Property-based testing Rebel semantics in the generated code

Alex L.E. Kok
alex.kok@student.uva.nl

October 16, 2017, 78 pages

Research supervisor: Jurgen J. Vinju
Host supervisor: Jorryt-Jan Dijkstra
Host organisation: ING, http://www.ing.nl

Universiteit van Amsterdam
Faculteit der Natuurwetenschappen, Wiskunde en Informatica
Master Software Engineering
http://www.software-engineering-amsterdam.nl

Contents

Abstract

Rebel is a domain specific language focused on the financial industry. Banking products can be specified in *Rebel*. The tool chain for *Rebel* can be used to check, simulate and visualize *Rebel* specifications to reason about the specified banking product. The tool chain for *Rebel* also provides some generators. These generators can generate a system based on *Rebel* specifications. These generated systems provide an *API* to work with the specified banking products.

Although the generated system is based on the *Rebel* specification(s), the generated code is not being checked against the *Rebel* specification(s). This means that the generated system is perhaps working as expected, or perhaps not. In this thesis we aim to improve this, by automatically testing the generated code using property-based testing and the *Rebel* language itself.

First we define the expected properties of *Rebel*, using the existing axioms of algebra as inspiration. Then we write these properties down as "events" in a new *Rebel* specification. We introduce our test framework, to automatically test this *Rebel* specification on the generated code. This is done as follows: the test framework uses the existing generator in the *Rebel* tool chain to generate the system for this *Rebel* specification. It then generates a test suite containing test cases for each "event" in this *Rebel* specification. As last, it runs the test suite against the generated system.

With this approach we identified some problems in the generated code that were unknown before. We have found precision errors, overflow/underflow errors and a compilation error. However, the number and the kind of bugs that can be found with this approach depend on the properties that were defined in the first place. We conclude that, by using this approach, the semantics of the generated code can be checked automatically on whether it satisfies the defined properties. The set of defined properties in this thesis is not complete for *Rebel*. Therefore, it is not the case that all the generated code is tested, but only the generated code concerning the defined properties is being tested.

Chapter 1

Introduction

Large systems often suffer from domain knowledge that is implicit, incomplete, out of date or contains ambiguous definitions. This is what *Rebel* aims to solve for the financial domain [1]. The toolchain of *Rebel* can be used to check, simulate and visualize the specifications, allowing to reason about the final product [2]. Checking is done based on bounded model checking by using the *Z3* solver.

Generators are being used to generate a software system from the *Rebel* specifications. The generated system provides an *API* in order to work with the specified product and handles the database connectivity. However, the implementation of the generated system is not checked against the specifications, meaning that the generated system is perhaps not doing what it is supposed to do according to its specifications. The aim of this project is to improve this, by automatically testing the generated system against a *Rebel* specification.

1.1 Problem statement

From the *Rebel* specifications, a system can be generated by the generator. However, neither the generator nor the generated program is being tested against the specification. Thus it could be that the generated system doesn't work according to what was specified in the *Rebel* specification. Although the generator should translate everything correctly, we cannot assume that it actually does translate it correctly for each case and that the implementation works as expected.

Currently, there are no tests for the generator or the generated system, during the development of the generator the results are being checked manually. Testing is a major cost factor in software development, with test automation being proposed as one of the solutions to reduce these costs [3]. We aim for an approach such that much of the testing is automated to reduce the time (and costs) needed for testing certain components of the generated system.

The main research question is as follows:

> How can the generator in the *Rebel* toolchain be tested automatically, by using the generated system, to check whether the implementation works as expected?

We investigate the following solution: generating tests based on a *Rebel* specification and then run these tests against the generated system.

Property-based testing is an approach to validate whether an implementation satisfies its specification [4, 5]. It describes what the program should or should not do. As described in [4]: "Property-based testing validates that the final product is free of specific flaws.". With property-based testing, a property is being defined which should hold on the system. Next, the property is being tested for a certain number of tries, using different input values to check whether the property holds. In case the property doesn't hold, it will result in a failure, reporting that there is a case in which the property

doesn't hold. This indicates that a bug in the system has been triggered.

Property-based testing has already shown a success in earlier studies [4, 6, 7], by detecting errors in a system that were not known before. In this thesis, we will use property-based testing to check the generator, by using the generated system to check whether the properties hold.

We hypothesize that there are yet unknown bugs in the generator, resulting in that the generated system does not work as expected. By using property-based testing we expect to detect bugs in the generator.

To answer the main research question, we will first answer the following research questions:

RQ 1: Which properties are expected to hold on the semantics of the generated code?

RQ 2: How can we test each property as automatically as possible to find bugs in the generator?

RQ 3: What kind of bugs can be found using this approach and how many?

The third research question is influenced by the first research question. When the expected properties are known, we can indicate what kind of bugs can be found by using this approach. Namely, bugs that invalidate these properties. These properties should be meaningful for *Rebel*, we focus on properties of *Rebel* when using the available operators and types in the *Rebel* language.

1.2 Solution direction

The expected properties which we would like to test on the generated code first have to be defined. This is the result of the first research question. The generator in the *Rebel* tool chain requires a *Rebel* specification as input to generate a *Scala* system (called "generated system" throughout this thesis). A *Rebel* specification contains the states, the data fields and the transitions between the states along with the pre- and post conditions of the transitions. The transitions in a *Rebel* specification are called "events". These levels of abstraction can be confusing. In Section 2.4 we describe the confusing terminologies and abstractions in detail to avoid this confusion throughout this thesis. *Rebel* is described in more detail in Section 2.1.

When the properties are defined, a *Rebel* specification can be created in which the properties are written down as "events" in the *Rebel* specification. Each property can be implemented as one "event" in the *Rebel* specification. Next, a test can be generated from each "event" in this *Rebel* specification. These tests can then be run against the generated system to check each property on the generated code. When a test fails, a bug has been found. In the next section we will describe this in more detail.

In order to run the test suite, we assume that the generated system can be compiled and that it can be run. But nothing more, such that our approach can be reused between different generators for *Rebel*. The specification which was used to generate the system should be syntactically and semantically correct. Which means that the *Rebel* type checker should not report any errors about the specification.

The test framework generates a test suite that can be run against the generated system. In case the test suite finishes without errors, it means that it did not find any bugs and that the generator satisfies the properties that were tested. This doesn't mean that there are no bugs in the generated system, instead, it means that our test suite was not able to find errors in the properties that it checks for. The generated system will probably still contain bugs which are not detected by using the test framework. In this case, improving the test framework might extend the number of bugs that it can find.

1.3 Research method

To check each property on the generated code, we divide this process in different phases. Most of the phases are executed by the test framework such that minimal manual steps are needed to test the defined properties. An overview of our approach is shown in Figure 1.1, each step is explained in detail in Chapter 4.

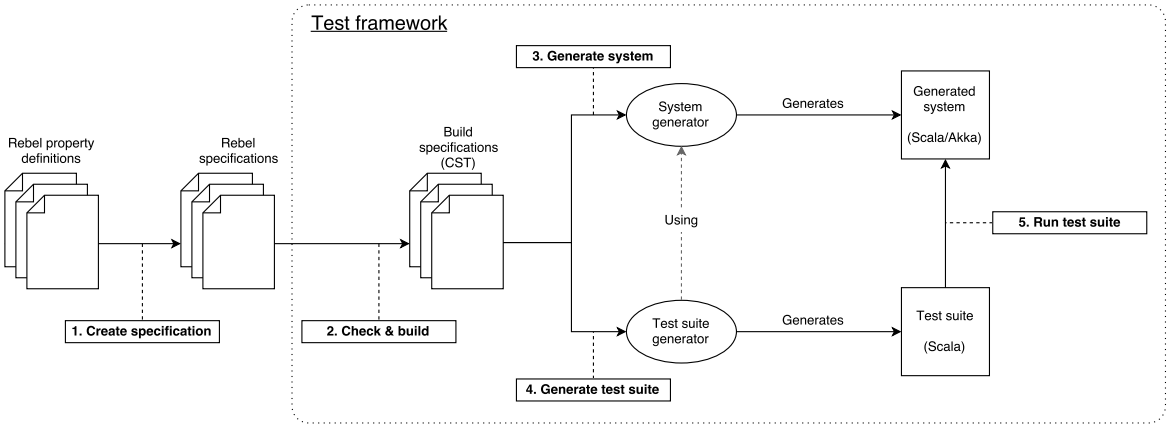


Figure 1.1: Overview of the test framework and the phases

We start off with defining the properties that are expected to hold on the semantics of the generated code. Coincidentally, the *Rebel* syntax is strong enough such that the defined properties can be written down in the *Rebel* syntax. This means that a specification can be created from these properties, in which each property is defined as an "event" in the *Rebel* specification (Figure 1.1, phase 1). Only this phase is done manually, the next phases are executed by the test framework.

This *Rebel* specification is checked by the type checker and then being built, resulting in a Concrete Syntax Tree (CST) (Figure 1.1, phase 2). The *Rebel* tool chain provides a generator to generate a Scala/Akka system by using the CST of the specification (Figure 1.1, phase 3). The same CST is used to generate the test suite (Figure 1.1, phase 4). The test suite consists of multiple tests based on the *events* in the CST. Note that, as described earlier in phase 1, the defined properties are written down as *events* in the *Rebel* specification.

The test suite is then being run against the generated system (Figure 1.1, phase 5). After running the test suite, we analyse the results of the experiment. When one or more tests are failing, a bug is found. An investigation of the failing case is needed to discover the actual bug is because the cause of the failing case is not clearly visible in the log.

We evaluate the test framework in each experiment using test coverage and the number of bugs found as metrics. Based on the results of an experiment, we improve the test framework and continue to the next experiment. In the next experiment we run the test framework again with the improvements, analyse the results and evaluate the test framework again.

The full source of our test framework is available on *Github*[1]. However, note that the test framework makes use of the Scala/Akka generator that is written by *ING* and is closed-source. Thus in order to run the test framework, access to the code of the generator is also required as the test framework depends on this generator.

[1] https://github.com/alexkok/master-thesis

1.4 Contribution & outline

In Chapter 2 we describe the background (*Rebel*, the generator and property-based testing). In Chapter 3 we provide definitions of the properties that are expected to hold when using the *Rebel* language and its toolchain. Allowing to reason about whether the properties are satisfied when using the generator and answering the first research question: Which properties are expected to hold on the semantics of the generated code? There were no existing property definitions of *Rebel*, so we provide a starting point for this with the focus on important properties of *Rebel*.

The defined properties are being used to check the generator. In Chapter 4 we describe this process in detail, which contributes to answering the second research question: How can we test each property as automatically as possible to find bugs in the generator?

In the experiments (Chapter 5, Chapter 6 and Chapter 7), the test framework is run with the set of defined properties. For each experiment we evaluate the results, investigate the failing tests and evaluate the test framework. The results of the experiments contribute to answering the third research question: What kind of bugs can be found using this approach and how many?

As last, we provide a discussion about the findings and answer the research questions in Chapter 8. Followed up by the conclusion in Chapter 9.

1.5 Related work

1.5.1 Axiom-Based Testing

In axiom-based testing (also known as property-based testing) axioms are defined which describe what the expected behaviour is of the system under test. It was introduced already in the early eighties, with *DAISTS* [8]. The axioms, which they write themselves, are being used as a basis for unit testing. The set of axioms describe the expected behaviour and are used to determine whether the implementation agrees with the defined axioms. Testing is automated, the user only defines the axioms and writes the implementation for this.

DAISTS focused on algebraic axioms, using the equality operator in the definitions. Axioms can also be specified in object-oriented style. An example of this is *ASTOOT* [9] which applies the ideas of axiom-based testing. Axioms are defined in an object-oriented style, describing the methods used and the expected outcome. Whereas in algebraic style, the axioms are written more in a functional notation (as is done in *DAISTS*). In this thesis, we use the algebraic style and use the equality as well as the inequality operators. Furthermore, we also have to define the expected behaviour of *Rebel* expression.

In [10] axioms are used to automatically generate tests from these. They use the *Concepts* in *C++* which contain the definitions of the axioms. Based on these *Concepts* they automatically generate tests for each defined axiom and run these tests to check whether the system under test satisfies these axioms. In this thesis, we define the properties (axioms) that are expected to hold in *Rebel* and then generate tests based on these definitions by using the generator. The generated tests will then be run against the generated system that can be generated from a *Rebel* specification. Our approach can be compared to the approach in [10], but we define the axioms in a *Rebel* specification and then run the generated tests against the system that was generated based on the *Rebel* specification that we created.

1.5.2 Random testing

Random testing is a technique in which random values are being used as input for the test cases. *QuickCheck* [6] and *Randoop* [11] are examples of random testing techniques. These differ in how they automatically test systems and what actually is being tested. *QuickCheck* is based on property-

based testing, which we also use throughout this thesis. *Randoop* on the other hand is based on feedback-directed random testing.

With feedback-directed random testing, random tests are generated which will immediately be run. The result of earlier test attempts can affect the next test that is being generated, which can be seen as feedback for the next generated test. This allows each test case to 'learn' from earlier attempts and to create unique tests.

Randoop is built for *Java* projects and checks some built-in specifications of *Java* that can't be checked by the compiler. The test cases are simple unit tests, consisting of a unique sequence of methods due to the feedback of earlier attempts. The method sequences are unique because it also checks whether the same case has already been checked. Since there can be unlimited sequences of methods to test, the test suite will be terminated after a defined timeout. Next, the result is determined and failing cases are being reported, although when using this approach it cannot determine whether the whole system is correct according to the *Java* specifications. Instead, it just wasn't able to find a case for which it fails. This is a useful approach to generate unique tests, but its goal is to check systems built-in *Java* and thus is not compatible with the semantics of *Rebel*. It works with calling the *Java* objects and using methods on those, while the generated system consists of mainly states and events. When using an approach like *Randoop* with random input values, it cannot be known whether the result of a specific transition was expected to succeed or fail.

Approaches like *QuickCheck* [6] and *Randoop* [11] enforce the system under test to be written in a specific language (*Haskell* for *QuickCheck*, *Java* for *Randoop*). For *QuickCheck* there are alternative solutions for other languages. In our case, we need to use *Rebel* when generating test cases, such that we test the generator when generating the tests. Another reason why we can't use a method like *Randoop* is that *Randoop* strictly checks for *Java* properties, which are not in line with the *Rebel* language.

1.5.3 Testing generated systems

Using domain-specific languages leads to the creation of code generators to automatically generate executable code [12]. This is also the case for *Rebel*, the toolchain provides some generators which use a *Rebel* specification as input. These generators and the resulting generated systems can be automatically tested too. In [12] they focus on testing non-functional properties, namely testing the performance of the generated code. In [13] the authors present a regression testing automation framework for a domain-specific language. They detect regressions in the generated systems by generating and executing test cases.

In this thesis, we also focus on automatically testing the generator (by using the generated system) but we check more basic functionalities that are specific to *Rebel* and its supported types.

