



University of
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An Introduction to Software Testing

<https://github.com/philmcminn/eyup-testing-spr2023>

Phil McMinn

[Video]

Who here *likes* software
testing?

Who here thinks testing is
hard?

Who thinks testing and
debugging are basically the
same thing?

Who thinks that testing is
to show that software
works?

Who thinks that testing is
to show that software
doesn't work?

Who thinks that the idea
behind testing is to
reduce risks involved in
using software?

Who thinks that the
testing is to help in the
development of
higher quality software?

Beizer's Maturity Model

Level 0: Testing is the same as debugging

The basic, least mature view of testing is that of **Level 0 – testing is the same as debugging.**

At Level 0 thinking, programmers get their programs to compile, then debug the programs with a few arbitrary inputs.

This view does not distinguish between a program's **incorrect behaviour** and a **mistake** within the program. It also does very little to help develop software that is reliable or safe.

(... and testing is **not the same** as debugging, as demonstrated later.)

Level 1:

The purpose of software testing is to show software works

A significant step up from the naive Level 0.

But, in any but the most trivial of programs, correctness is virtually impossible to either achieve or demonstrate!

(... another point we will return to later in the lecture.)

Level 2:

The purpose of software testing is to show software *doesn't* work

Although looking for failures is certainly a valid goal, it is also a negative goal.

If a company is organised where testers and developers are on different teams, you may have a situation where testers may enjoy finding problems, but the developers never want to find problems – they want the software to work!



“Excellent testing
can make you
unpopular with
almost everyone!”

— Bill McKee

Level 2 testing puts testers and developers into an adversarial relationship, which can be bad for team morale.

Beyond that, when our primary goal is to look for failures, we are still left wondering what to do if no failures are found:

Is our work done?

and if so...

Is our software very good *or* is our testing poor?

Level 3:

The purpose of software testing is not to show anything in particular, but just to reduce the risk of using software

Level 3 thinking lets us accept the fact that whenever we use software, we incur some risk.

Level 3 thinking lets us accept the fact that whenever we use software, we incur some risk.

The risk may be small, and the consequences unimportant, or the risk may be great and the consequences catastrophic, but risk is always there.

This allows us to realise that the entire development team wants the same thing – to reduce the risk of using the software.

In Level 3 testing, testing and developing go hand to hand to reduce risk.

Level 4: Testing is a mental discipline that helps all IT professionals develop higher quality software

Once the testers and developers are on the same “team”, or, testing is regarded as equally or even more important to development, an organisation can progress to **Level 4** testing.

Level 4 testing defines **testing as a mental discipline that increases quality.**

that helps all professionals develop higher quality software

Once the testers and developers are on the same “team”, or, testing is regarded as equally or even more important to development, an organisation can progress to **Level 4** testing.

Level 4 testing defines **testing as a mental discipline that increases quality**.

In the same way, Level 4 testing means that the purpose of testing is to improve the ability of the developers to produce higher quality software.



The best use of a spellchecker is not just to find misspelled words, but to improve our ability to spell.

Every time the spell checker finds an incorrectly spelled word, we have the opportunity to learn how to spell the word correctly.

The spell checker is the “expert” on spelling quality.

Beizer's Maturity Model –

- 0 The same activity as debugging
- 1 Purpose is to show software works
- 2 Purpose is to show software doesn't work
- 3 Purpose is to reduce the risk of using software
- 4 Purpose is to help all IT professionals engineer better software

Level 1:
The purpose of software testing
is to show software works

A significant step up from the naive Level 0.

But, in any but the most trivial of programs, correctness is virtually impossible to either achieve or demonstrate!

— — — — — ➔ *Why?*

Why Finding ALL Bugs is Impossible
or

Why Software Testing is Hard

The Problem of Exhaustive Testing

```
public int daysBetweenTwoDates(int year1, int month1, int day1,  
                                int year2, int month2, int day2)
```

The range of an **int** in Java is **-2,147,483,648** to **2,147,483,647** (or **2^{32}**)

