Principles of Software Construction: Objects, Design, and Concurrency

Specifications and unit testing, exceptions

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Quiz Time

Under “Quizzes → Lecture 4 Quiz” on Canvas.

Encapsulation / Information hiding

Remember this discussion from last week?

- Well designed objects protect internals from others
  - both internal state and implementation details
- Well-designed code hides all implementation details
  - Cleanly separates interface from implementation
  - Modules communicate only through interfaces
  - They are oblivious to each others' inner workings
- Hidden details can be changed without changing client!
- Fundamental tenet of software design

Who’s to blame?

```
Algorithms.shortestDistance(g, “Tom”, “Anne”);

> ArrayOutOfBoundsException
```

Who’s to blame?

```
Algorithms.shortestDistance(g, “Tom”, “Anne”);


> -1
```

Who’s to blame?

```
/**
 * This method finds the shortest
 * distance between two vertices.
 * It returns -1 if the two nodes
 * are not connected.
 */
function shortestDistance(…): number {…}
```

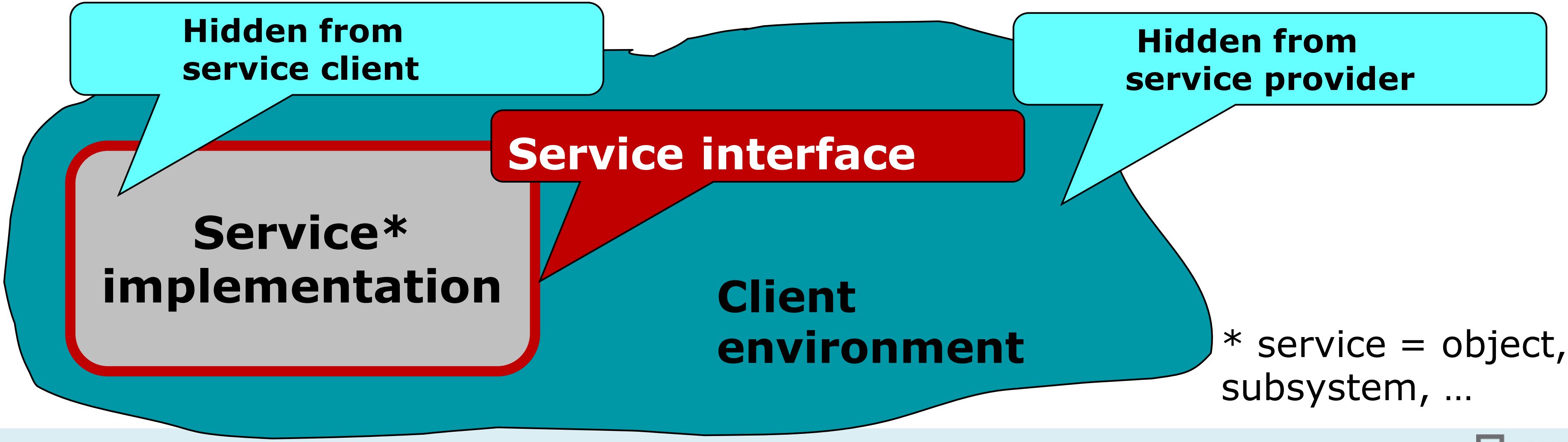
Who’s to blame?

```
/**
 * This method finds the shortest
 * distance between two vertices.
 * It returns -1 if the two nodes
 * are not connected.
 */
function shortestDistance(…): number {…}
```

Think of this (textual) specification as a “contract”

Most real-world code has a contract

- Imperative to build systems that scale!
- This is why we:
  - Encode specifications
  - Write tests



* service = object, subsystem, …

Today

Is about explicit >> implicit, key to quality assurance at scale

1. Exception Handling
2. Unit Testing
3. Specifications

Exceptions

What does this code do?

This is Java code

```
FileInputStream fIn = new FileInputStream(fileName);
if (fIn == null) {
  switch (errno) {
  case _ENOFILE:
     System.err.println(“File not found: “ + …);
     return -1;
  default:
     System.err.println(“Something else bad happened: “ + …);
     return -1;
  }
}
DataInput dataInput = new DataInputStream(fIn);
if (dataInput == null) {
  System.err.println(“Unknown internal error.”);
  return -1;  // errno > 0 set by new DataInputStream
}
int i = dataInput.readInt();
if (errno > 0) {
  System.err.println(“Error reading binary data from file”);
  return -1;
}  // The slide lacks space to close the file.  Oh well.
return i;
```

This is Java code

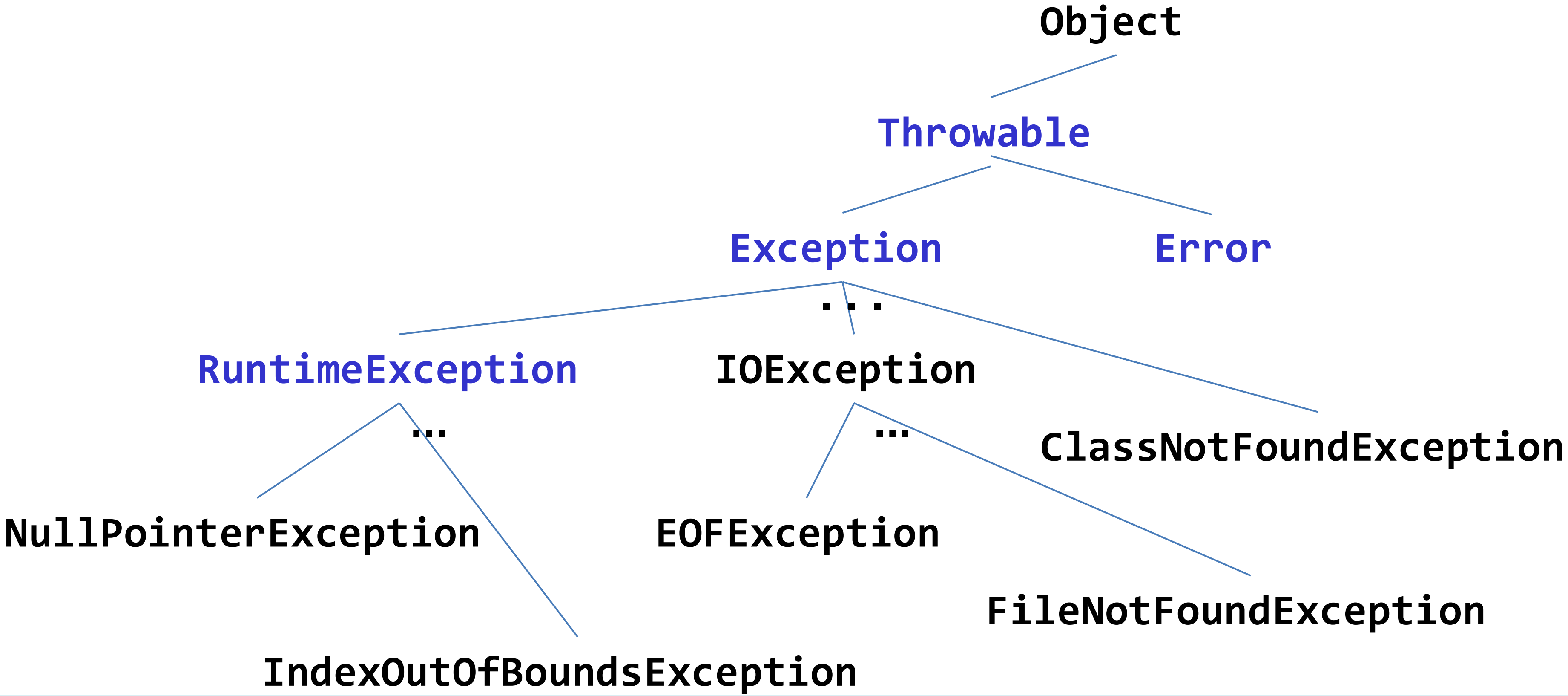
Compare to:

```java
try (FileInputStream fi = new FileInputStream(fileName)) {
    DataInput dataInput = new DataInputStream(fi);
    return dataInput.readInt();
} catch (FileNotFoundException e) {
    System.out.println("Could not open file " + fileName);
} catch (IOException e) {
    System.out.println("Couldn’t read file: " + e);
}
```