1.5.4 Product-line testing

In [14] the authors describe a way to efficiently test a software product line. A software product line consists of a set of software systems that share a common set of features. However, many different products can be created from such a software product line, adding a challenge to test each combination of those products. In [14] the authors introduce *IncLing*, which efficiently tests combinations of these products and take already executed combinations into account when selecting a new combination. To determine the possible combinations they use the *IPCL* algorithm introduced in [15], an algorithm that can be applied to determine the combinations of software product lines at the size and complexity found in projects in the industry.

IncLing executes its tests sequentially by selecting a combination of features that were not covered in the previous test. This is a different way of testing each possible combination and ensuring unique test cases. In this thesis, we basically define the possible combinations by defining the properties

(axioms) that we expect to hold in *Rebel*. Additionally, the input values are determined random, allowing different combinations as in values. However, we do not test combinations of the properties combined, but test each individually. In our approach there could be some overlap over the various defined properties.

1.5.5 Model-based testing

Model-based testing is an evolving technique to generate tests based on a model [16]. The model is used to describe the requirements to which the system under test. Essentially, the model is a "specification" of the inputs to the system under test. To avoid confusion with our thesis, we stick with "requirements" in this section.

From the data model, tests are being generated and run against the system under test. The expected outcomes of the test cases are known beforehand based on the requirements. Thus, after running the tests against the system under test, the actual results are compared to the expected results. When the results are different compared to each other, it indicates that there is an error.

In *Rebel* a banking product can be specified. Which is essentially the abstract model of the product. When using the model-based testing approach one could check a generated system with the *Rebel* specification that was used to generate that system. Another master's thesis was done in parallel on the same topic [17]. They use model-based testing to test the generated system and uses the *Rebel* specification that was used to generate the system as data model. They use the existing solver that is available in the *Rebel* tool chain to generate tests. Next, they run each test against the generated system.

Although the topics are similar, the approach and the results are different. We will describe the differences in between these approaches in detail shortly. The results are different in that the bugs found are different. For example, they found distribution errors while we found precision errors. It is also important to note that we have only used one generator throughout our thesis, while [17] uses multiple generators.

We expect that some bugs found in the other generators can be detected with our approach too, such as the incorrect implementations for certain operators. When the properties have been defined for those, we should be able to detect those. However, we did not find such errors in the generator that we used when testing the properties that we defined. However, the vice-versa is also possible, their approach could probably find the bug we have found. Although they are depended on the traces that are being generated by the solver.

We discuss the differences in input, the test cases and the number of tests between these approaches:

Input specification(s)

The first difference are the input specifications that are being used to test the generated system. In our approach we create a new *Rebel* specification based on the defined properties. This can be done due to the fact that the *Rebel* syntax is strong enough to write the properties down in *Rebel*. Then we use this specification to generate tests for the generated system.
With the model-based testing approach in [17], existing *Rebel* specifications are used as model to test the generated system. The *Rebel* specifications for the model are the same specifications as those that were used to generate the system.

From this, we can conclude that: in our approach we test the generated system on certain properties. Exactly these properties should then be tested for all *Rebel* specifications. Thus we test things that should hold for all *Rebel* specifications. While with the model-based testing approach only specific *Rebel* specifications are being tested on the generated system. Allowing to reason about specific *Rebel* specifications, but requires test runs for each specification. While with our approach, we run

the test framework once and reason about all *Rebel* specifications.

Tests

Another difference is the way how the tests are being determined and generated. In our approach we generate a test case for each "event" in the *Rebel* specification. Remember that the properties are being written down as "events" in the *Rebel* specification that we create. Thus we know exactly what we test. A test case consists of checking the property 100 times with random input values. These test cases can be considered "unit tests" as each test checks one and only one property definition. We first generate all the test cases and then run the test suite against the generated system.

In [17] they use the *SMT* solver to generate a test case. Note that they use existing *Rebel* specifications as input, which already define the possible transitions for a specific banking product. Due to the *SMT* solver that they use, the actual test cases are unknown as these are determined by the *SMT* solver. The test cases can differ in each run and thus cannot exactly know the contents of each test. However, due to the solver they assume that the test case is valid and thus finds bugs when a test fails.

Thus we generate unit tests and run the whole test suite against the generated system. While in [17] they use the *SMT* solver to generate the tests at runtime, requiring to have both the solver and the generated system to be running available while the test framework is running.

Number of tests

The number of tests that are done also differ. Since we generate unit tests for each property, many tests are being generated. Additionally, each test consists of checking a property 100 times with random input values. Despite of the many generated tests, the execution time of the whole test suite is considerably fast since each test is considerably small. Although we did not measure the efficiency in our experiments specifically.

In [17] they generate a test case by using the *SMT* solver. The test is then run against the generated system, checks the result and continuous to the next test by repeating this process. Executing such a test case can be considered slower compared to our test cases. Although we test each property 100 times in a single test case, increasing this amount would affect the execution time too. However, we can reason about properties on all *Rebel* specifications while they can reason about a existing *Rebel* specifications.

Chapter 2

Background and context

2.1 Rebel

Rebel is a domain specific language that focuses on the banking industry [1]. Banking products can be specified in the language, with the use of *Rebel* types like *Money*, *IBAN* and *Percentage*. In Subsection 2.1.1 an example of a *Rebel* specification is described.

The tool chain of *Rebel* allows to check, visualize and simulate the specified banking product. For checking and simulation an efficient, state-of-the-art SMT solver is being used called *Z3*, which is developed by *Microsoft* [18]. *Rebel* is written in *Rascal* and is developed by the *ING* in corporation with the *CWI*. Currently, the tool chain of *Rebel* is also written in *Rascal*.

Checking a *Rebel* specification is based on Bounded Model Checking [1]. The *Rebel* specification is being translated to SMT constraints, next, the *Z3* solver is being used to check whether the specification is consistent. An inconsistent specification means that a counter example has been found (meaning that a trace is found for which an invariant doesn't hold). It is bounded since it only checks if a counter example can be found within a predefined number of steps. Besides checking the specification, the specification can also be simulated. For simulation, the SMT solver is also being used to determine whether a transition can happen. After successfully checking the specification, meaning that no counter examples could be found, the result is still that the specification 'might' be valid. As the checking method is bounded, it stops at a certain point (which, in the *Rebel* toolchain, is defined as the maximum depth of the traces that can be used for checking). This means that there can still be a long or untested trace for which the invariant doesn't hold.

From the *Rebel* specification, a system can be generated by using a generator which is developed by *ING*. The generators are also written in *Rascal*. This requires a specification that is consistent and that does not trigger errors by the type checker.

2.1.1 A Rebel example

In Listing 2.1 an example of a simple bank account specification is shown in *Rebel*. In this specification, an account can be opened and money can be deposited to an opened account.

```
module simple_account.Account
import simple_account.Library

specification Account {
  fields {
    accountNumber: IBAN @key
    balance: Money
  }
  events {
    openAccount[]
    deposit []
  }
  lifeCycle {
    initial init -> opened: openAccount
    opened -> opened: deposit
    final opened
  }
}
```

Listing 2.1: A simple account specification in *Rebel*.

The *module* keyword describes the module of this specification. The *import* statement is used to import logic from another file, which we will cover when describing the *events* block. The specification of the account itself is defined in the *specification* block, which consists of the following three blocks:

Fields

The *fields* block describes which data is available in this bank account. In this case, *accountNumber* and *balance* which are of type *IBAN* and *Money* respectively. The *accountNumber* is used as identifier for this account specification, because of the *@key* notation behind the type.

Life cycle

The *lifeCycle* block describes the life cycle, it can be seen as the life cycle of a finite state machine. It describes the states and the transitions between them. It also defines the *initial* and *final* state. Note that the transitions between these states are the events that have been defined in the specification.

Events

In the *events* block the events for this specification are described. The optional parameters of the event definition can be overloaded inside the brackets. Note that the implementation of the events are not described here. This is defined in another file called *Library*, shown in Listing 2.2.

```
module simple_account.Library
import simple_account.Account

event openAccount[minimalDeposit: Money = EUR 0.00](initialDeposit: Money) {
    preconditions {
        initialDeposit  >= minimalDeposit;
    }
    postconditions {
        new this.balance == initialDeposit;
    }
}
event deposit(amount: Money) {
    preconditions {
        amount > EUR 0.00;
    }
    postconditions {
        new this.balance == this.balance + amount;
    }
}
```

Listing 2.2: The library for the simple account example in *Rebel*.

An event definition can consist of *preconditions*, *postconditions* and a *sync* block. Each of those can only occur once in an event definition. The *sync* block defines that each operation inside that block should execute synchronously, without the interaction of other events in the meanwhile. However, in this simple specification the *sync* block is not used.

The *preconditions* and *postconditions* blocks contain expressions and can use functions. These functions can be defined in *Rebel* too. The *new* keyword in the *postconditions* block describe that the value of the field should be updated when the event transition takes place.

2.1.2 Rebel checkers versus our approach

A *Rebel* specification can be checked by the *Rebel* tool chain, while we are checking properties when using the generator. Additionally, the *Rebel* tool chain also has a type checker. In this section we aim to solve this confusion by describing both in more detail.

The *Rebel* tool chain contains a checker which checks a *Rebel* specification using bounded model checking. It is limited in that it only checks a *Rebel* specification, by trying to find cases in which the invariant doesn't hold. It does not do anything with *Rebel* specifications without an invariant. Thus, it only checks a *Rebel* specification and is not able to check or test the implementation of the generator or the generated system. The input is a set of *Rebel* specifications, only these *Rebel* specifications are being checked, nothing more. It only supports checking a *Rebel* specification. Due to this it cannot be used on the generated system, as this is written in *Scala*.

The type checker in the *Rebel* tool chain is used to determine whether certain expressions are allowed in *Rebel*. Operations like $+$, $-$, $*$ and $/$ can be used in *Rebel*, but these are not compatible with each and every type. For example, a *Money* value cannot be multiplied by another *Money* value. Such errors should be prevented by the type checker. The type checker will also be taken into account when defining the properties in Chapter 3.

In our property-based testing approach we check whether certain properties hold when using the generator. These properties describe the expected working of the *Rebel* language. Due to the syntax of *Rebel*, we can define a *Rebel* specification containing these properties. The type checker will prevent type-related errors in the property definitions. Our test framework uses this *Rebel* specification to check whether these properties hold when using the generator. Thus, all defined properties are being checked by only running the test framework once.

This means that, in our approach, we test whether the generated code works as expected for every *Rebel* specification that can be created. While the existing checker in the *Rebel* tool chain, that uses bounded model checking, only checks whether a *Rebel* specification is consistent. This existing checker is not able to check whether the generated system is working as expected. In our approach we check the generated system, but we only check parts of the whole implementation. Namely, the parts which are covered by the defined properties.

2.2 The Scala/Akka generator

There are multiple generators developed within *ING*. The generators are different in that the resulting product is written in a different language or uses a different implementation, like database or messaging layer. Each generator is written in *Rascal*.

The Scala/Akka generator is one of these generators. It generates a system that is written in *Scala*, uses *Akka* [19] as actor system and uses *Cassandra* [20] as database. This generator is often used within experiments inside *ING* and is considered the most mature generator among the currently developed generators. Because of this, it's interesting if we encounter yet unknown problems in the generator itself or the resulting system. We will only make use of this generator throughout this thesis.

A specification can be defined in terms of a Labeled Transition System [1], containing the states, the data fields and the transitions between the states along with the pre- and post conditions of the transitions. The generated system is based on these states and transitions defined in *Rebel*, resulting in a system that works like an Extended Finite State Machine. Thus the generated program also implements it like states and transitions between them. An instance of a banking product can have fields and is in a specific state. In order to go to another state, a transition can be done which might have pre- or post conditions. In case there are pre- or post conditions, these have to be satisfied in order to successfully complete a transition.

Rebel introduces custom types, such as *IBAN*, A library or own implementation is used for the custom types available in *Rebel*. An example is the *Money* type, which is available in the *Squants* [21] library. The generated system uses this library to deal with the *Money* type and its operations. Another example is the *Percentage* type, which is simply translated by calling a method `percentage()`. In order to conclude that the generated program is doing something incorrectly, we have to specify what the expected properties are in *Rebel*.

2.3 Property-based testing

With property-based testing properties are defined and being tested. It uses random values as input and checks whether the defined property holds. After a certain number of succeeding cases the test succeeds and the next property is being checked.

A well-known tool which is based on property-based testing is *QuickCheck*, which is written for *Haskell* [6]. It tests the properties automatically by using random input values. For each property *QuickCheck* tries to find counter examples, which are a set of values for which the desired property does not hold. If 100 test cases are succeeding in a row, it goes on to the next property. In case it found a counter example, it will try to minimize the values to try to report the edge case of the failure. However, one might have properties that only hold under certain conditions. For this *QuickCheck* allows using preconditions. Although, this doesn't work well for every case as *QuickCheck* will just generate new pairs of values in case the precondition didn't hold for the generated set of values. An example of this is where 2 of the input values have to be equal, the chance that this happens with random values is rather low. *QuickCheck* will try to generate new values each time, with a maximum of 1000 tries by default. In case this maximum is reached, it reports the case as "untested" and

continues to the next property. Note that these values of 100 and 1000 are the default values, these can be adjusted when needed.

Due to the effectiveness of *QuickCheck*, many ports for other languages were written. Most ports implement the basics of *QuickCheck*, additionally, each port could have added extra features. Examples of some ports are *FortressCheck* (for *Fortran*) [22] and *ScalaCheck* (for *Scala*) [23]. *FortressCheck* supports polymorphic types and, unlike *QuickCheck*, heavily uses reflection for its value generation to solve certain problems with polymorphic constructs. Although *Scala* supports polymorphism, *ScalaCheck* does not test this [22].

There is no *QuickCheck* implementation for *Rebel*. This is not interesting for *Rebel* because it is a declarative language, it does not execute. However, when testing the generated code it is interesting, which is what we do in this thesis. Since the generated system is written in *Scala*, *ScalaCheck* might be applicable for us. However, this would result in using *ScalaCheck* as a black box, implementing the random functionality ourselves makes sure we know what is going on. Thus resulting in a white box implementation for our test framework.We can also modify it to our needs when we want to improve our test suite. One of the things that we want to improve is to generate values under certain conditions. For example, if a property only holds under a certain condition, the chance that random values satisfy the condition can be very low. Resulting in a test case that wouldn't do anything most of the time. An example of such a property is *Symmetry* ($x = y \implies y = x$). Additionally, we might also need to slightly interact with other components, such as the messaging layer, that the generated system uses. This could make the implementation more complicated when using *ScalaCheck* due to the format of a property test when using *ScalaCheck*.

2.4 Terminology

In this thesis there are some levels of abstraction, the terminology used throughout this theses can cause confusion. Words like "specification", "properties" and "tests" generally can have a different meaning depending on the context. In this section, we describe the confusing terminologies and abstractions in detail.