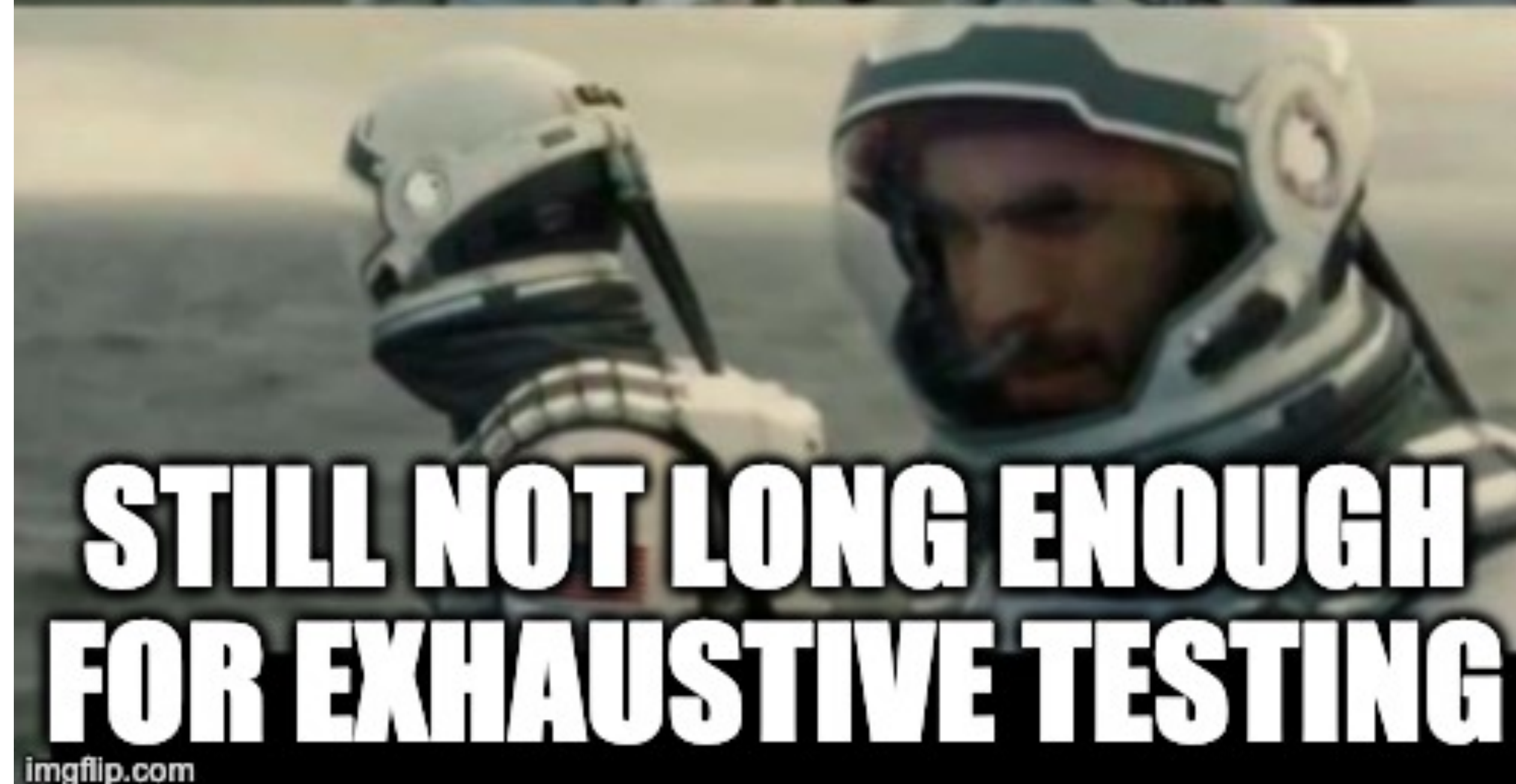
With six ints that's $2^{32 \times 6}$ or 2^{192} ($\approx 6 \times 10^{57}$) unique inputs to try!

Suppose each input takes ≈ 1 nanosecond to execute.

It would take 10^{41} years to try them all!



1 hour here is 7 years on earth



**STILL NOT LONG ENOUGH
FOR EXHAUSTIVE TESTING**

The Halting Problem and Software Testing

The Halting Problem in Computer Science is basically the problem of not knowing if a program will terminate given some input.

If we give an arbitrary program an input, it has been proven that no program can be written that can say whether that original program will terminate.

And this is true in software testing: we don't know if, given our test inputs, whether the program being tested will get stuck in an infinite loop!

Meaning that in general, exhaustive testing is not be just intractable, it's uncomputable too.



“Software testing
can only show the
presence, not the
absence of bugs”

— Edsger Dijkstra

	Tractable problems	Intractable problems	Uncomputable problems
Description	Can be solved efficiently	Method for solving exists, but is hopelessly time consuming	Cannot be solved by any computer program
Computable in theory	😎	😎	😭
Computable in practice	😎	🤔	😭
Example	Find the shortest route on a map	Decryption	Finding all bugs in a computer program

The Oracle Problem

Even if we could

1) execute all software with all inputs

(i.e., if software testing was a **tractable** problem)

2) guarantee the software terminated with each input

(i.e., if software testing was a **computable** problem)

We would still need to solve the **oracle problem** – how to know, given some input to a software system, **that the output it gives is the correct one.**

The Oracle Problem

a human being makes a **manual** judgment

e.g. an **assertion in JUnit**

In software testing an **oracle** is **something** or **someone** who can determine if a **software output is correct**



ORACLE®

No, not the company!



But we don't need every single input to ensure the program is working... right ...?

But **how do we choose** that subset of inputs?

This is the essence of the software testing problem.

We need to choose a set of inputs that will reveal as much information about the quality of the software as possible.

But **we don't know** that we've selected all the inputs that will reveal all of the bugs.