Exceptions

- Split control-flow into a “normal” and an “erroneous” branch
  - Compare “if/else”
- Inform caller of problem by transfer of control
- Where do exceptions come from?
  - Program can raise them explicitly using ‘throw’
  - Underlying virtual machine (JVM) can generate
- Semantics
  - Propagates up call stack until exception is caught, or main method is reached (terminates program!)

The exception hierarchy in Java (messy)



Object

Throwable

Exception

Error

...

RuntimeException

IOException

ClassNotFoundException

…

…

NullPointerException

EOFException

FileNotFoundException

IndexOutOfBoundsException

Control-flow of exceptions

This is Java code

```
public static void test() {
    try {
        System.out.println("Top");
        int[] a = new int[10];
        a[42] = 42;
        System.out.println("Bottom");
    } catch (NegativeArraySizeException e) {
        System.out.println("Caught negative array size");
    }
}

public static void main(String[] args) {
    try {
        test();
    } catch (IndexOutOfBoundsException e) {
        System.out.println"("Caught index out of bounds");
    }
}
```

Control-flow of exceptions

This is Java code

```java
public static void test() {
    try {
        System.out.println("Top");
        int[] a = new int[10];
        a[42] = 42;
        System.out.println("Bottom");
    } catch (NegativeArraySizeException e) {
        System.out.println("Caught negative array size");
    }
}

public static void main(String[] args) {
    try {
        test();
    } catch (IndexOutOfBoundsException e) {
        System.out.println"("Caught index out of bounds");
    }
}
```

Handle errors at a level you choose, not necessarily in the low-level methods where they originally occur.

This is Java code

Exception Handling

Undeclared vs. Declared

```
int divide(int a, int b) {
  return a / b;
}
```

```
String read(String path) throws
                       IOException {
  return Files.lines(Path.of(path))
     .collect(Collectors.joining(“\n”));
}
```

This is Java code

Exception Handling

Undeclared vs. Declared

```
int divide(int a, int b) {
  return a / b;
}
```

```
String read(String path) throws
                      IOException {
  return Files.lines(Path.of(path))
     .collect(Collectors.joining(“\n”));
}
```

Unchecked vs. Checked

```
divide(4, 3); // Compiles
                 fine
```

```
read(“test.txt”); // Unhandled
  exception: java.io.IOException
```

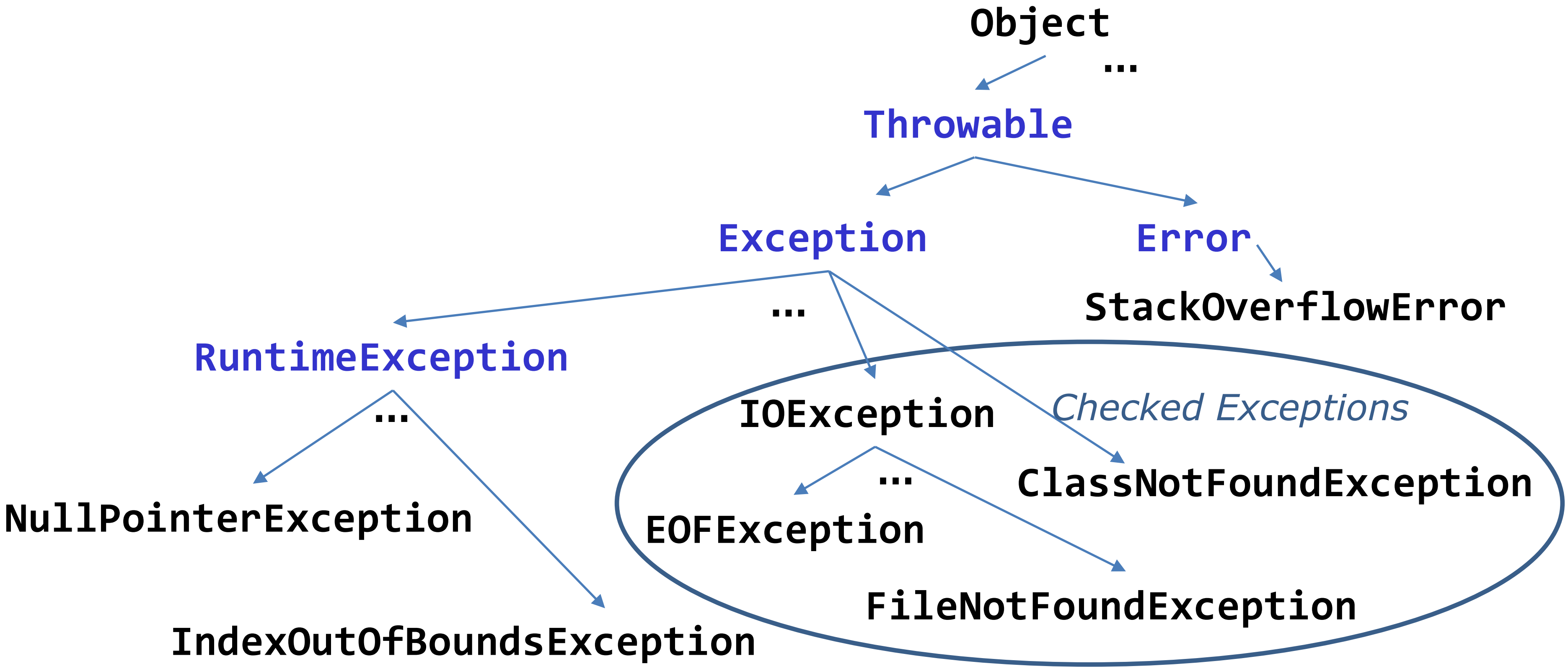
Exception Handling

Handling unchecked exceptions is not enforced by the compiler

These are quite common

- E.g., all exceptions in C++
- In Java: any exception that extends Error or RuntimeException