Specification
: In this thesis we use the word "specification" exclusively to indicate banking products described in the *Rebel* language. This includes the state machines (life cycle), pre and post-conditions and logical invariants.

Properties
: We use the word "property" to describe semantic properties of the *Rebel* language. The set of properties we introduce in this thesis can be seen as a partial "specification" of the semantics of *Rebel*, but we do not use this word to avoid confusion. We stick with "properties".

Implicative property
: A "property" that uses the implication ($\implies$) operator in its definition.

Generator(s)
: The generator(s) that can be used to generate a system based on a "specification". When using the term "the generator", we refer to the Scala/Akka generator which is the only generator that we use throughout this thesis.

Test framework
: The test framework that was developed during this thesis. Which builds the specification, generates a system from the specification by using the generator, generates the test suite and runs the test suite against the generated system.

Tests
: The generated tests by the "test framework", intended to check whether a certain "property" holds.

Test suite
The collection of generated tests by the "test framework", along with its configurations which can be run to test the generated system. Note that the test suite initially doesn't exist. Instead, it is being generated and added to "the generated system" when we run the "test framework".

Events
The event definitions in a "specification", these define the transitions between the states.

Scala Build Tool (SBT)
The tool that is used to compile and run the "generated system" and the "test suite".

Concrete Syntax Tree (CST)
A "specification" can be checked and built. This results in a "CST" containing the data of the specification. This "CST" is being used by the toolchain of *Rebel* and by the "test framework".

Chapter 3

Properties of Rebel

Rebel introduces custom types, like *IBAN*, *Percentage* and *Money* and allows operations on those [1]. But what are the expected properties of the generator? In this chapter, we will try to answer the first research question:

RQ 1: Which properties are expected to hold on the semantics of the generated code?

To answer this question, we first describe a way how we can determine the properties. Followed by the property definitions that will be used throughout this thesis, with a motivation why these properties are expected to hold. The properties that are defined in this chapter will be used in our experiments (Chapter 5, Chapter 6 and Chapter 7).

3.1 Determining the properties

Currently, there are no definitions available of which properties are expected in *Rebel*. Due to the missing definitions of these types, it means that we first have to define what the expected properties on these types are and substantiate these. Only then we can determine whether the generator is working as expected with these properties.

There are many operations available among the available types in *Rebel*. We are not able to define all the properties that exist in the *Rebel* language, because this is not effective for the scope of this thesis. Our goal is to show that this approach works. Next, one can write all the relevant properties down and use the test framework to test these properties automatically. During this thesis we will focus on the *Money* type, considering this is the most important type for a bank and has the highest priority to be implemented correctly.

For types like *Integer*, the axioms of algebra can be used as inspiration to determine whether the implementation is correct. An *Integer* in *Rebel* is most likely translated to an *Integer* in the generated system too, with perhaps the expectation that these have the same properties in *Scala*. However, it is not possible to rely on the *Integer* definition of a specific language. Because another generator might generate a system in another language or might implement it differently in the same language. Would that mean that the properties of that other language should now hold on the *Integer* type? Well, as this is not defined for *Rebel*, this is unknown. In this chapter, we will define properties that are expected to hold when using the *Money* type in *Rebel*. The properties that we define are based on the known axioms in algebra [24, 25, 26]. We provide an explanation of why a certain property is expected in *Rebel*.

The *Money* type can be seen as a currency with an amount value. The amount of a *Money* value can have multiple decimals depending on the currency. Thus, the amount can be seen as a floating number. Does this mean that it inherits the computational properties of Floating-Point Arithmetic, as defined in the IEEE standards 754 or 854? Since the *Rebel* is intended to be a formal specification

language for banking products, we don't expect that the described problems with this arithmetic are intended to exist on the *Money* type. Considering high volume flows within a bank in terms of *Money*, using the Floating-Point Arithmetic properties can result in the known precision, overflow and underflow errors as described in [27]. Such errors could be avoided by using the *Money* type. The author of [28] also describes that the intention of the *Money* type is to avoid this:

> "You should absolutely avoid any kind of floating point type, as that will introduce the kind of rounding problems that Money is intended to avoid." – Martin Fowler [28]

In [28] the operations that can be done with the *Money* type are described, which are: *+*, -, ***, *allocate*, $<$, $>$, $\leq$, $\geq$ and $=$. Where the allocate method is used instead of the division (/) operation. This is due to the division problem, requiring a number to be rounded off at a certain time. For example, when splitting 1 EUR by 3, each part would be 33 cents with the consensus of two decimals. However, what is done with the last cent that is left? This is the problem that is being solved by the allocate method, representing the ratio in which the rest amount should be allocated (where the last cent would go to in this case) [28]. The *allocate* method is a thing that *Rebel* does not have, instead, it just allows the use of the division operator. Because of this, we expect the division problem to occur while running the test framework.

The amount of a *Money* value is often rounded when it is being represented to the user, as it could have many decimals. The representation of the *Money* value is up to the business on how this is done, as there are multiple factors influencing this. Instead, we only focus on the internal value that is used when operating with the *Money* type.

It is unsupported to use operations on *Money* values when using values that are of different currencies. This could be done by taking the exchange rates into account, as described in [28]. However, this is not implemented in *Rebel* yet and thus it is unsupported to use operations on it when using different currencies.

When using equality both the currency and the amount are taken into account, which should be equal for both variables. In case of different currencies, it is not considered equal, even if the amount would be equal.

We say that the amount of a *Money* value in *Rebel* should hold the exact value as if we would calculate the same expression by ourselves. The representation of the *Money* value to the customer is up to the business.

3.2 Property definitions

The properties that we define are based on the known axioms in algebra, although not every property is relevant or holds for each type in *Rebel*.

For example, it isn't possible to multiply two *Money* types with each other in order to support the multiplicative property. It is unknown to which dimension "*Money* squared" belongs, this does not occur in the financial domain. Because of this, detecting this prevents such mistakes. When this is accidentally defined in the *Rebel* specification, the type checker would detect and report this as an error. Division has a similar case, as something cannot be divided a *Money* type.

Instead we can use these operations with *Money* in combination with other types, such as *Integer* and *Percentage*. The type checker for *Rebel* will be used to determine these combinations. Due to this, one property definition can lead to different possible combinations which can be used. This results in multiple property definitions when using different types, for each definition a unique name is being defined to identify each separate property definition.

We can separate the properties into two categories: "Field properties" and "Properties of equal-

ity and inequality". In the following sections we describe these categories in detail along with the properties in the category. These property definitions will be used throughout the thesis. Additionally we will describe some property definitions that were added to this list of properties in the third experiment (Chapter 7).

3.2.1 Field properties

The field properties define the behaviour of addition, multiplication, subtraction and division on rational and real numbers[1]. As described in [26], such operations can be used to determine the sum and the product of such values:

> "Along with the set **R** of real numbers we assume the existence of two operations called *addition* and *multiplication*, such that for every pair of real numbers x and y we can form the *sum* of x and y, which is another real number denoted by x + y, and the *product* of x and y, denoted by xy or by x . y." – Tom M. Apostol [26]

These operations are also available when using the *Money* type in *Rebel* and are expected to apply these operations on the amount value[2]. However, not every combination is possible in *Rebel* when it comes to using these operations. This is because *Rebel* does not support certain combinations. We define the following properties in this category:

Associativity

Formula	Property name	Variable (Type)
$(x + y) + z = x + (y + z)$	associativeAddition	x : Money
		y : Money
		z : Money
$(x \cdot y) \cdot z = x \cdot (y \cdot z)$	associativeMultiplicationInteger1	x : Integer
		y : Integer
		z : Money
$(x \cdot y) \cdot z = x \cdot (y \cdot z)$	associativeMultiplicationInteger2	x : Money
		y : Integer
		z : Integer
$(x \cdot y) \cdot z = x \cdot (y \cdot z)$	associativeMultiplicationPercentage1	x : Money
		y : Percentage
		z : Integer
$(x \cdot y) \cdot z = x \cdot (y \cdot z)$	associativeMultiplicationpercentage2	x : Integer
		y : Money
		z : Percentage

Table 3.1: Associativity when using *Money*

The law of associativity is known on addition and multiplication [24]. It defines that the order in which certain operations are done does not affect the result of the whole expression. In Table 3.1 we define possible combinations for this property, which are accepted by the type checker of *Rebel*.

[1] https://en.wikipedia.org/wiki/Field_(mathematics)

[2] We do not claim that the *Money* type in *Rebel* is a field. As it does not support each described operation when only using *Money*. Instead, we use the field definitions to determine the properties on the *Money* type.

Non-associativity

Formula	Property name	Variable (Type)
$(x - y) - z \neq x - (y - z)$	nonassociativity	x : Money
		y : Money
		z : Money

Table 3.2: Non-associativity when using *Money*

In contrast to associativity (Associativity), non-associativity describes that the order of the arguments does affect the result of the whole expression. As we can see in Table 3.2 subtraction is a relation where this property holds. An exception to this would be when each argument is zero.

Commutativity

Formula	Property name	Variable (Type)
$x + y = y + x$	commutativeAddition	x : Money
		y : Money
$x \cdot y = y \cdot x$	commutativeMultiplicationInteger1	x : Integer
		y : Money
$x \cdot y = y \cdot x$	commutativeMultiplicationInteger2	x : Money
		y : Integer
$x \cdot y = y \cdot x$	commutativeMultiplicationPercentage1	x : Percentage
		y : Money
$x \cdot y = y \cdot x$	commutativeMultiplicationpercentage2	x : Money
		y : Percentage

Table 3.3: Commutativity when using *Money*

These properties are based on the commutative law [24]. The result of an addition or multiplication does not vary when swapping the input variables. Because of the *Money* type, we can only do addition on *Money* values with other *Money* values. As described in earlier, it is not possible to multiply two *Money* variables with each other, but it is possible to multiply it by an *Integer* or *Percentage*. Also in this case, the order shouldn't matter if we would put the *Money* value as the first input parameter to multiplication or the other way around.

Anticommutativity

Formula	Property name	Variable (Type)
$x - y = -(y - x)$	anticommutativity	x : Money
		y : Money

Table 3.4: Anticommutativity when using *Money*

Commutativity described the commutative properties. Note that the properties in Commutativity only use addition and multiplication. Subtraction is an operation that is anticommutative as swapping the order of the two arguments is negates the result. The anticommutative property thus negates the

result of swapping the two arguments, intending to result in the actual value again, as shown in Table 3.4.

Identity

Formula	Property name	Variable (Type)
$x + 0 = x$	additiveIdentity1	x : Money
$0 + x = x$	additiveIdentity2	x : Money
$x \cdot 1 = x$	multiplicativeIdentity1	x : Money
$1 \cdot x = x$	multiplicativeIdentity2	x : Money

Table 3.5: Identity when using *Money*

The identity relation describes a function that returns the same value as the value that was given as input. For additivity, this entails the addition of zero to the input value and for multiplicativity, this entails multiplying the value by 1. Also, the Commutativity property holds here, as the order does not matter in which this function is applied. Since it is not possible to just add 0 to a *Money* value, the 0 showed in Table 3.5 must be defined in a *Money* format. Thus it must have the same currency as the parameter, with the amount of 0. The *Integer* type can be used for multiplication.

Inverse

Formula	Property name	Variable (Type)
$x + (-x) = 0$	additiveInverse1	x : Money
$(-x) + x = 0$	additiveInverse2	x : Money

Table 3.6: Inverse when using *Money*

The inverse relation describes (for additivity) that using addition with the input parameter and the negative of the input parameter, results in the value zero. Note that the operation is used on the *Money* type, so the expected value is 0 with the same currency as the currency of the input parameter. Although the inverse relation could also be used with multiplication and division (defined as $x \cdot (1/x) = 0$), it is not possible to use this definition in our case. As we cannot divide something by a *Money* type, which is why we only define the inverse relation using addition.

Distributivity

Formula	Property name	Variable (Type)
$x \cdot (y + z) = x \cdot y + x \cdot z$	distributiveInteger1	x : Money
		y : Integer
		z : Integer
$(y + z) \cdot x = y \cdot x + z \cdot x$	distributiveInteger2	x : Integer
		y : Money
		z : Money
$x \cdot (y + z) = x \cdot y + x \cdot z$	distributivePercentage1	x : Percentage
		y : Money
		z : Money
$(y + z) \cdot x = y \cdot x + z \cdot x$	distributivePercentage2	x : Percentage
		y : Money
		z : Money

Table 3.7: Distributivity when using *Money*

The law of distributivity is another well-known law [24]. Unlike Associativity, the order does matter here when using different operations. These operations can be used on *Money* and since we can see *Money* as a number, this property is also expected on this type. Remember that it is not possible to multiply *Money* types with each other. Thus the variable types are an important part of these properties, in Table 3.7 property definitions are shown based on this property.

3.2.2 Properties of equality and inequality

The properties in this category are mainly using the equality ($=$, $\neq$) and inequality ($<$, $>$, $\leq$, $\geq$) operators in their definitions. For the property names we abbreviate these operations with the naming *LT*, *GT*, *LET* and *GET* respectively. The following property definitions belong to this category:

Property of Zero

Formula	Property name	Variable (Type)
$x \cdot 0 = 0$	multiplicativeZeroProperty1	x : Money
$0 \cdot x = 0$	multiplicativeZeroProperty2	x : Money

Table 3.8: Property of Zero when using *Money*

The property of zero on multiplication states that if something is multiplied by zero, the result will always be zero. Since *Rebel* allows the use of multiplication on the *Money* type, it's possible to multiply it by 0. The order in which this happens shouldn't matter. Since the value of a *Money* variable is based on a decimal number, this property states that the value will be exactly 0 (or 0.00 in the representation of a *Money* value). It should not contain any decimals that would make the amount bigger than zero.

Reflexivity

Formula	Property name	Variable (Type)
$x = x$	reflexiveEquality	x : Money
$x \leq x$	reflexiveInequalityLET	x : Money
$x \geq x$	reflexiveInequalityGET	x : Money

Table 3.9: Reflexivity when using *Money*

The reflexive property is defined as a relation of a type with itself [25]. An instance of type *Money* should be equal to itself. The inequality relations *smaller or equal to* and *greater or equal to* should hold too, as we can compare *Money* variables.

Symmetry

Formula	Property name	Variable (Type)
$x = y \implies y = x$	symmetric	x : Money
		y : Money

Table 3.10: Symmetry when using *Money*

Reflexivity described relations on the same variable of the *Money* type. When two different variables are used, the order should not matter and thus it should work in both ways. Which is known as the symmetric property [25].

Antisymmetry

Formula	Property name	Variable (Type)
$x \leq y \wedge y \leq x \implies x = y$	antisymmetryLET	x : Money
		y : Money
$x \geq y \wedge y \geq x \implies x = y$	antisymmetryGET	x : Money
		y : Money

Table 3.11: Antisymmetry when using *Money*

The antisymmetric relation describes that whenever there is a relation from x to y and a relation from y to x, then x and y should be equal. The *lower or equal than* ($\leq$) and *greater or equal than* ($\geq$) relations fit in this category, as shown in Table 3.11. This antisymmetric relation is also expected to hold, as the *Money* type supports these operations.

