Property-Driven Development

XP Days Germany
7. November 2019

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johanneslink.net

Property-Based Testing
+
Test-Driven Development

Beispiel-basierte Tests

Ein *Beispiel* zeigt, dass unser Code
bei ganz konkreten Eingaben
ein ganz konkretes Ergebnis liefert.

```
@Test
void reverseList() {
   List<Integer> aList = Arrays.asList(1, 2, 3);
   Collections.reverse(aList);
   assertThat(aList).containsExactly(3, 2, 1);
}
```

Properties

Eine *Property* zeigt, dass unser Code
für eine Klasse von Eingaben (Vorbedingung)
bestimmte allgemeine Eigenschaften (Invarianten)
erfüllt.

```
Collections.reverse(List aList):

   // Vorbedingungen?
   // Nachbedingungen und Invarianten?
```

```
Collections.reverse(List aList):

   // Vorbedingungen?
   // Nachbedingungen und Invarianten?
```

Vorbedinungen

- Beliebige Liste - aber nicht null

Invarianten

- Länge der Liste bleibt gleich
- Alle Elemente bleiben erhalten
- Nach reverse ist das erste Elemente das letzte
- 2 x reverse erzeugt wieder das Original

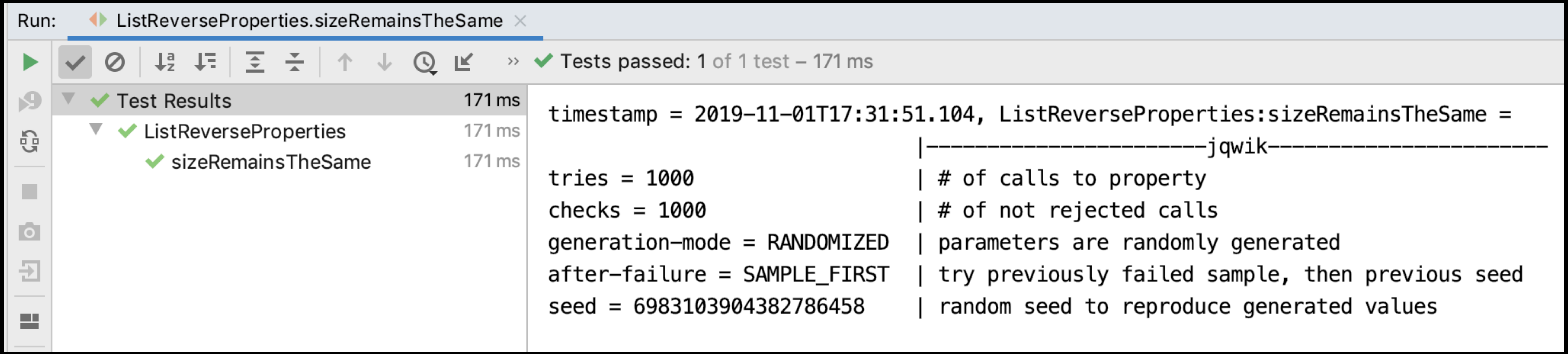
Eine Property als Java Code

```java
boolean theSizeRemainsTheSame(List<Integer> original) {
   List<Integer> reversed = reverse(original);
   return original.size() == reversed.size();
}


private <T> List<T> reverse(List<T> original) {
   List<T> clone = new ArrayList<>(original);
   Collections.reverse(clone);
   return clone;
}
```

Jqwik

```java
@Property
boolean theSizeRemainsTheSame(@ForAll List<Integer> original) {
   List<Integer> reversed = reverse(original);
   return original.size() == reversed.size();
}
```