Java’s exception hierarchy (messy)



Object

…

Throwable

Exception

Error

StackOverflowError

…

RuntimeException

…

IOException

Checked Exceptions

…

ClassNotFoundException

NullPointerException

EOFException

FileNotFoundException

IndexOutOfBoundsException

Checked vs. unchecked exceptions

- **Checked exception**
  - Must be caught or propagated, or program won't compile
  - **Exceptional condition that programmer must deal with**
- **Unchecked exception**
  - No action is required for program to compile…
    - But uncaught exception will cause failure at runtime
  - Usually indicates a **programming error**
- Error
  - Special unchecked exception typically thrown by VM
  - Recovery is usually impossible

Benefits of exceptions (summary)

- You can’t forget to handle common failure modes
  - Explicit > implicit
  - Compare: using a flag or special return value
- Provide high-level summary of error
  - Compare: core dump in C/C++
- Improve code structure
  - Separate normal code path from exceptional
  - Error handling code is segregated in catch blocks
- Ease task of writing robust, maintainable code

This is Java code

Defining & using Exception Types

```java
class BufferBoundsException extends Exception {
  public BufferBoundsException(String message) {
    ...
  }
}

void atIndex(int[] buff, int i) throws BufferBoundsException {
  if (buff.length <= i)
    throw new BufferBoundsException(“...”);
  return buff[i];
}
```

This is Java code

Exception Handling

- It’s still wise to guard for “obvious” unchecked exceptions

```
if (arr.length > 10)
  return arr[10];
```

- Or explicitly signal the problem, recall:

```
if (buff.length <= i)
  throw new BufferBoundsException(“...”);
return buff[i];
```

- Why is this better than letting the index fail?

This is Java code

Exception Handling

- It’s still wise to guard for “obvious” unchecked exceptions

```java
if (arr.length > 10)
  return arr[10];
```

- Or explicitly signal the problem, recall:

```java
if (buff.length <= i)
  throw new BufferBoundsException(“...”);
return buff[i];
```

- Why is this better than letting the index fail?
  - `BufferBoundsException` can be a checked exception!
  - Which forces someone to handle it
  - Here, we declared: `atIndex(int[] buff, int i) throws BufferBoundsException`
  - So every calling method must handle it, or throw it on

This is Java code

Guidelines for using exceptions

- Document all exceptions thrown by each method in the specification
  - Unchecked as well as checked (EJ Item 74)
  - But don’t *declare* unchecked exceptions!
- Include failure-capture info in detail message (EJ Item 75)

```java
throw new IllegalArgumentException(
    "Quantity must be positive: " + quantity);
```

This is Java code

Guidelines for using exceptions (2)

- Document all exceptions thrown by each method in the specification
  - Unchecked as well as checked (EJ Item 74)
  - But don’t *declare* unchecked exceptions!
- Include failure-capture info in detail message (EJ Item 75)

```java
throw new IllegalArgumentException(
    "Quantity must be positive: " + quantity);
```

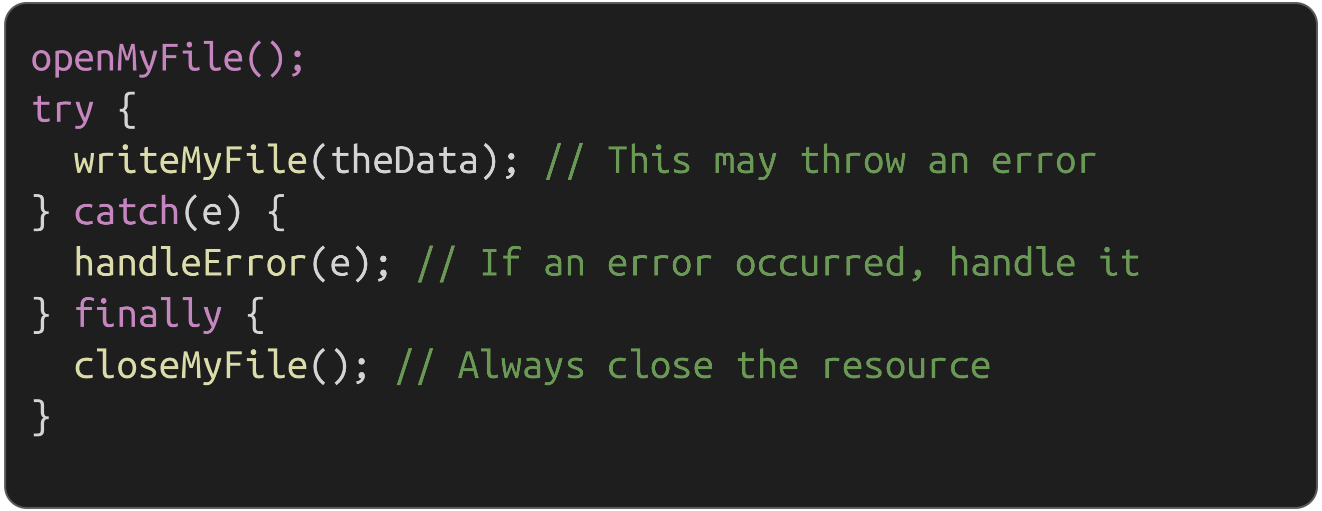
- Don’t ignore exceptions (EJ Item 77)

```java
try {
   processPayment(payment);
}
catch (Exception e) {  // BAD!
}
```

Cleanup

This is JavaScript code

Exception handling often also supports cleaning up



```
openMyFile();
try {
  writeMyFile(theData); // This may throw an error
} catch(e) {
  handleError(e); // If an error occurred, handle it
} finally {
  closeMyFile(); // Always close the resource
}
```

https://developer.mozilla.org/en-US/docs/Web/JavaScript/Guide/Control_flow_and_error_handling

Manual Resource Termination

Is ugly and error-prone, especially for multiple resources

- Even good programmers usually get it wrong
  - Sun’s Guide to Persistent Connections got it wrong in code that claimed to be exemplary
  - Solution on page 88 of Bloch and Gafter’s Java Puzzlers is badly broken; no one noticed for years
- 70% of the uses of `close` **in the JDK itself** were wrong in 2008!
- Even the “correct” idioms for manual resource management are deficient

