Principles of Software Construction: Objects, Design, and Concurrency

Specifications and unit testing, exceptions

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Encapsulation / Information hiding

Remember this discussion from last week?

- Well designed objects project 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?

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

> 0
```

Who’s to blame?

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

Who’s to blame?

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

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

What is a contract?

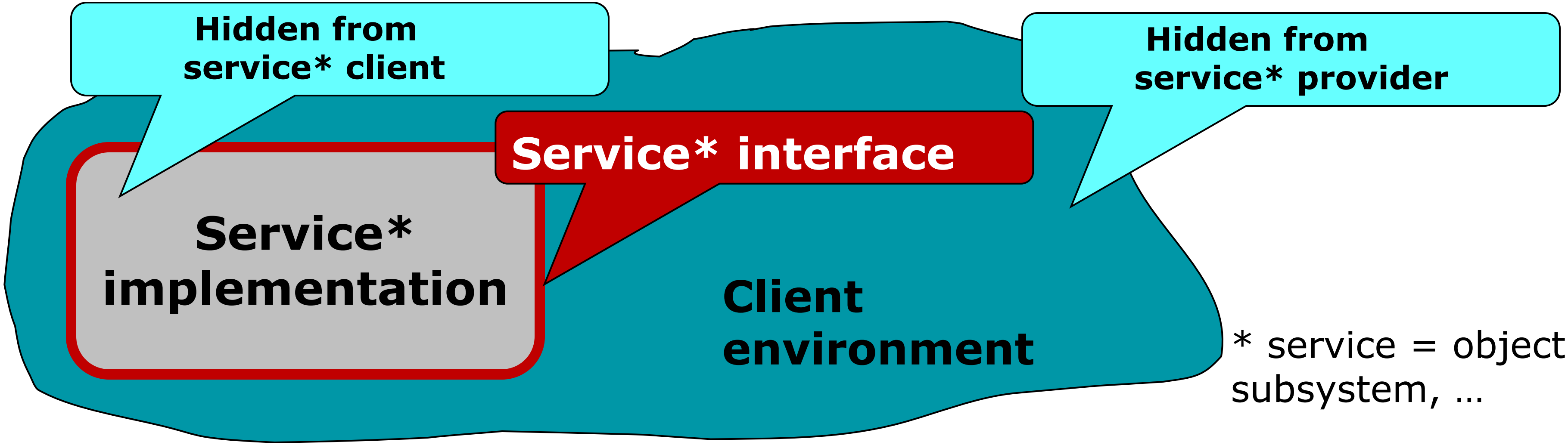
- Agreement between an object and its user
    - What object provides, and user can count on
- Includes:
    - Method signature (type specifications)
    - Functionality and correctness expectations
    - Sometimes: performance expectations
- **What** the method does, not **how** it does it
    - **Interface** (API), not **implementation**

Method contract details

- 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
- Method contract structure
    - Preconditions: what method requires for correct operation
    - Postconditions: what method establishes on completion
    - Exceptional behavior: what it does if precondition violated
- Defines correctness of implementation – we’ll come back to this later today

Most real-world code has a contract

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



* service = object, subsystem, …

Today

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;
```

Compare to:

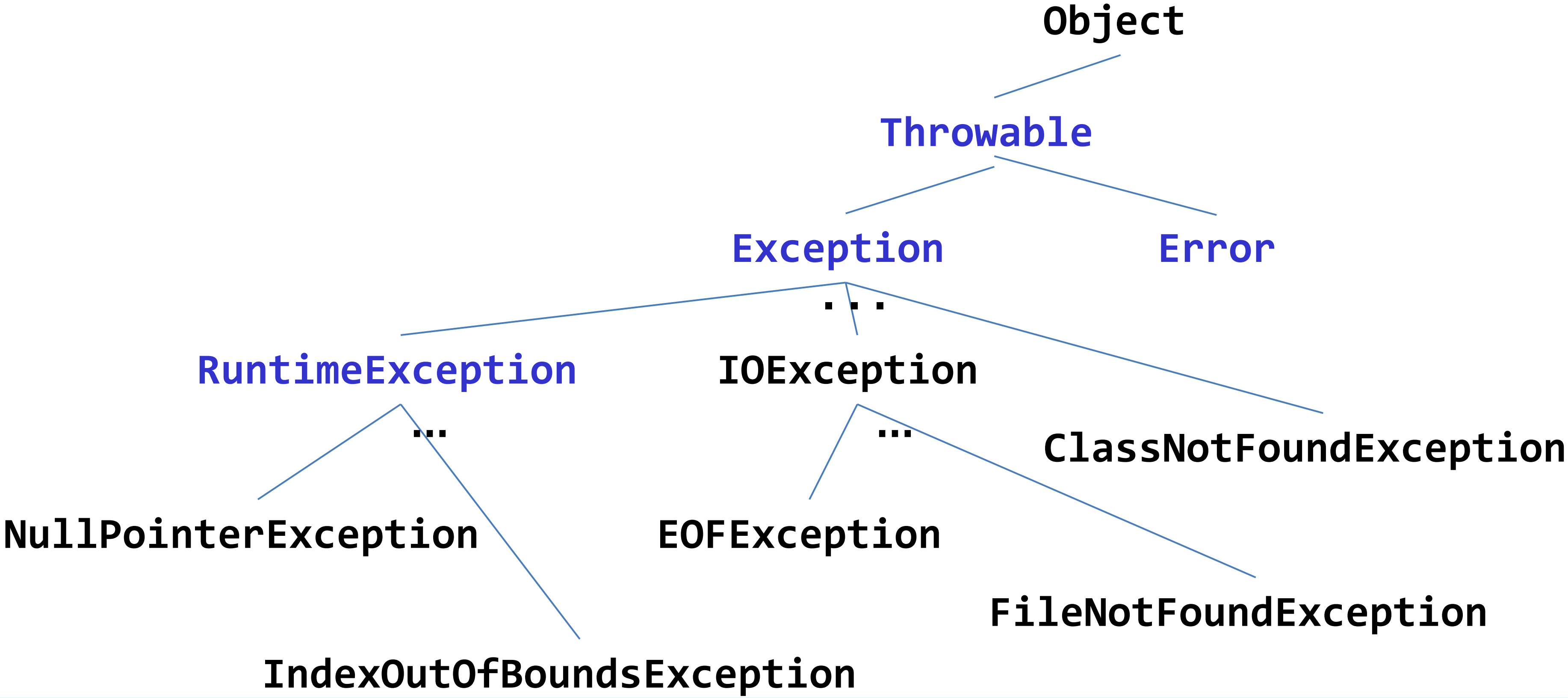
This is Java code

```java
FileInputStream fileInput = null;
try {
    fileInput = new FileInputStream(fileName);
    DataInput dataInput = new
DataInputStream(fileInput);
    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);
} finally {
    if (fileInput != null) fileInput.close();
}
```

