

# Property-Based Testing

Using jqwik for Java

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# Testing 101

# The Novice Programmer

Everyone likes to reimplement stuff from scratch; in that spirit, let us code our own sum function:

```
public int mySum(int a, int b) {  
    int accumulator = a;  
    while(b > 0) {  
        accumulator++;  
        b--;  
    }  
    return accumulator;  
}
```

How should one proceed to test it? Many will write something like this:

```
@Test  
public int mySumTest() {  
    assertEquals(2, sum(1, 1));  
    assertEquals(4, sum(2, 2));  
    assertEquals(8, sum(4, 4));  
}
```

Everything is awesome! All tests are passing!...

# The Lurking Bug

There's indeed a bug in the implementation. Look at the code very carefully:

```
public int mySum(int a, int b) {  
    int accumulator = a;  
    while(b > 0) {  
        accumulator++;  
        b--;  
    }  
    return accumulator;  
}
```

What happens when you try something like `mySum(2, -3)`?

```
Expected -1; got 2.
```

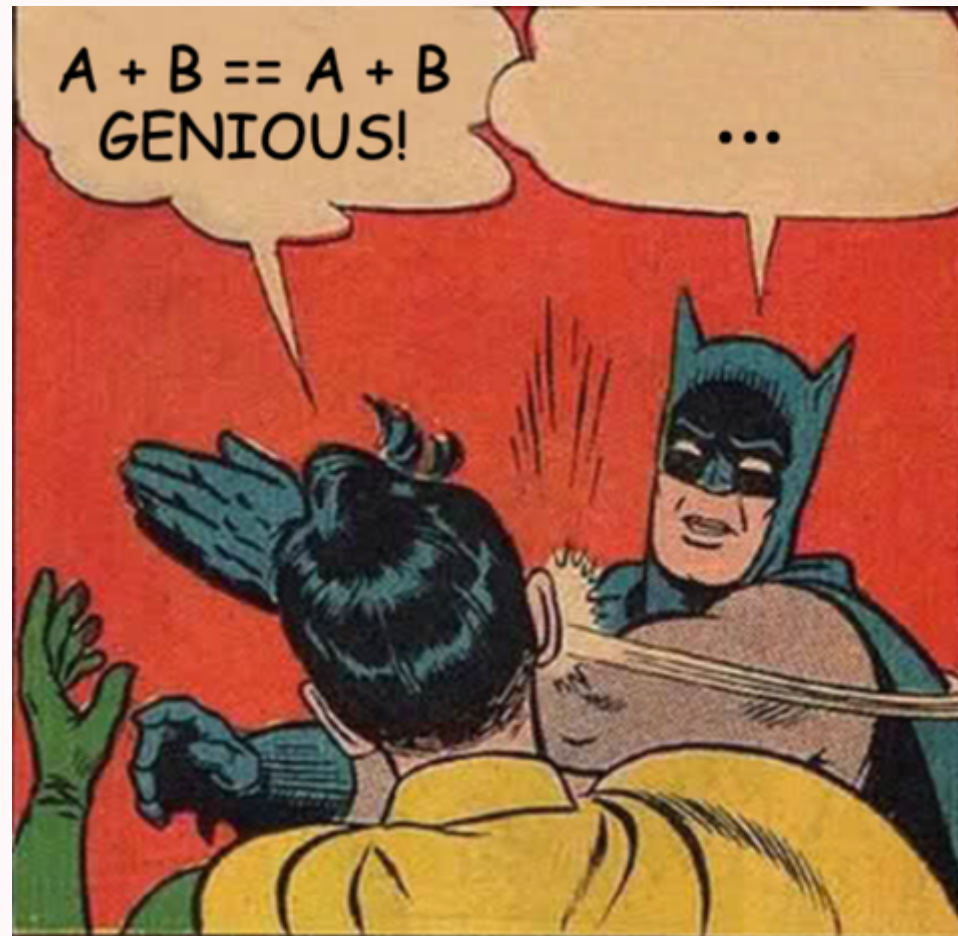
# The Intermediate Programmer

*But that is stupid! Why don't we use the + operator?* — an older student.

```
public int mySum(int a, int b) {  
    return a + b;  
}
```

*... and proceed to test for a range!* — the same older student.

```
@Test  
public int mySumTest() {  
    for (int a = -100; a < 100; a++)  
        for (int b = -100; b < 100; b++)  
            assertEquals(a + b, sum(a, b));  
}
```



# The problem of testing

- ... we test what we know. Because if we knew what we didn't know, we would do it right.
- ... so how can we test what we don't know?