Why Finding ALL Bugs is Impossible, or: Why Software Testing is Hard

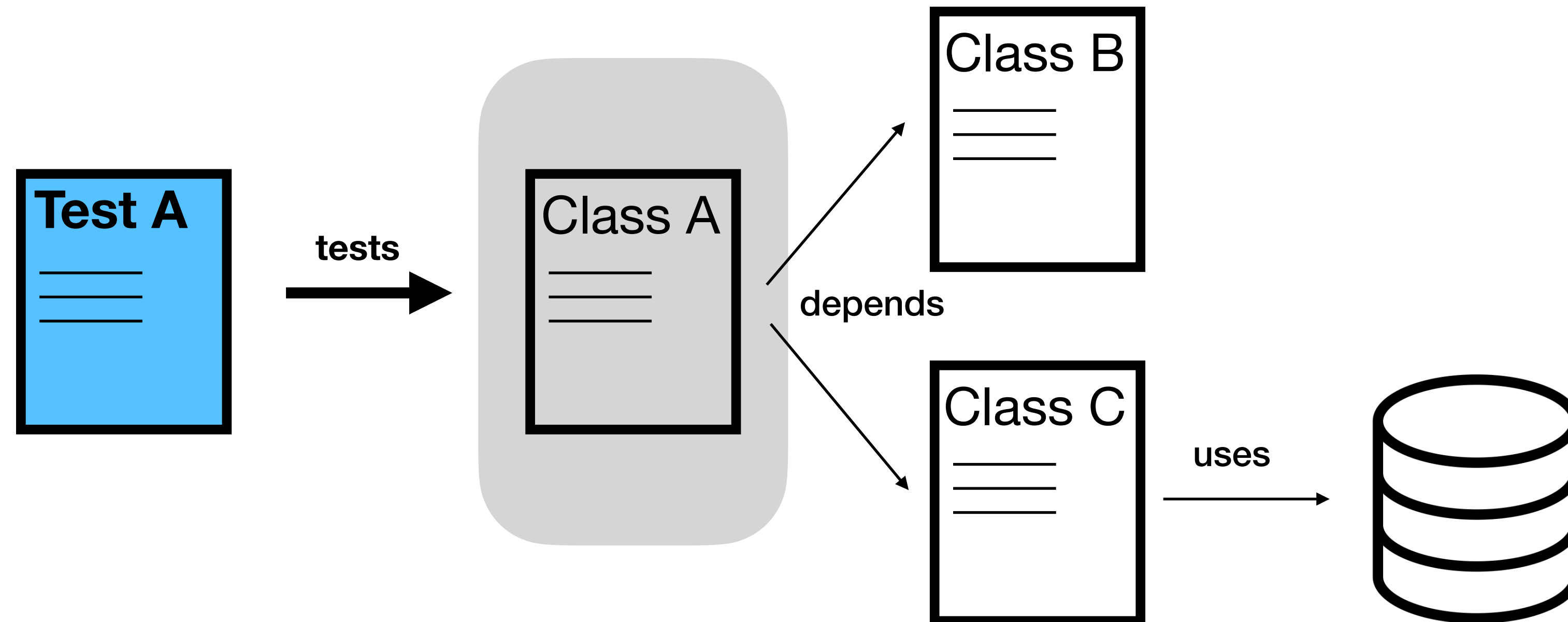
- 1 Executing all inputs for any non-trivial program is **intractable**
- 2 Ensuring the software will terminate with every input is **undecidable**
- 3 Recognising correct/incorrect outputs given their corresponding inputs is at least as hard as building the software in the first place – **the oracle problem**

Types of Testing

Unit Testing

A unit is an individual component of a system, such as a class or an individual method.

Testing units in isolation is called **unit testing**.

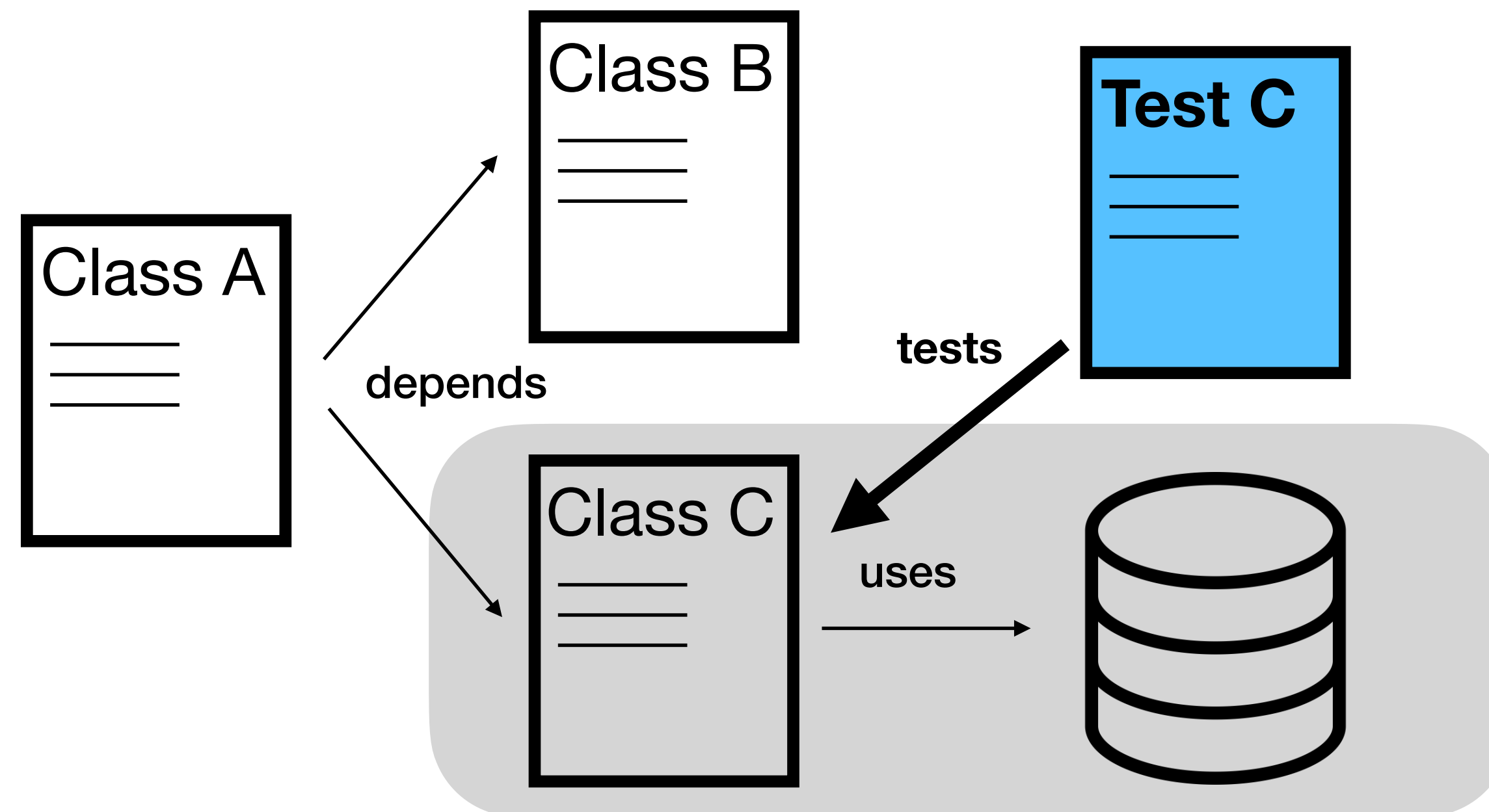


Integration Tests

Testing in isolation is not enough. Sometimes code goes “beyond” the system’s borders and uses other (often external) components – for example, a database.