Exceptions

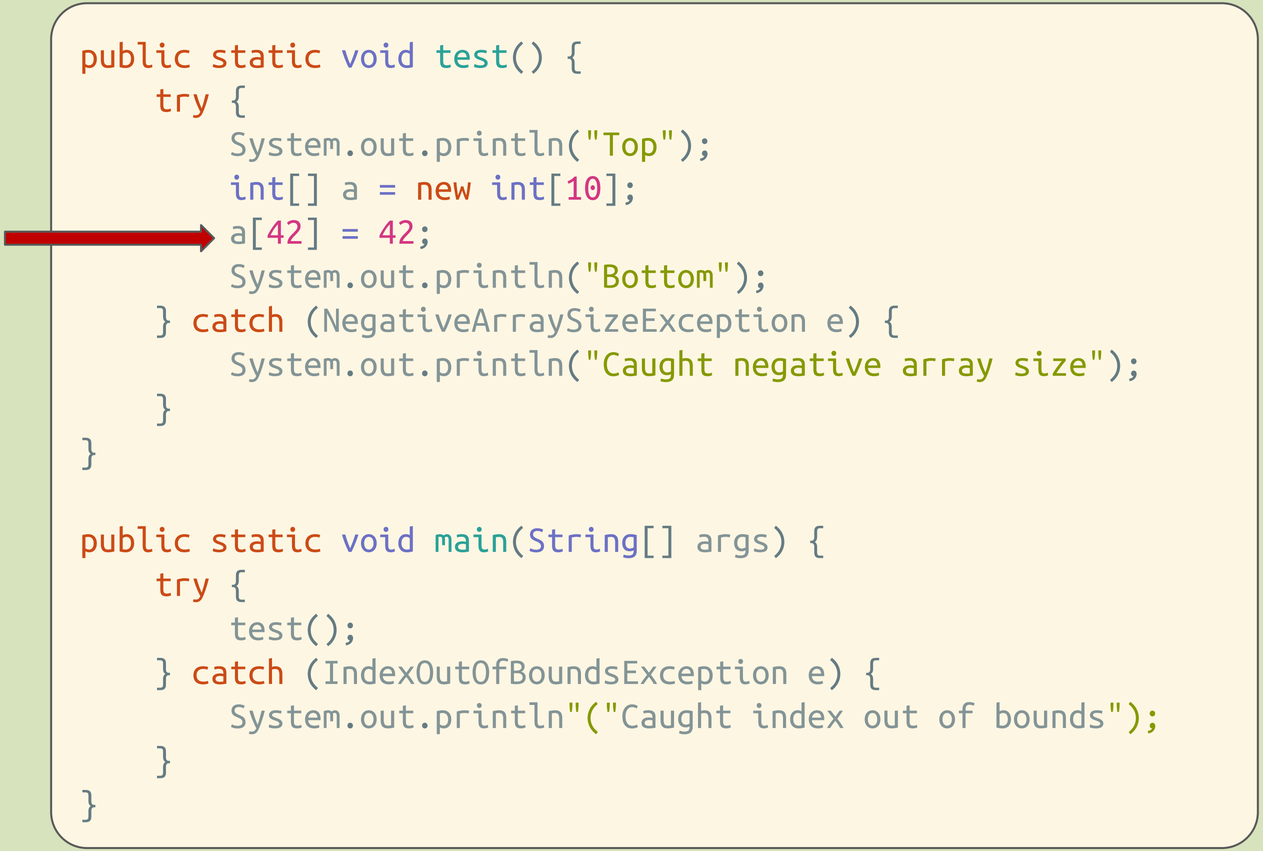
- Split control-flow into a “normal” and an “erroneous” branch
  - Compare “if/else”
- Inform caller of problem by transfer of control
- Where do exceptions come from?
  - Program can throw explicitly using throw
  - Underlying virtual machine (JVM) can generate
- Semantics
  - Propagates up call stack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

The exception hierarchy in Java (messy)



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
```

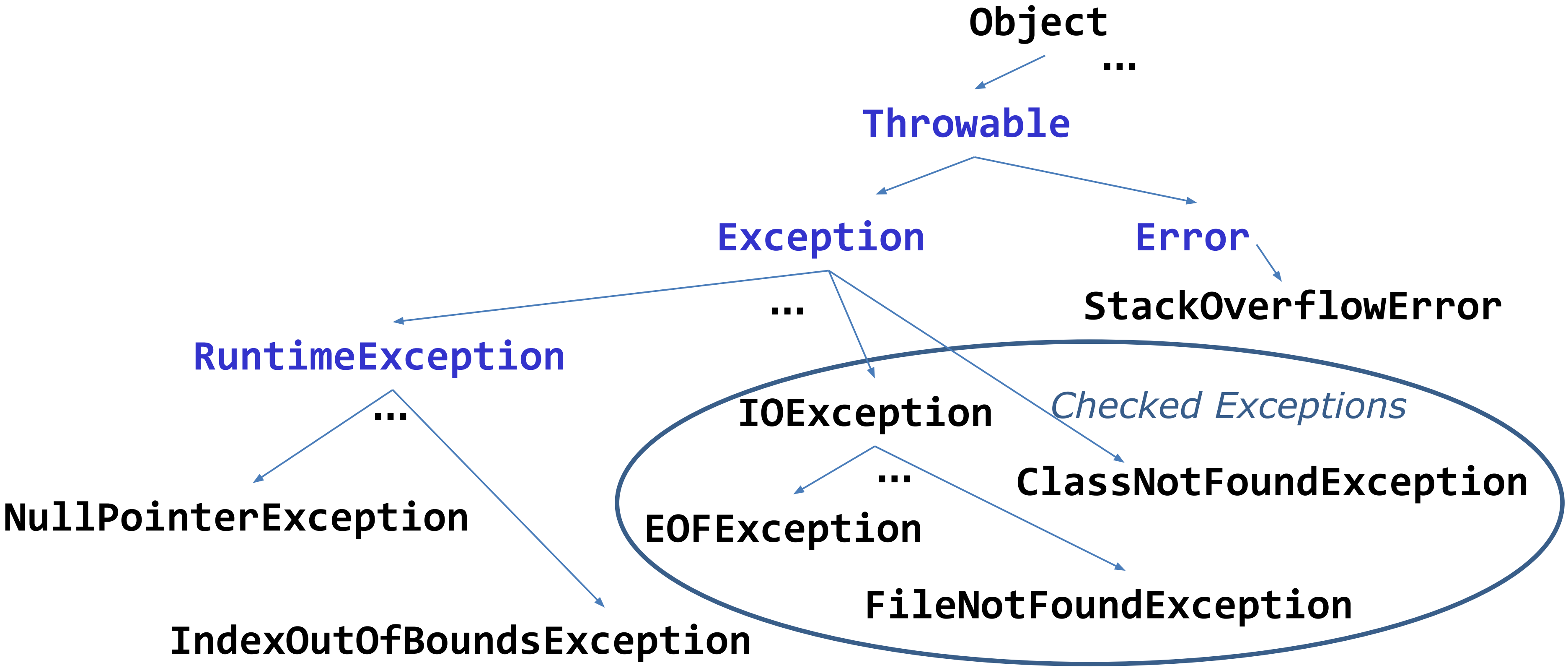
Exception Handling

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)



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