Run: ListReverseProperties.sizeRemainsTheSame

✓ Tests passed: 1 of 1 test – 171 ms

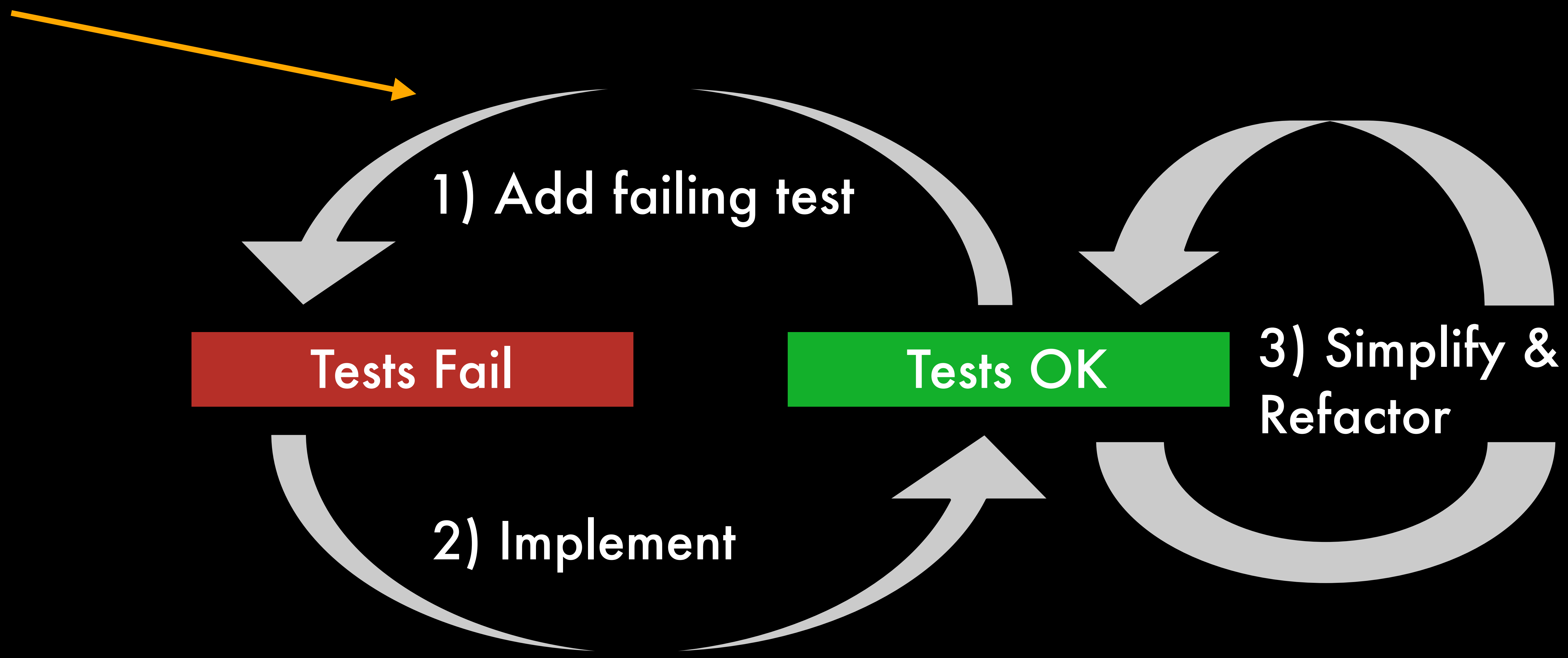
✓ Test Results	171 ms
✓ ListReverseProperties	171 ms
✓ sizeRemainsTheSame	171 ms

```
timestamp = 2019-11-01T17:31:51.104, ListReverseProperties:sizeRemainsTheSame =
                                  |----------------------jqwik----------------------
tries = 1000                      | # of calls to property
checks = 1000                     | # of not rejected calls
generation-mode = RANDOMIZED      | parameters are randomly generated
after-failure = SAMPLE_FIRST      | try previously failed sample, then previous seed
seed = 6983103904382786458        | random seed to reproduce generated values
```

Test-Driven Development

Inbox

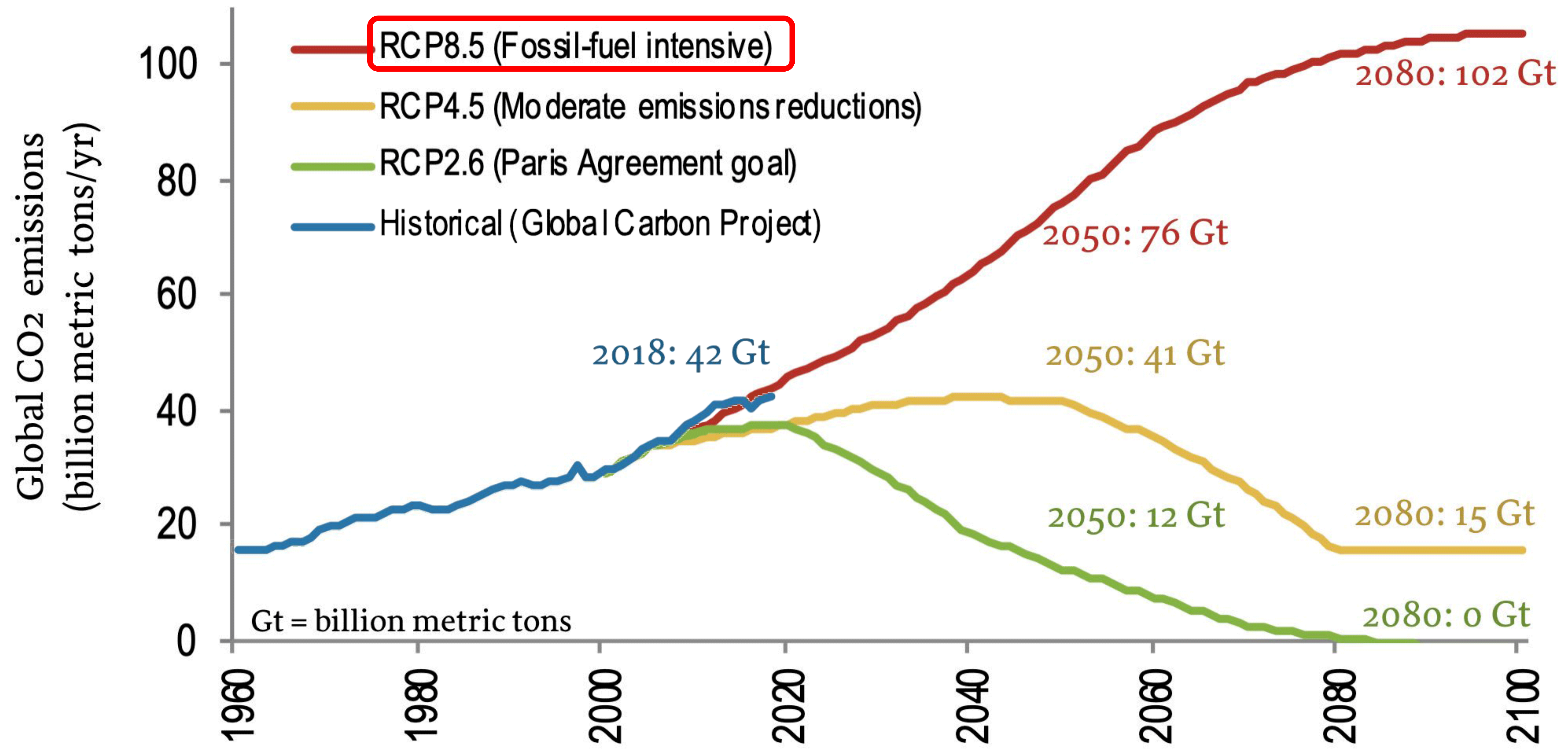
- Testidee 1
- Testidee 2
- Testidee 3
- ...