Transitivity

Formula	Property name	Variable (Type)
$x = y \land y = z \implies x = z$	transitiveEquality	x : Money
		y : Money
		z : Money
$x < y \land y < z \implies x < z$	transitiveInequalityLT	x : Money
		y : Money
		z : Money
$x > y \land y > z \implies x > z$	transitiveInequalityGT	x : Money
		y : Money
		z : Money
$x \leq y \land y \leq z \implies x \leq z$	transitiveInequalityLET	x : Money
		y : Money
		z : Money
$x \geq y \land y \geq z \implies x \geq z$	transitiveInequalityGET	x : Money
		y : Money
		z : Money

Table 3.12: Transitivity when using *Money*

Operations can be done on the *Money* types. The transitive properties [25] on the (in)equality operators should still hold on the *Money* type as we can compare the *Money* values.

Additivity

Formula	Property name	Variable (Type)
$x = y \implies x + z = y + z$	additiveEquality	x : Money
		y : Money
		z : Money
$x = y \land z = a \implies x + z = y + a$	additiveEquality4params	x : Money
		y : Money
		z : Money
		a : Money

Table 3.13: Additivity when using *Money*

Addition was earlier mentioned for the Commutativity and Associativity properties. The properties mentioned here extend these by defining properties that are true when the input values are equal. When using the addition operator such that the resulting values on both sides remain the same, as shown in Table 3.10, it should not break the equality property on the resulting values.

Division

Formula	Property name	Variable (Type)
$x \cdot y = z \implies x = z/y$	division1	x : Money
		y : Integer
		z : Money
$x = z \cdot y \implies x/y = z$	division2	x : Money
		y : Integer
		z : Money

Table 3.14: Division when using *Money*

When using division with the *Money* type, it is not possible to use a *Money* value as the denominator. A *Money* type can be dived by an *Integer*, thus we can define the division properties by using both the *Money* and *Integer* type. Note that the denominator cannot be zero, as division by zero is not possible.

Trichotomy

Formula	Property name	Variable (Type)
$x < y \vee x = y \vee x > y$	trichotomy	x : Money
		y : Money

Table 3.15: Trichotomy when using *Money*

The law of trichotomy defines that for every pair of arbitrary real numbers, exactly one of the relations $<$, $=$, $>$ holds. We can define a property for this when using *Money*, as shown in Table 3.15.

3.2.3 Additional properties of equality and inequality

For the third experiment (Chapter 7), the property definitions for division have been updated and additional properties have been added to the list of defined properties. These extra properties can be put in the category of equality and inequality properties and are using the implication ($\implies$) sign in its definitions.

Division

Formula	Property name	Variable (Type)
$\text{round}(x \cdot y) = \text{round}(z) \implies \text{round}(x) = \text{round}(z/y)$	divisionEquality1	x : Money y : Integer z : Money
$\text{round}(x) = \text{round}(z \cdot y) \implies \text{round}(x/y) = \text{round}(z)$	divisionEquality2	x : Money y : Integer z : Money
$x = y \wedge z \neq 0 \implies x/z = y/z$	divisionEquality3	x : Money y : Money z : Integer
$x < y \wedge z > 0 \implies x/z < y/z$	divisionInequalityLT1	x : Money y : Money z : Integer
$x < y \wedge z < 0 \implies x/z > y/z$	divisionInequalityLT2	x : Money y : Money z : Integer
$x > y \wedge z > 0 \implies x/z > y/z$	divisionInequalityGT1	x : Money y : Money z : Integer
$x > y \wedge z < 0 \implies x/z < y/z$	divisionInequalityGT2	x : Money y : Money z : Integer

Table 3.16: Updated definition of Division when using *Money*

The initial property definitions for *Division* did not take the division problem into account and thus had to be updated. The updated definitions are using the *round()* method to prevent the occurrence of the division problem. The *round()* method rounds the value to 4 decimals and uses the "HALF_UP" rounding technique, this is described in more detail in Chapter 7. In addition to this modification, more property definitions have been added for division, as shown in Table 3.16.

Additivity

Formula	Property name	Variable (Type)
$x = y \implies x + z = y + z$	additiveEquality	x : Money
		y : Money
		z : Money
$x = y \land z = a \implies x + z = y + a$	additiveEquality4params	x : Money
		y : Money
		z : Money
		a : Money
$x < y \implies x + z < y + z$	additiveInequalityLT	x : Money
		y : Money
		z : Money
$x > y \implies x + z > y + z$	additiveInequalityGT	x : Money
		y : Money
		z : Money

Table 3.17: Additivity when using *Money*

For additivity, additional property definitions are added that use inequality, as shown in Table 3.17. The existing ones (described in the first 2 rows) only used equality in its definitions.

Subtraction

Formula	Property name	Variable (Type)
$x = y \implies x - z = y - z$	subtractiveEquality	x : Money
		y : Money
		z : Money
$x < y \implies x - z < y - z$	subtractiveInequalityLT	x : Money
		y : Money
		z : Money
$x > y \implies x - z > y - z$	subtractiveInequalityGT	x : Money
		y : Money
		z : Money

Table 3.18: Subtraction when using *Money*

The property definitions concerning subtraction are kind of similar to those of Additivity. It uses subtraction instead of addition in its definition. Nevertheless, to check whether the properties holds for subtraction we defined these properties as shown in Table 3.18.

Multiplication

Formula	Property name	Variable (Type)
$x = y \implies x \cdot z = y \cdot z$	multiplicativeEquality	x : Money
		y : Money
		z : Integer
$x < y \land z > 0 \implies x \cdot z < y \cdot z$	multiplicativeInequalityLT1	x : Money
		y : Money
		z : Integer
$x < y \land z < 0 \implies x \cdot z > y \cdot z$	multiplicativeInequalityLT2	x : Money
		y : Money
		z : Integer
$x > y \land z > 0 \implies x \cdot z > y \cdot z$	multiplicativeInequalityGT1	x : Money
		y : Money
		z : Integer
$x > y \land z < 0 \implies x \cdot z < y \cdot z$	multiplicativeInequalityGT2	x : Money
		y : Money
		z : Integer

Table 3.19: Multiplication when using *Money*

The property definitions for multiplication are looking similar to those of Division. The property definitions described in Table 3.19 are different in that these use the multiplication operator along with the inequality symbols.

3.3 Conclusion

In this chapter, we focused on the properties when using the *Money* type in *Rebel*. The research question lead as follows: Which properties are expected to hold on the semantics of the generated code?

Since there was no definition available of the types in *Rebel*, it was required to define the properties in detail. Describing what the expected behaviour is when operating with the types and which operations are allowed on each type. In this chapter, we have defined a set of properties that are expected to hold with *Rebel*. These property definitions will be used in the experiments to test the generator.

The properties are based on the axioms in algebra, but the requirements of *Rebel* have been taken into account when it comes to using certain operations with certain types. The defined properties are separated into 2 categories: “Field properties” and “Properties of equality and inequality”.

The properties that are defined in this chapter will be used to test the generator. However, it is not true that there are no bugs in the generator in case every property holds. It does mean that there were no errors found in the properties that are being checked. Many properties can be defined within the *Rebel* language, the properties defined in this chapter are certainly not all the properties that exist in *Rebel*.

3.4 Threats to validity

Lack of properties

We defined a set of properties that are expected to hold in *Rebel*. This can be seen as an incomplete set, as many more properties can hold and can be expected when using *Rebel*. The set of properties we defined are aimed to cover many operations when using the *Money* type, as this is considered the most important type for a bank.

We have used the axioms of algebra as inspiration for the property definitions in this chapter. We did not specify *Rebel*, as we have not defined all the operators and all the important properties of it. This leads to a threat of validity for the next chapters in that this affects the answer to our third research question: What kind of bugs can be found using this approach and how many? A complete list of property definitions in *Rebel* could result in more bugs, and thus affect the answer to this research question. For this, a profound study should be done on how *Rebel* works exactly, describing all the expected properties in *Rebel*.

Invalid definitions

We defined some properties that are expected to hold on *Rebel* types, specifically when using the *Money* type. We already discussed the lack of properties, but it could be the case that some of our definitions are invalid. We also assume that these properties do hold on *Rebel* types.

Some might disagree with certain properties that we have defined, which leaves this as a threat to the first research question: Which properties are expected to hold on the semantics of the generated code? But when this is the case, the properties can be updated when needed. When we encounter a bug in our experiments by using the properties in the following chapters, the designers or implementers of *Rebel* might disagree with the fact that it's a bug (a false-positive). However, this issue is then getting known by using this approach, which does not mark this as a major threat.

Minimum number properties

We defined many properties in this chapter. This might lead to questions like: is this the minimal (or optimal) number of property definitions in order to detect the bugs found in the experiments? Because having a minimal (or optimal) set of properties would mean that there are less tests needed to test the same thing, resulting in that less time is required to run the test framework. The answer to this question is no, this is out of scope for this thesis. This leads to a threat to answering our third research question: What kind of bugs can be found using this approach and how many?

Some of the defined properties might be overlapping each other. It might be possible to lower the number of properties that have to be defined. However, the purpose of each property on what it tests is different. So one should be careful when determining some property unnecessary. For this thesis, we used known axioms of algebra as inspiration and defined some properties for *Rebel*.

Chapter 4

Test mechanics

In order to check whether the defined properties in Chapter 3 hold when using the generator, we need to determine how the test framework should work. In this chapter we will try to answer the following research question:

RQ 2: How can we test each property as automatically as possible to find bugs in the generator?

We use property-based testing as testing technique. The aim of this project is to test the implementation of the generator and trying to find, yet unknown, bugs in it. Unfortunately, we cannot test the properties right away on the generator, but we aim to test the properties as automatic as possible. To check the generator, we use the system that it generates. In order to do that, a valid *Rebel* specification is required. In this chapter, we describe how the test framework is setup such that it can automatically check whether the defined properties hold when using the generator.

4.1 The test framework

A *Rebel* specification can be created with the property definitions. Which can then be used to generate the test cases. The collection of resulting test cases is the content of the test suite, which we can be run against the generated system. We can divide this process into different phases. The goal of the test framework is to combine most of the required phases such that each defined property is being checked as automatic as possible. An overview of the phases and the test framework is shown in Figure 4.1.

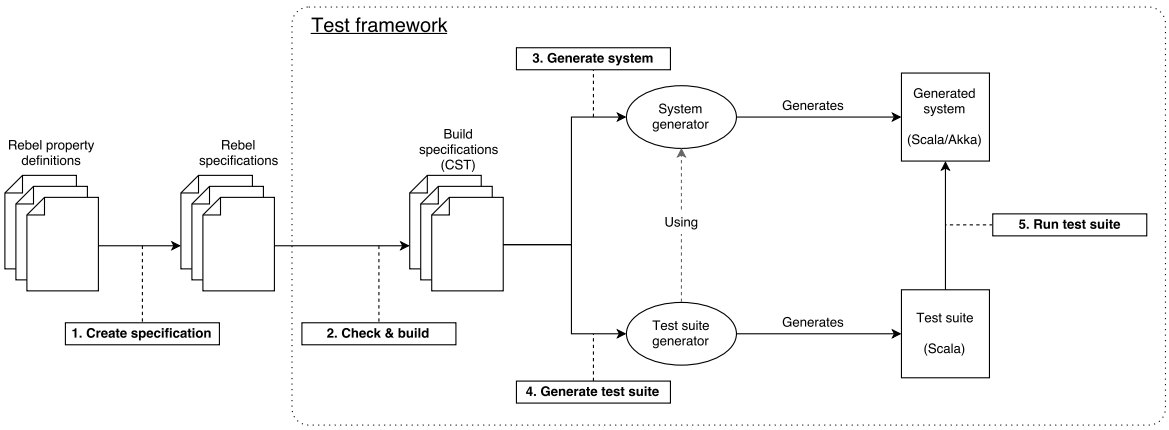


Figure 4.1: Overview of the test framework and the phases

The phases are defined as follows:

1. Create specification

2. Check & build
3. Generate system
4. Generate test suite
5. Run test suite

We will describe each phase in detail in the next sections. Additionally, we will define some evaluation criteria which will be used to evaluate the test framework. The *Reflexitivity* property will be used to demonstrate each phase. More specifically: the case of *Reflexivity* when using equality, called *ReflexiveEquality* throughout this thesis. The definition of *ReflexiveEquality* is shown in Table 4.1.

Formula	Variable	Type
$x = x$	x	Money

Table 4.1: Property definition of *ReflexiveEquality*

4.1.1 Create specification

The generator requires a consistent *Rebel* specification in order to generate a system. Coincidentally, the *Rebel* syntax is strong enough to write down the defined properties in *Rebel*. This opens the possibility to create a *Rebel* specification containing the property definitions and to reuse the generator when generating the tests. This way, we can be sure that we check exactly the same code as which would be used when using a real *Rebel* specification. A real specification means, for example, a specific bank account specification written in *Rebel*. This is a convenient choice, because the generator is being checked this way and it opens the ability to use the same approach with different generators.

We can use the event blocks in *Rebel* to write down the properties. An event describes a transition from one state to another and accepts parameters. Additionally, it can have pre- and post conditions, where the post conditions state what happens when the transaction is being executed. In Listing 4.3 the event definition for the *ReflexiveEquality* property written in *Rebel* is shown.

```
1 event reflexiveEquality(x: Money) {
2     postconditions {
3         new this.result == ( x == x );
4     }
5 }
```

Listing 4.3: The event definition for the *ReflexiveEquality* property.

The event name and the parameters are used to generate a test case from this event definition. To check whether the property was fulfilled given a certain set of parameters, we store the result in a data field called *result*[1]. The test suite uses the value of this field, to determine the result. In case the result value is *false* during testing, a bug has been found.

Besides the event definition, we need to write the actual *Rebel* specification to be able to generate a system from it. The specification describes the fields, the events it uses and the life cycle of the state machine. Since we are only interested in testing the events, we can hold the specification itself to a minimum. The life cycle consists of 2 states, the initial and final state. The transition between these states is the event we defined, *ReflexiveEquality*. In Listing 4.4 a specification used for one property is shown. In the case of multiple properties, we can add these to the events block. In the life cycle, we can comma separate the transitions.

[1]The *new* keyword is used to indicate that the field should be updated when the transition takes place.

```
module gen.specs_money.MoneyExample
import gen.specs_money.MoneyExampleLibrary

specification MoneyExample {
  fields {
        id: Integer @key
    result: Boolean
  }

  events {
    reflexiveEquality []
  }

  lifeCycle {
    initial init -> result: reflexiveEquality
    final result
  }
}
```

Listing 4.4: The event definition for the *ReflexiveEquality* property.