```
class BufferBoundsException extends Throwable {
  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

```
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?
  - `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 (Item 75)

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

This is Java code

Guidelines for using exceptions (2)

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

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

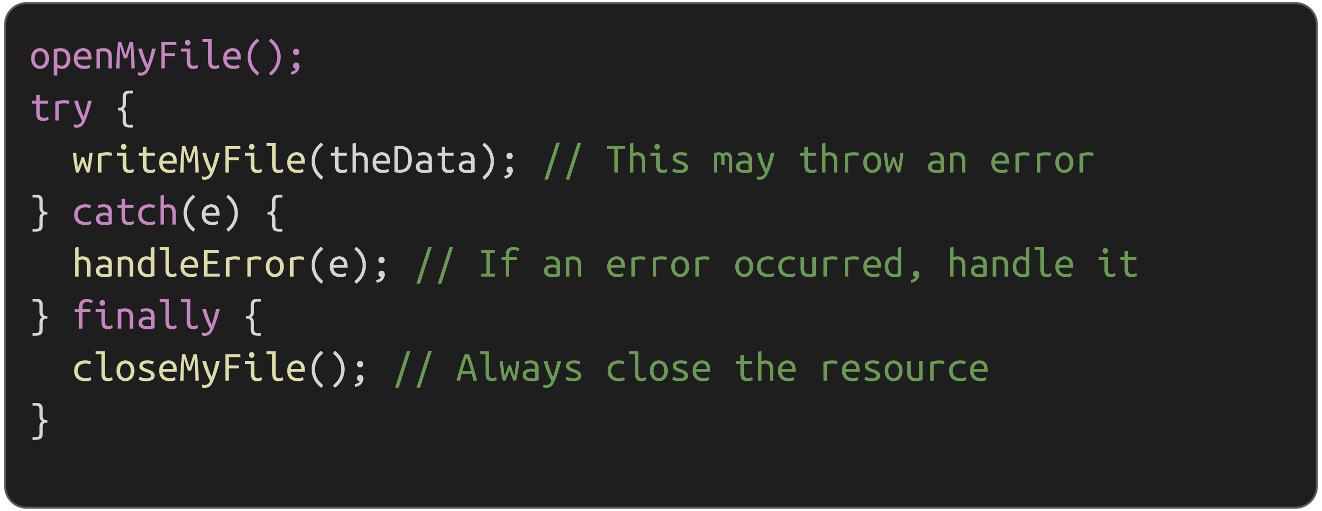
- Don’t ignore exceptions (EJ Item 77)

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

This is JavaScript code

Cleanup

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!

```
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`’
- Python has ‘`with`’ for resource management (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

Exceptions Across Languages

Use what you have

- When possible, be explicit
  - Use the compiler to enforce, where possible
  - Proactively avoid corner-cases, where not
    - Unchecked exceptions, JS/TS
- Make exceptions part of your contract