Property-Driven Development

by Example

CO_2 Emissionen



(R. Kopp, Rutgers Climate Institute; aktualisiert von R. Kopp nach Kopp et al. 2014)

Quellen und weitere Details: www.ClimateFactsNow.org

Kata: CO_2-Budget

- Wie lange können wir noch CO_2 in die Luft blasen, um mit einer Wahrscheinlichkeit von 66% unter 2 Grad Erderwärmung zu bleiben?
- Stand 2018:
  - Restbudget 420 Gt CO_2
  - Jährlicher Ausstoß ca. 42 Gt

Specification

```
int remainingYears(
    int initialBudget,
    int startingAnnualEmission,
    int annualChange
)
```

- Preconditions: **`initialBudget`** and **`startingAnnualEmission`** must be >= 0
- **`annualChange`** is applied every year on the previous year's annual starting in the 2nd year
- The year in which the budget is eventually used up still counts as one year
- If the budget starts with 0 the remaining years are also 0
- If the budget is never used up return Integer.MAX_VALUE

Inbox

```
remainingYears(0, 42, 4) -> 0
remainingYears(100, 10, 0) -> 10
remainingYears(105, 10, 0) -> 11
remainingYears(100, 20, -2) -> 8
remainingYears(100, 20, +2) -> 5
remainingYears(100, 20, -10) -> Integer.MAX_VALUE
remainingYears(170, 42, -4) -> 5
remainingYears(170, 42, -8) -> Integer.MAX_VALUE
```

Inbox

```
remainingYears(0, 42, 4) -> 0
remainingYears(100, 10, 0) -> 10
remainingYears(105, 10, 0) -> 11
remainingYears(100, 20, -2) -> 8
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```

Inbox

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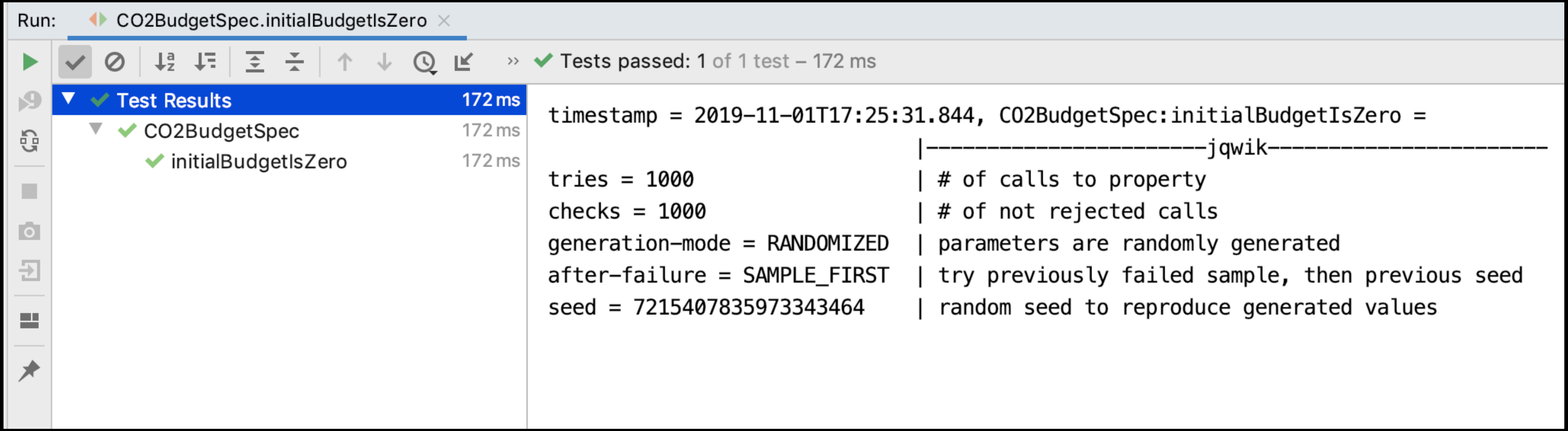
remainingYears(170, 42, -4) -> 5
remainingYears(170, 42, -8) -> Integer.MAX_VALUE
```

```java
class CO2BudgetSpec {
    @Example
    void initialBudgetIsZero() {
        assertEquals(0, CO2Budget.remainingYears(0, 42, 4));
    }
}
```

```java
public class CO2Budget {
    static int remainingYears(int initialBudget, int startingAnnualEmission, int annualChange) {
        return 0;
    }
}
```

```java
class CO2BudgetSpec {
    @Property
    void initialBudgetIsZero(
        @ForAll @IntRange(min = 0) int startingAnnual,
        @ForAll int annualChange
    ) {
        assertEquals(0, CO2Budget.remainingYears(0, startingAnnual, annualChange));
    }
}
```