Integration tests test the integration between our code and that of external parties.

Example: Testing methods that access a database via SQL queries. Do our methods obtain the right data from the database?

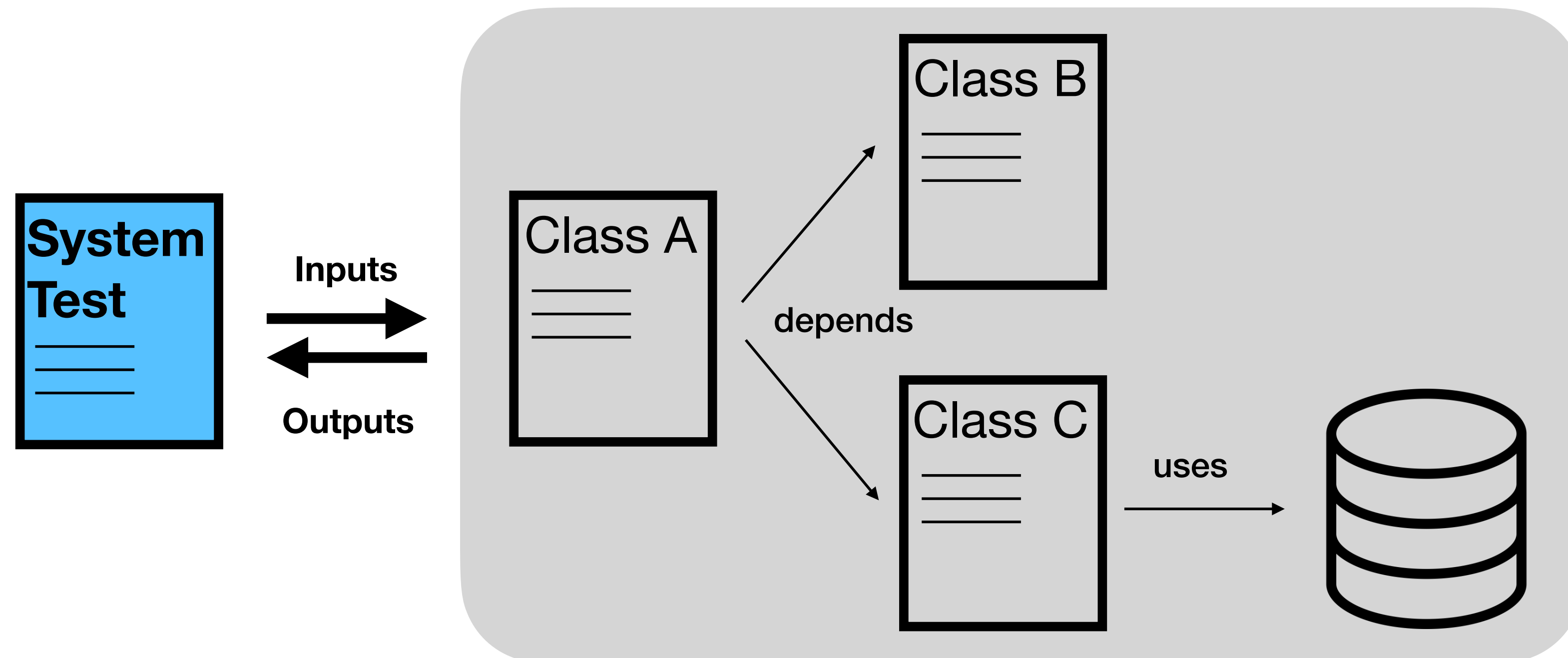


System Tests

To get a more realistic view of the software we should also perform more realistic tests with it – with all its database, front-end, and other components.

We do not care about how the system works from the inside.

We care that given certain inputs, certain outputs are provided by the system.

