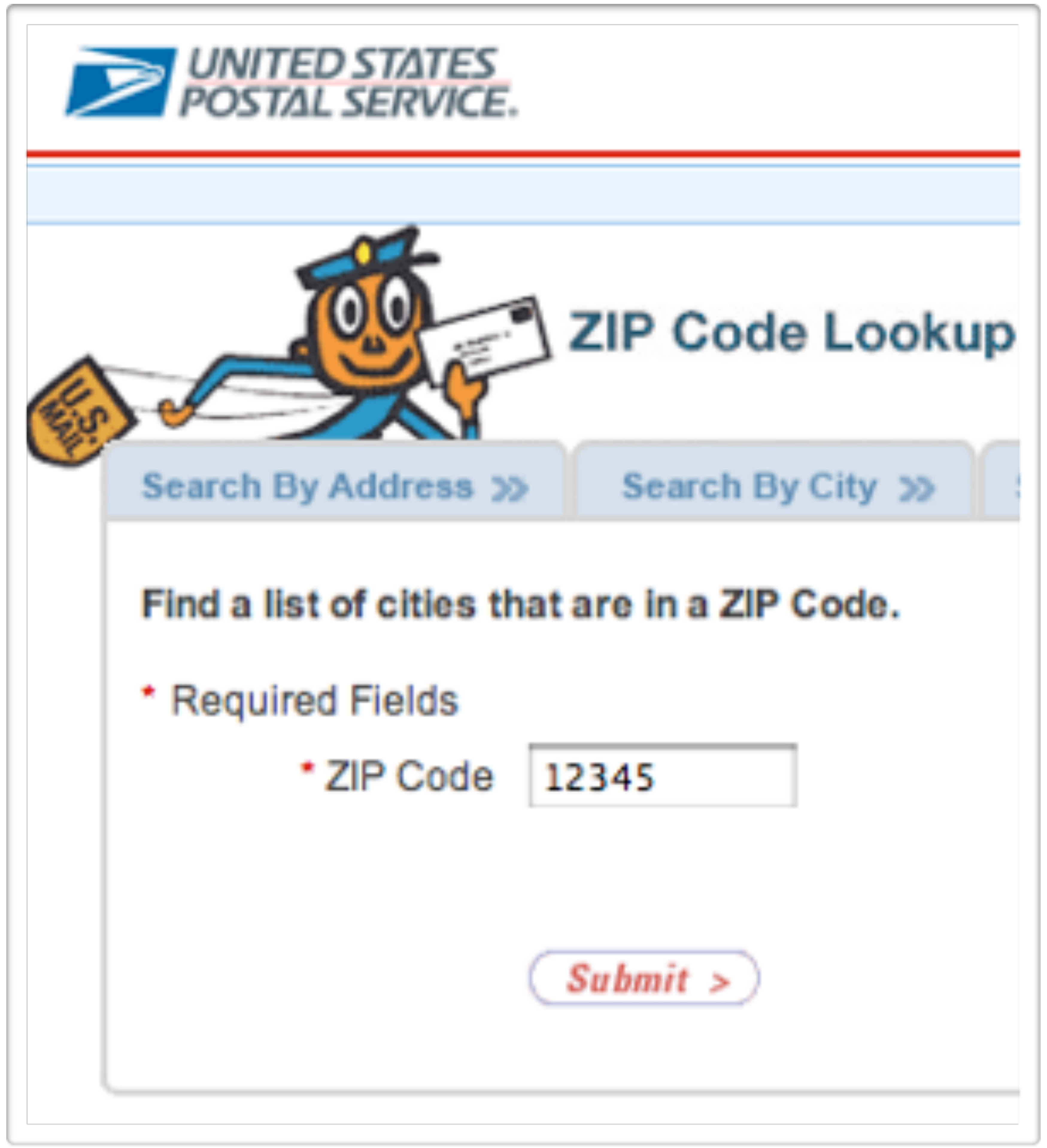




Find a list of cities that are in a ZIP Code.

* Required Fields

* ZIP Code 12345

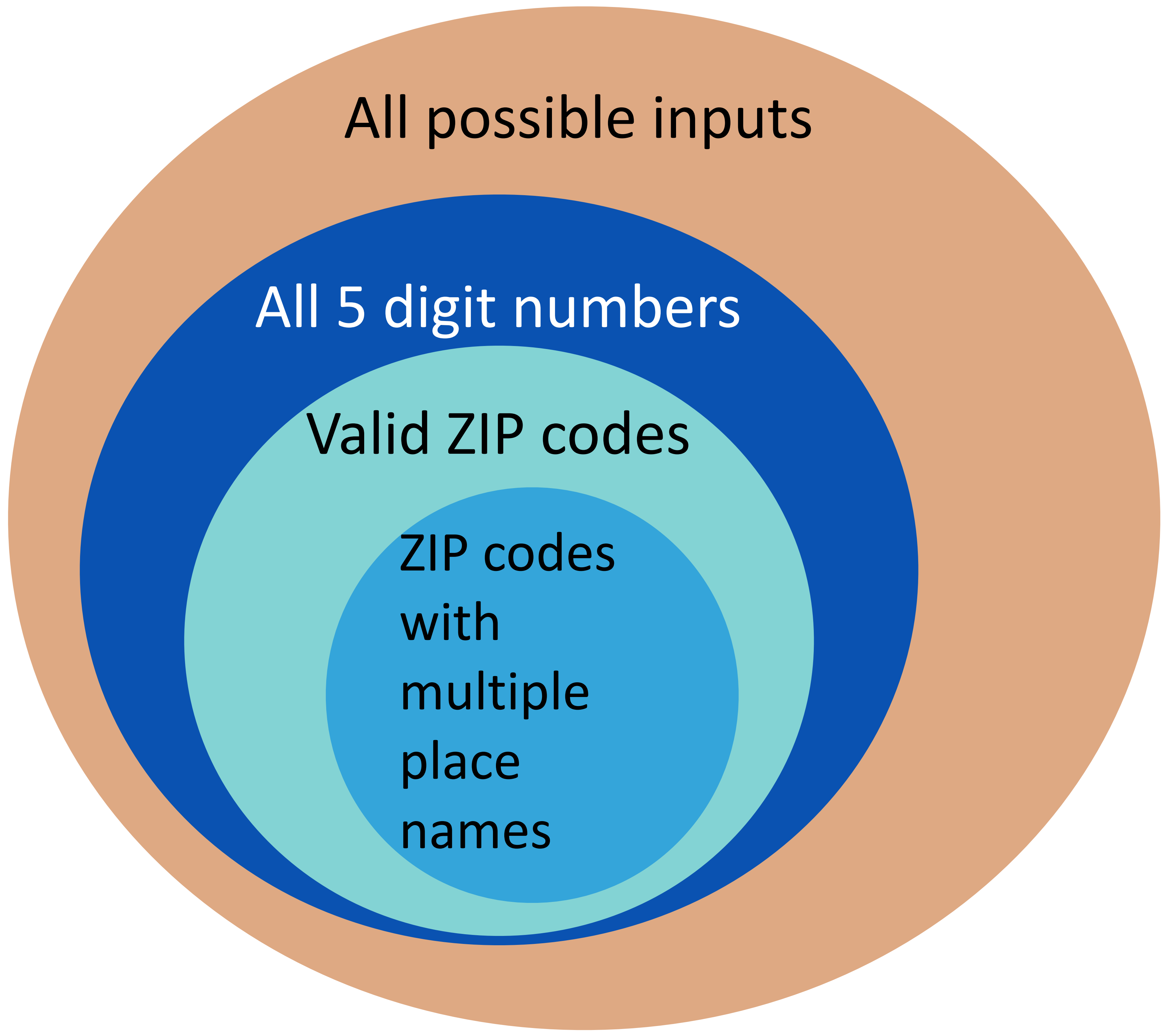
Building Test Suites From Specs: Zip Code Lookup

Equivalence classes:

- Not a 5 digit number
- A 5 digit numbers: A valid ZIP code;
  With one place name; With multiple place names;
  Not a valid ZIP code

Generate at least one input from each class,
plus boundaries (e.g. 4 digit, 6 digit numbers, nothing)

Encode the expected output of the system for each test



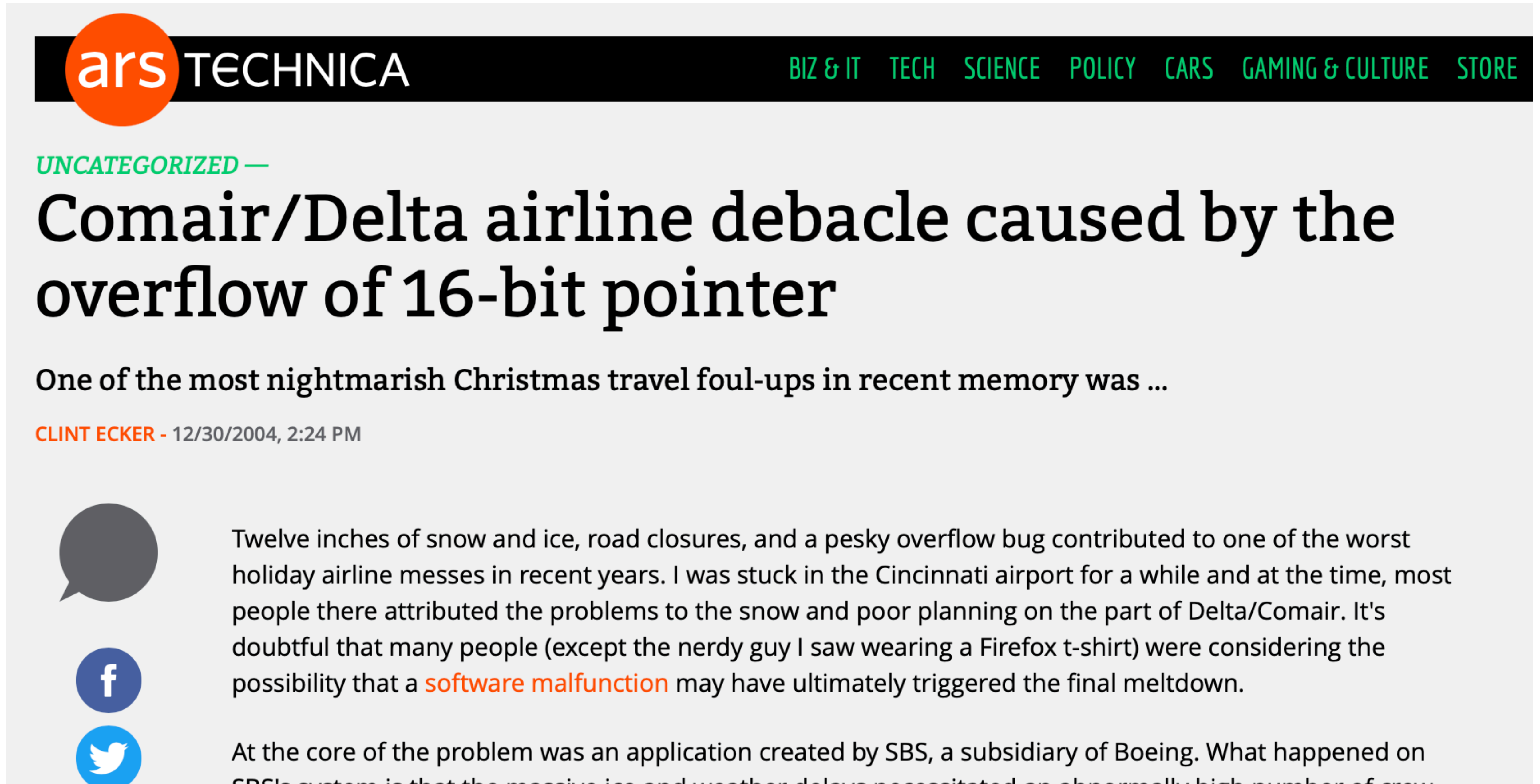
Make sure regions have the right boundaries