Run:
CO2BudgetSpec.initialBudgetIsZero
Tests passed: 1 of 1 test – 172 ms
Test Results 172 ms
CO2BudgetSpec 172 ms
initialBudgetIsZero 172 ms

```
timestamp = 2019-11-01T17:25:31.844, CO2BudgetSpec:initialBudgetIsZero =
                                    |-----------------------jqwik-----------------------
tries = 1000                        | # of calls to property
checks = 1000                       | # of not rejected calls
generation-mode = RANDOMIZED        | parameters are randomly generated
after-failure = SAMPLE_FIRST        | try previously failed sample, then previous seed
seed = 7215407835973343464          | random seed to reproduce generated values
```

Behalten wir das Beispiel?

```java
@Example
void initialBudgetIsZero() {
    assertEquals(0, CO2Budget.remainingYears(0, 42, 4));
}
```

```java
@Property
void initialBudgetIsZero(
    @ForAll @IntRange(min = 0) int startingAnnual,
    @ForAll int annualChange
) {
    assertEquals(0, CO2Budget.remainingYears(0, startingAnnual, annualChange));
}
```

Inbox

```
✓ remainingYears(0, 42, 4) -> 0
▸ remainingYears(100, 10, 0) -> 10
  remainingYears(105, 10, 0) -> 11
  remainingYears(100, 20, -2) -> 8
  remainingYears(100, 20, +2) -> 5
  remainingYears(100, 20, -10) -> Integer.MAX_VALUE
  remainingYears(170, 42, -4) -> 5
  remainingYears(170, 42, -8) -> Integer.MAX_VALUE
```

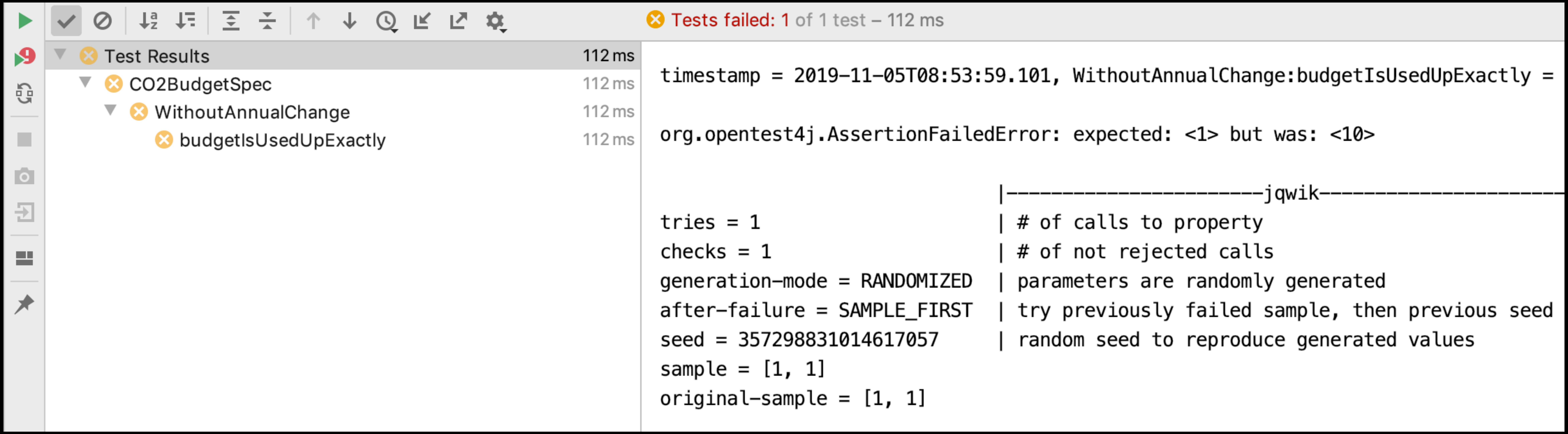
```java
class CO2BudgetSpec…
    @Group
    class WithoutAnnualChange {
        @Example
        void budgetIsUsedUpExactly() {
            assertEquals(10, CO2Budget.remainingYears(100, 10, 0));
        }
    }
```

```java
static int remainingYears(int initialBudget, int startingAnnualEmission, int annualChange) {
    if (initialBudget == 0) {
        return 0;
    }
    return 10;
}
```

```java
@Example
void budgetIsUsedUpExactly() {
    assertEquals(10, CO2Budget.remainingYears(100, 10, 0));
}
```