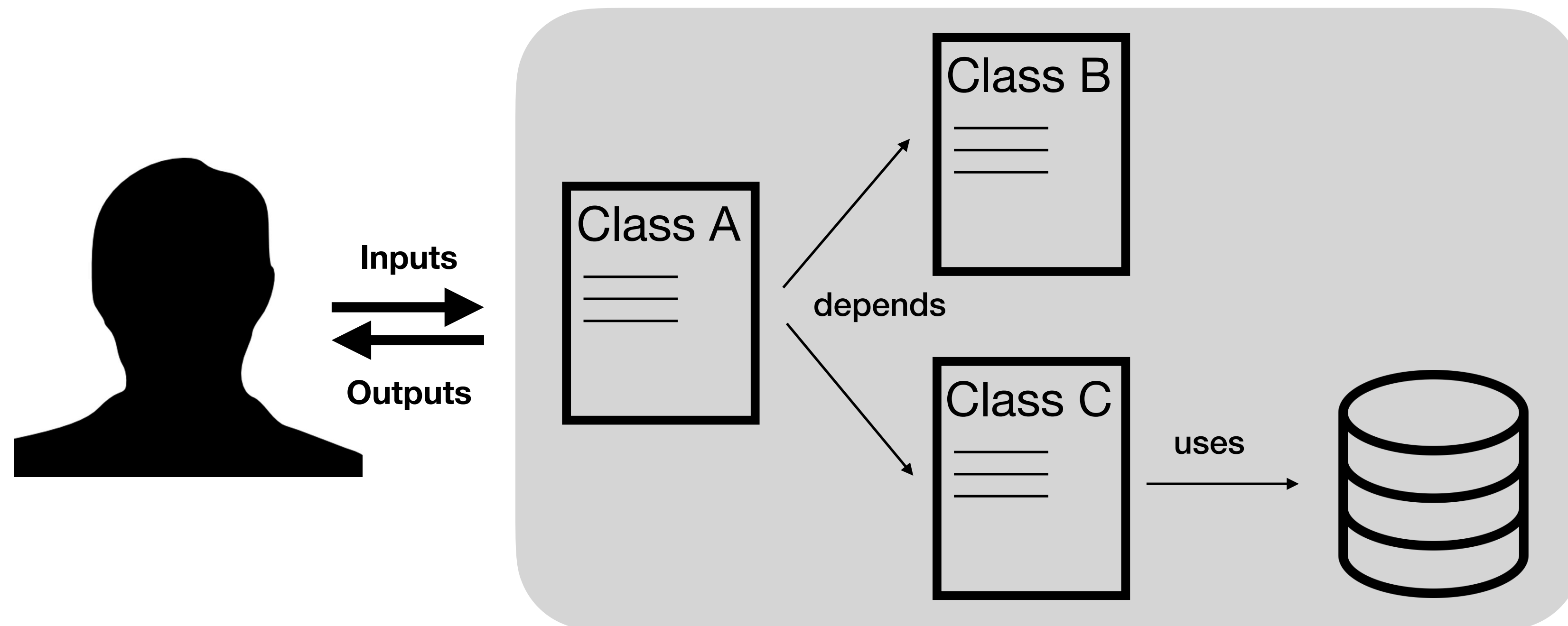


Manual Tests

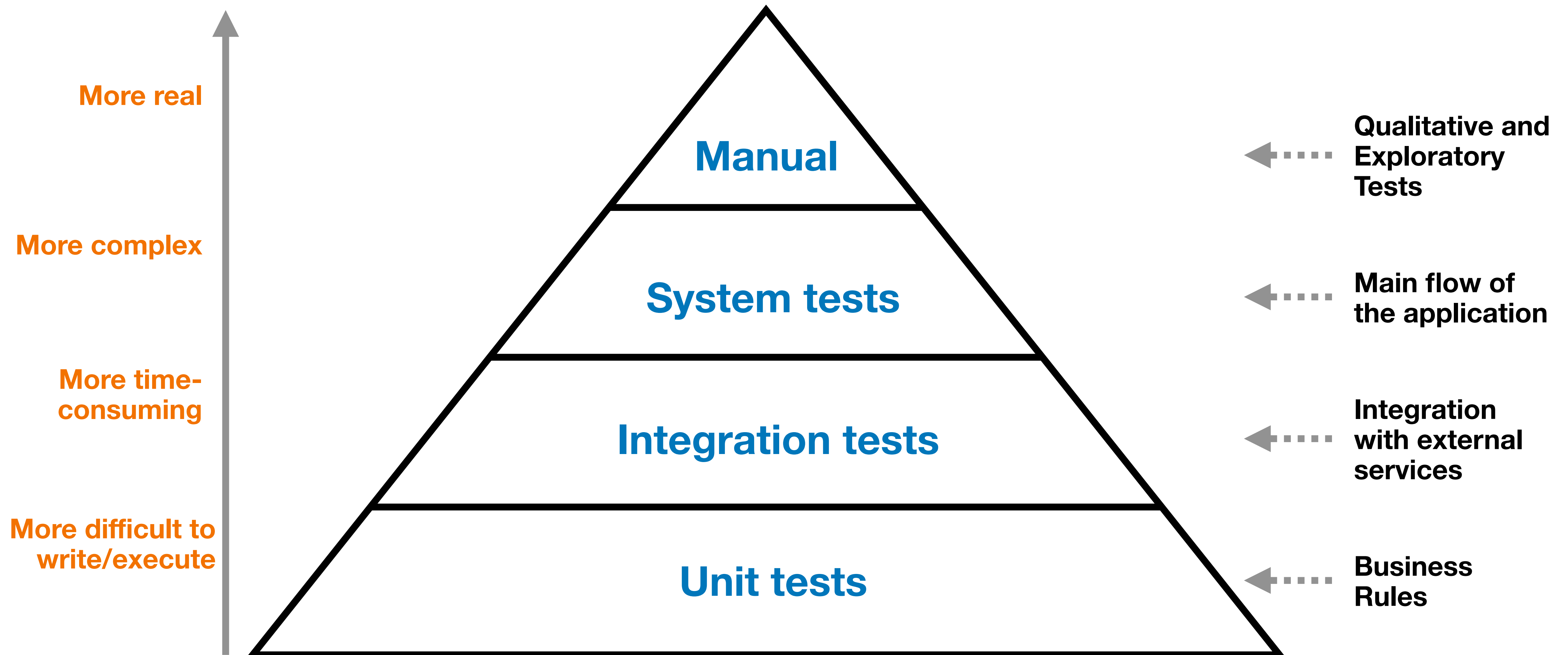
Not everything can be tested easily in an automated fashion, particularly where there are qualitative judgements (e.g., the quality of a search engine's results).

Furthermore, we may need to explore real system behaviour to know what automated tests to write.

Manual tests are system tests performed manually by a human.