Outline

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

Functional correctness

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

Functional correctness

- Compiler ensures types are correct (type-checking)
    - Prevents many runtime errors, such as “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 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.
 }
```

This is Java code

Binary search from java.util.Arrays

Q: Who’s 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

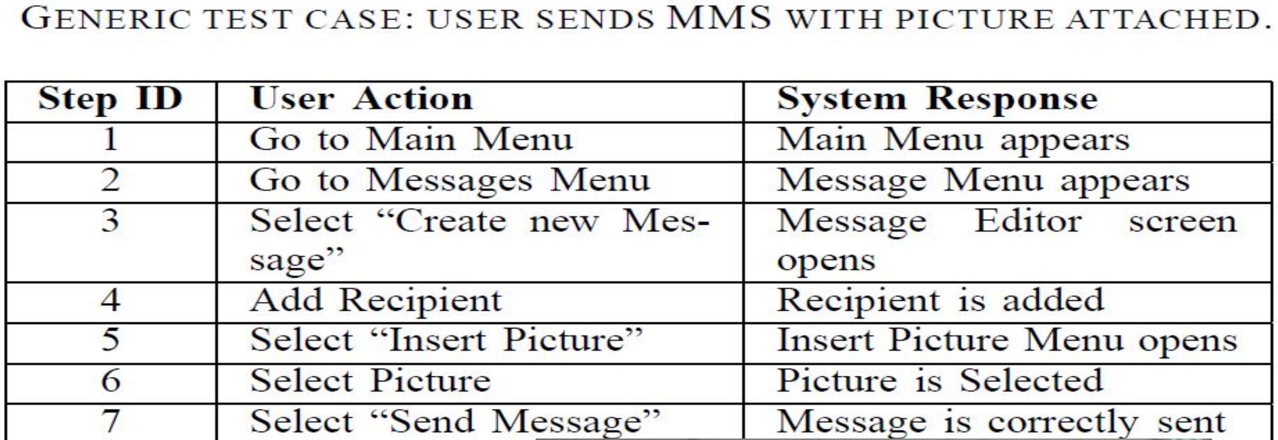
Binary search from java.util.Arrays

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.

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

Automated testing

- Execute a program with specific inputs,
  check output for expected values
- Easier to test small pieces than testing user interactions
- Set up testing infrastructure
- **Execute tests regularly**
  - After *every* change

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?

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

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

Testing

Are we done?

This is Java code

Testing

How do we know this works?

Testing

Are we done?

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

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

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

Testing

This is Java code

How do we know this works?

Testing

Are we done?

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

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

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

Testing

This is Java code

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
}
```

Boundary Value Testing

This is Java code

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

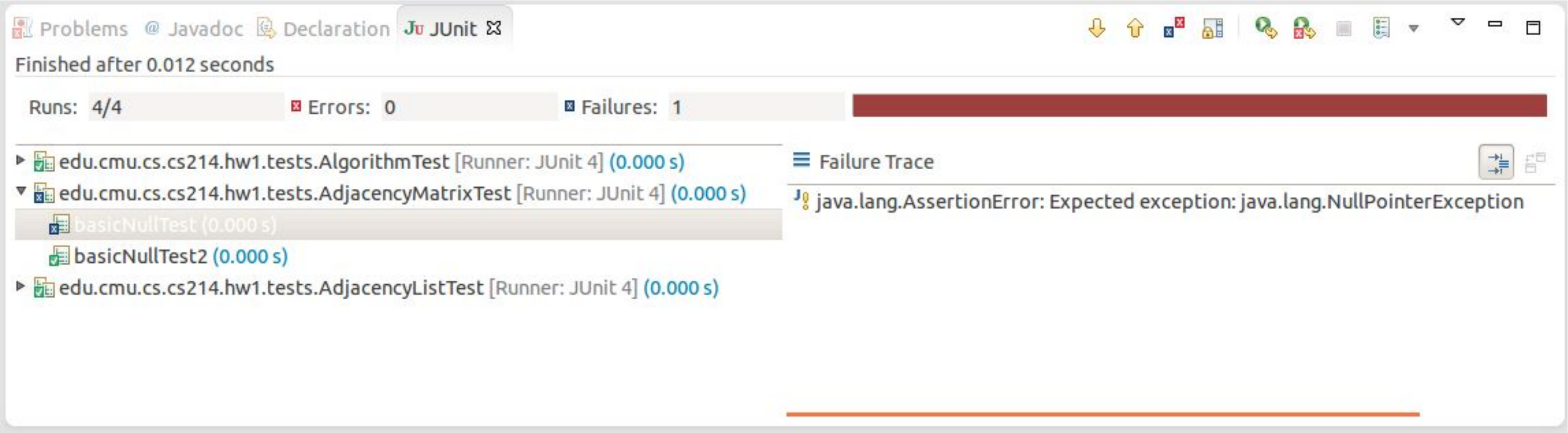
```java
int isPos(int x) {
  return x >= 0;  // What if?
}

@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)
```