This is Java code

The solution: try-with-resources

Automatically closes resources!

```java
try (DataInputStream dataInput =
        new DataInputStream(new FileInputStream(fileName))) {
    return dataInput.readInt();
} catch (IOException e) {
    ...
}
```

Exceptions Across Languages

Alas, try-with-resources does not exist in JS/TS

- Neither does ‘`throws`’

Exception structures differ radically across languages

- Most languages have ‘`try/catch`’ and ‘`throw`’
    - Some have ‘`finally`’
- Some languages have resource management support
    - Python has ‘with’ (since 2006), C# has ‘`using`’
    - Java’s try-with-resources was added in 2011
- Go returns an error-typed value, to be checked for nullity

In summary

Use exceptions to report failure

- Make exceptions part of your contract via comments (Java, JS, TS)
- Use `finally` statements to clean up resources
- In Java, use checked exceptions to enforce that recoverable exceptions are handled

Outline

1. Exception Handling
2. **Unit Testing**
3. Specifications

Functional Correctness

- Compiler ensures types are correct (type-checking)
  - Prevents many runtime errors, like “Method Not Found” and “Cannot add boolean to int”

Functional Correctness

- Compiler ensures types are correct (type-checking)
  - Prevents many runtime errors, like “Method Not Found” and “Cannot add boolean to int”
- How to ensure functional correctness, beyond type correctness?

One option: Formal verification

- Use mathematical methods to prove correctness with respect to the formal specification
- Formally prove that all possible executions of an implementation fulfill the specification
- Manual effort; partial automation; not automatically decidable

Another option: Testing

- Executing the program with selected inputs in a controlled environment
- Goals
  - Reveal bugs, so they can be fixed (main goal)
  - Assess quality
  - Clarify the specification, documentation
- Testing is related to contracts
  - Because we need to know what to test!

Re: Formal verification, Testing

“Beware of bugs in the above code; I have only proved it correct, not tried it.”

Donald Knuth, 1977

“Testing shows the presence, not the absence of bugs.”

Edsger W. Dijkstra, 1969

Q: Who's more right, Dijkstra or Knuth?

```java
public static int binarySearch(int[] a, int key) {
    int low = 0;
    int high = a.length - 1;

    while (low <= high) {
        int mid = (low + high) / 2;
        int midVal = a[mid];

        if (midVal < key)
             low = mid + 1
         else if (midVal > key)
             high = mid - 1;
         else
             return mid; // key found
     }
     return -(low + 1);  // key not found.
 }
```

Spec: sets `mid` to the average of `low` and `high`, truncated down to the nearest integer.

Fails if `low + high` > MAXINT (2^{31} - 1)
Sum overflows to negative value

Binary search from java.util.Arrays

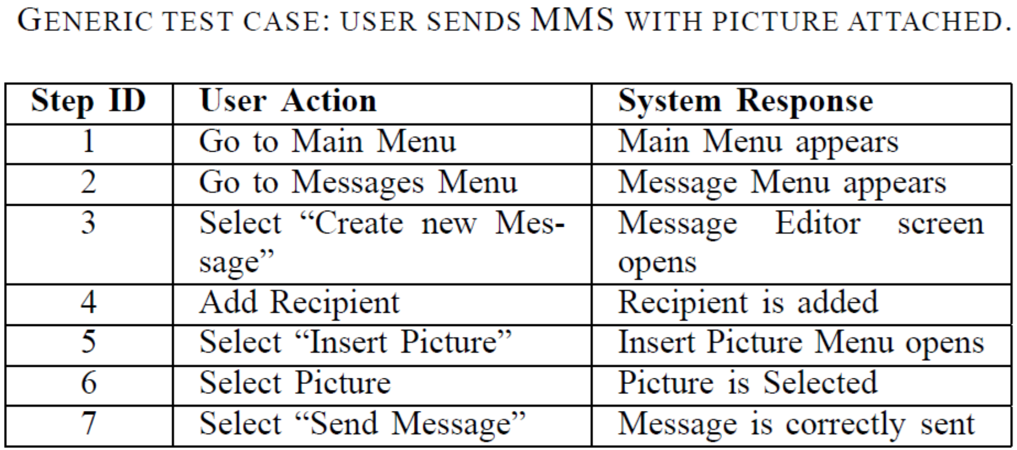
A: They’re Both Right

- There is no silver bullet! Use all the tools at your disposal
  - Careful design
  - Testing
  - Formal methods (where appropriate)
  - Code reviews
  - …
- You’ll still have bugs, but hopefully fewer.

How to test?

Manual Testing

- Live System?
- Extra Testing System?
- Check output / assertions?
- Effort, Costs?
- Reproducible?



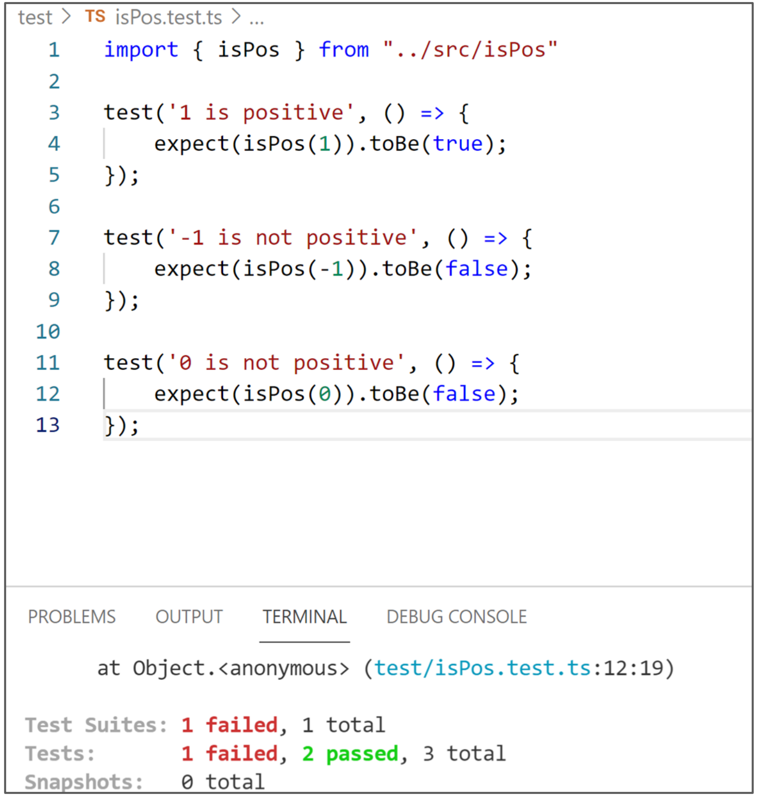
GENERIC TEST CASE: USER SENDS MMS WITH PICTURE ATTACHED.