Select “special” values of a range

- Boundary values;
- Barely legal, barely illegal inputs;
- => boundary testing

Integer overflow is a problem: may be implicit

- ComAir problem when a list got more than 32767 elems
- https://arstechnica.com/uncategorized/2004/12/4490-2/



UNCATEGORIZED —

Comair/Delta airline debacle caused by the overflow of 16-bit pointer

One of the most nightmarish Christmas travel foul-ups in recent memory was ...

CLINT ECKER - 12/30/2004, 2:24 PM

Twelve inches of snow and ice, road closures, and a pesky overflow bug contributed to one of the worst holiday airline messes in recent years. I was stuck in the Cincinnati airport for a while and at the time, most people there attributed the problems to the snow and poor planning on the part of Delta/Comair. It's doubtful that many people (except the nerdy guy I saw wearing a Firefox t-shirt) were considering the possibility that a software malfunction may have ultimately triggered the final meltdown.

At the core of the problem was an application created by SBS, a subsidiary of Boeing. What happened on

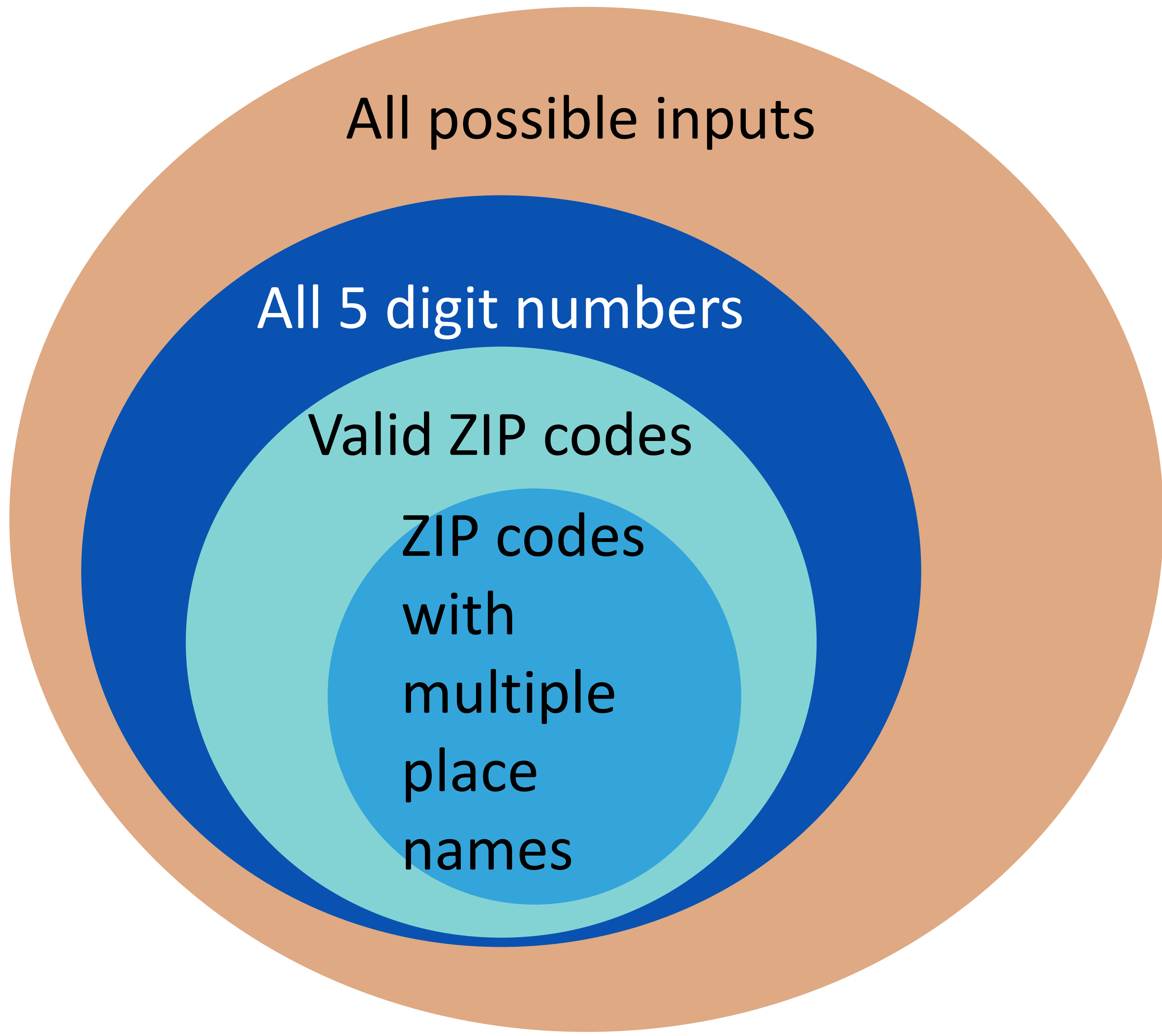
Building Tests from Specifications (TDD)

When delivering a feature, must deliver tests to ensure it keeps working in the future

You may have specific domain knowledge that future developers do not

Specs are hard to interpret and check, automated tests are easy

Beyoncé rule: “If you liked it, you should have put a ~~ring~~ test on it”



Building Test Suites for Code (“Whitebox” Testing)

Examine the code of SUT

- Enumerate all public methods and observable behaviors
- Write tests that execute those methods and check those behaviors

A “good” test suite executes and checks all of the possible behaviors of our code

```
function getPlaceNames(input: string): string[] {
  try{
    if(input.length == 5) {
      const zip = parseInt(input);
      if (isValidZipcode(zip)) {
        const place = getPrimaryPlace(zip);
        if(hasMorePlaces(parsed)){
          return [place].concat(otherPlaces(zip))
        }
        return [place];
      }
    }
    throw new Error("Invalid zip code")
  }catch(err){
    throw new Error("Invalid zip code")
  }
}
```

Do our tests execute all of the code?

Idea: Measure portion of code executed by test suite

- If not sufficient, write new test inputs to execute more code.