4.1.2 Check & build

Now that there is a specification containing the properties, the specification can be built. This results in a CST of the specification that the test framework can use to generate the tests. This is done by using the existing toolchain that is available for *Rebel*.

Building the specification means that the specification is being checked and returns a CST of the specification when the specification is consistent. Building also does more, like flattening the specifications, but this is not relevant for this thesis. The CST required in order to generate a system from it by using the generator. The CST is also used by the test framework to generate the test suite.

4.1.3 Generate system

The generator will be used to generate a system from the specification that we have created. This system which will be used to check each property. Note that the generated system is assumed to be runnable. As otherwise the test suite, that will be generated by the test framework (in the next phase), cannot be run against the generated system.

4.1.4 Generate test suite

The test suite requires some configuration to work with the generated system. The test framework first initializes the test suite, then generates the test cases.

Although this generator is the most mature and often used in experiments within *ING*, it is still used as a prototype. The resulting system is not production ready, as this requires some more actions. One of these is that the resulting system should have tests which test the generated system. The generated system doesn't contain anything that's related to testing yet. So to make use of the testing libraries in *Scala*, we will need to add the test dependencies to the build file of the project and add a configuration file for *Akka*. This is done when we initialize the test suite and can be found in the source. We do not cover this in detail here since there are no custom settings in there, rather it is default configuration that is only required to make the messaging layer work for the test suite. The configuration can be found in the source of the test framework.

The test framework is build up such that it first starts the generated system, followed by running the test suite against it. Thus when running the test suite (next phase), the generated system will automatically be started.

The test framework can traverse the CST and generate a test case for each event. A test case is generated by using the templating feature of *Rascal*, where we fill in event specific data as shown in Listing 4.5. The resulting test case of *ReflexiveEquality* is shown in Listing 4.6.

```
public str snippetTestCase(str eventName, list[str] params, int tries) {
  return "\"work with <eventName>\" in {
           generateRandomParamList(<convertParamsToList(params)>, <tries>).foreach {
             data: List[Any] =\> {
               checkAction(<eventName>(
                 <for (i <- [0..size(params)]) {>
                     // Iterate over params. Use getMappedType for the casting again
                     data(<i>).asInstanceOf[<getMappedTypeForParam(params[i])>]
                     // Add a comma if needed
                     <if (i != size(params)-1) {>,<}>
                   <}>
                 )
               )
             }
           }
         }";
}
```

Listing 4.5: Test case snippet

```
    "work with ReflexiveEquality" in {
      generateRandomParamList(List("Money"), 100).foreach {
        data: List[Any] => {
          checkAction( ReflexiveEquality(data(0).asInstanceOf[Money]) )
        }
      }
    }
```

Listing 4.6: An example of a generated test

The functions `generateParamList()` and `checkAction()` are utility functions that are defined in the template that is used for a test file. The `generateRandomParamList()` method generates tuples of random values that are used as parameters. `checkAction()` is a method that executes the given event and checks whether the resulting value of the result field was *true*. A test file consists of the utility functions and all of the snippets that were generated.

4.1.5 Run test suite

The test suite can be run with *SBT* by using `sbt test`. The log shows detailed information about the tests and shows a summary when the test suite has finished. When running the test framework with the specification that we created in Subsection 4.1.1 the test suite finishes successfully, as shown in Listing 4.7.

```
[info] MoneySpec
[info] - should work with ReflexiveEquality (3 seconds, 686 milliseconds)
[info] ScalaTest
[info] Run completed in 36 seconds, 957 milliseconds.
[info] Total number of tests run: 1
[info] Suites: completed 1, aborted 0
[info] Tests: succeeded 1, failed 0, canceled 0, ignored 0, pending 0
[info] All tests passed.
> Done testing
> ** Tests successful! **
```

Listing 4.7: Log output of the test suite concerning *ReflexiveEquality*.

Looking at the run time of this specific run, it shows us that the *ReflexiveEquality* test case was executed within 4 seconds. While running the whole test suite took almost 37 seconds. This difference is due to the fact that the generated system is being started first, as described in Subsection 4.1.4.

The log clearly shows which test cases were run and whether these failed or not. Now that we have a working case, how does this work in case of a test failed? We can simulate a bug by modifying the generator that we use. Let's say that we have a translation error in the generator, such that the equality (==) operator would be translated to a not equal (!=) operator in the generated system. The results show a detailed stack trace of what went wrong along with the input values, such that the issue can be reproduced. Listing 4.8 shows the output after modifying the generator.

```
[info] MoneySpec
[info] - should work with ReflexiveEquality *** FAILED *** (1 second, 278 milliseconds)
[info]  java.lang.AssertionError: assertion failed: expected CurrentState(Result,Initialised
    (Data(None,Some(true)))), found CurrentState(Result,Initialised(Data(None,Some(false))))
    : With command: ReflexiveEquality(-940003591.28 EUR)
[info]  at scala.Predef$.assert(Predef.scala:170)
[info]  at akka.testkit.TestKitBase$class.expectMsg_internal(TestKit.scala:388)
[info]  at akka.testkit.TestKitBase$class.expectMsg(TestKit.scala:382)
[info]  at MoneySpec.expectMsg(MoneySpecSpec.scala:15)
[info]  at MoneySpec.checkAction(MoneySpecSpec.scala:86)
[info]  at MoneySpec$$anonfun$1$$anonfun$apply$mcV$sp$1$$anonfun$apply$mcV$sp$2.apply(
    MoneySpecSpec.scala:174)
[info]  at MoneySpec$$anonfun$1$$anonfun$apply$mcV$sp$1$$anonfun$apply$mcV$sp$2.apply(
    MoneySpecSpec.scala:173)
[info]  at scala.collection.immutable.List.foreach(List.scala:381)
[info]  at MoneySpec$$anonfun$1$$anonfun$apply$mcV$sp$1.apply$mcV$sp(MoneySpecSpec.scala
    :172)
[info]  at MoneySpec$$anonfun$1$$anonfun$apply$mcV$sp$1.apply(MoneySpecSpec.scala:172)
[info]  ...
[info] ScalaTest
[info] Run completed in 35 seconds, 883 milliseconds.
[info] Total number of tests run: 1
[info] Suites: completed 1, aborted 0
[info] Tests: succeeded 0, failed 1, canceled 0, ignored 0, pending 0
[info] *** 1 TEST FAILED ***
> Done testing
> ** Some tests failed! **
```

Listing 4.8: Log output after modifying the generator

4.1.6 Test framework evaluation

The tests are generated based on the defined properties. After running the test framework, we evaluate the results and check what can be improved. The evaluation is done to be sure that the properties that we have defined are being tested (automatically) by the test framework and that we are able to find bugs with this approach. We define the following criteria to evaluate the test framework after each iteration:

Coverage

The coverage metric is used to check whether the properties are actually being tested. In case something in the system is not covered by the tests, it could be that the properties were not being tested. For example, this could happen if our test framework generates an incorrect test suite in the fourth phase (Subsection 4.1.4). Checking the coverage shows that the properties are being tested by the test suite.

An open-source library called *Scoverage* [29] is used to determine the test coverage. It creates a detailed report about the coverage. Since the generated system uses *SBT* as build tool, we use the open-source plug-in *sbt-scoverage*[2] to integrate the tool with *SBT*. The tool could report the test coverage incorrectly, causing it to be a threat for our evaluation. We also tried to use another tool, *JaCoCo* [30] but this tool didn't determine the coverage as expected, resulting in reporting 0% coverage every time.

Mutation coverage could also be a way to evaluate the test framework. *PIT* is a known tool for mutation testing, but it currently cannot meaningfully mutate *Scala* [31]. We stick with using test coverage.

We are using random input data in our experiments, which can affect the results of the coverage reports. However, multiple runs often report the same coverage. In our experiments, we will run the test framework multiple times and take the coverage report that is equal in most of these runs. This report is then used for the evaluation.

The coverage report shows how many statements exist in the generated system and how many of those were covered. Additionally, it does the same for branches, which is the number of different execution paths that could be taken. We will use the statement coverage and the total percentage of coverage. The coverage report also shows which parts of each statement have been executed, it shows green highlighting for covered parts and red highlighting for uncovered parts. The coverage highlighting for the *ReflexiveEquality* property described in this chapter highlights everything green, meaning that the whole statement was executed, as shown in Figure 4.2.

```
case ReflexiveEquality(x) => {
    checkPostCondition((nextData.get.result.get == ((
        x == x
    ))), "new this.result == ( x == x )")
}
```

Figure 4.2: Test coverage example for *ReflexiveEquality*

The logic of a specification is defined in one *Class* in the generated system, which is called *Logic* and prefixed by the *Rebel* specification name. We will only look at these classes to check to which extent the properties have been tested, using the highlighting that shows the coverage.

[2] https://github.com/scoverage/sbt-scoverage

The generated system also contains some other logic that is more related to how it communicates with other instances when it is deployed, which is not something that is covered by the properties we defined in Chapter 3. As a result, we will not be able to bring the test coverage to 100%. However, all files in the generated system will be used to determine the overall coverage percentage[3]. Since we use the same generated system to determine the coverage, the higher the coverage, the more complete it tests the defined properties in the generated system.

Number of bugs

The number of bugs found by an experiment also describes how effective the experiment was. Although this cannot be a hard criterion, as it can vary per case. Consider that the system was already tested thoroughly, such that the bugs that this test suite would have found are already solved. This would mean that the number of bugs found would remain 0, thus wouldn't have any effect as criteria. It is still an interesting part, as the number of bugs found proofs that the test framework is able to find bugs. Because of this, we will report on this criterion and take it into account.

4.2 Conclusion

The research question for this chapter lead as follows:

> How can we test each property as automatically as possible to find bugs in the generator?

Existing approaches often require the system under test to be written in the same language. This was not possible when testing the generator in our case. In our case, the generator is being used to generate a system, against which the test suite will run. Our approach is similar to *QuickCheck* in that we use random input values and test each property multiple times. It differs in that we use a *Rebel* specification and the generated system to check whether the properties hold when using the generator. Unlike *QuickCheck*, we do not use mitigation techniques to pinpoint the edge cases.

We demonstrated a full cycle based on one property, which indicated that this approach works to check a property. A full cycle consists of the following 5 phases:

1. Create specification
2. Check & build
3. Generate system
4. Generate test suite
5. Run test suite

The first step is done manually by translating the properties to a *Rebel* specification. The test framework is able to execute the other phases, which can be found in the `Main.rsc` file in the source code.

For the experiments, all the properties defined in Chapter 3 will be used. This results in a bigger specification, which can be used to test the generator automatically by using the test framework. After running the test framework, we evaluate it on the coverage and number of bugs found metrics. The event definitions of each property defined in Chapter 3 can be found in the Appendix A. The event definitions for the additional properties that were added in the third experiment (Chapter 7) can be found in Appendix B.

[3]Library files are not included when determining the coverage

4.3 Threats to validity

Uncompilable system

When the generated system is unable to compile, the test framework cannot proceed. Because it cannot run the generated test suite against the generated system in that case. Although such errors could be detected by the test framework, it is out of scope for this thesis. It is hard to argue whether the compilation error would be a bug or something else, as it can have many causes.

When running the test framework, it can still occur that the generated system is unable to compile. We will see this back in Chapter 5. The test framework terminates when the generated system cannot compile. Affecting the bugs that we could find to answer the third research question: What kind of bugs can be found using this approach and how many?

Random input

A threat to our approach is that we are probably not generating enough random input to detect all bugs. This affects the amount of bugs we find in each experiment as well as the kind of bugs that we might find to answer the third research question: What kind of bugs can be found using this approach and how many? Also, in case we do not find any bugs, it could be that there are no bugs in the system anymore. Or that we do not generate enough random input to detect additional bugs. Or that our set of properties are not complete, as described in Chapter 3. Since we do only check for the properties we have defined, the first option is not the case. This approach does not find all the bugs in the system, but only checks the system with the properties that we have defined.

One system

Only one generator is being used throughout this thesis. However, it would be useful to make the test framework compatible with the other generators and generated systems too. This enables reasoning about the different implementations and its generators. Some changes are required to make the test framework compatible with these systems. By doing so, every generated system for which a generator is built by *ING* can be checked based on the same properties, resulting in that the defined properties are checked thoroughly on every system and that inequalities can be detected between the different generators. Testing multiple generators can result in finding more bugs, which can affect our results to the third research question: What kind of bugs can be found using this approach and how many?

A threat in doing so is that one of the other generators might not support some translations of each expression that is used in the specification that we created. Thus the test framework can also be used to check whether every expression variant is taken into account by the generator. Unfortunately, an error in this translation would be blocking, in that it can lead to a generated system that is not able to compile. Resulting in that the test framework cannot proceed to run the test suite on the generated system. This could be used as a way to check the generators too. Although compilation errors were not the aim of the project, as compilation errors can have many causes, the test framework can still be used to detect those to a certain extent.

Whitebox implementation

We use property-based testing as testing technique and implemented the required functionality ourselves, resulting in a white-box implementation. This means that we expect that our values generation is working correctly too. In case this isn't working correctly, a fix is required. This is a threat to our second research question: How can we test each property as automatically as possible to find bugs in the generator? Because this would mean that a property cannot be tested automatically and that this can be improved (by fixing it). In turn, it can also affect the bugs that we could find to answer the third research question.

Another way how this could be done was to check how the custom types were generated to *Scala*. And

then generate a *Scala* test project using the same types. Writing property tests for each type could achieve the same goal when it comes to checking the implementation of this component in the generated system. However, if we would follow this approach, we wouldn't use the generator to translate the *Rebel* expressions to *Scala*. This results in that the generator itself is still not being tested. With our approach, we test the generator and are able to find errors in the generator. Although we cannot conclude that the generator is implemented correctly when the generated test suite runs successfully, rather we can conclude that the properties it checks for are satisfied.

Chapter 5

Experiment 1: Using random input

The properties that we defined in Chapter 3 are translated into test cases as described in Chapter 4. In this experiment, we expect to find some bugs that were unknown before by using the test framework. When we have triggered some bugs, an investigation is needed to check what the cause is of that bug. Next, we can categorize the bugs found to partially answer the third research question: What kind of bugs can be found using this approach and how many?

5.1 Method

In the first experiment, each property will be tested 100 times with random input values. This means that if the property holds for 100 tests, it is reported to be successfully satisfying the property. This is a similar approach compared to what *QuickCheck* does when checking properties. Unlike *QuickCheck*, the test framework does not shrink the input values to come with minimum values for which the case fails. Instead, it will just report the values that were used when the property failed.

5.2 Results

Two runs are being done to detect bugs in the generator in this experiment because the first run terminated quickly. The test framework was unable to proceed in testing every property in this run.