Step ID	User Action	System Response
1	Go to Main Menu	Main Menu appears
2	Go to Messages Menu	Message Menu appears
3	Select "Create new Message"	Message Editor screen opens
4	Add Recipient	Recipient is added
5	Select "Insert Picture"	Insert Picture Menu opens
6	Select Picture	Picture is Selected
7	Select "Send Message"	Message is correctly sent

How to test?

Automated Testing

- Execute a program with specific inputs
  - Check output for expected values
- Test small pieces of the program
  - Easier than testing user interactions
- Set up testing infrastructure
  - Execute tests regularly
  - Typically, after every change



```
import { isPos } from "../src/isPos"

test('1 is positive', () => {
    expect(isPos(1)).toBe(true);
});

test('-1 is not positive', () => {
    expect(isPos(-1)).toBe(false);
});

test('0 is not positive', () => {
    expect(isPos(0)).toBe(false);
});
```

```
      at Object.<anonymous> (test/isPos.test.ts:12:19)

Test Suites: 1 failed, 1 total
Tests:       1 failed, 2 passed, 3 total
Snapshots:   0 total
```

This is Java code

Testing

How do we know this works?

```
int isPos(int x) {
  return x >= 1;
}
```

This is Java code

Testing

How do we know this works?

```java
int isPos(int x) {
  return x >= 1;
}

@Test
void testIsPos() {
  assertTrue(isPos(1));
}
```

Testing

Are we done?

Testing

This is Java code

How do we know this works?

Testing

Are we done?

```java
int isPos(int x) {
  return x >= 1;
}

@Test
void testIsPos() {
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@Test
void testNotPos() {
  assertFalse(isPos(-1));
}
```

This is Java code

Testing

How do we know this works?

Testing

Are we done?

```
int isPos(int x) {
  return x >= 0;  // What if?
}

@Test
void testIsPos() {
  assertTrue(isPos(1));
}

@Test
void testNotPos() {
  assertFalse(isPos(-1));
}
```

This is Java code

Testing

How do we know this works?

Testing

Are we done?

```java
int isPos(int x) {
  return x >= 0;  // What if?
}

@Test
void test1IsPos() {
  assertTrue(isPos(1));
}

@Test
void test0IsNotPos() {
  assertFalse(isPos(0)); // Fails
}
```

This is Java code

Boundary Value Testing

We cannot test for every integer.

Choose *representative* values:
1 for positives, -1 for negatives

And *boundary cases*: 0 is a likely candidate for mistakes

- Think like an attacker

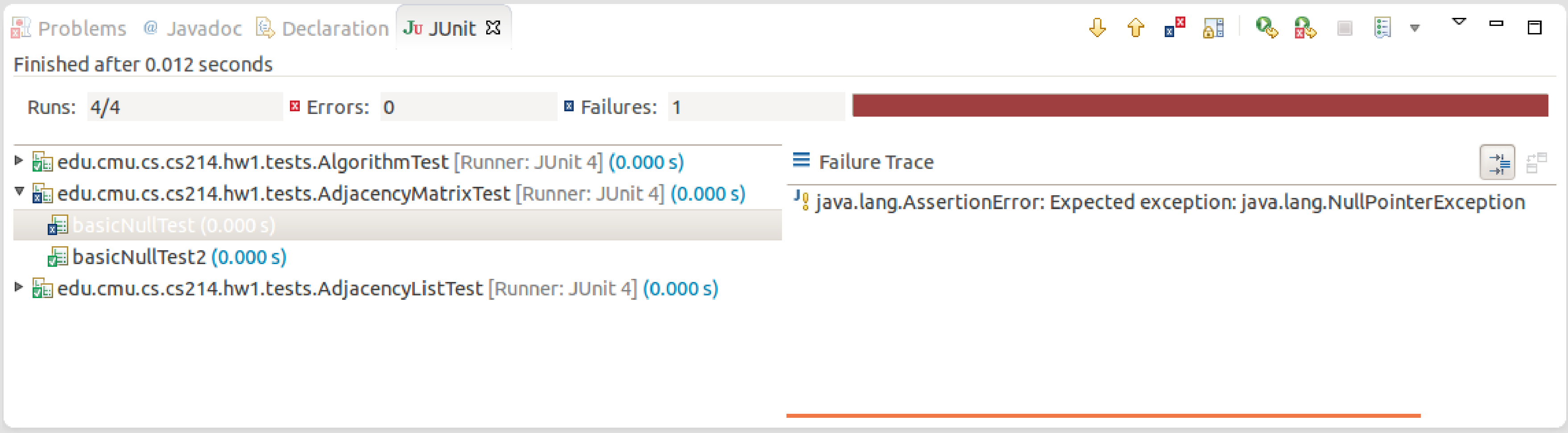
```
int isPos(int x) {
  return x >= 0;  // What if?
}

@Test
void test1IsPos() {
  assertTrue(isPos(1));
}

@Test
void test0IsNotPos() {
  assertFalse(isPos(0)); // Fails
}
```

Unit Tests

- For “small” units: methods, classes, subsystems
  - Unit is smallest testable part of system
  - Test the parts before assembling them
  - Intended to catch local bugs
- Typically (but not always) written by developers
- Many small, fast-running, independent tests
- Few dependencies on other system parts or environment
- Insufficient, but a good starting point

For Java: JUnit

- Popular unit-testing framework for Java
- Easy to use
- Tool support available, e.g., IntelliJ integration



Finished after 0.012 seconds

Runs: 4/4 Errors: 0 Failures: 1

- edu.cmu.cs.cs214.hw1.tests.AlgorithmTest [Runner: JUnit 4] (0.000 s)
- edu.cmu.cs.cs214.hw1.tests.AdjacencyMatrixTest [Runner: JUnit 4] (0.000 s)
  - basicNullTest (0.000 s)
  - basicNullTest2 (0.000 s)
- edu.cmu.cs.cs214.hw1.tests.AdjacencyListTest [Runner: JUnit 4] (0.000 s)

Failure Trace

```
java.lang.AssertionError: Expected exception: java.lang.NullPointerException
```