This requires a notion of *coverage*

- Statement coverage
- Branch coverage

If something is not covered, it is definitely not tested

If something is covered, it might be tested

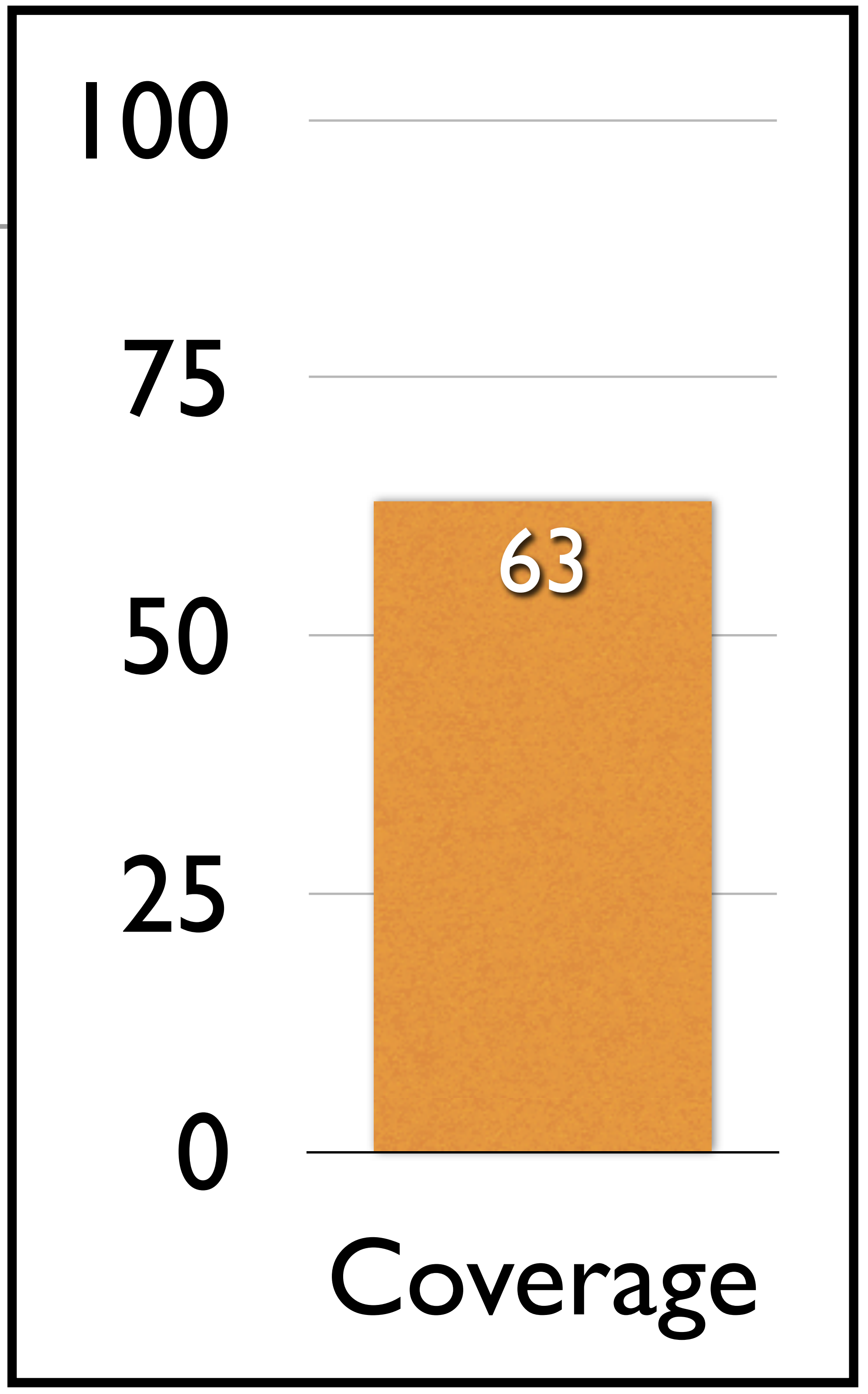
Statement Coverage

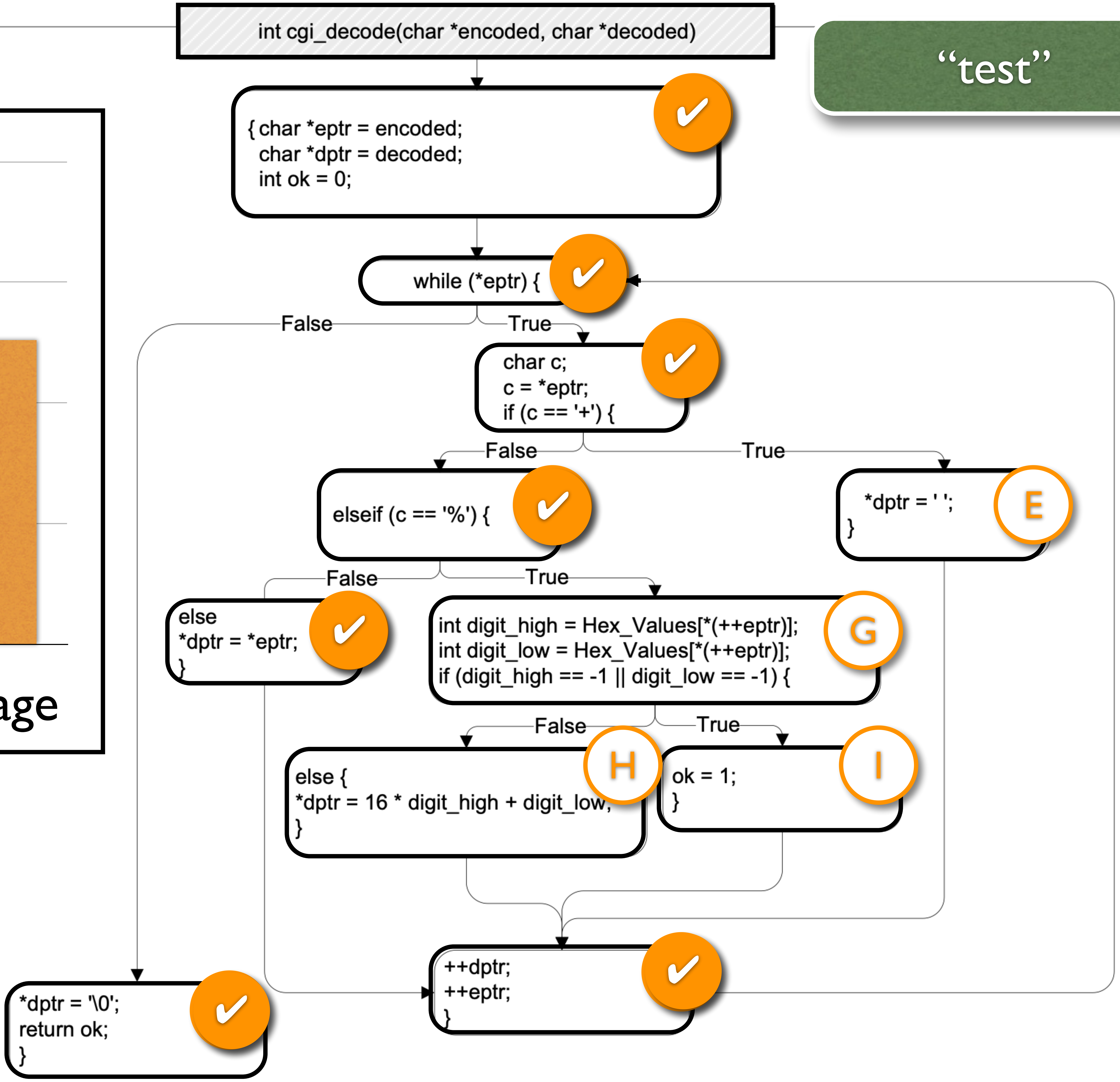
Adequacy criterion: ***each statement executed at least once***

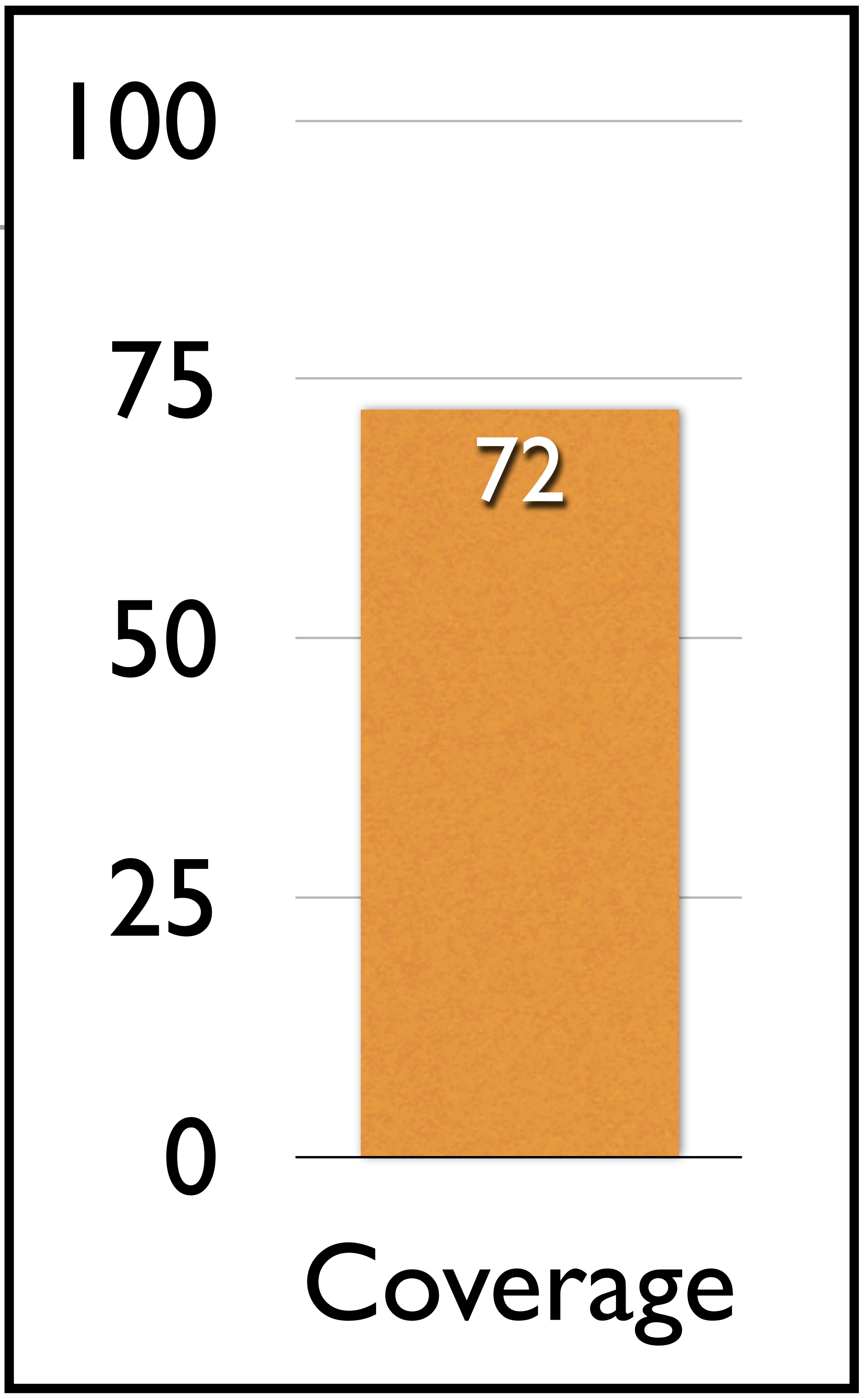
Coverage:

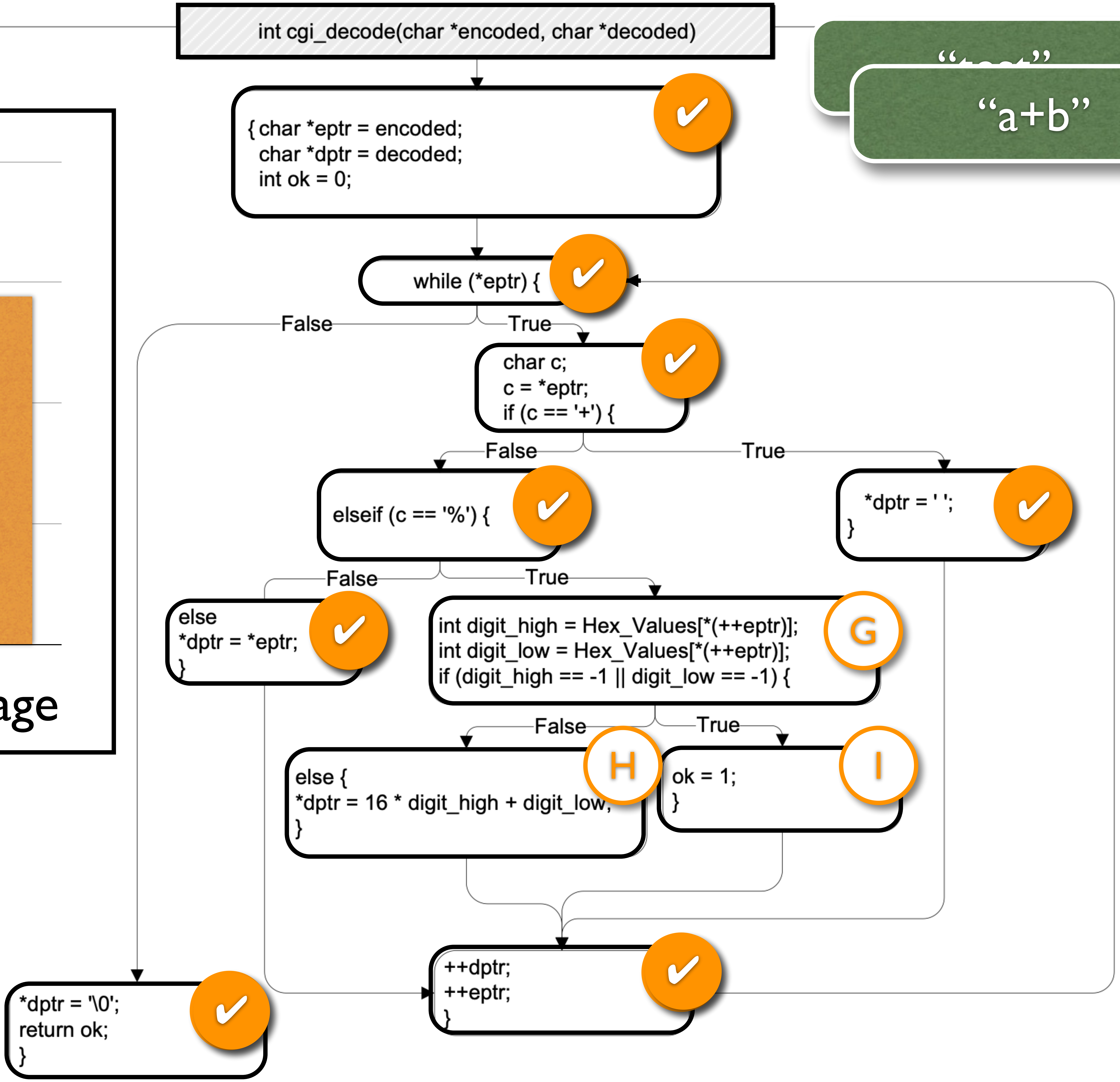
$$\frac{\#\text{executed statements}}{\#\text{statements}}$$

“test”




```
int cgi_decode(char *encoded, char *decoded)

{ char *eptr = encoded;
  char *dptr = decoded;
  int ok = 0;

while (*eptr) {

char c;
c = *eptr;
if (c == '+') {

*dptr = ' ';
}

elseif (c == '%') {

else
*dptr = *eptr;
}

int digit_high = Hex_Values[*(++eptr)];
int digit_low = Hex_Values[*(++eptr)];
if (digit_high == -1 || digit_low == -1) {

else {
*dptr = 16 * digit_high + digit_low;
}

ok = 1;
}

++dptr;
++eptr;
}

*dptr = '\0';
return ok;
}
```

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*dptr = '\0';
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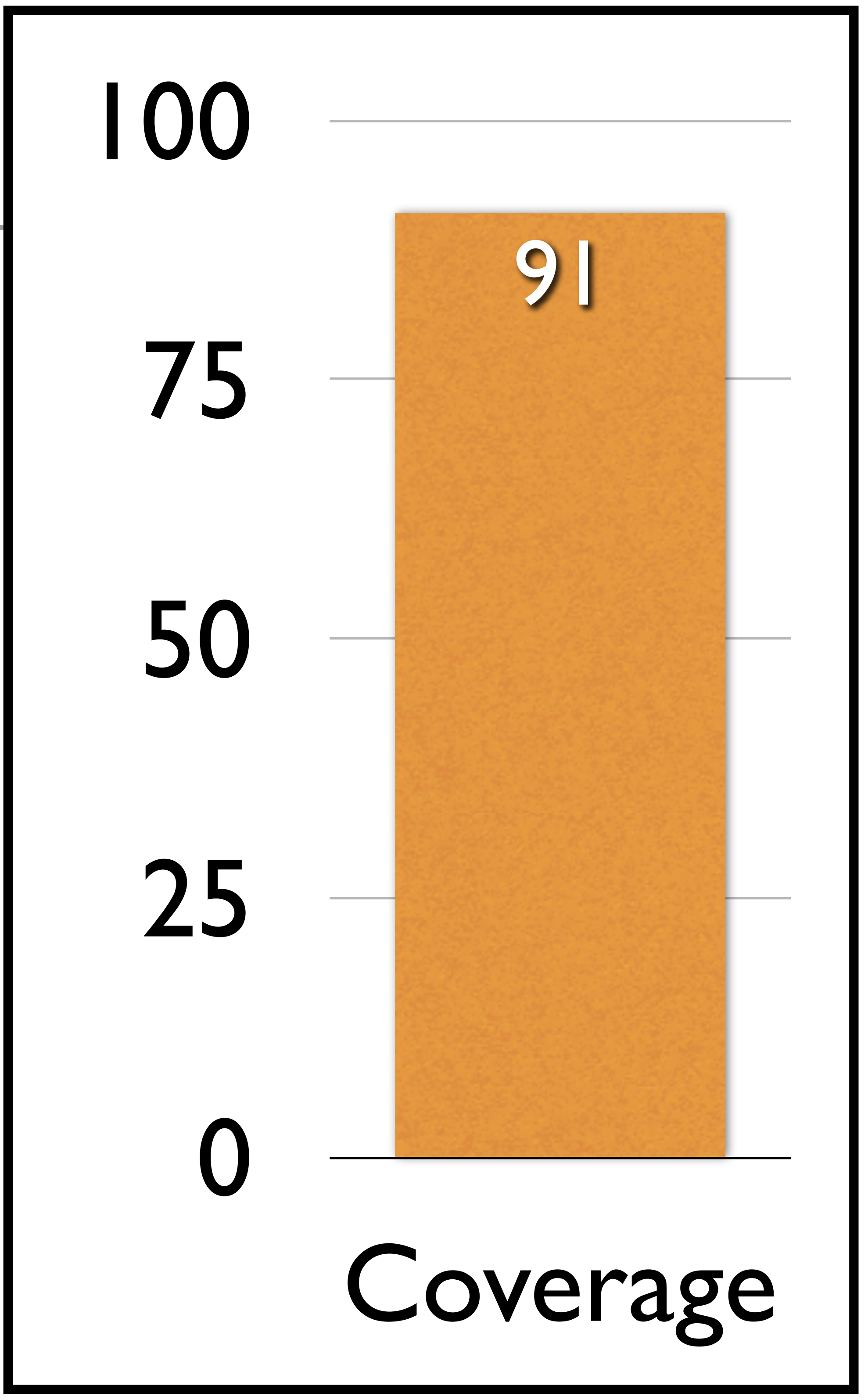
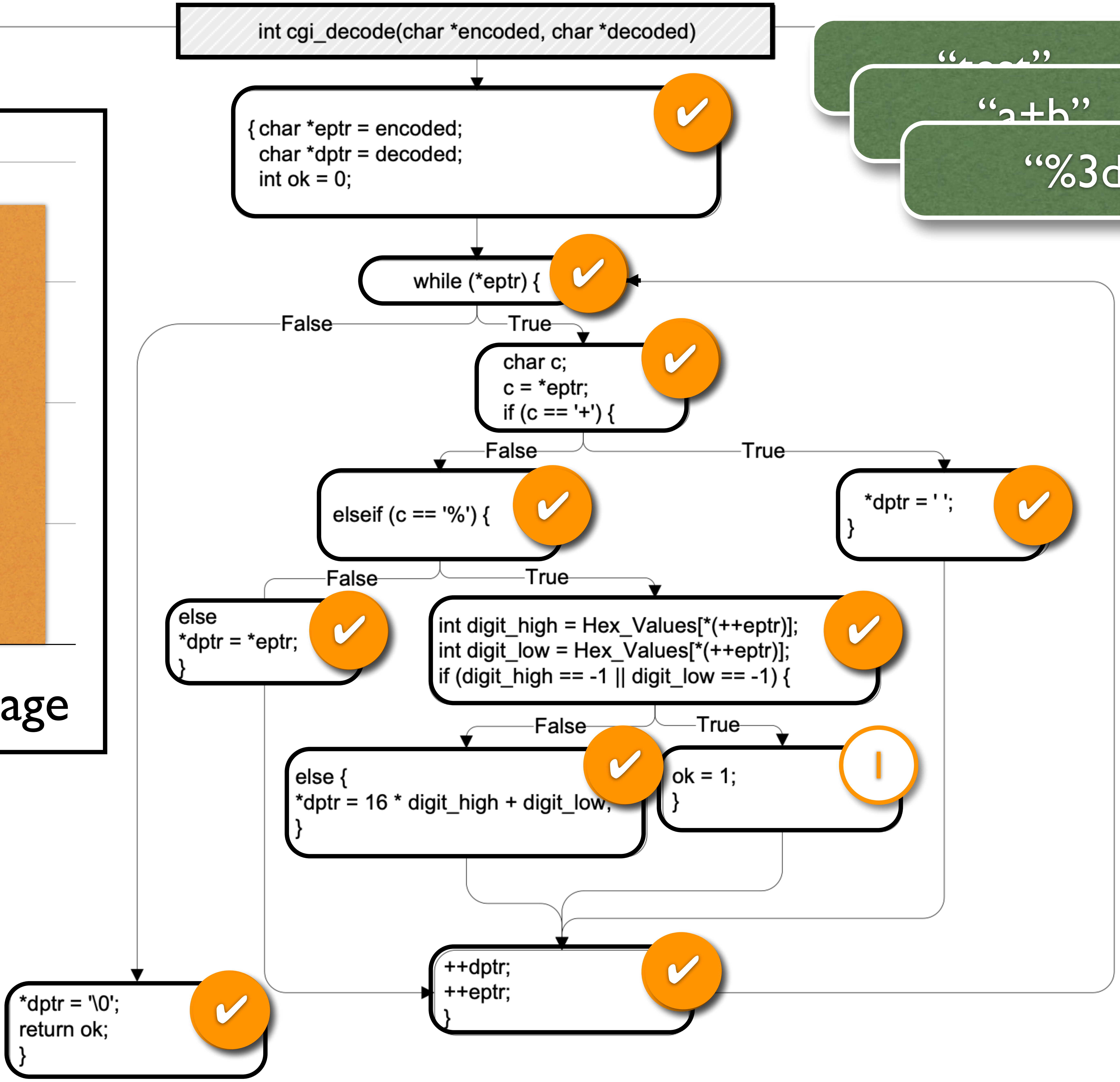
}
```

"test"

"a+b"