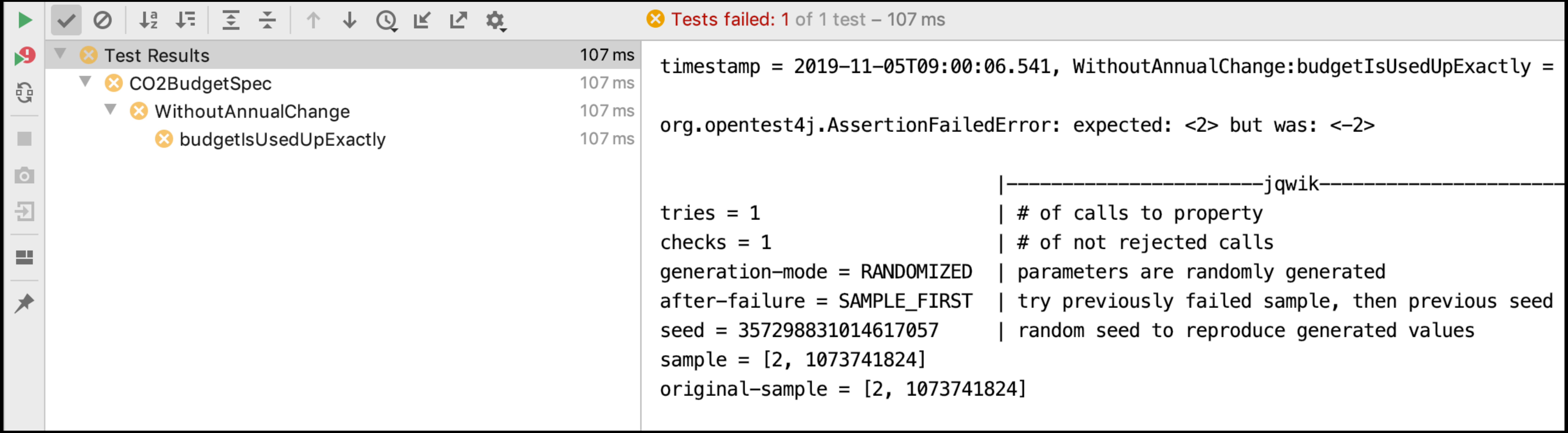
```java
@Property
void budgetIsUsedUpExactly(
        @ForAll @IntRange(min = 1) int initialBudget,
        @ForAll @IntRange(min = 1) int startingAnnual
) {
    assertEquals(????, CO2Budget.remainingYears(initialBudget, startingAnnual, 0));
}
```

```java
@Property
void budgetIsUsedUpExactly(
        @ForAll @IntRange(min = 1) int remainingYears,
        @ForAll @IntRange(min = 1) int startingAnnual
) {
    int initialBudget = startingAnnual * remainingYears;
    assertEquals(remainingYears, CO2Budget.remainingYears(initialBudget, startingAnnual, 0));
}
```


Tests failed: 1 of 1 test – 112 ms
Test Results 112 ms
CO2BudgetSpec 112 ms
WithoutAnnualChange 112 ms
budgetIsUsedUpExactly 112 ms

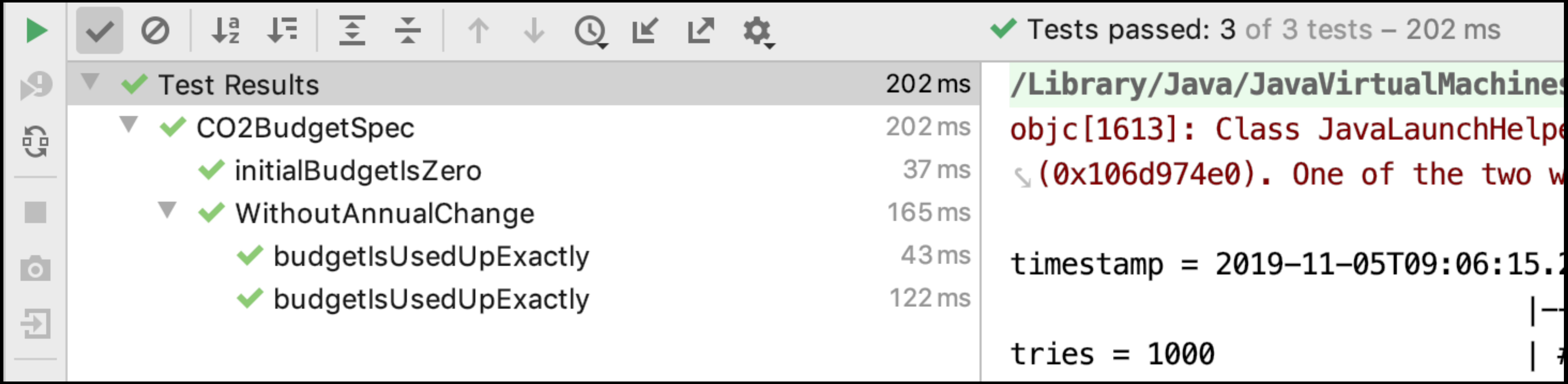
```
timestamp = 2019-11-05T08:53:59.101, WithoutAnnualChange:budgetIsUsedUpExactly =

org.opentest4j.AssertionFailedError: expected: <1> but was: <10>

                                |-----------------------jqwik-----------------------
tries = 1                       | # of calls to property
checks = 1                      | # of not rejected calls
generation-mode = RANDOMIZED    | parameters are randomly generated
after-failure = SAMPLE_FIRST    | try previously failed sample, then previous seed
seed = 357298831014617057       | random seed to reproduce generated values
sample = [1, 1]
original-sample = [1, 1]
```

```java
static int remainingYears(int initialBudget, int startingAnnualEmission, int annualChange) {
    if (initialBudget == 0) {
        return 0;
    }
    return initialBudget / startingAnnualEmission;
}
```