The Test Triangle



[Video]

Unit Testing in JUnit

A JUnit Test Class and a Test

```
import org.junit.jupiter.api.Test;

public class TriangleTest {

    @Test
    public void shouldClassifyEquilateral() {
        // Test code goes here...
    }

    // ...
}
```

Tests are annotated with `@Test`
JUnit then knows which methods
are test methods and which are
helper methods

The Ingredients of a Test

```
import org.junit.jupiter.api.Test;

import static org.junit.jupiter.api.Assertions.assertEquals;

public class TriangleTest {

    @Test
    public void shouldClassifyEquilateral() {
        Triangle.Type result = Triangle.classify(10, 10, 10);
        assertEquals(Triangle.Type.EQUILATERAL, result);
    }

    // ...
}
```

We start by making method call(s) to set up the test and to the part of the system we want to test.

The Ingredients of a Test

```
import org.junit.jupiter.api.Test;

import static org.junit.jupiter.api.Assertions.assertEquals;

public class TriangleTest {

    @Test
    public void shouldClassifyEquilateral() {
        Triangle.Type result = Triangle.classify(10, 10, 10);
        assertEquals(Triangle.Type.EQUILATERAL, result);
    }

    // ...
}
```

We then write
assertion
statements to check
the **actual result** is
the one we
expected.

JUnit Assertions

```
import org.junit.jupiter.api.Test;

import static org.junit.jupiter.api.Assertions.assertEquals;

public class TriangleTest {

    @Test
    public void shouldClassifyEquilateral() {
        Triangle.Type result = Triangle.classify(10, 10, 10);
        assertEquals(Triangle.Type.EQUILATERAL, result);
    }

    // ...
}
```

The `assertEquals` method is a part of JUnit and specifically checks that some **expected value** is **equal** to the **actual one** returned from the unit being tested.

JUnit has a plethora of assertion types for checking relationships between actual and expected outputs.

These include `assertTrue(booleanVariable)`, `assertNull(reference)`, assertions on arrays and more. See:

<https://junit.org/junit5/docs/current/api/org.junit.jupiter.api/org/junit/jupiter/api/Assertions.html>

Checking for Exceptions with `assertThrows`

```
@Test
public void shouldThrowExceptionWithInvalidTriangle() {
    assertThrows(InvalidTriangleException.class, () -> {
        Triangle.classify(0, 0, 0);
    });
}
```

```
@Test
public void shouldThrowExceptionWithInvalidTriangle() {
    Exception e = assertThrows(InvalidTriangleException.class, () -> {
        Triangle.classify(0, 0, 0);
    });
    assertEquals("(0, 0, 0) is not a valid triangle", e.getMessage());
}
```

A more elaborate version that also checks the exception message.

Arguably such checks make the test more **brittle**.

“**import static**” means importing a static method from another class and using it as if it were in the current class

Each test method is annotated with **@Test**

Assert that a method's return value is as expected with **assertEquals**

Assert that an exception is thrown as expected with **assertThrows**

```
package uk.ac.shef.com3529;

import org.junit.jupiter.api.Test;

import static org.junit.jupiter.api.Assertions.assertEquals;
import static org.junit.jupiter.api.Assertions.assertThrows;

public class TriangleTest {

    @Test
    public void shouldClassifyEquilateral() {
        Triangle.Type result = Triangle.classify(10, 10, 10);
        assertEquals(Triangle.Type.EQUILATERAL, result);
    }

    @Test
    public void shouldClassifyIsocoles() {
        Triangle.Type result = Triangle.classify(5, 10, 10);
        assertEquals(Triangle.Type.ISOSCELES, result);
    }

    @Test
    public void shouldClassifyIsocolesWhenSidesAreOutOfOrder() {
        Triangle.Type result = Triangle.classify(10, 10, 5);
        assertEquals(Triangle.Type.ISOSCELES, result);
    }

    @Test
    public void shouldThrowExceptionWithInvalidTriangle() {
        assertThrows(InvalidTriangleException.class, () -> {
            Triangle.classify(0, 0, 0);
        });
    }
}
```

How do Software Failures Happen?

A Method and its Tests

```
public static Set<Character> duplicateLetters(String s) {
    // lower case the string and remove all characters that are not letters
    s = s.toLowerCase().replaceAll("[^a-z.]", "");

    // initialise the result set
    Set<Character> duplicates = new TreeSet<>();

    // iterate through the string
    for (int i = 0; i < s.length(); i++) {
        char si = s.charAt(i);

        // iterate through the rest of the string, checking for the same letter
        for (int j = i; j < s.length(); j++) {
            char sj = s.charAt(j);

            if (si == sj) {
                // a match has been found, add it to the result set
                duplicates.add(si);
            }
        }
    }

    return duplicates;
}
```

A Method and its Tests

```
public class StringUtilsTest {  
  
    @Test  
    public void shouldReturnRepeatedChar() {  
        Set<Character> resultSet = duplicateLetters("software testing");  
        assertTrue(resultSet.contains('t'));  
    }  
  
    @Test  
    public void shouldNotReturnNonRepeatedChar() {  
        Set<Character> resultSet = duplicateLetters("software debugging");  
        assertFalse(resultSet.contains('t'));  
    }  
}
```

PASSED

FAILED


```
public static Set<Character> duplicateLetters(String s) {  
    // lower case the string and remove all characters that are not letters  
    s = s.toLowerCase().replaceAll("[^a-z.]", "");  
  
    // initialise the result set  
    Set<Character> duplicates = new TreeSet<>();  
  
    // iterate through the string  
    for (int i = 0; i < s.length(); i++) {  
        char si = s.charAt(i);  
  
        // iterate through the rest of the string, checking for the same letter  
        for (int j = i; j < s.length(); j++) {  
            char sj = s.charAt(j);  
  
            if (si == sj) {  
                // a match has been found, add it to the result set  
                duplicates.add(si);  
            }  
        }  
    }  
  
    return duplicates;  
}
```

This method contains a bug. Or more precisely, a **defect**.