```
int cgi_decode(char *encoded, char *decoded)
```

```
{ char *eptr = encoded;
  char *dptr = decoded;
  int ok = 0;
```

```
while (*eptr) {
```

```
char c;
c = *eptr;
if (c == '+') {
```

```
elseif (c == '%') {
```

```
*dptr = ' ';
}
```

```
else
*dptr = *eptr;
}
```

```
int digit_high = Hex_Values[*(++eptr)];
int digit_low = Hex_Values[*(++eptr)];
if (digit_high == -1 || digit_low == -1) {
```

```
else {
*dptr = 16 * digit_high + digit_low;
}
```

```
ok = 1;
}
```

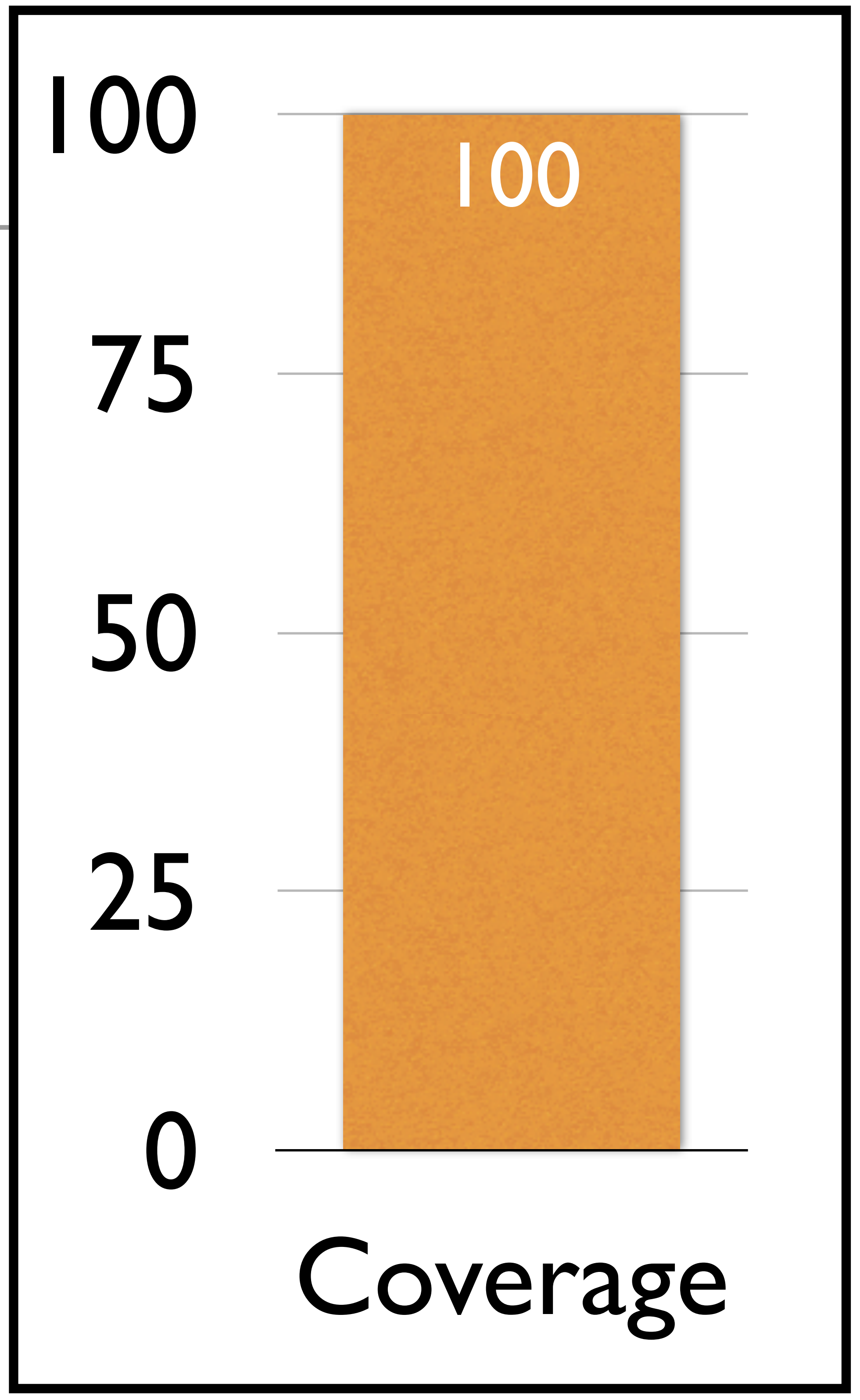
```
++dptr;
++eptr;
}
```

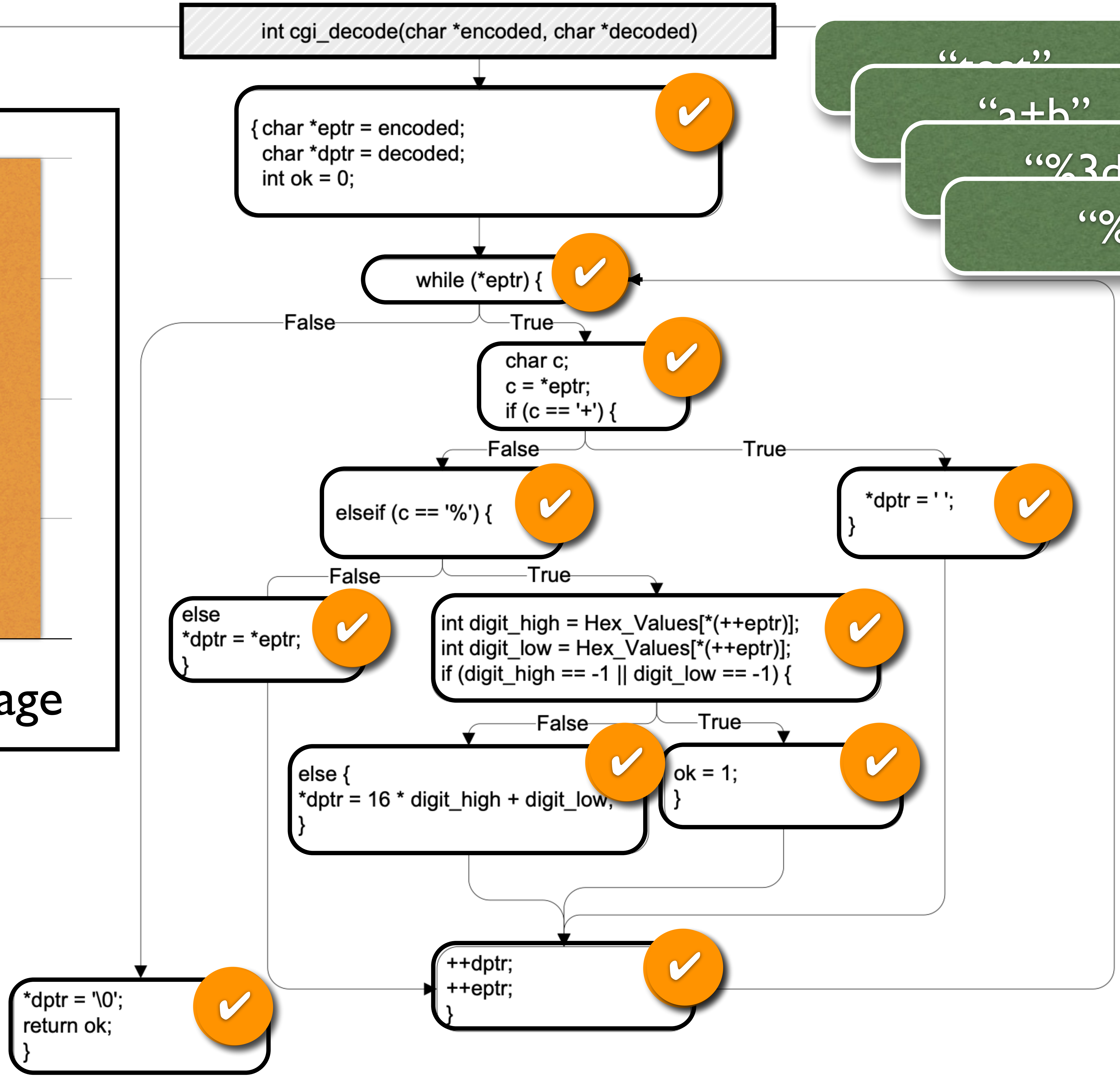
```
*dptr = '\0';
return ok;
}
```

"test"

"a+b"

"%3d"





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*dptr = ' ';
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*dptr = *eptr;
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else {
*dptr = 16 * digit_high + digit_low;
}

ok = 1;
}

++dptr;
++eptr;
}

*dptr = '\0';
return ok;
}
```

"test"

"a+b"

"%3d"

"%g"

