Property-Based Testing

Using jqwik for Java

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Testing 101 Property Based Testing jqwik

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) {
    a++;
    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) {
    a++;
    b--;
  }
  return accumulator;
}
```

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

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

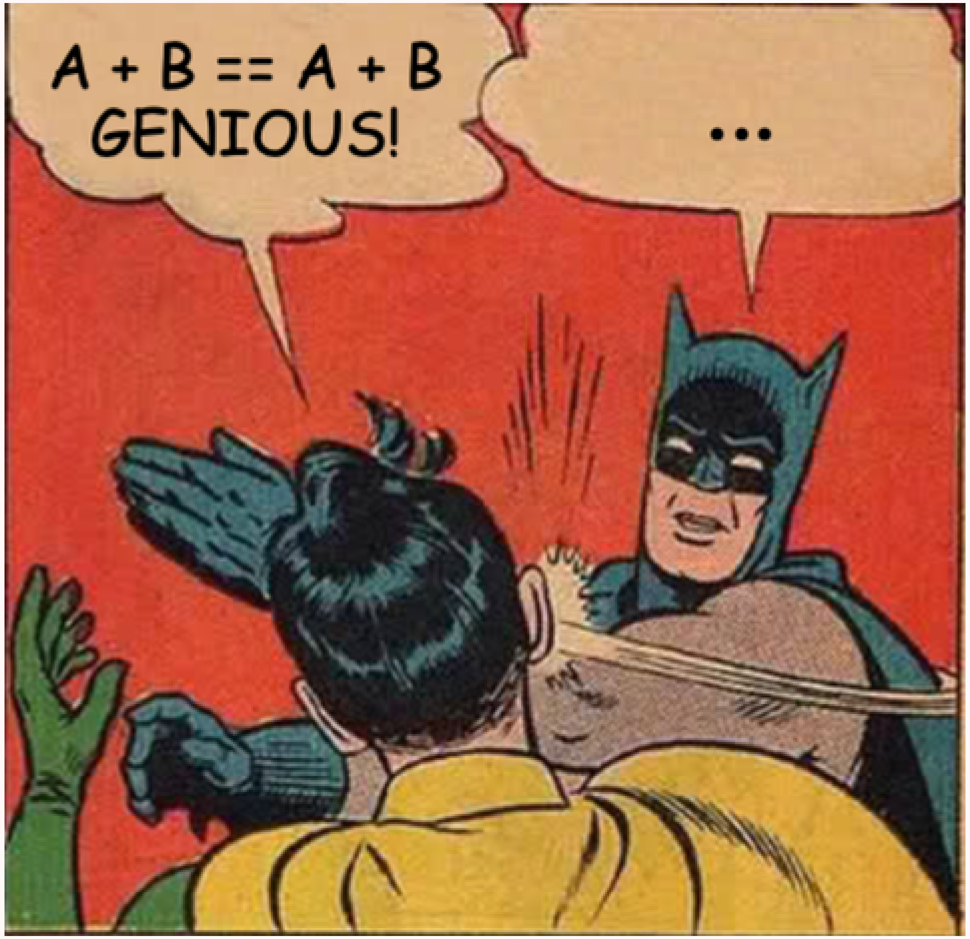
The Intermediate Programmer

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 = 0; a < 1000; a++)
    for (int b = 0; b < 1000; b++)
      assertEquals(a + b, sum(a, b));
}
```


A + B == A + B
GENIOUS!
...

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 is the same as summing a-1 with b+1:
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  $a + b = b + a$
- Summing a with b is the same as summing a−1 with b+1:
  $a + b = (a-1) + (b+1)$
- 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 paths and seeds);
- ... Shrinking (smallest cases that reproduce the bug).

Arbitraries

- An **Arbitrary** is a **random generator** of a particular class (or primitive);
- 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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  - Booleans
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- You can also define your own Arbitraries, either by:
  - **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

- 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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- 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

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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- It's easier if you think about numbers. Imagine that a bug triggers with **negative numbers**; as soon as the computer finds that -5234153245 leads to an error, it can **try to shrink it**.

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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 {
    testCompile group: 'org.junit.jupiter', name: 'junit-jupiter', version: '5.6.2'
    testCompile group: 'net.jqwik', name: 'jqwik', version: '1.2.7'
}
```

Notice that we need to use JUnit5 instead of JUnit4.

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:

```java
@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:

```java
@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:

```
                              |-------------------jqwik-------------------
tries = 1000                  | # of calls to property
checks = 1000                 | # of not rejected calls
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="2590839883092073 43",
          afterFailure = AfterFailureMode.RANDOM_SEED)
public void testDoubleReverse(@ForAll List<Integer> list) {
  assert(reverseList(reverseList(list)).equals(list));
}
```

Shrinking

The 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));
}
```

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

```java
@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
public void testMovingBounds(@ForAll List<ArenaView.ACTION> actions)
    throws IOException {

  Hero hero = new Hero(new Position(2, 2));
  Arena arena = new Arena(5, 5, hero);
  ArenaViewMock view = new ArenaViewMock(actions);
  GameController controller = new GameController(arena, view);

  while (view.hasMoreActions()) {
    controller.step();

    assert (hero.getPosition().getX() >= 0);
    assert (hero.getPosition().getY() >= 0);

    assert (hero.getPosition().getX() < arena.getWidth());
    assert (hero.getPosition().getY() < arena.getHeight());
  }
}
```

Mocking for PBT

In this second example we had to create a specialized **mock** for the ArenaView class:

```java
public class ArenaViewMock extends ArenaView {
  private List<ACTION> actions;

  public ArenaViewMock(List<ACTION> actions)
      throws IOException {
    super(null, null);
    this.actions = actions;
  }

  @Override
  public ACTION getAction() throws IOException {
    ACTION action = actions.get(0);
    actions.remove(0);
    return action;
  }

  @Override
  public void draw() throws IOException { // Do nothing }

  public boolean hasMoreActions() { return actions.size() > 0; }
}
```