Tests failed: 1 of 1 test – 107 ms
Test Results 107 ms
CO2BudgetSpec 107 ms
WithoutAnnualChange 107 ms
budgetIsUsedUpExactly 107 ms

```
timestamp = 2019-11-05T09:00:06.541, WithoutAnnualChange:budgetIsUsedUpExactly =

org.opentest4j.AssertionFailedError: expected: <2> but was: <-2>

                              |-----------------------jqwik-----------------------
tries = 1                     | # of calls to property
checks = 1                    | # of not rejected calls
generation-mode = RANDOMIZED  | parameters are randomly generated
after-failure = SAMPLE_FIRST  | try previously failed sample, then previous seed
seed = 3572988310146170571    | random seed to reproduce generated values
sample = [2, 1073741824]
original-sample = [2, 1073741824]
```

```java
@Property
void budgetIsUsedUpExactly(
        @ForAll @IntRange(min = 1, max = 1000) int remainingYears,
        @ForAll @IntRange(min = 1, max = Integer.MAX_VALUE / 1000) int startingAnnual
) {
    int initialBudget = startingAnnual * remainingYears;
    assertEquals(remainingYears, CO2Budget.remainingYears(initialBudget, startingAnnual, 0));
}
```



Tests passed: 3 of 3 tests – 202 ms

```
Test Results                          202 ms
  CO2BudgetSpec                       202 ms
    initialBudgetIsZero                37 ms
    WithoutAnnualChange               165 ms
      budgetIsUsedUpExactly            43 ms
      budgetIsUsedUpExactly           122 ms
```

```
/Library/Java/JavaVirtualMachines
objc[1613]: Class JavaLaunchHelpe
(0x106d974e0). One of the two w

timestamp = 2019-11-05T09:06:15.
                                   |--
tries = 1000                       | #
```

Inbox

```
✓ remainingYears(0, 42, 4) -> 0
✓ remainingYears(100, 10, 0) -> 10
▸ remainingYears(105, 10, 0) -> 11
  remainingYears(100, 20, -2) -> 8
  remainingYears(100, 20, +2) -> 5
  remainingYears(100, 20, -10) -> Integer.MAX_VALUE
  remainingYears(170, 42, -4) -> 5
  remainingYears(170, 42, -8) -> Integer.MAX_VALUE
```

```java
@Property
void budgetIsUsedUpWithRemainder(
        @ForAll @IntRange(min = 1, max = 1000) int remainingYears,
        @ForAll @IntRange(min = 5, max = Integer.MAX_VALUE / 1000) int startingAnnual,
        @ForAll @IntRange(min = 1, max = 4) int remainder
) {
    int initialBudget = startingAnnual * remainingYears - remainder;
    assertEquals(remainingYears, CO2Budget.remainingYears(initialBudget, startingAnnual, 0));
}
```

```java
static int remainingYears(int initialBudget, int startingAnnualEmission, int annualChange) {
    if (initialBudget == 0) {
        return 0;
    }
    return -Math.floorDiv(-initialBudget, startingAnnualEmission);
}
```

```java
@Property
void budgetIsUsedUp(
        @ForAll @IntRange(min = 1, max = 1000) int remainingYears,
        @ForAll @IntRange(min = 5, max = Integer.MAX_VALUE / 1000) int startingAnnual,
        @ForAll @IntRange(min = 0, max = 4) int remainder
) {

    int initialBudget = startingAnnual * remainingYears - remainder;
    assertEquals(remainingYears, CO2Budget.remainingYears(initialBudget, startingAnnual, 0));
}
```

```
[WithoutAnnualChange:budgetIsUsedUp] (1000) remainder is 0 =
    false (812) : 81 %
    true  (188) : 19 %
```

Inbox

- ✓ `remainingYears(0, 42, 4) -> 0`
- ✓ `remainingYears(100, 10, 0) -> 10`
- ✓ `remainingYears(105, 10, 0) -> 11`
- `remainingYears(100, 20, -2) -> 8`
- ▶ `remainingYears(100, 20, +5) -> 4`
- `remainingYears(100, 20, -10) -> Integer.MAX_VALUE`
- `remainingYears(170, 42, -4) -> 5`
- `remainingYears(170, 42, -8) -> Integer.MAX_VALUE`

```
@Group
class WithAnnualChange {
    @Example
    void budgetIsUsedUpWithIncrease() {
        assertEquals(4, CO2Budget.remainingYears(100, 20, +5));
    }
}
```

```
org.opentest4j.AssertionFailedError:
    Expected :4
    Actual   :5
```

```
static int remainingYears(int initialBudget, int startingAnnualEmission, int annualChange) {
    …
    int remaining = -Math.floorDiv(-initialBudget, startingAnnualEmission);
    if (annualChange == 5) {
        remaining -= 1;
    }
    return remaining;
}
```

The Big Refactoring: Replace Algorithm

```java
static int remainingYears(int initialBudget, int startingAnnualEmission, int annualChange) {
    if (initialBudget == 0) {
        return 0;
    }
    int remaining = -Math.floorDiv(-initialBudget, startingAnnualEmission);
    if (annualChange == 5) {
        remaining -= 1;
    }
    return remaining;
}
```

```java
    int remaining = 0;
    int budget = initialBudget;
    while(budget > 0) {
        budget -= startingAnnualEmission;
        remaining++;
    }
```

```java
@Property
void budgetIsUsedUpWithIncrease(
        @ForAll @IntRange(min = 1, max = 1000) int remainingYears,
        @ForAll @IntRange(min = 0, max = Integer.MAX_VALUE/1000) int startingAnnual,
        @ForAll @IntRange(min = 0) int annualIncrease
) {
    int initialBudget = ???; // irgendwas mit der Mitternachtsformel
    assertEquals(
        remainingYears,
        CO2Budget.remainingYears(initialBudget, startingAnnual, annualIncrease)
    );
}
```

Zu kompliziert und nicht intuitiv!