# Property-Based Testing

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- Summing  $a$  with  $b$  and then with  $c$  is the same as:

$$a + (b + c) = (a + b) + c$$

## Challenge

Suppose you don't have access to the  $+$  operator. How can we implement a test that uses the above properties to verify if our sum is working?

# So what is PBT?

- ... usage of Arbitraries;
- ... usage of Statistics to cover the search space and provide confidence;
- ... usage of Properties to specify the external behavior of our system and search for counter-examples;

So nice things:

- ... Reproducibility (via seeds);
- ... Shrinking (smallest cases that reproduce the bug).



**Arbitraries**

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- If you recall discrete mathematics, it's the equivalent of saying:
  - *for a given  $x$ , where  $x$  is a natural number*
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  - Numbers (`Integers`, `Double...`)
  - Booleans
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  - **Mapping built-in** Arbitraries;
  - Creating them from **scratch**.
- There are things that make an Arbitrary more useful than being **merely a random generator**, which is (next slide)...

# Statistics

## ... Statistics

- The **small-scope hypothesis** claims that **most inconsistent models have counterexamples within *small bounds***;
- Think about most bugs you find in code that involves integers:
  - **Zero** tends to be problematic... So does **-1** and **1**...

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  - And **Infinity** and **-Infinity**...
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- Can you think of **ArrayList**'s that usually triggers buggy code?
  - The **empty list**!
- PBT frameworks call this **biased** search, and considers it for you;
- It is up to the Arbitrary to define their **bias**.

**Shrinking**

# Shrinking

Imagine testing if your *hero* can walk out of the *arena*.

If we do a **random search**, we might end up with a counter example that is similar do this:

```
[UP, DOWN, RIGHT, LEFT, LEFT, UP, LEFT, UP, DOWN, DOWN, RIGHT, LEFT, UP, LEFT, UP,  
DOWN, RIGHT, LEFT, RIGHT, UP, LEFT, UP, DOWN, DOWN, LEFT, LEFT, UP, LEFT, UP, DOWN,  
LEFT, LEFT, LEFT, UP, LEFT, UP, DOWN, DOWN, RIGHT, LEFT, UP, LEFT, UP, DOWN, LEFT,  
LEFT, LEFT, UP, LEFT, UP, DOWN, DOWN, LEFT, LEFT, UP, LEFT, UP, DOWN, LEFT, LEFT,  
LEFT, UP, LEFT, UP, DOWN, DOWN, RIGHT, LEFT, UP, LEFT, UP, DOWN, LEFT, LEFT, LEFT,  
UP, LEFT, UP, DOWN, DOWN, RIGHT, LEFT, UP, LEFT, UP, DOWN, LEFT, LEFT, LEFT, UP]
```

Can we do **better** (what is better?)

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Can you think of **strategies** to shrink an `ArrayList`?

**jqwik**

# jqwik

The main purpose of **jqwik** is to bring **Property-Based Testing** (PBT) to the **JVM**.

A **property** is supposed to describe a **generic invariant** or **post-condition** of your code, given some **precondition**.

**jqwik** will then try to **generate** many **value sets** that fulfill the precondition hoping that one of the generated sets can **falsify** a **wrong assumption**.