This is Java code

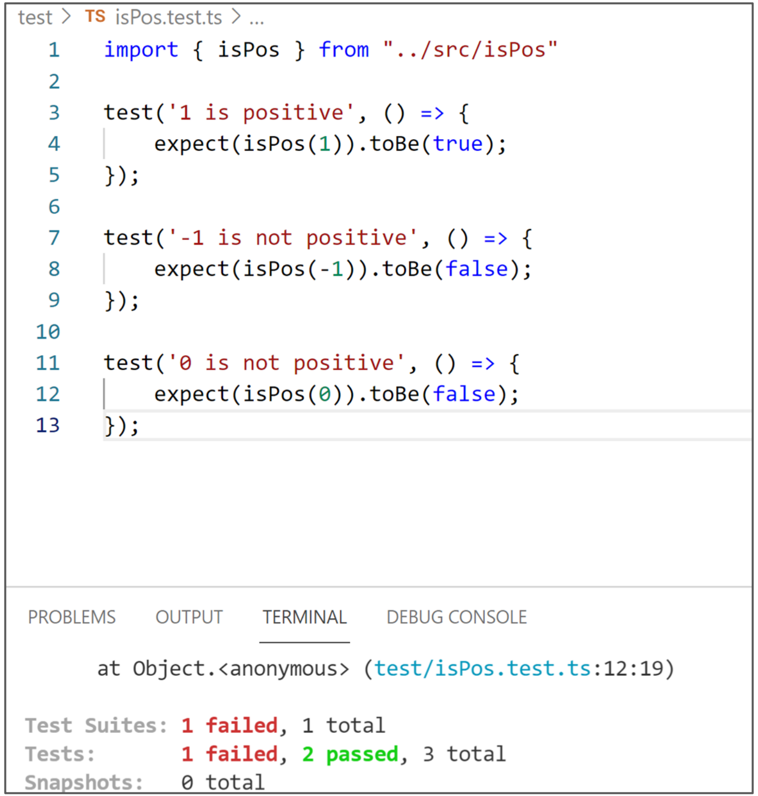
For Java: JUnit

Syntax:

```
import static org.junit.Assert.*;

class PosTests {

  @Before
  void setUp() {
    // Anything you want to run
       before each test
  }

  @Test
  void test1IsPos() {
    assertTrue(isPos(1));
  }
}
```

For TS: Jest

- In particular, ts-jest
  - Many other options; your choice
- Requires a few files:
  - jest.config.js, to specify testing mode
  - package.json with (ts-)jest dependencies
- Provides useful features:
  - ‘test’, ‘expect’ (= ‘assert’)
  - ‘toBe’ (identity), ‘toEqual’ (equality)
  - ‘fn’, for Mocking (later)



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});

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    expect(isPos(0)).toBe(false);
});
```

```
      at Object.<anonymous> (test/isPos.test.ts:12:19)

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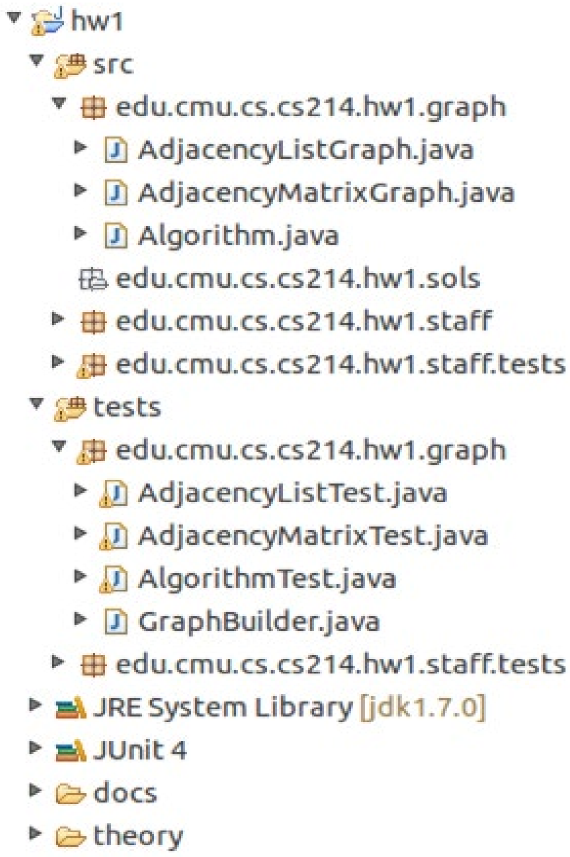
Test organization

- Conventions (not requirements)
- Have a test class FooTest for each public class Foo
- Have a source directory and a test directory
  - Store FooTest and Foo in the same package
  - Tests can access members with default (package) visibility



```
▼ hw1
  ▼ src
    ▼ edu.cmu.cs.cs214.hw1.graph
      ▶ AdjacencyListGraph.java
      ▶ AdjacencyMatrixGraph.java
      ▶ Algorithm.java
      edu.cmu.cs.cs214.hw1.sols
    ▶ edu.cmu.cs.cs214.hw1.staff
    ▶ edu.cmu.cs.cs214.hw1.staff.tests
  ▼ tests
    ▼ edu.cmu.cs.cs214.hw1.graph
      ▶ AdjacencyListTest.java
      ▶ AdjacencyMatrixTest.java
      ▶ AlgorithmTest.java
      ▶ GraphBuilder.java
    ▶ edu.cmu.cs.cs214.hw1.staff.tests
  ▶ JRE System Library [jdk1.7.0]
  ▶ JUnit 4
  ▶ docs
  ▶ theory
```

Writing Testable Code

- Think about testing when writing code
  - Unit testing encourages you to write testable code
- Modularity and testability go hand in hand
  - Same test can be used on multiple implementations of an interface!
- Test-Driven Development
  - A design and development method in which you write tests before you write the code
  - Writing tests can expose API weaknesses!

Run Tests Often

- You should only commit code that passses all tests…
- So run tests before every commit
- If test suite becomes too large & slow for rapid feedback
  - Run local package-level tests (“smoke tests”) frequently
  - Run all tests nightly
  - Medium sized projects often have thousands of test cases
- Continuous integration (CI) servers help to scale testing
  - We ask you to use GitHub Actions in this class

Outline

1. Exception Handling
2. Unit Testing
3. **Specifications – to be continued on Tuesday**

Specifications and testing are closely related

Q: What exactly do you test given some method?

- What it claims to do: specification testing – **the contract**
- What it does: structural testing (next week)

How to Encode Specifications?

Formal frameworks exist, to capture pre- and post-conditions

- E.g., ‘`requires arr != null`’
- Useful for formal verification
- But rarely used
  - Takes a lot of effort, and doesn’t scale well

How to Encode Specifications?

More common: prose specification.

```
/**
 * This method finds the shortest
 * distance between two vertices.
 * It returns -1 if the two nodes
 * are not connected.
 */
function shortestDistance(…): number {…}
```

Recall the earlier example?
(Probably too unstructured)

What is a contract?

- Agreement between an object and its user
  - Defines method's and caller's responsibilities
  - Analogy: legal contract
    - If you pay me this amount on this schedule…
    - I will build a room with the following detailed spec
    - Some contracts have remedies for nonperformance
- **What** the method does, not **how** it does it
  - **Interface** (API), not **implementation**
- Defines correctness of implementation – we'll come back to this later today

How to Encode Specifications?