Where is the defect? How does it cause the method to fail?

Defects

Software failures always start with the execution of one or more defects in the code.

A **defect** is simply a piece of **faulty, incorrect code**.

A defect may be a part of or a complete program statement, or may correspond to statements that *don't exist that should exist*.

Although programmers are responsible for making defects in the code, they may not be technically always be at fault – the problem may have arisen, for example, from a poorly specified set of requirements.

```
public static Set<Character> duplicateLetters(String s) {
    // lower case the string and remove all characters that are not letters
    s = s.toLowerCase().replaceAll("[^a-z.]", "");

    // initialise the result set
    Set<Character> duplicates = new TreeSet<>();

    // iterate through the string
    for (int i = 0; i < s.length(); i++) {
        char si = s.charAt(i);

        // iterate through the rest of the string, checking for the same letter
        for (int j = i; j < s.length(); j++) {
            char sj = s.charAt(j);

            if (si == sj) {
                // a match has been found, add it to the result set
                duplicates.add(si);
            }
        }
    }

    return duplicates;
}
```

The defect in our example is with the second loop initialiser.

It should start iterating at $i + 1$ to check for duplicates of the character at i , not at i itself (which is guaranteed to be identical!)

Infections

An **infection** is what happens when the defect is executed, and the program's state is affected.

When a program's state is infected it starts to work incorrectly:

- Variables start to take on the wrong values
- Decisions made in the program are evaluated incorrectly, and the execution path deviates from the correct one.

But at this point, it has not affected the output of the program (and the fault, so far, has had no observable effect).


```
public static Set<Character> duplicateLetters(String s) {
    // lower case the string and remove all characters that are not letters
    s = s.toLowerCase().replaceAll("[^a-z.]", "");

    // initialise the result set
    Set<Character> duplicates = new TreeSet<>();

    // iterate through the string
    for (int i = 0; i < s.length(); i++) {
        char si = s.charAt(i);

        // iterate through the rest of the string, checking for the same letter
        for (int j = i; j < s.length(); j++) {
            char sj = s.charAt(j);

            if (si == sj) {
                // a match has been found, add it to the result set
                duplicates.add(si);
            }
        }
    }

    return duplicates;
}
```

The infection in our example causes the loop starts iterating an index in the string too early.

This further causes each character in the string to be added to the **duplicates** set. But at this point, there is nothing observably wrong with the program.

Failures

A **failure** occurs when the infection propagates to the output of the program.

That is, the program is observably behaving incorrectly.

```

public static Set<Character> duplicateLetters(String s) {
    // lower case the string and remove all characters that are not letters
    s = s.toLowerCase().replaceAll("[^a-z.]", "");

    // initialise the result set
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    // iterate through the string
    for (int i = 0; i < s.length(); i++) {
        char si = s.charAt(i);

        // iterate through the rest of the string, checking for the same letter
        for (int j = i; j < s.length(); j++) {
            char sj = s.charAt(j);

            if (si == sj) {
                // a match has been found, add it to the result set
                duplicates.add(si);
            }
        }
    }

    return duplicates;
}

```

Failures therefore depend on when programs deliver observable outputs. In our example, we interrogate the return value of the method in our tests, causing a **test failure**.

But during execution of the whole software, the method may be used internally by another method and a failure may happen much later, in a different place.

Failures vs Test Failures

We therefore need to distinguish between failures and test failures.

Failures are when software behaves incorrectly when run as a whole in production.

Test failures are when tests themselves fail because either:

(a) the test revealed a software failure

(b) the test itself was incorrect, for example it made an incorrect assertion about the behaviour of the software.

Testing vs Debugging

We can also now debunk the idea that testing and debugging are the same.

Testing is the process of evaluating software by observing its execution.

Debugging is the process of tracking failures/test failures back to the defects that were ultimately responsible for them.

How do Software Failures Happen?