[jqwik documentation](#)

# Gradle

To use **jqwik**, you just need to add the following to your build.gradle:

```
test {  
    useJUnitPlatform {  
        includeEngines ('junit-jupiter', 'jqwik')  
    }  
}  
  
dependencies {  
    testImplementation 'org.junit.jupiter:junit-jupiter-api:5.6.0'  
    testImplementation 'net.jqwik:jqwik:1.5.1'  
}
```

# Properties

To define a **property**, we just need to add the `@Property` annotation to our test:

```
class TestNumbers {  
    @Property  
    public void testSumAssociativity(@ForAll int a, @ForAll int b, @ForAll int c) {  
        assert((a + b) + c == a + (b + c));  
    }  
}
```

Notice that our test receives **three parameters** (a, b, and c) and that we are saying that the property should **hold for all** possible values using the `@ForAll` annotation.

# Parameter Generation

**jqwik** is capable of generating parameters for a **wide range of types**: Strings, all kinds of numerical types, booleans, characters, Lists, Sets, Streams, Arrays, ...

Here we are testing if reversing any integer list twice results in the same list:

```
@Property
public void testDoubleReverse(@ForAll List<Integer> list) {
    assert(reverseList(reverseList(list)).equals(list));
}

public <T> List<T> reverseList(List<T> list) {
    ArrayList<T> reversed = new ArrayList<>();

    for (T e : list) reversed.add(0, e);

    return reversed;
}
```

# Constraining Parameters

Sometimes we want to constrain the generated parameters. For example, the following test:

```
@Property
public void testDivision(@ForAll int number) {
    assertEquals(1, number / number);
}
```

Does not work if the number is zero, so we can use the `@Positive` annotation to constrain the number:

```
@Property
public void testDivision(@ForAll @Positive int number) {
    assertEquals(1, number / number);
}
```

Maybe this should also work for negative numbers!



# Constraining Parameters

There are several types of constraints that can be applied:

- `@WithNull(value = 0.1)` If we want to generate null values, value is the percentage of null values to generate.
- `@Unique` Prevents repeated values in a list.
- `@StringLength(value = 0, min = 0, max = 0)` A fixed size string or between min and max characters.
- `@Chars(value = {})`, `@CharRange(from = 0, to = 0)`, `@NumericChars`, `@LowerChars`, `@UpperChars`, `@AlphaChars`, `@WhiteSpace` Several ways to constraint character generation.
- `@NotEmpty`, `@Size(value = 0, min = 0, max = 0)` To constraint the size of generated lists.
- `@Positive`, `@Negative`, `@IntRange(min = 0, max)`, `@DoubleRange(min = 0.0, max)`, ... To constraint generated numbers.

# Constraining Parameterized Types

If we want to constrain the generation of **contained parameter types** we can annotate the parameter type **directly**:

```
@Property
public void testListSumPositive(@ForAll @NotEmpty List<@Positive Integer> list) {
    assert(sum(list) > 0);
}

private int sum(List<Integer> list) {
    int sum = 0;
    for (int e : list) sum += e;
    return sum;
}
```

This property does not hold, why?

# Arbitrary

If the **default generators** are **not enough**, we can use the `@Provide` annotation and `Arbitrary` class to create **new generators**:

Fixing the `testDivision` test:

```
@Property
public void testDivision(@ForAll("notZero") int number) {
    assertEquals(1, number / number);
}

@Provide
Arbitrary<Integer> notZero() {
    return Arbitraries.integers().filter(n -> n != 0);
}
```

With arbitraries we can generate `integers()`, `strings()`, ... which we can then restrict using functions like `filter(f)`, `map(f)`, `greaterOrEqual(n)`, `alpha()`, `numeric()`, `ofLength(n)`, ...

# Combining Arbitraries

We can even combine *arbitraries* using the `combine` and `as` methods, sprinkled with some Java lambda magic:

```
@Property void testWithPlates(@ForAll("carPlates") String plate) {  
    // do some testing using plate  
}  
  
@Provide  
Arbitrary<String> carPlates() {  
    return Combinators.combine(  
        Arbitraries.strings().alpha().ofLength(2),  
        Arbitraries.strings().numeric().ofLength(2),  
        Arbitraries.strings().numeric().ofLength(2)  
    ).as((s1, s2, s3) -> s1.toUpperCase() + "-" + s2 + "-" + s3);  
}
```