Method contract structure:

- Preconditions: what method requires for correct operation
- Postconditions: what method establishes on completion
- Exceptional behavior: what it does if precondition violated

How to Encode Specifications?

Document:

- Every parameter
- Return value
- Every exception (checked and unchecked)
- What the method does, including
  - Primary purpose
  - Any side effects
  - Any thread safety issues
  - Any performance issues

How to Encode Specifications?

Document:

- Every parameter
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- What the method does, including
  - Primary purpose
  - Any side effects
  - Any thread safety issues
  - Any performance issues

Do **not** document implementation details

- Known as overspecification

This is Java code

Docstring Specification

```
class RepeatingCardOrganizer {
  ...








  public boolean isComplete(CardStatus card) {
    return card.getResults().stream()
      .filter(isSuccess -> isSuccess)
      .count() >= this.repetitions;
  }
}
```

This is Java code

Docstring Specification

```java
class RepeatingCardOrganizer {
  ...
  /**
   * Checks if the provided card has been answered correctly the required
number of times.
   * @param card The {@link CardStatus} object to check.
   * @return {@code true} if this card has been answered correctly at least
{@code this.repetitions} times.
   */
  public boolean isComplete(CardStatus card) {
    return card.getResults().stream()
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Docstring Specification

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number of times.
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   * @return {@code true} if this card has been answered correctly at least
{@code this.repetitions} times.
   */
  public boolean isComplete(CardStatus card) {
    // IGNORE THIS WHEN SPECIFICATION TESTING!
  }
}
```

This is Java code

Docstring Specification

```java
/**
 * Checks if the provided card has been answered correctly the required number of times.
 * @param card The {@link CardStatus} object to check.
 * @return {@code true} if this card has been answered correctly at least {@code this.repetitions} times.
 */
public boolean isComplete(CardStatus card);

// What is specified?
```

This is Java code

Docstring Specification

```java
  /**
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number of times.
   * @param card The {@link CardStatus} object to check.
   * @return {@code true} if this card has been answered correctly at least
{@code this.repetitions} times.
   */
  public boolean isComplete(CardStatus card);

  // What is specified?
  // - Parameter type (no constraints)
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This is Java code

Docstring Specification

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  // So what do we test?
```

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   */
  public boolean isComplete(CardStatus card);

@Test
public void testIsCompleteSingleSuccess() {
  CardRepeater repeater = new RepeatingCardOrganizer(1); // Single repetition
  CardStatus cs = new CardStatus(new FlashCard("", ""));
  cs.recordResult(true); // Single Success
  assert???(repeater.isComplete(cs));
}
```

This is Java code

Docstring Specification

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number of times.
   * @param card The {@link CardStatus} object to check.
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{@code this.repetitions} times.
   */
  public boolean isComplete(CardStatus card);

@Test
public void testIsCompleteSingleSuccess() {
  CardRepeater repeater = new RepeatingCardOrganizer(1); // Single repetition
  CardStatus cs = new CardStatus(new FlashCard(“”, “”));
  cs.recordResult(true); // Single Success
  assertTrue(repeater.isComplete(cs));
}
```

This is Java code

Docstring Specification

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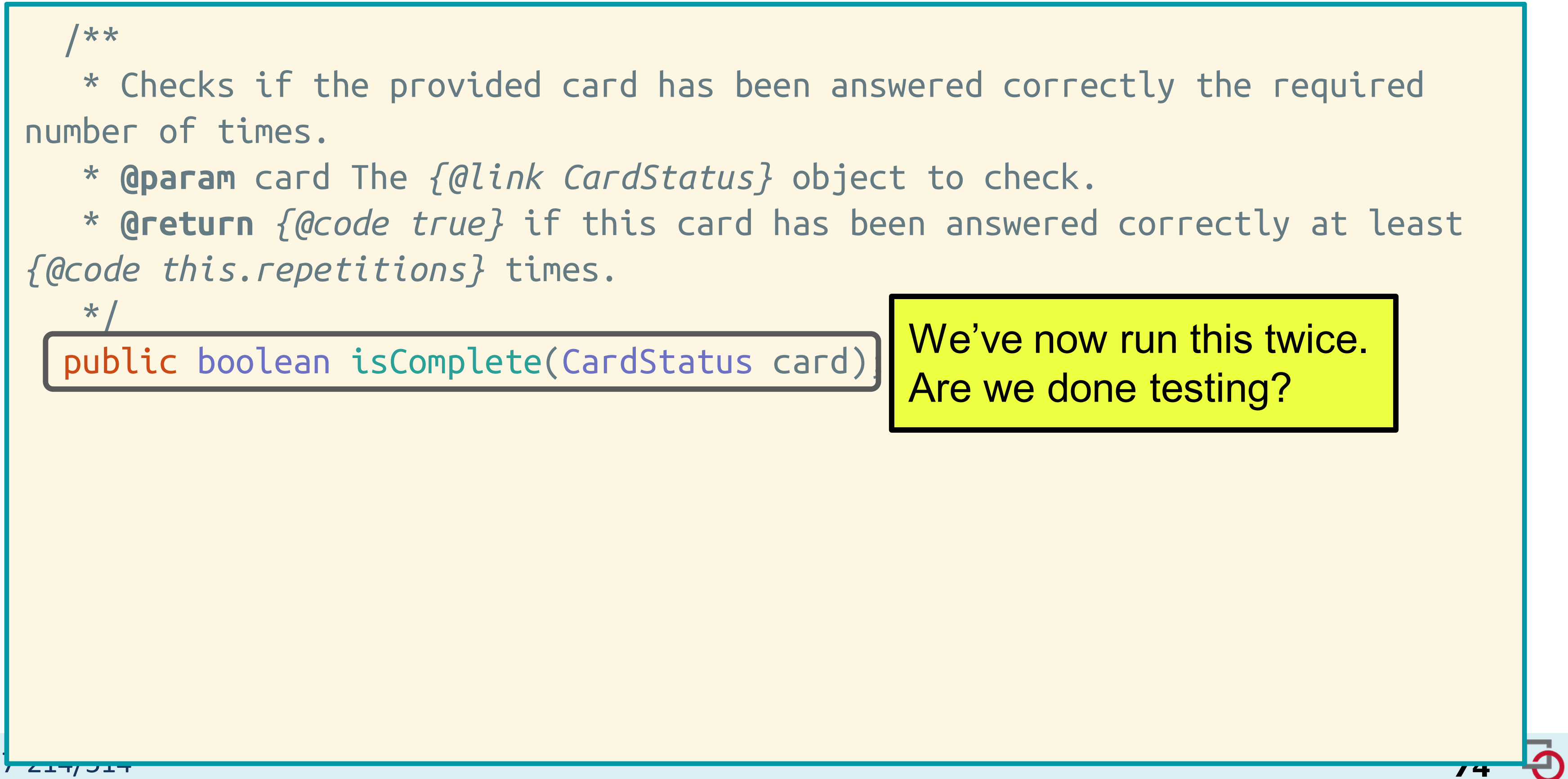
  /**
   * Checks if the provided card has been answered correctly the required
number of times.
   * @param card The {@link CardStatus} object to check.
   * @return {@code true} if this card has been answered correctly at least
{@code this.repetitions} times.
   */
  public boolean isComplete(CardStatus card);