5.2.1 First run

The first run results into a termination of the run due to a compile error in the generated system. Although we made the assumption that the generated system should be compilable, this error came from a property definition that was expected to hold, namely *AssociativeMultiplicationInteger1*. Which is why we can consider this as an error that is found when using the test framework. The error describes that an overloaded method cannot be applied to the *Money* type, as shown in Listing 5.9.

```
[error] MoneySpec.scala:316: overloaded method value * with alternatives:
[error]  (x: Double)Double <and>
[error]  (x: Float)Float <and>
[error]  (x: Long)Long <and>
[error]  (x: Int)Int <and>
[error]  (x: Char)Int <and>
[error]  (x: Short)Int <and>
[error]  (x: Byte)Int
[error] cannot be applied to (squants.market.Money)
[error]         Initialised(Data(result = Some(((((x * y)) * z) == (x * ((y * z)))))))
[error]                                                                 ^
[error] MoneySpec.scala:441: overloaded method value * with alternatives:
[error]  (x: Double)Double <and>
[error]  (x: Float)Float <and>
[error]  (x: Long)Long <and>
[error]  (x: Int)Int <and>
[error]  (x: Char)Int <and>
[error]  (x: Short)Int <and>
[error]  (x: Byte)Int
[error] cannot be applied to (squants.market.Money)
[error]           checkPostCondition((nextData.get.result.get == ((((x * y)) * z) == (x *
    ((y * z))))), "new this.result == ( (x*y)*z == x*(y*z) )")
[error]                                                                                 ^
[error] two errors found
[error] (compile:compileIncremental) Compilation failed
[error] Total time: 79 s, completed 4-aug-2017 13:03:45
> Done testing
> ** Some tests failed! **
```

Listing 5.9: Log output first test run resulting in a termination.

The error log does not clearly indicate what exactly went wrong. It doesn't show clearly which property is causing this error. Also, it does not describe what the types of the variables were. Investigating the generated system reveals that both errors were happening when dealing with the *AssociativeMultiplicationInteger1* property. This means that the variables x, y and z are of type *Integer*, *Integer*, *Money* respectively. Temporarily disabling this property allows the test framework to proceed further.

5.2.2 Second run

After disabling the *AssociativeMultiplicationInteger1* property, the test framework was able to run completely. This results in 7 failing tests. For each test, the input values for which the property doesn't hold are logged such that the error can be reproduced. In Table 5.1 an overview of the failing properties, along with its input values (x, y and z) are shown.

Property name	x	y	z
DistributivePercentage1	0.51	-311254801.77 EUR	-707194075.77 EUR
DistributivePercentage2	0.93	2089630160.75 EUR	-1316628389.49 EUR
DistributiveInteger2	-883022216	-298435082.93 EUR	715725888.96 EUR
AssociativeMultiplicationPercentage2	840296462	1771903729.60 EUR	0.53
DistributiveInteger1	-1790274467.41 EUR	1691684272	1449321647
AssociativeMultiplicationInteger2	-1852801029.34 EUR	-1309504561	1880170895
AssociativeMultiplicationPercentage1	-352883323.42 EUR	0.27	294211708

Table 5.1: Overview of failing tests along with its input values

5.3 Analysis

For each failed test we investigate what went wrong. The first four tests reveal precision problems when using the *Money* type in calculations. The latter three tests were also failing because of these precision problems. However, these tests were also failing after the precision errors were fixed. Thus, for the latter 3 tests, another version of the generated system was used, which contains the fixes for the precision problems. This is done such that we are able to reveal the other errors that these properties can reveal.

DistributivePercentage1

This property uses a *Percentage* value and two *Money* values for its tests. The values are named x, y and z respectively. To check this failing test, we check the results of the intermediate calculations in the formula that is being used. In Table 5.2 the values are shown for which the test case failed, along with the intermediate calculations. The intermediate calculations seem to be fine, as the results are almost the same when we compare the results of the *Scala* evaluation and the expected result. The resulting left-hand side of the expression contains a precision error, which is caused when multiplying a *Percentage* (the x variable) with a *Money* type (the result of $y+z$ in this case).

Variable	Value	Type
x	0.51	Percentage
y	-311254801.77 EUR	Money
z	-707194075.77 EUR	Money
Formula	**Scala result**	**Expected result**
x*(y+z) == (y*x)+(z*x)	false	true
x*(y+z)	**-519408927.54539996 EUR**	**-519408927.5454 EUR**
(y*x)+(z*x)	-519408927.5454 EUR	-519408927.5454 EUR
y+z	-1018448877.54 EUR	-1018448877.54 EUR
y*x	-158739948.9027 EUR	-158739948.9027 EUR
z*x	-360668978.6427 EUR	-360668978.6427 EUR

Table 5.2: DistributivePercentage1: Precision error when multiplying a *Percentage* with *Money*

DistributivePercentage2

This test case looks similar as DistributivePercentage1. It uses the same type of variables, but the expression is slightly different. In Table 5.3 the result and the intermediate calculations of a failing case are shown. What can be seen here is that the precision error occurs when the *Money* type is multiplied by the *Percentage* type. While with DistributivePercentage1 it was the other way around.

Variable	**Value**	**Type**
x	0.93	Percentage
y	2089630160.75 EUR	Money
z	-1316628389.49 EUR	Money
Formula	**Scala result**	**Expected result**
(y+z)*x == (y*x)+(z*x)	false	true
(y+z)*x	718891647.2718 EUR	718891647.2718 EUR
(y*x)+(z*x)	718891647.2718001 EUR	718891647.2718 EUR
y+z	773001771.26 EUR	773001771.26 EUR
y*x	**1943356049.4975002 EUR**	**1943356049.4975 EUR**
z*x	**-1224464402.2257001 EUR**	**-1224464402.2257 EUR**

Table 5.3: DistributivePercentage1: Precision error when multiplying a *Money* with *Percentage*

DistributiveInteger2

This case uses *Integer* in conjunction with the *Money* type. Earlier cases showed that there was a precision error when using the *Percentage* and *Money* types. Since the *Percentage* type is translated to a *Double* in the generated system, it can be expected that there would be precision problems occurring. As this is a known issue with types that use floating-point arithmetic [27]. This case reveals that a precision error also occurs when multiplying *Money* with an *Integer*. In the intermediate calculations when investigating a failing test with its values are shown in Table 5.4. The last two rows, in boldface, show that a precision error occurs when *Money* is multiplied by an *Integer*.

Variable	**Value**	**Type**
x	-883022216	Integer
y	-298435082.93 EUR	Money
z	715725888.96 EUR	Money
Formula	**Scala result**	**Expected result**
(y+z)*x == y*x + z*x	false	true
(y+z)*x	-368477052257036740 EUR	-368477052257036762.48 EUR
y*x + z*x	-368477052257036796 EUR	-368477052257036762.48 EUR
y+z	417290806.03 EUR	417290806.03 EUR
y*x	**263524808260992384 EUR**	**263524808260992372.88 EUR**
z*x	**-632001860518029180 EUR**	**-632001860518029135.36 EUR**

Table 5.4: DistributiveInteger2: Precision error when multiplying *Money* with an *Integer*

AssociativeMultiplicationPercentage2

The earlier cases already shown a precision error when using *Double* and *Integer* in conjunction with *Money*. This case triggers the same problem, but also reveals that the same thing happens when multiplying an *Integer* with *Money*. While with DistributiveInteger2 it was the other way around. The intermediate calculations are shown in Table 5.5, the calculation of multiplying an *Integer* with *Money* is shown in boldface. Additionally, this case shows that the small precision errors can cause a noticeable difference, which lead to a difference of 130 EUR in this case (in the *Scala* results).

Variable	**Value**	**Type**
x	840296462	Integer
y	1771903729.60 EUR	Money
z	0.53	Percentage
Formula	**Scala result**	**Expected result**
(x*y)*z == x*(y*z)	false	true
(x*y)*z	789129950543366910 EUR	789129950543366877.856 EUR
x*(y*z)	789129950543366780 EUR	789129950543366877.856 EUR
x*y	**1488924434987484670 EUR**	**1488924434987484675.2 EUR**
y*z	939108976.688 EUR	939108976.688 EUR

Table 5.5: AssociativeMultiplicationPercentage2: Precision error causing bigger differences

DistributiveInteger1

This case also uses three variables: *x*, *y* and *z*. Which are of type *Money*, *Integer* and *Integer* respectively. In Table 5.6 the different values are shown of the calculation between *Scala* and the expected result. In boldface, it shows how the addition of two (positive) integers results in a negative value. This is because the resulting value of the addition would be bigger than the maximum value of what an *Integer* type can hold. This results occurrence is called integer overflow [32]. The operation that is being done does not check or prevent this overflowing behaviour. Although this could be expected when using the *Integer* type, it can lead other errors classes of vulnerabilities, including stack and heap overflows [33], when this is not being prevented.

Variable	**Value**	**Type**
x	-1790274467.41 EUR	Money
y	1691684272	Integer
z	1449321647	Integer
Formula	**Scala result**	**Expected result**
x*(y+z) == (x*y)+(x*z)	false	true
x*(y+z)	2065907589620385223.57 EUR	-5623262698769382599.79 EUR
(x*y)+(x*z)	-5623262698769382599.79 EUR	-5623262698769382599.79 EUR
y+z	**-1153961377**	**3141005919**
x*y	-3028579159080673575.52 EUR	-3028579159080673575.52 EUR
x*z	-2594683539688709024.27 EUR	-2594683539688709024.27 EUR

Table 5.6: DistributiveInteger1: *Integer* overflows when using addition

AssociativeMultiplicationInteger2

For this case three variables are used: *x*, *y* and *z*, which are of type *Money*, *Integer* and *Integer* respectively. In Table 5.7 the values of a failing test case are shown, along with the intermediate formula steps. On the left-hand side of the expression, we see the expected results, while on the right-hand side there is a big difference between the *Scala* result and the expected result (shown in boldface in Table 5.7). The result value of the operation would become smaller than the minimum value of what an *Integer* value can be. When this happens, an integer underflow occurs which results in the value being "wrapped" to the maximum value [32], and then being used to calculate further. This underflow results in an unexpected amount, which we can see back in the results. The operation neither checks for underflowing an *Integer* value nor does it prevent it.

Variable	**Value**	**Type**
x	-1852801029.34 EUR	Money
y	-1309504561	Integer
z	1880170895	Integer
Formula	**Scala result**	**Expected result**
(x*y)*z == x*(y*z)	false	true
(x*y)*z	4561676263499657218201... EUR[1]	4561676263499657218201... EUR
x*(y*z)	**3877739486117270379.94 EUR**	**4561767263499657218201769467.30 EUR**
x*y	2426251398546224819.74 EUR	2426251398546224819.74 EUR
y*z	-2092906591	-2462092362461952095

Table 5.7: AssociativeMultiplicationInteger2: *Integer* underflows when using multiply

AssociativeMultiplicationPercentage1

In this case there are three variables: *x*, *y* and *z*, which are of type *Money*, *Percentage* and *Integer* respectively. In Table 5.8 the values and intermediate calculations are shown of a failing case, such that we can reason about the results. The row in boldface shows a precision error when comparing the results of *Scala* and the expected result with each other. This issue is caused by the *Percentage* that is being used. In the implementation, the *Percentage* is being translated into a *Double* value. In this case, this *Double* value is then being multiplied with an *Integer*. This results in a *Double* value containing a precision error, which is related to the problems with floating-point arithmetic [27].

[1] This value has been truncated for readability. The exact value is "4561767263499657218201769467.30 EUR". The same counts for the "Expected result" column.

Variable	Value	Type
x	-352883323.42 EUR	Money
y	0.27	Percentage
z	294211708	Integer
Formula	**Scala result**	**Expected result**
(x*y)*z == x*(y*z)	false	true
(x*y)*z	-28032049433190944 EUR	-28032049433190942.3672 EUR
x*(y*z)	-28032049433190948 EUR	-28032049433190942.3672 EUR
x*y	-95278497.3234 EUR	-95278497.3234 EUR
y*z	**79437161.16000001**	**79437161.16**

Table 5.8: AssociativeMultiplicationPercentage1: A precision error when using *Percentage*

Additionally, we can see a difference in the results on the left-hand and right-hand side of the expression evaluation in *Scala*. Whereas the intermediate step for the left-hand side is calculated correctly. This also hints to the bug in the *Money* type which we already found when testing the *DistributiveInteger2* property. For the right-hand side, we cannot say this immediately, as there is already an error in the intermediate step.

This property revealed a precision error when the *Percentage* type is being used. The *Percentage* is being translated to a *Double* value, causing operations with it to have precision errors. In this case the *Percentage* is being multiplied by an *Integer*.

5.4 Evaluation criteria

When looking at the coverage results, it is notable that the condition for the if-clause of the implicative properties is often not being triggered. Resulting in that it always returns *true*, as this is how it was specified in the specification (the else-clause of an implicative property). This is caused by the random values that are being used as input. An example of this is the *TransitiveEquality* property ($x = y \wedge y = z \implies x = z$). When relying on random data, there is a seldom chance that 3 values are equal to each other. Thus we could optimize the random values such that the condition holds, such that we also test these properties such that the if-clause is triggered. In Figure 5.1 the coverage for the *TransitiveEquality* property, green highlighting indicates the statements that are executed, while red highlighting indicates statements that were not checked at all.

```
case TransitiveEquality(x, y, z) => {
      checkPostCondition((nextData.get.result.get == ((
          if ((x == y && y == z)) x == z
          else true))))
      , "new this.result == ( (x == y && y == z) ? x == z : True )")
}
```

Figure 5.1: Test coverage of an implicative property (*TransitiveEquality*)

The first criteria to evaluate an experiment was to determine the test coverage. The implicative properties are not covered when using random values as input data. The other properties, which do not use implication, are fully tested though. In Figure 5.2 the results of the coverage report are shown, with a total of 87,80% coverage. The file with its name ending with "Logic" contain the

implementation of the properties. The other 12,20% code is not tested, but this part is also not related to the implementation of the properties. Because of this, it is not required to achieve the full 100% coverage. Note that the coverage does not include the coverage over the libraries that the system uses. Some implementation details are depended on the libraries that the generated system use, thus it can not be concluded that 87,80% of the system is now tested.

Lines of code:	766	Files:	4	Classes:	5	Methods:	13
Lines per file	191,50	Packages:	4	Clases per package:	1,25	Methods per class:	2,60
Total statements:	902	Invoked statements:	792	Total branches:	48	Invoked branches:	32
Ignored statements:	0						
Statement coverage:	87,80 %			Branch coverage:	66,67 %		

Class	Source file	Lines	Methods	Statements	Invoked	Coverage		Branches	Invoked	Coverage	
MoneySpecificationLogic	MoneySpecification.scala	643	7	885	789		89,15 %	48	32		66,67 %

Figure 5.2: Test coverage report of the first experiment

The branch coverage is reported to be 66,67%. This is caused by the implicative properties that are being translated to *if-else* statements, where the *else* branch is translated to *true*. Furthermore the coverage could be increased as not every part of the condition of implicative properties are being checked, as we have seen in Figure 5.1.