Branch Coverage

Adequacy criterion: ***each branch in the CFG executed at least once***

$$\text{coverage: } \frac{\textit{\# executed branches}}{\textit{\# branches}}$$

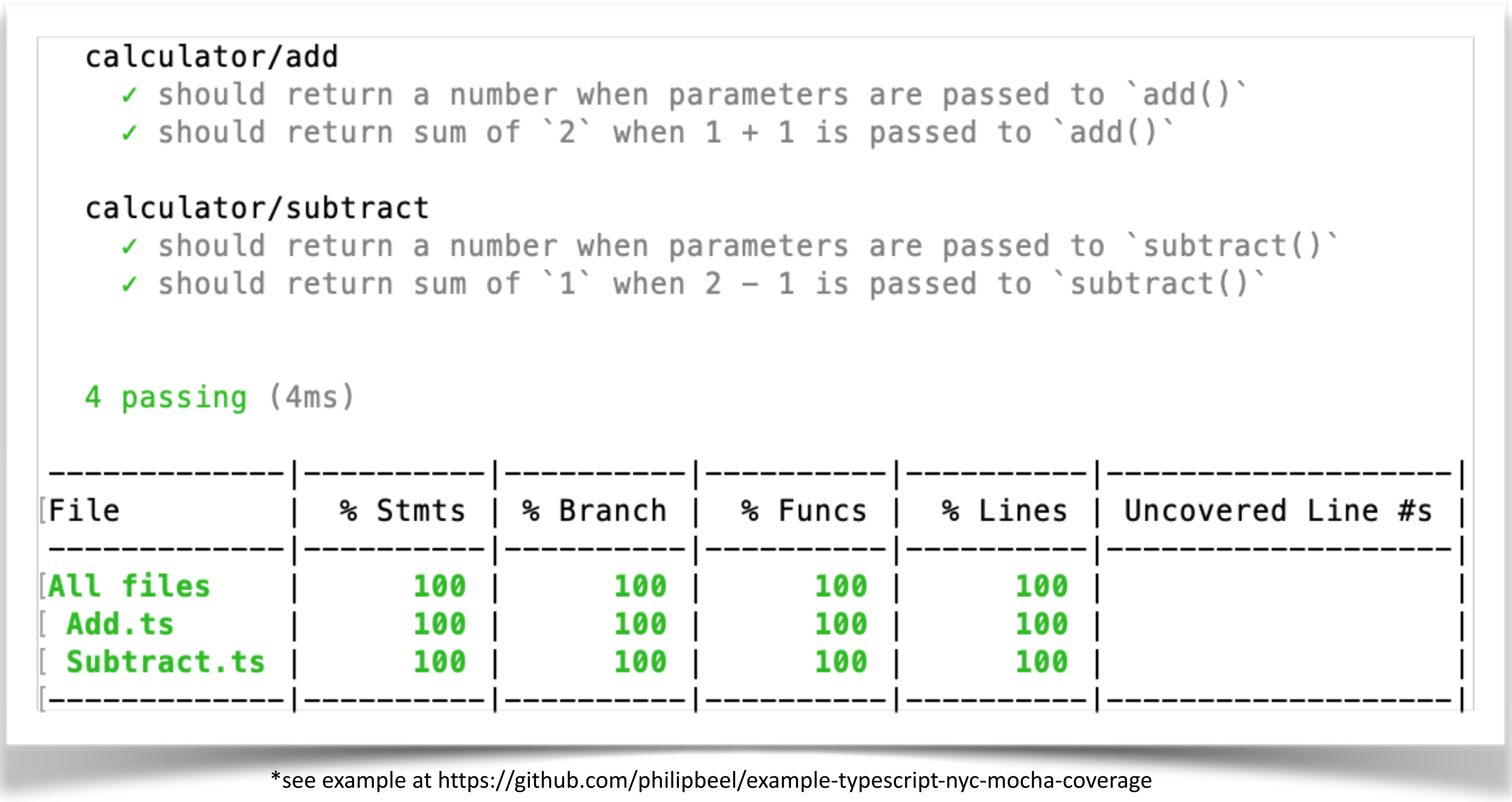
Subsumes statement coverage because traversing all edges implies traversing all nodes

Most widely used criterion in industry

Branch Coverage Measures

Coverage is computed automatically while the tests execute

`jest --coverage`



```
  calculator/add
    ✓ should return a number when parameters are passed to `add()`
    ✓ should return sum of `2` when 1 + 1 is passed to `add()`

  calculator/subtract
    ✓ should return a number when parameters are passed to `subtract()`
    ✓ should return sum of `1` when 2 - 1 is passed to `subtract()`


  4 passing (4ms)

-------------|----------|----------|----------|----------|-------------------|
[File        |  % Stmts | % Branch |  % Funcs |  % Lines | Uncovered Line #s |
-------------|----------|----------|----------|----------|-------------------|
[All files   |      100 |      100 |      100 |      100 |                   |
[ Add.ts     |      100 |      100 |      100 |      100 |                   |
[ Subtract.ts|      100 |      100 |      100 |      100 |                   |
[-------------|----------|----------|----------|----------|-------------------|
```

*see example at https://github.com/philipbeel/example-typescript-nyc-mocha-coverage

Every Branch Executed != Every Behavior

In this example, all branches are covered by the test

However: magic will crash under certain inputs

```
function magic(x: number, y: number) {
  let z = 0;
  if (x !== 0) { ✅ T1
    z = x + 10;
  } else { ✅ T2
    z = 0;
  }
  if (y > 0) { ✅ T1
    return y / z;
  } else { ✅ T2
    return x;
  }
}
test(“100% branch coverage", () => {
  expect(magic(1, 22)).toBe(2); //T1
  expect(magic(0, -10)).toBe(0); //T2
});
```

100% Coverage may be Impossible

Branch coverage

- Dead Branches e.g., `if (x < 0) A; else if (x == 0) B; else if (x > 0) C;`
- `(x > 0)` test will always succeed

Statement coverage

- Dead code (e.g., defensive programming)

Pareto’s Law

Approximately 80% of defects come from 20% of modules

Good Tests have Strong Oracles

Test oracle defines criteria for when test should fail

Strong oracles check all observable behaviors and side-effects

How to determine an oracle?

- Function returns the exact “right” answer
- Function returns an acceptable answer
- Returns the same value as last time
- Function returns without crashing
- Function crashes (as expected)

How to evaluate the strength of test oracles?

Goal: “A good test suite finds all of the bugs”

Problem: How to know the bugs that we could make?

Strawman — “Seeded Faults”

- Create N variations of the codebase, each with a single manually-written defect
- Evaluate the number of defects detected by test suite
- Test suite is “good” if it finds all of the bugs you can think of

Mutation Analysis tests the Tests

Idea: What bugs could be represented by a single, one-line "mutation" to the program?

```
public contains(location: PlayerLocation): boolean {
  return (
    location.x + PLAYER_SPRITE_WIDTH / 2 > this._x &&
    location.x - PLAYER_SPRITE_WIDTH / 2 < this._x + this._width &&
    location.y + PLAYER_SPRITE_HEIGHT / 2 > this._y &&
    location.y - PLAYER_SPRITE_HEIGHT / 2 < this._y + this._height
  );
}
```

Correct code for 'Contains" in IP1

```
public contains(location: PlayerLocation): boolean {
  return (
    location.x + PLAYER_SPRITE_WIDTH / 2 < this._x &&
    location.x - PLAYER_SPRITE_WIDTH / 2 < this._x + this._width &&
    location.y + PLAYER_SPRITE_HEIGHT / 2 > this._y &&
    location.y - PLAYER_SPRITE_HEIGHT / 2 < this._y + this._height
  );
}
```

Mutated (and buggy) code for 'Contains" in IP1

Mutation Analysis tests the Tests

Automatically mutates SUT to create mutants, each a single change to the code

Runs each test on each mutant, until finding that a mutant is detected by a test

Can be a time-consuming process to run, but fully automated

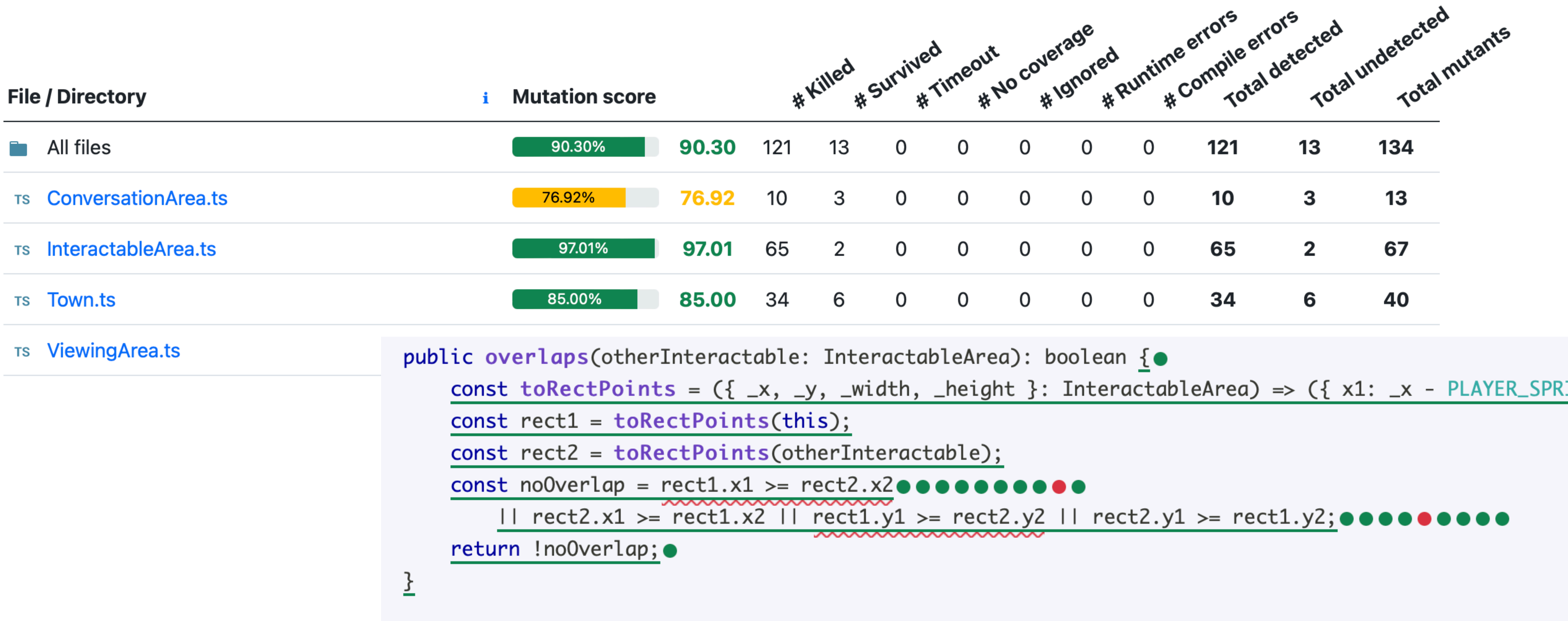
State-of-the-art mutation analysis tools:

- Pit (JVM)
- Stryker (JS/TS, C#, Scala)

Mutation Report Shows Undetected Mutants

Mutants “detected” are bugs that are found

Mutants “undetected” might be bugs, or could be equivalent to original program (requires a human to tell)



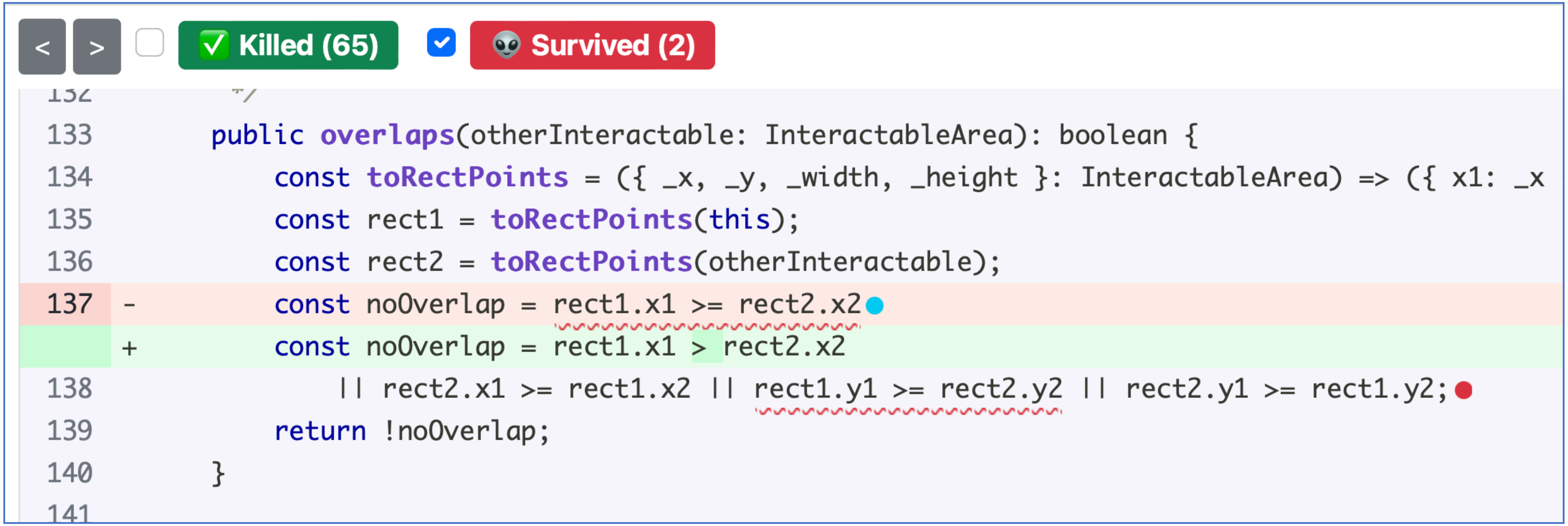
File / Directory	Mutation score		# Killed	# Survived	# Timeout	# No coverage	# Ignored	# Runtime errors	# Compile errors	Total detected	Total undetected	Total mutants
All files	90.30%	90.30	121	13	0	0	0	0	0	121	13	134
TS ConversationArea.ts	76.92%	76.92	10	3	0	0	0	0	0	10	3	13
TS InteractableArea.ts	97.01%	97.01	65	2	0	0	0	0	0	65	2	67
TS Town.ts	85.00%	85.00	34	6	0	0	0	0	0	34	6	40
TS ViewingArea.ts												

```
public overlaps(otherInteractable: InteractableArea): boolean {🟢
    const toRectPoints = ({ _x, _y, _width, _height }: InteractableArea) => ({ x1: _x - PLAYER_SPR
    const rect1 = toRectPoints(this);
    const rect2 = toRectPoints(otherInteractable);
    const noOverlap = rect1.x1 >= rect2.x2🟢🟢🟢🟢🟢🟢🟢🟢🔴🟢
        || rect2.x1 >= rect1.x2 || rect1.y1 >= rect2.y2 || rect2.y1 >= rect1.y2;🟢🟢🟢🟢🔴🟢🟢🟢🟢
    return !noOverlap;🟢
}
```

Use Mutation Analysis While Writing Tests

When you feel “done” writing tests, run a mutation analysis

Inspect undetected mutants, and try to strengthen tests to detect those mutants

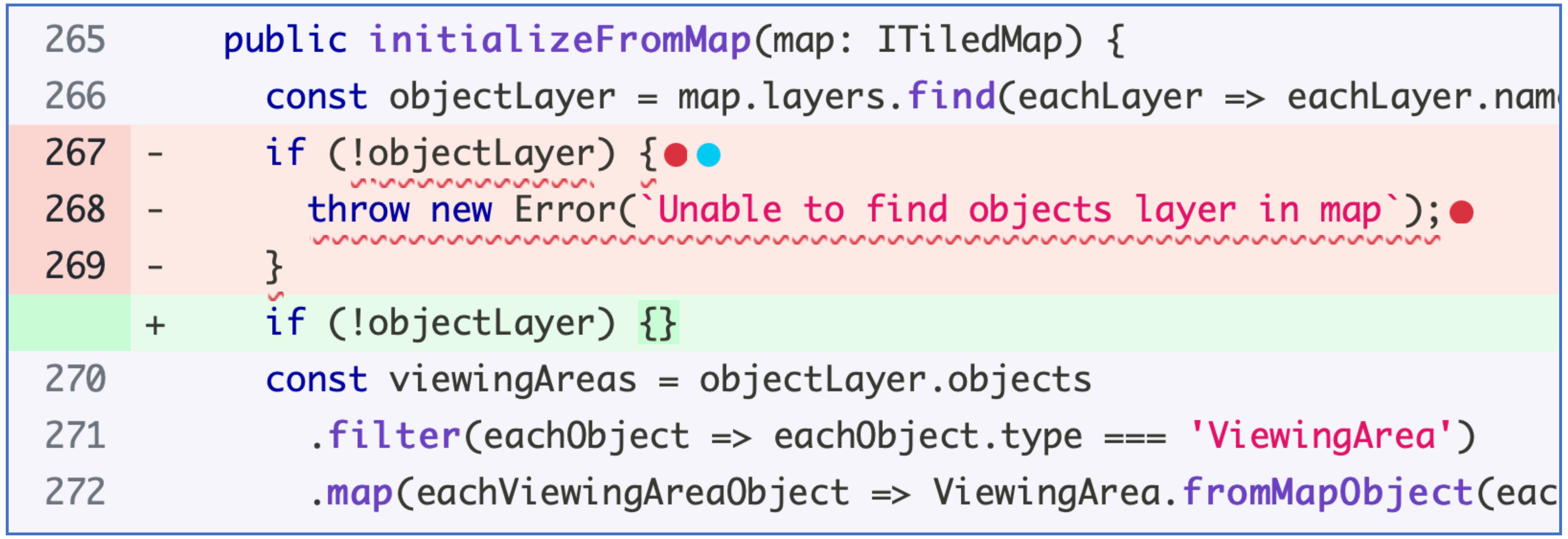


```
     */
    public overlaps(otherInteractable: InteractableArea): boolean {
        const toRectPoints = ({ _x, _y, _width, _height }: InteractableArea) => ({ x1: _x
        const rect1 = toRectPoints(this);
        const rect2 = toRectPoints(otherInteractable);
-       const noOverlap = rect1.x1 >= rect2.x2
+       const noOverlap = rect1.x1 > rect2.x2
            || rect2.x1 >= rect1.x2 || rect1.y1 >= rect2.y2 || rect2.y1 >= rect1.y2;
        return !noOverlap;
    }
```

Detailed mutation report for “overlaps” method - two mutants were not detected!

Undetected Mutants May Not Be Bugs

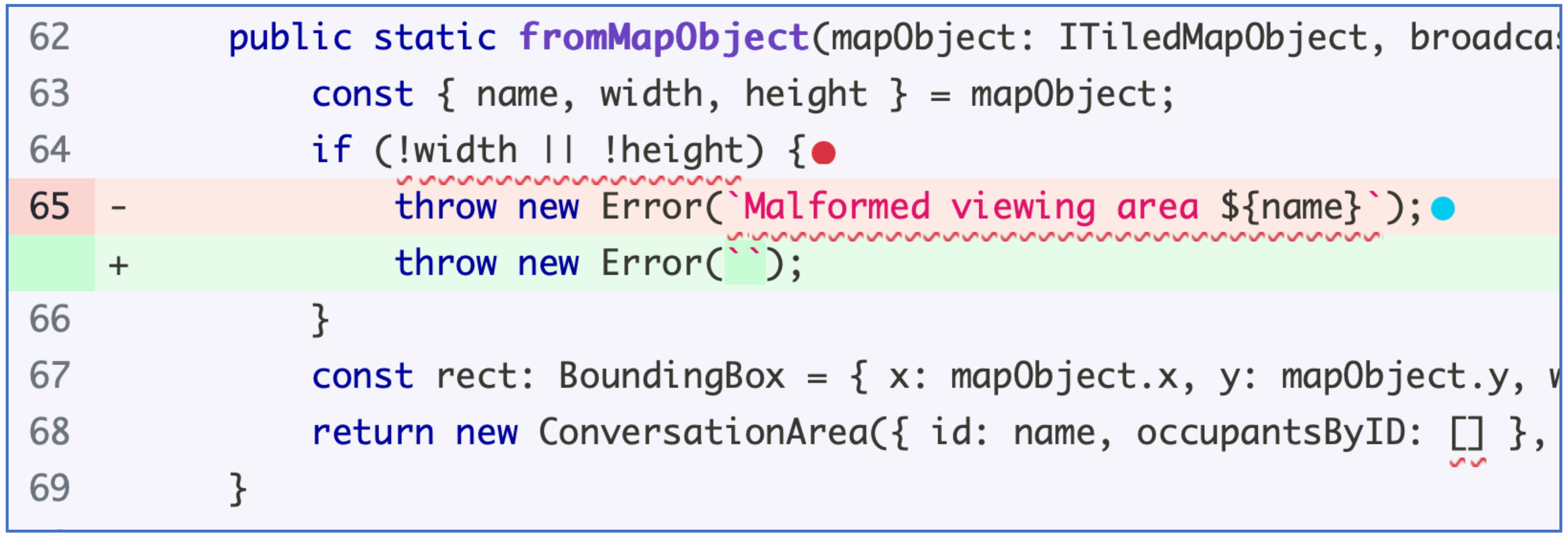
Unfortunately, we can not automatically tell if an undetected mutant is a bug or not



```
    public initializeFromMap(map: ITiledMap) {
      const objectLayer = map.layers.find(eachLayer => eachLayer.nam
-     if (!objectLayer) {
-       throw new Error(`Unable to find objects layer in map`);
-     }
+     if (!objectLayer) {}
      const viewingAreas = objectLayer.objects
        .filter(eachObject => eachObject.type === 'ViewingArea')
        .map(eachViewingAreaObject => ViewingArea.fromMapObject(eac
```