@Test
public void testIsNotCompleteSingleFailure() {
  CardRepeater repeater = new RepeatingCardOrganizer(1); // Single repetition
  CardStatus cs = new CardStatus(new FlashCard(“”, “”));
  cs.recordResult(false); // Single failure
  assertFalse(repeater.isComplete(cs));
}
```

This is Java code

Docstring Specification



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   */
  public boolean isComplete(CardStatus card)
```

We've now run this twice.
Are we done testing?

Specification vs. Structural Testing

You can test for different objectives:

- Structural Testing: consider implementation
    - Optimize for various kinds of code coverage
        - Line, Statement, Data-flow, etc. -- More next week
    - By some definitions, we are done. Full line coverage, branch coverage.
        - Which is rarely enough

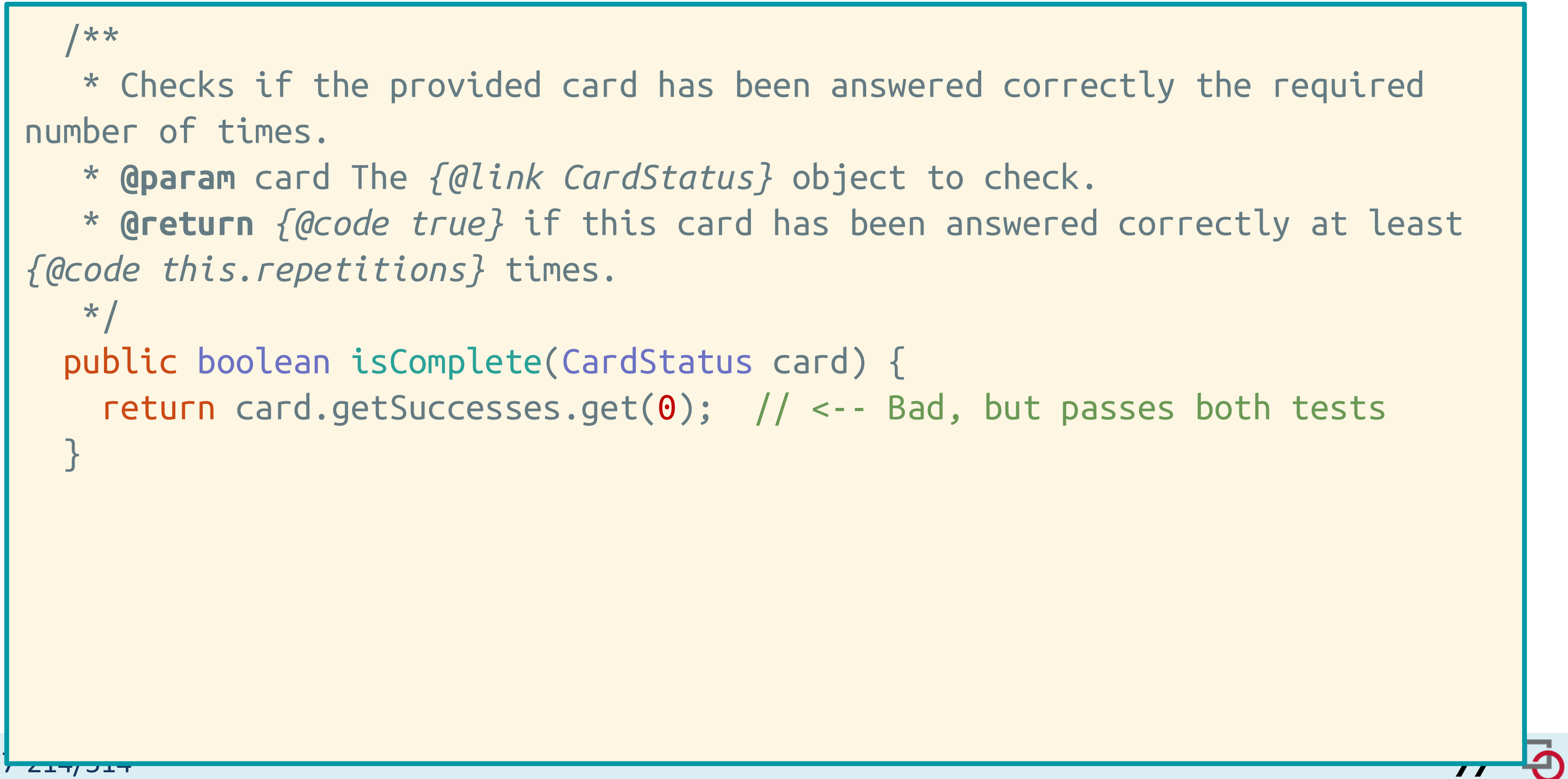
Specification vs. Structural Testing

You can test for different objectives:

- Structural Testing: consider implementation
  - Optimize for various kinds of code coverage
    - Line, Statement, Data-flow, etc. -- More next week
  - By some definitions, we are done. Full line coverage, branch coverage.
    - Which is rarely enough
- Specification-based testing: test solely the specification
  - Ignores implementation, use inputs/outputs only
  - Cover all specified behavior
  - Do not rely on code; consider corner-cases
    - Think like an attacker

This is Java code

Specification vs. Structural Testing



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number of times.
   * @param card The {@link CardStatus} object to check.
   * @return {@code true} if this card has been answered correctly at least
{@code this.repetitions} times.
   */
  public boolean isComplete(CardStatus card) {
    return card.getSuccesses.get(0);  // <-- Bad, but passes both tests
  }
```

Outlook

- Next Tuesday: a systematic approach to testing
    - Introducing *coverage* for structural testing, strategies for covering specifications
- Homework 2 is all about testing
    - Specification-testing the FlashCard system based on documentation
    - Structural testing of the Java UI to achieve complete branch coverage

Summary

- Being explicit about program behavior is important
  - Helps you detect bugs
  - Forces handling of special cases -- a key source of bugs
  - Increases transparency of your program’s interface
- Specification comes in multiple forms
  - Explicit contracts, formal or informal
  - Compile-time signals, e.g. through exceptions
  - Testing helps clarify, often improve specifications
    - TDD takes this to the extreme
    - You rarely know your code until you test it