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

This is Java code

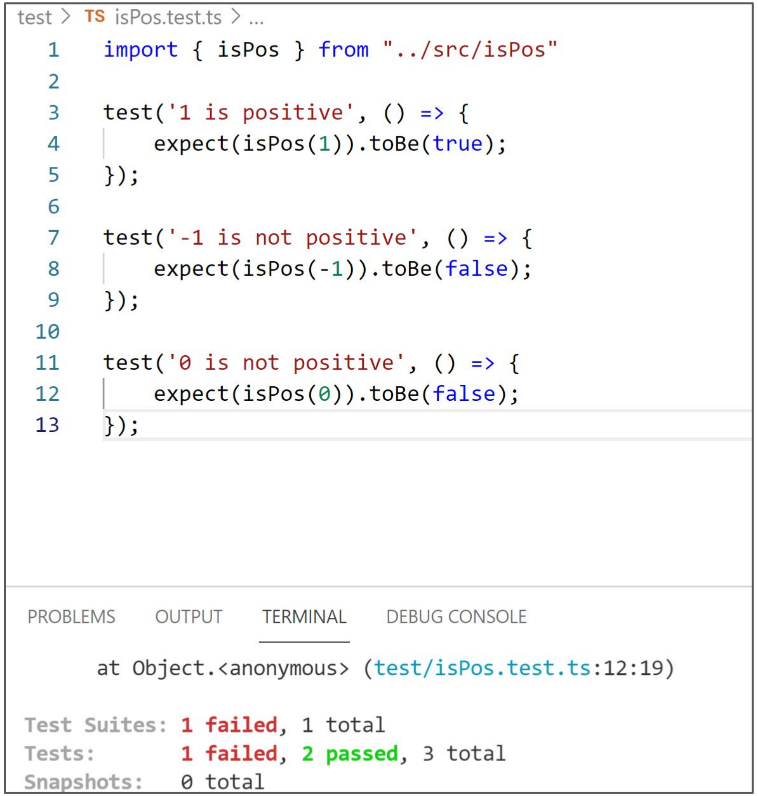
For Java: JUnit

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’, ‘toEqual’
  - ‘fn’, for Mocking (later)

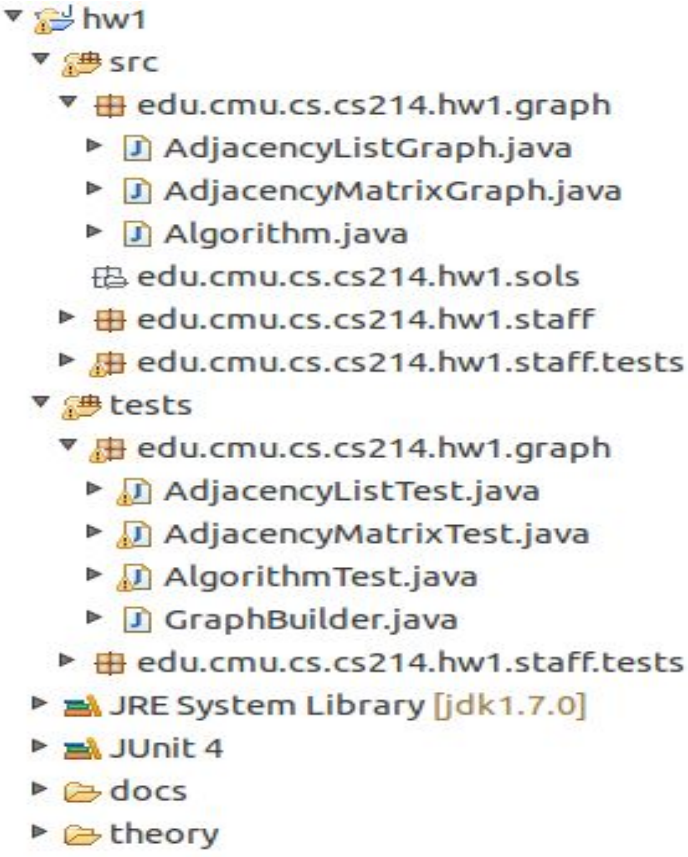


```
import { isPos } from "../src/isPos"

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
```

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**

Outlook

Homework 2 is all about testing

- Specification-testing the FlashCard system
- Some structural testing as well
  - More next Tuesday, also on coverage, test-case design
- To be released soon

Summary

- Being explicit about program behavior is ideal
  - 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