The second criterion that we defined is the number of bugs that we have found by doing the experiment. By using this approach we found a total of 8 bugs. A compilation error (1x), overflow/underflow errors (2x) and precision errors (5x). Many of these precision errors originated from the library that is used for the *Money* type, for which we created an issue on *Github*[2]. An improvement to the test framework, such that the implicative properties are also covered, might result in more bugs that can be found.

5.5 Conclusion

In this first experiment, we tested each property that was defined in Chapter 3 100 times with using random values as input. First, the test suite terminated due to a compilation error. After disabling the causing property (temporarily), a total of 7 tests were failing. In this experiment, we managed to find precision errors and overflow/underflow errors. Additionally, we found a compilation error when using a property which was expected to hold. The precision errors that were related to the *Money* type were reported. These bugs are fixed in the next version of the generator.

Although many properties were tested successfully, the test framework also indicates that the implicative properties were satisfied. However, when looking at the statement coverage of the implicative properties, we saw that the if-clause is often not being triggered. Meaning that it would call the else-clause which simply returns true. When relying on random data, there is a seldom chance that the if-clause is being triggered. Thus we could optimize the generated input values such that these satisfy the condition for the if-clause.

5.6 Threats to validity

Fixed amount of tries

The 100 tries to check a property is a fixed number that is being used, but why exactly this number and not a higher or lower number? It might be the case that some errors are not triggered because of this fixed amount. Running more cases might be revealing an additional error, or it might not.

[2]https://github.com/typelevel/squants/issues/265

In case it doesn't, it means that the test framework just requires more time to run the whole test suite, while it does not have an effect on the results. 100 seems to be an amount that works such that it consistently reports the same amount of failing tests however, this has checked by running it the test runs multiple times, also with using numbers like 300 or 50 for the amount. Also *QuickCheck* uses this amount to check a property. During this thesis, we stick with 100 as the number of tries. Finding the optimal number of tries is left as future work, thus remaining as a threat to validity in this approach.

The optimal amount of tries would be a useful addition when answering our second research question: How can we test each property as automatically as possible to find bugs in the generator? Although we focus on automatically testing the properties, not mentioning the efficiency. Increasing the efficiency of the test framework would result in less time required to run it. Also, adding more properties would increase the time required to run the test suite. It might also be the case that increasing the number of tries would result in finding additional bugs. Thus leading to a threat to answering the third research question: What kind of bugs can be found using this approach and how many?

Amount of test runs

The test framework has been executed several times for this experiment. With each run, 7 tests were failing, which consistently were the same tests on every run. Because of this, we assumed that the causes of these failures were the same, as the same tests failed on each run. However, the causes might not have been the same for these runs, thus remaining as a threat to validity to answering our third research question. Because the causes of the failing tests could be different and might reveal additional bugs.

Unfixed issue

Unfortunately, the compilation error has not been fixed throughout this project however, it is an open issue on *Github*[3]. The property causing this issue is disabled in order to continue running the test framework. This prevents the test framework from detecting bugs that could be found by this property.

[3]https://github.com/typelevel/squants/issues/281

Chapter 6

Experiment 2: Improving coverage

Some bugs were found by using random input values in the first experiment. However, the implicative properties were not effectively checked in terms of triggering the if-clause when using random input values. This is what we aim to improve in this experiment, expecting to detect more bugs.

6.1 Method

We can separate the properties that we have in 2 different categories: those using implication ($\Longrightarrow$) and those that do not. The defined properties are being separated over two specifications according to which category these belong. We name these specifications *MoneyExpressions* and *MoneyConditionals*. For the *MoneyConditionals* specification (the implicative properties), another way of generating the random values would be more useful. The random input values will be optimized such that the condition of the if-clause of these properties are being satisfied. For the other specification (*MoneyExpressions*), the earlier approach (random values as input) can still be used. We do not need to change this functionality for these cases since the properties can be used with random values.

In the *MoneyConditionals* specification, the condition to trigger the if-clauses will be added to the preconditions of each event definition in *Rebel*, such that these can be used to generate the values matching this clause. The updated event definition of the *Symmetric* property is shown in Listing 6.10 for example. Where the preconditions have been added to the event definition.

```
1 event symmetric(x: Money, y:Money) {
2     preconditions {
3         x == y;
4     }
5     postconditions {
6         new this.result == ( (x == y) ? y == x : False );
7     }
8 }
```

Listing 6.10: The updated event definition of the *Symmetric* property

When generating the test suite, the events are being traversed. In case an event with some preconditions is found, it generates a list of tuples containing the values that satisfy the condition to trigger the if-clause. Which is different compared to the generated tests in Chapter 5. The size of the tuples depends on the arity of the event from which the test is being generated.

The first difference is that it now uses our custom generator to determine the input values, instead of the built-in random generator in *Java*. A list of tuples, containing values which satisfy the if-clause of the implication, is being generated. Our custom generator is a simple proof of concept in order to check if this will actually result in more failing tests. This custom generator basically consists of multiple methods which are being called based on the event name. In Listing 6.11 this behaviour

is shown for the *Symmetric* and *Division1* event. The *String* parameter of these methods is a way how we can pattern match on the event name in *Rascal*. In case the event couldn't be handled, an exception is thrown.

```
1  private list[Expr] genTestValueForEvent("Symmetric") {
2      Expr moneyValue = genRandomMoney();
3      return [moneyValue, moneyValue];
4  }
5  private list[Expr] genTestValueForEvent("Division1") {
6      real moneyAmountX = genRandomDouble();
7      real intAmountY = genRandomInteger();
8      real moneyAmountZ = moneyAmountX * intAmountY;
9      str currency = genRandomCurrency();
10     return [convertToMoney(currency, moneyAmountX), converToExpr(intAmountY), convertToMoney(currency,
           moneyAmountZ)];
11 }
12 private default list[Expr] genTestValueForEvent(str eventName) {
13     throw "genTestValueForEvent not implemented for event <eventName>";
14 }
```

Listing 6.11: Values generation for *Symmetric* and *Division1*, including the fall-back case.

This means that the way how we determine these values is basically hard-coded, requiring to have knowledge about the if-clause itself. Note that this doesn't make this approach very dynamic, but the result will consist of a list of tuples that satisfy the if-clause. These tuples will be used as input for the test case that will be generated.

However, the input values that are generated now are fixed when we use them directly in a test case, which completely removes the randomness of the input values when running the test suite multiple times. It would be better to keep the randomness, such that the input values are different on each run. To solve this problem, we mutate the values in the list with a random operation, such that the values are sort of random again. The tuples still have to satisfy the condition to trigger the if-clause, as this was the actual intention. So the second difference compared to the first experiment, is that for each tuple in the list, we will generate a random operation and use that operation to mutate the values inside the tuple. To ensure that the tuple values still satisfy the condition of the if-clause, each value in the tuple will be mutated by the same operation. In Listing 6.12 an example of a generated test case is shown.

```
"work with Antisymmetry" in {
     Seq((USD(1593.62), USD(1593.62)), (USD(2869.78), USD(2869.78)),
        (EUR(4676.80), EUR(4676.80)), (USD(1850.29), USD(1850.29)),
        // ... // More values in the list
        (USD(9501.16), USD(9501.16)), (- EUR(149.67), - EUR(149.67)),
        (- EUR(159.67), - EUR(159.67)), (EUR(8015.77), EUR(8015.77)))
     .foreach {
       data: (Money, Money) => {
         val randomOperation = genRandomOperation(genRandomOperator("Money", true),
             generateRandomMoney(data._1.currency), generateRandomInteger(true),
             generateRandomInteger(false), generateRandomPercentage(true),
             generateRandomPercentage(false), Random.nextInt(10))

         checkAction(Symmetry(
            randomOperation(data._1),
            randomOperation(data._2)
            )
         )
       }
     }
   }
```

Listing 6.12: Resulting test case with semi-random values. Omitted some input tuples for readability.

The list of values are generated by using our custom generator, the number of tuples in the list can be defined when generating the test suit. A method `genRandomOperation()` has been added to the template, which is used to mutate the fixed values in the list. After all the `checkAction()` method is being called to check the result.

Now that the input values for the implication events should always satisfy the condition of the if-clause, we can also update the specification such that the else-clause of the expression always returns *False*. This can be seen in Listing 6.10. This results in a failing case again in case the precondition was not met. When this happens, it indicates that there's a problem with either our value generator or with the generator itself.

6.2 Results

Running the test framework with these changes results in 2 additional failing tests compared to the first experiment (Chapter 5). An overview of the failing properties and the used input values are shown in Table 6.1. The log of the test run reports that the precondition was not met when using these input values, as shown in Listing 6.13.

Property name	x	y	z
Division1	-16729.90 USD	830	-20.16
Division2	-44.68 USD	870	-38870.47

Table 6.1: Failing tests overview along with its input values

```
[info] MoneyConditionals
[info] - should work with Additive4params (7 seconds, 224 milliseconds)
[info] - should work with AntisymmetryLET (5 seconds, 493 milliseconds)
[info] - should work with Symmetric (5 seconds, 344 milliseconds)
[info] - should work with Division2 *** FAILED *** (23 milliseconds)
[info]  java.lang.AssertionError: assertion failed: expected CommandSuccess(Division2
    (-16729.90 USD,830,-20.16 USD)), found CommandFailed(NonEmptyList(PreConditionFailed(x
    == z*y)))
[info] - should work with Division1 *** FAILED *** (127 milliseconds)
[info]  java.lang.AssertionError: assertion failed: expected CommandSuccess(Division1(-44.68
     USD,870,-38870.47 USD)), found CommandFailed(NonEmptyList(PreConditionFailed(x*y == z))
    )
// ...
```

Listing 6.13: Precondition failed error in *Division1* and *Division2*.

6.3 Analysis

The values used in the test case should be correct since we generated these values such that they satisfy the condition of the if-clause and thus they should satisfy the preconditions. Note that the conditions of the if-clause were added as preconditions in the *MoneyConditionals* specification, which causes the error. As the *PreConditionFailed* error is thrown by the system when the input values do not satisfy the preconditions.

For *Division1* it states that the condition `x*y == z` failed. The values used for x, y and z were *-44.68 USD*, *870* and *-38870.47 USD* respectively. The result of $x * y$ = *-44.68 USD * 870 = -38871.60 USD*. This should be equal to z. In fact, the input of z was slightly different, *-38870.47 USD*.

Remember that the input values are being mutated by a random operation that we have added to the test cases. This difference is caused by the precision error when operating with the *Money* type, which was found in Chapter 5. The random operation that was done was causing this behaviour. The same goes for the error with *Division2*, where `x == z*y` should hold. The values of x, y and z are *-16729.90 USD*, *830*, *-20.16 USD* respectively. The result of $z * y$ = *-16732.80 USD*, which is not equal to the expected value *-16729.90 USD* (the value of x).

The first experiment already described the precision problem and how it could be fixed. To solve this problem, we modify the generator such that the precision error is fixed when generating the system. Then the test framework is being executed again to check whether both tests are succeeding. This resulted in the same amount of tests that were failing, which means that we found a different case now. In Table 6.2 an overview of the used input values are shown[1]. The log reported that one case still fails on the precondition check, while the other case just reports values for which the result is *false*, as shown in Listing 6.14.

Property name	**x**	**y**	**z**
Division1	1.5043478260... USD	-779	-1171.8869565217... USD
Division2	-3328.8254545454... USD	-129	25.8048484848... USD

Table 6.2: Failing tests overview, after fixing precision errors

[1]The decimals have been truncated for readability, Listing 6.14 shows the exact values

```
[info] MoneyConditionalsSpec:
[info] MoneyConditionals
[info] - should work with Additive4params (7 seconds, 24 milliseconds)
[info] - should work with AntisymmetryLET (3 seconds, 66 milliseconds)
[info] - should work with Symmetric (4 seconds, 361 milliseconds)
[info] - should work with Division2 *** FAILED *** (670 milliseconds)
[info]  java.lang.AssertionError: assertion failed: expected CommandSuccess(Division2
    (-3328.82545454545454545454545454555 USD,-129,25.804848484848484848484848484848 USD))
    , found CommandFailed(NonEmptyList(PreConditionFailed(x == z*y)))
[info] - should work with Division1 *** FAILED *** (316 milliseconds)
[info]  java.lang.AssertionError: assertion failed: expected CurrentState(Result,Initialised
    (Data(None,Some(true)))), found CurrentState(Result,Initialised(Data(None,Some(false))))
    : With command: Division1(1.5043478260869565217391304347826O9 USD
    ,-779,-1171.88695652173913043478260869565 2 USD)
// ...
```

Listing 6.14: Precondition failed error in *Division1* and *Division2*.

The test concerning *Division2* shows that the precondition check fails. If we look at the input values, it can be seen that the *Money* values are a fractional number. As it contains many decimals and it rounds up at the end. When operating with this rounded value, the resulting value is also slightly different. As the generated system is implemented such that the preconditions are being checked first, the *PreConditionFailed* exception is thrown. This leads to the issue of the division problem in which a number cannot be equally divided. When defining the properties in Chapter 3, we did not take this into account. Instead, we defined that it should contain the exact value, which cannot be done in this case. This should be defined in order to determine whether this is expected or incorrect.

When looking at *Division1*, we see another case as the input values passed the precondition checks. This indicates that the values satisfy the condition to trigger the if-clause of the property. However, the result of the if-clause returns *false*, showing us that the property does not hold when using these input values. Thus a case has been found for which the *Division1* property doesn't hold. The investigation of the intermediate calculation steps are shown in Table 6.3. Note that the *Division1* property is defined as $x \cdot y = z \implies x = z/y$.

Variable	**Value**	**Type**
X	1.5043478260869565217391304347826O9 USD	Money
Y	-779	Integer
Z	-1171.88695652173913043478260869565 2 USD	Money
Formula	**Scala result**	**Expected result**
x*y == z	true	false
x == z/y	false	false
x*y	-1171.88695652173913043478260869565 2 USD	-1171.88695652173913043478260869565**211** USD
z/y	1.5043478260869565217391304347826O8 USD	1.5043478260869565217391304347826O8 USD

Table 6.3: Division1: Difference in rounding

In the results, we can see that the expected values do not match the property either. Although in *Scala* the first expression is considered *true*. Since the expected results also return *false* for the intermediate calculations, the input values might not fully satisfy the condition to trigger the if-clause. Which could be an implementation error in our values generator. However, it's notable that in *Scala* the condition was first considered to hold since it passed the precondition checks. This indicates that

there is a rounding error happening in the system, which triggered this case.

Unfortunately, we are unable to trace back how the input values used for this tests were exactly determined. As these are build up by using randomly generated values and then mutating these by a random operation (as described in Section 6.1). Nevertheless, the results show that there is also an unexpected rounding going on when executing *x*y* in *Scala*. As the expected value contains some additional decimals compared to the result from *Scala*.