Muster- und Strategien für gute Properties

- Validity Testing
- Postconditions
- Metamorphic Properties
- Inductive Testing
- Model-based Testing

https://johanneslink.net/how-to-specify-it/

Metamorphic Properties

The basic idea is this: even if the expected result of a function call such as tree.insert(key, value) may be difficult to predict, we may still be able to express an expected relationship between this result, and the result of a related call.

For example, if we insert an additional key into tree before calling insert(key, value), we might expect the additional key to be inserted into the result also.

John Hughes in "How to Specify it!"

https://www.dropbox.com/s/tx2b84kae4bw1p4/paper.pdf

Metamorphic Properties von `remainingYear()`

- Wenn wir `annualChange` **vergrößern**, dann **nehmen** die verbleibenden Jahre **ab oder bleiben gleich**
- Wenn wir `annualChange` **so groß wie** `startingAnnual` **machen**, dann nehmen die verbleibenden Jahre um mindestens 1 ab; das Minimum bleibt aber 1

```java
@Property
boolean increasingAnnualChangeCanOnlyDecreaseRemainingYears(
        @ForAll("increasingCo2Emission") Tuple3<Integer, Integer, Integer> params,
        @ForAll @IntRange(min = 1, max = 50) int increase
) {
    int initialBudget = params.get1();
    int startingAnnual = params.get2();
    int annualChange = params.get3();

    int remaining =
        CO2Budget.remainingYears(initialBudget, startingAnnual, annualChange);
    int remainingWithIncreasedAnnualChange =
        CO2Budget.remainingYears(initialBudget, startingAnnual, annualChange + increase);

    return remaining >= remainingWithIncreasedAnnualChange;
}
```

Generiere Werte mit Abhängigkeiten

- initialBudget zwischen 1 und 1000000
- startingAnnual zwischen 1 und 2 x initialBudget
- annualChange zwischen 0 und +startingAnnual

```
@Provide
Arbitrary<Tuple3<Integer, Integer, Integer>> increasingCo2Emission() {
    Arbitrary<Integer> initialBudget = Arbitraries.integers().between(1, 1000000);
    return initialBudget.flatMap(budget -> {
        Arbitrary<Integer> startingAnnual = Arbitraries.integers().between(1, budget * 2);
        return startingAnnual.flatMap(starting -> {
            Arbitrary<Integer> annualChange = Arbitraries.integers().between(1, starting);
            return annualChange.map(change -> Tuple.of(budget, starting, change));
        });
    });
}
```

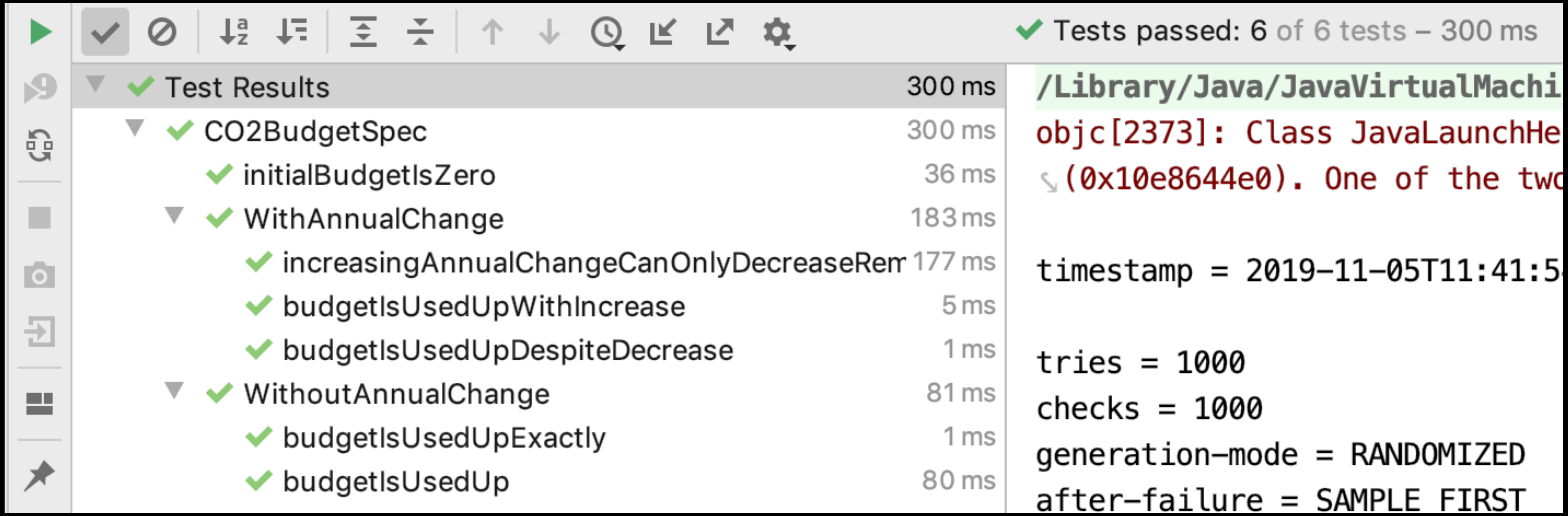
```
WithAnnualChange:increasingAnnualChangeCanOnlyDecreaseRemainingYears =
 org.opentest4j.AssertionFailedError:
  Property [WithAnnualChange:increasingAnnualChangeCanOnlyDecreaseRemainingYears]
  falsified with sample [(251,9,5), 1]

                              |-------------------jqwik-------------------
tries = 84                    | # of calls to property
checks = 84                   | # of not rejected calls
seed = -5778725557855097949   | random seed to reproduce generated values
sample = [(251,9,5), 1]
```

```java
static int remainingYears(int initialBudget, int startingAnnualEmission, int annualChange) {
    int remaining = 0;
    int budget = initialBudget;
    int annualEmission = startingAnnualEmission;
    while(budget > 0) {
        budget -= annualEmission;
        remaining++;
        annualEmission += annualChange;
    }
    return remaining;
}
```