1. The program location containing a **defect** is reached during execution.



Defect

2. The defect **infects** the state of the program



Infection

3. The infection propagates to the program's output causing a **failure**.

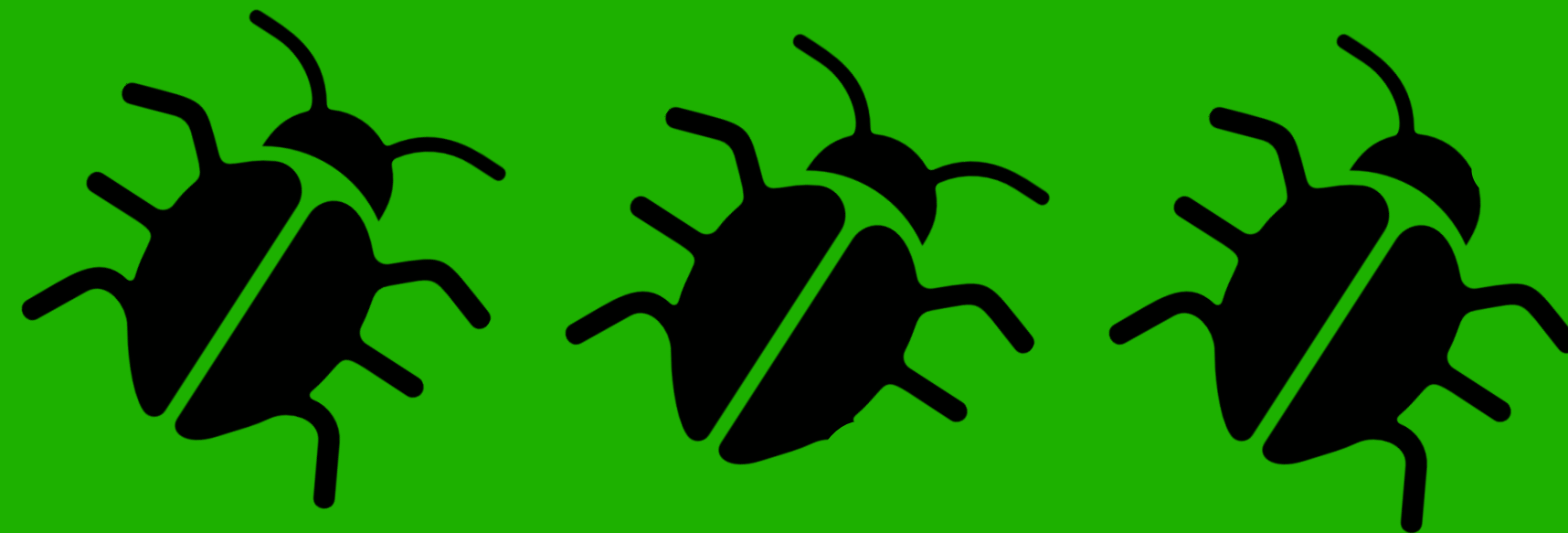


Failure

Defect, Infection or Failure?

a.k.a.

Spot the *DIF*ference!



Haiping runs his Python program to predict final degree classifications for students given their first year module results.

It produces several lines of output, but then crashes with an error.

Is this an example of a
defect, infection, or a failure?

FAILURE!

Siobhan is writing a Java method, where she forgets to assign an object to a reference, meaning that it is NULL.

Is this an example of a
defect, infection, or a failure?

DEFECT!

Ramsay is writing a program to calculate student marks. One function is to find the best student for his assignment. His program mistakenly starts iterating over his array of marks from position 1 instead of 0. But position 0 corresponded to a poor student anyway, so the program still returned the right answer.

Is this an example of a
defect, infection, or a failure?

INFECTION!

Emma is testing her Ruby on Rails application. All the tests pass, but later it turns out she misunderstood one of the client's requirements.

Is this an example of a
defect, infection, or a failure?

... IT DEPENDS

Join us again for ...

Spot the *DIF*ference!



```

public static Set<Character> duplicateLetters(String s) {
    // lower case the string and remove all characters that are not letters
    s = s.toLowerCase().replaceAll("[^a-z.]", "");

    // initialise the result set
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    // iterate through the string
    for (int i = 0; i < s.length(); i++) {
        char si = s.charAt(i);

        // iterate through the rest of the string, checking for the same letter
        for (int j = i; j < s.length(); j++) {
            char sj = s.charAt(j);

            if (si == sj) {
                // a match has been found, add it to the result set
                duplicates.add(si);
            }
        }
    }

    return duplicates;
}

```

Defects are not always reached (executed)

Consider what happens if the inputs string **s** is empty.

A good test suite needs to exercise as much of the software as possible.

We will come back to this in later in the module.

Defects may not always cause infections

Consider a defect where the loop test is reversed (i.e. “>” is used instead of “<”)

For empty strings, the defect would be executed, but no variables take on the wrong values and the loop body is *not* executed – as normal.

So for this specific input, there is no infection.

```
public static Set<Character> duplicateLetters(String s) {
    // lower case the string and remove all characters that are not letters
    s = s.toLowerCase().replaceAll("[^a-z.]", "");

    // initialise the result set
    Set<Character> duplicates = new TreeSet<>();

    // iterate through the string
    for (int i = 0; i > s.length(); i++) {
        char si = s.charAt(i);

        // iterate through the rest of the string, checking for the same letter
        for (int j = i + 1; j < s.length(); j++) {
            char sj = s.charAt(j);

            if (si == sj) {
                // a match has been found, add it to the result set
                duplicates.add(si);
            }
        }
    }

    return duplicates;
}
```

Infections may not always propagate to the output

Consider what happens with the original defect if the inputs string `s="stst"`.

The defect is executed and the characters `"s"` and `"t"` are entered into the `duplicates` set too early, but the overall output is correct.

```
public static Set<Character> duplicateLetters(String s) {
    // lower case the string and remove all characters that are not letters
    s = s.toLowerCase().replaceAll("[^a-z.]", "");

    // initialise the result set
    Set<Character> duplicates = new TreeSet<>();

    // iterate through the string
    for (int i = 0; i < s.length(); i++) {
        char si = s.charAt(i);

        // iterate through the rest of the string, checking for the same letter
        for (int j = i; j < s.length(); j++) {
            char sj = s.charAt(j);

            if (si == sj) {
                // a match has been found, add it to the result set
                duplicates.add(si);
            }
        }
    }

    return duplicates;
}
```


Test cases need to reveal failures

The method fails with both tests, but only one of the tests “revealed” the failure (by causing a test failure).

```
public class StringUtilsTest {  
  
    @Test  
    public void shouldReturnRepeatedChar() {  
        Set<Character> resultSet = duplicateLetters("software testing");  
        assertTrue(resultSet.contains('t'));  
    }  
  
    @Test  
    public void shouldNotReturnNonRepeatedChar() {  
        Set<Character> resultSet = duplicateLetters("software debugging");  
        assertFalse(resultSet.contains('t'));  
    }  
}
```

PASSED

FAILED

How Software Failures are *Detected* by Test Cases. The **RIPR** model

Defect **R**eached



State **I**nfected



Infection **P**ropagated



Failure **R**evealed



[Video]