## Another Arbitrary Example

A prime number cannot be divided by any(?) other number:

```
@Provide
Arbitrary<Integer> primeNumbers() {
    return Arbitraries.integers().greaterOrEqual(2).filter(n -> isPrime(n));
}

private boolean isPrime(Integer n) {
    for(int i=2;i<=Math.sqrt(n);i++)
        if(n%i==0) return false;
    return true;
}

@Property void testWithPrimes(
    @ForAll @IntRange(min = 2) int number,
    @ForAll("primeNumbers") int prime) {
    assert(prime == number || prime % number != 0);
}
```

# Output

The result of a test in jqwik looks something like these:

```
tries = 1000          | -----jqwik-----  
checks = 1000         | # of calls to property  
generation-mode = RANDOMIZED | parameters are randomly generated  
after-failure = PREVIOUS_SEED | use the previous seed  
seed = 529692752344469023 | random seed to reproduce generated values
```

In this report we can see the number of test runs for this property (**tries**), number of calls that were not rejected (**checks**), how values were generated (**generation-mode**), if we should keep using the same seed if a property check fails (**after-failure**), and which seed was used (**seed**).

# Configuring Runs

We can change some configuration parameters for each test:

```
@Property(tries = 2000,  
          seed="259083988309207343",  
          afterFailure = AfterFailureMode.RANDOM_SEED)  
public void testDoubleReverse(@ForAll List<Integer> list) {  
    assert(reverseList(reverseList(list)).equals(list));  
}
```

# Shrinking

One advantage of using arbitraries instead of just using random data generators, is that arbitraries know how to **shrink**:

```
@Property
public void testDifferenceAssociativity(
    @ForAll int a,
    @ForAll int b,
    @ForAll int c) {
    assert((a - b) - c == a - (b - c));
}
```

tries = 1	-----jqwik-----
checks = 1	# of calls to property
generation-mode = RANDOMIZED	# of not rejected calls
after-failure = PREVIOUS_SEED	parameters are randomly generated
seed = -1077203421743176744	use the previous seed
sample = [0, 0, -1]	random seed to reproduce generated values
original-sample = [-304, -133, -84]	

This allows us to find smaller examples that are easier to understand.



# An Hero example...

Testing if the arena bounds are correctly checked:

```
@Property
public void testArenaBounds(@ForAll @IntRange(min = 1, max = 100) int width,
                             @ForAll @IntRange(min = 1, max = 100) int height,
                             @ForAll int x,
                             @ForAll int y) {
    Arena arena = new Arena(width, height, null);

    assert(x >= 0 || !arena.isInBounds(new Position(x, y)));
    assert(y >= 0 || !arena.isInBounds(new Position(x, y)));
    assert(x < arena.getWidth() || !arena.isInBounds(new Position(x, y)));
    assert(y < arena.getHeight() || !arena.isInBounds(new Position(x, y)));
}
```

# ...or two!

Testing if the hero never leaves the arena:

```
@Property
void allArenasAreClosed(
    @ForAll @IntRange(min = 3, max = 50) int width,
    @ForAll @IntRange(min = 3, max = 50) int height,
    @ForAll List<GUI.@From("moveActions") ACTION> actions) {

    RandomArenaBuilder rab = new RandomArenaBuilder(width, height, 0);
    Arena arena = rab.createArena();
    HeroController controller = new HeroController(arena);

    for (GUI.ACTION action : actions) {
        controller.step(null, action, 100);
        assert (controller.getModel().getHero().getPosition().getX() > 0);
        assert (controller.getModel().getHero().getPosition().getY() > 0);
        assert (controller.getModel().getHero().getPosition().getX() < width - 1);
        assert (controller.getModel().getHero().getPosition().getY() < height - 1);
    }
}
```

# Custom Arbitrary

In this second example, we created a custom arbitrary that return only movement actions:

```
@Provide
Arbitrary<GUI.ACTION> moveActions() {
  return Arbitraries.of(
    GUI.ACTION.UP,
    GUI.ACTION.RIGHT,
    GUI.ACTION.DOWN,
    GUI.ACTION.LEFT);
}
```