Inbox

- ✓ `remainingYears(0, 42, 4) -> 0`
- ✓ `remainingYears(100, 10, 0) -> 10`
- ✓ `remainingYears(105, 10, 0) -> 11`
- ▸ `remainingYears(100, 20, -2) -> 8`
- ✓ `remainingYears(100, 20, +2) -> 5`
- `remainingYears(100, 20, -10) -> Integer.MAX_VALUE`
- ▸ `remainingYears(170, 42, -4) -> 5`
- `remainingYears(170, 42, -8) -> Integer.MAX_VALUE`

```java
@Group
class WithAnnualChange {
    @Example
    void budgetIsUsedUpDespiteDecrease() {
        assertEquals(8, CO2Budget.remainingYears(100, 20, -2));
        assertEquals(5, CO2Budget.remainingYears(170, 42, -4));
    }
}
```



```
Tests passed: 6 of 6 tests – 300 ms

Test Results                                      300 ms
  CO2BudgetSpec                                   300 ms
    initialBudgetIsZero                            36 ms
    WithAnnualChange                              183 ms
      increasingAnnualChangeCanOnlyDecreaseRem    177 ms
      budgetIsUsedUpWithIncrease                    5 ms
      budgetIsUsedUpDespiteDecrease                 1 ms
    WithoutAnnualChange                            81 ms
      budgetIsUsedUpExactly                         1 ms
      budgetIsUsedUp                               80 ms
```

```
/Library/Java/JavaVirtualMachi
objc[2373]: Class JavaLaunchHe
(0x10e8644e0). One of the two

timestamp = 2019-11-05T11:41:5

tries = 1000
checks = 1000
generation-mode = RANDOMIZED
after-failure = SAMPLE_FIRST
```

Inbox

- ✓ remainingYears(0, 42, 4) -> 0
- ✓ remainingYears(100, 10, 0) -> 10
- ✓ remainingYears(105, 10, 0) -> 11
- ✓ remainingYears(100, 20, -2) -> 8
- ✓ remainingYears(100, 20, +2) -> 5
- ▸ remainingYears(100, 20, -10) -> Integer.MAX_VALUE
- ✓ remainingYears(170, 42, -4) -> 5
- ▸ remainingYears(170, 42, -8) -> Integer.MAX_VALUE

```java
@Example
void budgetIsNotUsedUpDueToDecrease() {
    assertEquals(
            Integer.MAX_VALUE,
            CO2Budget.remainingYears(100, 20, -10)
            );
    assertEquals(
            Integer.MAX_VALUE,
            CO2Budget.remainingYears(170, 42, -8)
    );
}
```

```java
static int remainingYears(int initialBudget, int startingAnnualEmission, int annualChange) {
    …
    while(budget > 0) {
        if (annualEmission <= 0) {
            return Integer.MAX_VALUE;
        }
        budget -= annualEmission;
        …
    }
    return remaining;
}
```

Ideen für Properties

- Wenn CO2-Budget nicht ausläuft, dann ändert auch eine Verringerung von `annualStartingEmission` nichts daran
- Wenn `initialBudget` > 0,
  `annualStartingEmission` = 0 und `annualChange` <= 0,
  dann läuft das CO2-Budget nie aus
- Wenn `initialBudget` > 0,
  `annualStartingEmission` < `initialBudget` und
  `annualChange` <= `annualStartingEmission`,
  dann läuft das CO2-Budget nie aus

Inbox

- ✓ `remainingYears(0, 42, 4) -> 0`
- ✓ `remainingYears(100, 10, 0) -> 10`
- ✓ `remainingYears(105, 10, 0) -> 11`
- ✓ `remainingYears(100, 20, -2) -> 8`
- ✓ `remainingYears(100, 20, +2) -> 5`
- ✓ `remainingYears(100, 20, -10) -> Integer.MAX_VALUE`
- ✓ `remainingYears(170, 42, -4) -> 5`
- ✓ `remainingYears(170, 42, -8) -> Integer.MAX_VALUE`

Tipps für Property-Driven Development

- Starte mit einem Beispiel…

  … dann verallgemeinere das Beispiel zu einer Property
- Properties dürfen "schwächer" sein als eine vollständige fachliche Spezifikation
- Verwende die bekannten Muster für gute Properties
- Erstelle zusätzliche Properties, um die Implementierung auf Stabilität und "unknown Unknowns" zu testen
- Sammle Properties schon beim Erstellen der Inbox

Slides:

http://johanneslink.net/downloads/PropertyDrivenDevelopment.pdf

Blog Series:

http://blog.johanneslink.net/2018/03/24/property-based-testing-in-java-introduction/

Feedback

XP DAYS GERMANY