This mutant is *equivalent* to the original program: Even without this check for undefined, an error is still thrown when the undefined layer is dereferenced

This mutant is *equivalent* to the original program: Even though the error message changed, the specification doesn't indicate what error message should be thrown.

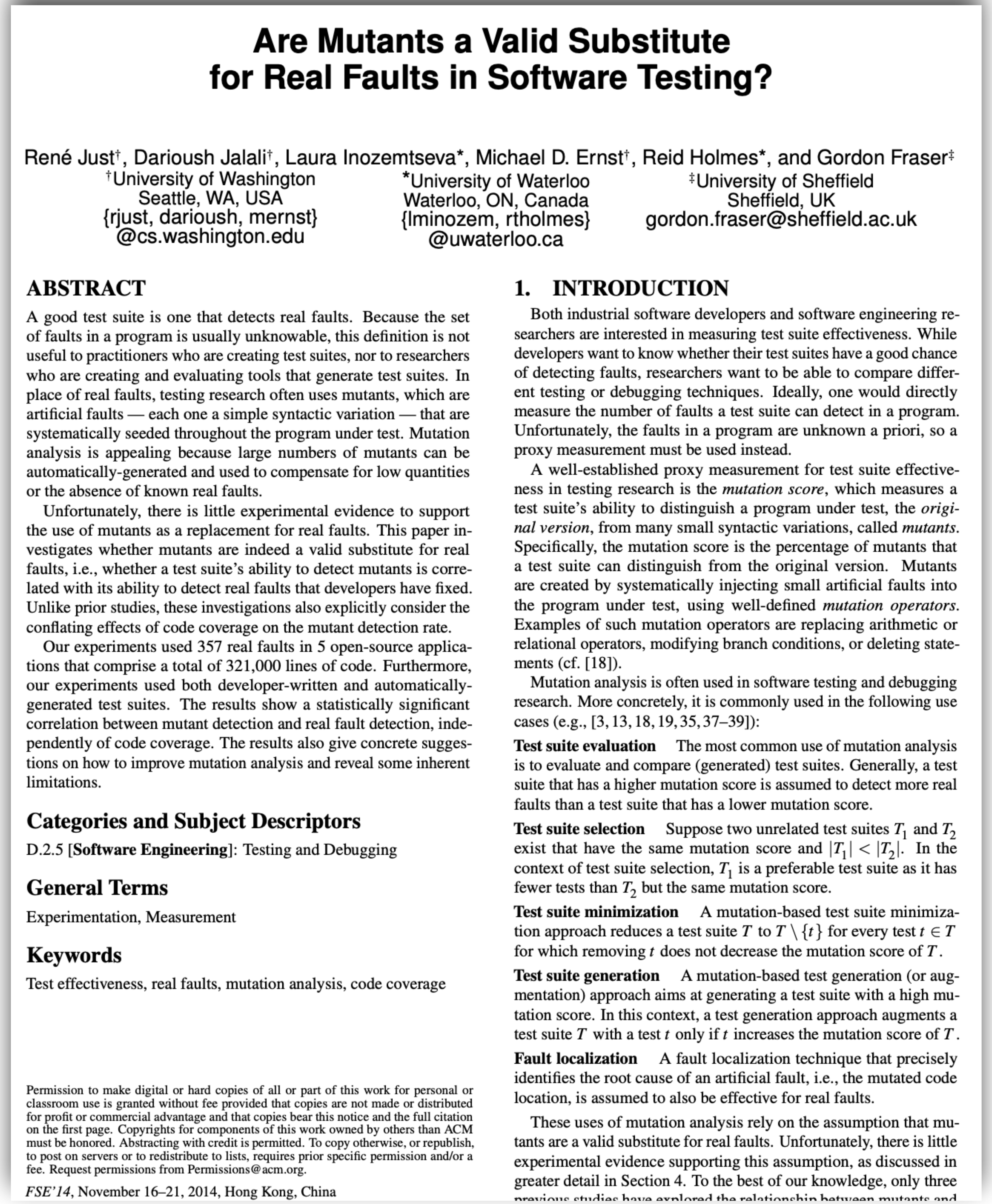


```
    public static fromMapObject(mapObject: ITiledMapObject, broadca
        const { name, width, height } = mapObject;
        if (!width || !height) {
-         throw new Error(`Malformed viewing area ${name}`);
+         throw new Error(``);
        }
        const rect: BoundingBox = { x: mapObject.x, y: mapObject.y, w
        return new ConversationArea({ id: name, occupantsByID: [] },
    }
```

Mutants are a Valid Substitute for Real Faults

Do mutants really represent real bugs?

- Researchers have studied whether a test suite that finds more mutants also finds more real faults
- Conclusion: For the 357 real faults studied, yes
- This reproduced in many other contexts



Are Mutants a Valid Substitute for Real Faults in Software Testing?

René Just[†], Darioush Jalali[†], Laura Inozemtseva[*], Michael D. Ernst[†], Reid Holmes[*], and Gordon Fraser[‡]

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ABSTRACT

A good test suite is one that detects real faults. Because the set of faults in a program is usually unknowable, this definition is not useful to practitioners who are creating test suites, nor to researchers who are creating and evaluating tools that generate test suites. In place of real faults, testing research often uses mutants, which are artificial faults — each one a simple syntactic variation — that are systematically seeded throughout the program under test. Mutation analysis is appealing because large numbers of mutants can be automatically-generated and used to compensate for low quantities or the absence of known real faults.

Unfortunately, there is little experimental evidence to support the use of mutants as a replacement for real faults. This paper investigates whether mutants are indeed a valid substitute for real faults, i.e., whether a test suite's ability to detect mutants is correlated with its ability to detect real faults that developers have fixed. Unlike prior studies, these investigations also explicitly consider the conflating effects of code coverage on the mutant detection rate.

Our experiments used 357 real faults in 5 open-source applications that comprise a total of 321,000 lines of code. Furthermore, our experiments used both developer-written and automatically-generated test suites. The results show a statistically significant correlation between mutant detection and real fault detection, independently of code coverage. The results also give concrete suggestions on how to improve mutation analysis and reveal some inherent limitations.

Categories and Subject Descriptors

D.2.5 [**Software Engineering**]: Testing and Debugging

General Terms

Experimentation, Measurement

Keywords

Test effectiveness, real faults, mutation analysis, code coverage

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1. INTRODUCTION

Both industrial software developers and software engineering researchers are interested in measuring test suite effectiveness. While developers want to know whether their test suites have a good chance of detecting faults, researchers want to be able to compare different testing or debugging techniques. Ideally, one would directly measure the number of faults a test suite can detect in a program. Unfortunately, the faults in a program are unknown a priori, so a proxy measurement must be used instead.

A well-established proxy measurement for test suite effectiveness in testing research is the *mutation score*, which measures a test suite's ability to distinguish a program under test, the *original version*, from many small syntactic variations, called *mutants*. Specifically, the mutation score is the percentage of mutants that a test suite can distinguish from the original version. Mutants are created by systematically injecting small artificial faults into the program under test, using well-defined *mutation operators*. Examples of such mutation operators are replacing arithmetic or relational operators, modifying branch conditions, or deleting statements (cf. [18]).

Mutation analysis is often used in software testing and debugging research. More concretely, it is commonly used in the following use cases (e.g., [3, 13, 18, 19, 35, 37–39]):

Test suite evaluation The most common use of mutation analysis is to evaluate and compare (generated) test suites. Generally, a test suite that has a higher mutation score is assumed to detect more real faults than a test suite that has a lower mutation score.

Test suite selection Suppose two unrelated test suites T_1 and T_2 exist that have the same mutation score and $|T_1| < |T_2|$. In the context of test suite selection, T_1 is a preferable test suite as it has fewer tests than T_2 but the same mutation score.

Test suite minimization A mutation-based test suite minimization approach reduces a test suite T to $T \setminus \{t\}$ for every test $t \in T$ for which removing t does not decrease the mutation score of T.

Test suite generation A mutation-based test generation (or augmentation) approach aims at generating a test suite with a high mutation score. In this context, a test generation approach augments a test suite T with a test t only if t increases the mutation score of T.

Fault localization A fault localization technique that precisely identifies the root cause of an artificial fault, i.e., the mutated code location, is assumed to also be effective for real faults.

These uses of mutation analysis rely on the assumption that mutants are a valid substitute for real faults. Unfortunately, there is little experimental evidence supporting this assumption, as discussed in greater detail in Section 4. To the best of our knowledge, only three previous studies have explored the relationship between mutants and

Activity: strengthening a test suite

Enhance transcript server tests to improve line coverage and mutation coverage

Download on Module 11 webpage

Review

Now you should be able to

- Explain what makes a good test, and give examples and counter examples
- Explain goals for a test suite, and sketch how how to judge whether it does