6.4 Evaluation criteria

To evaluate this experiment, we use the version of the generator in which the precision problems related to the *Money* type are fixed. This is done because otherwise the precision errors would cause more tests to fail. Additionally this would cause that the rounding errors found Section 6.3 would not be triggered.

When looking at the coverage report concerning a specific implicative property, it can be seen that the else-clause of the implication is not being triggered anymore. This was also the intention of the modification done in this experiment, as the if-clause is actually what we wanted to check in this experiment. In Figure 6.1 the coverage highlighting of *TransitiveEquality* is shown.

```
case TransitiveEquality(x, y, z) => {
      checkPostCondition((nextData.get.result.get == ((
          if ((x == y && y == z)) x == z
          else false
      ))), "new this.result == ( (x == y && y == z) ? x == z : False )")
}
```

Figure 6.1: Test coverage for *TransitiveEquality* in second experiment

The expectation was that the test framework could be improved, such that the test coverage on the generated system would become higher. In the first experiment we found that the implicative properties were not tested thoroughly. This is what has been improved in this experiment. The coverage report does not indicate a huge difference compared to the first experiment (Chapter 5). The total test coverage is 88,87%, which is slightly higher (1,07%) than the results in the first experiment. The report is shown in Figure 6.2. Note that the properties have been categorized in this experiment, this is also visible in the coverage report (there are now two "Logic" files, one for each category).

Lines of code:	945	Files:	7	Classes:	9	Methods:	25
Lines per file	135,00	Packages:	4	Clases per package:	2,25	Methods per class:	2,78
Total statements:	988	Invoked statements:	878	Total branches:	48	Invoked branches:	24
Ignored statements:	0						
Statement coverage:	88,87 %			Branch coverage:	50,00 %		

Class	Source file	Lines	Methods	Statements	Invoked	Coverage		Branches	Invoked	Coverage	
MoneyExpressionsLogic	MoneyExpressions.scala	475	7	581	553		95,18 %	0	0		100,00 %
MoneyConditionalsLogic	MoneyConditionals.scala	283	7	379	319		84,17 %	48	24		50,00 %

Figure 6.2: Test coverage report of the second experiment

It is notable from the coverage report that the branch coverage is exactly 50%. This amount is lower than what it was in the first experiment. However, in this experiment the implicative properties are being tested thoroughly, which was not the case in the first experiment. Considering that the else-clause of the implicative properties is not being triggered, the test coverage will never become

100%. Which is not a problem in that sense, as we don't intend to test the else-clause. We are more interested in the result of the if-clause of these implicative properties. This is also true for the branch coverage, which can be expected to be 50%. Although the first experiment reported a higher amount for this, it was not testing the implicative properties good enough in the first experiment.

The other criteria we use was the number of bugs that we have found. Using this approach 2 more tests were failing compared to the first experiment in Chapter 5. The division problem was not taken into account when defining the properties, which resulted in these failing cases.

When defining the properties, it was stated that the value should be the exact value, while this is not possible with division. This results in a threat to the definition of this property. Because of this, we consider the bugs that were found as false positives. Although, because of this it might be the case that the actual bugs it might be able to find, are being hidden because of this. Resulting in false negatives: bugs that exist in the system, but are not found by the test framework.

6.5 Conclusion

In this experiment, we generated the input values such that the condition of the implicative properties are satisfied. This revealed 2 additional failing cases that are triggering the division problem and indicating a rounding issue. The generated system tries to hold the exact value, which triggers this situation. It is reasonable that the system tries to hold the exact value, but it is also unclear from the property definitions what should happen in this case.

When defining the properties in Chapter 3, we said that a value should be precise. However, it is not possible to do this for all division cases. This depends on the input values when testing the property. Because of this, we consider the bugs that were found as false positives. The definition of the property has to be updated in order to specify what should happen in case such a division error occurs. Due to this error, it might be the case that existing bugs in the generator are not being detected with this approach.

In this experiment we found false positives and haven't found additional bugs when testing the implicative properties. The use of implicative properties might not be as effective as using properties that do not. Although more functionalities from the generator are being used, and thus being tested, by this approach. Which wouldn't be the case when the implicative properties are being removed. The if-statements and preconditions were not being used in the first experiment Chapter 5. The property definitions should be updated such that it is known what should happen in this case of division. In the next experiment we will focus on improving this.

6.6 Threats to validity

Incorrect value generation

We have implemented a custom value generator to generate values for each test case. A random operation is being done on these values to make these random again. There could be an error in the implementation that incorrect values are being created. In Chapter 4 we described a similar threat concerning incorrect value generation. In this case, the traceability of how the values were created is hard because of the random operation.

We have seen such an error when running this experiment multiple times. It sometimes happened that there were additional tests failing. Although these do not trigger in every run, leaving it as a threat to this approach. The error that caused these test to fail was that the preconditions are not met. This was only the case for some properties that are using "smaller than" ($<$) and "greater than" ($>$) in its definitions. The input values are set to all zeros, which results in the condition $0 > 0$, which results in *false*. There is a high probability that this is caused by the random operation that

is being done to mutate the input values. As mentioned earlier, the traceability for this is hard and since it does not happen regularly, fixing this issue is left as future work. Leaving it as a threat to our results.

Chapter 7

Experiment 3: Automatic value generation

In the second experiment (Chapter 6), we found that the property definition for using division with the *Money* type wasn't clear enough in that it couldn't be satisfied the way how it was specified. In this experiment we aim to improve this, by updating the existing definition such that the property can now be checked.

A limitation in the second experiment was that the value generation was not very dynamic when new property definitions were being added. It should be possible to add additional properties to the specification, such that these properties are being tested automatically by the test framework. To do this, the value generator should be updated too, such that it uses the preconditions in the event definitions to determine the input values. Additional properties can then be added to test the generator.

In this experiment we will use the updated version of the generator, in which the precision errors that were found in the first experiment are fixed. This is done, such that we can focus on possible additional errors that might occur.

7.1 Method

The property definitions of *Division* is being updated for this experiment because the first definition did not take the division problem into account. There was also no definition for rounding the value, as the value was expected to hold the exact value. We will update the definition by implementing a rounding function, such that these properties can be tested by the test framework.

Besides updating the property definitions for *Division*, additional property definitions are being added to test more of the generator. However, as we have seen in the second experiment, the values generator was not very dynamic. Which resulted in that it had to be modified in case an implicative property is being added to the specification. This is the second thing that should be improved, such that additional (implicative) properties do not require modifications to the values generator.

7.1.1 Updating property definitions

Initially, there were only 2 property definitions that were using division, which both are being updated. In order to check for the values such that the property definition can be used, we implement a `round()` method in the *Rebel* specification. This *round* method is intended to return a value which can be used to define the expected behaviour when using division with the *Money* type.

In addition to updating the existing properties that are using division, more properties can be added which were not defined earlier. Additional properties might also lead to additional bugs that the test

framework can detect. For example, properties of inequality when using division, as the ones that were defined for division only used equality. We add more properties to the existing set of property definitions that we defined for *Rebel*: Properties for division, multiplication, additivity and subtraction.

The additional property definitions for division, multiplication, additivity and subtraction fall under the "Properties of equality and inequality" category and are defined in Subsection 3.2.3, along with the updated definitions. To sum up, the updated and added property definitions are: *divisionEquality*, *divisionInequality*, *additiveEquality*, *additiveInequality*, *subtractiveEquality*, *subtractiveInequality*, *multiplicativeEquality* and *multiplicativeInequality*.

Some properties using division are now using the `round()` method in its definition. *Rebel* does not provide a way to round a value, which is why we need to define the function in the specification. In *Rebel*, a function is defined as an expression that is being executed whenever the function is being called. Unfortunately, there is currently no way in *Rebel* to write down the *Scala* implementation of this *round* function. As a workaround, we define the implementation as a *String* and modify the generator such that the content of the *String* (removing the quotes) will be the implementation of the function. The *round* method rounds the *Money* value to a maximum of 4 decimals.

In *Java* (and thus in *Scala*), there are different rounding methods available. These consist of the rounding modes described in the IEEE 854 standard and additional rounding modes as described in [34]. The fifth decimal in our *round()* method is being rounded by using the "HALF_UP" rounding mode (described in [34]). We chose for the "HALF_UP" as this is more in line with our expectations and this mode is perhaps the most commonly used rounding mode when rounding financial numbers. However, we also analyse the effects of using some of the other available rounding modes. The implementation of the *round()* method in the *Rebel* specification is shown in Listing 7.15.

```
1 function round(money: Money): Money =
2     "money.currency(money.amount.setScale(4, RoundingMode.HALF_UP))";
```

Listing 7.15: The *round()* function in the *Rebel* specification.

7.1.2 Improving dynamicallity

The additional properties that are being added also use implication in their definitions. In the second experiment (Chapter 6), the value generator was not dynamic enough in that it requires modifications to the implementation for each implicative property that is being added. In this experiment, we aim to improve this, by using the defined preconditions to determine the input values.

A custom value generator is being created that uses the preconditions to determine the input values. Note that this can be seen as an update to the earlier value generator that was created in Chapter 6. This value generator parses the preconditions and intends to generate values based on these conditions. Since the expressions inside the preconditions can become complex, we focus on a limited version of it. Limited in the sense that we support all of the properties that we defined in Chapter 3, but other expressions that were not used in our definitions might be unsupported.

Most properties are using single variables in its precondition statements. Some are using expressions on the left-hand or right-hand side of a statement, but not on both sides. The value generator that we implement will not support using expressions on both the left-hand and right-hand side, as generating values matching the condition can result in complex formulas. With expressions, we mean a combination of operators with literals and variables. Instead, the value generator requires having at least a variable on one side of the expression.

The code to generate the tuples of input values is shown in Listing 7.16. We can separate this

process into the following steps:

1. Initialize value generation data (Line 7)
2. Traverse and handle statements (Line 9-13)
3. Generate values for remaining, unassigned, variables (Line 15-18)
4. Add values to resulting list (Line 21)

```
1  public list[list[Expr]] genValues(str eventName, Preconditions? preconditions, list[Parameter] transitionParams,
       int amount) {
2      println("\> Generating values for event <eventName>");
3
4      list[list[Expr]] valueList = [];
5      for (int i <- [0..amount]) {
6          calculatedParams = (); // Clear old data
7          paramGenData = ("<p.name>" : <p.tipe, -9999.00, 9999.00, true> | p <- transitionParams);
8
9          // Calculating
10         for(/Statement s <- preconditions) {
11             <lhs, rhs, operator> = extractStatementData(s.expr);
12             handleConditionStatement(operator, lhs, rhs);
13         }
14
15         // Check whether all are determined, if not, determine those using the randomValueProps data
16         for (Parameter p <- transitionParams, !calculatedParams["<p.name>"]?) {
17             calculatedParams["<p.name>"] = calculateExpression(p.name);
18         }
19
20         // Add to list
21         valueList += [[getExprForVar("<p.name>") | p <- transitionParams]];
22     }
23     return valueList;
24 }
```

Listing 7.16: Code to generate the list of input values for an event.

In the following sections we describe each step in detail.

1. Initialize value generation data (Line 7)

To generate a single value, some data is being held to keep track of the conditions which the generated value should fulfil. These conditions are the minimum value, the maximum value and whether the zero value is allowed. Additionally, the result type of the variable is stored, used when generating the final value. This data is stored in a tuple and called *RandomValueProps* by using an *alias* in *Rascal*. This definition is shown in Listing 7.17.

```
1 // Minimum: including. So: if 0, then 0 can be a result value when determining it random.
2 // Maximum: including. So: if 10, then 10.00 is max result value when determining random.
3 alias RandomValueProps = tuple[Type valueType, real min, real max, bool allowZero];
```

Listing 7.17: The definition of *RandomValueProps* in *Rascal*.

The value generator initializes the *RandomValueProps* for each input variable. Setting the minimum and maximum value to a default value and allowing zero by default.

2. Traverse and handle statements (Line 9-13)

Each statement in the preconditions block is being checked. The *handleStatement()* method handles each statement. The actions done by this method depend on the operators used in the statement that

is being handled.

In case of an expression that only contains variables and uses equality (for example, $x == y$), the value generator assigns a random value to x and assigns the same value to y. In case of inequality (for example, $x < y$ or $x > y$), the value generator also assigns a random value to x and adjusts the minimum or maximum bounds of the y value such that it satisfies the condition.

In case there is an expression on one side (for example, $x * y == z$), the expression will be evaluated first. In this case, random values will be assigned to x and y. Next, the expression can be evaluated and the result of that is being assigned to z. The same is done with inequality relations, but then the minimum or maximum bounds are being set based on the operator.

As mentioned earlier, having expressions on both the left-hand and the right-hand side of the expression is unsupported. The *handleStatement()* method will throw an error in case this happens.

3. Generate values for remaining, unassigned, variables (Line 15-18)

When handling each expression, some variables already get an assigned value. However, some variables might only have their *RandomValueProps* updated but do not have an assigned value yet. In this step, the variables that do not have an assigned value, are being assigned a value based on their *RandomValueProps*.

4. Add values to resulting list (Line 21)

The values that have been determined are being added to the list of generated input values. In the end, the list is being returned, containing all the generated input values that match the preconditions of the event.

7.2 Results

Running the test framework with the addition of the properties defined in (Subsection 3.2.3) results in no additional failing tests compared to the first experiment. Remember that the test framework is run with the generator in which the precision problems related to the *Money* type are fixed (otherwise there would be additional failing tests, due to the precision problems).

There are still 3 failing tests in total, which are not fixed in the generator yet. These bugs have already been reported in the first experiment and thus are not new in this experiment.

7.3 Analysis

The tests are succeeding due to the implementation of the *round()* method. It rounds the value of *Money* to 4 decimals using the "HALF_UP" rounding mode. The number 4 is chosen here to ensure that the property definitions should hold up to a precision of 4 decimals when using the round method. However, this can be modified in case a bigger precision is preferred. Changing the precision number to 6 or 8 decimals does not change the results when looking at the number of failing tests. Also, changing the rounding mode to "DOWN" does not affect our results. Although, when using a bigger precision in combination with another rounding mode, such as "FLOOR" or "TOP", can result in some failing tests. This is being caused by an edge case in which the difference would be slightly off between the two values.

We stay with the implementation of "HALF_UP" as rounding mode, as this is more in line with our expectations and this mode is perhaps the most commonly used rounding mode when rounding financial numbers. This rounding mode is also described as a "requirement for many financial calculations" [34]. One might want to use the "DOWN" rounding mode because a bank would prevent

losing money because of this rounding issue. When this is the case, it can always be changed in the *Rebel* specification when needed, we stick with "HALF_UP" as rounding mode.

For this experiment, additional property definitions have been added to test the generator. The value generator now determines the values based on the preconditions of the properties. Thus the additional properties used in this experiment did not require more effort than writing these down in the *Rebel* specification. Compared to the second experiment (Chapter 6) this is a huge improvement, as it does not require the developer to modify the value generator when implicative properties are being added.

Another way how the values could be generated is by using existing solvers. Since the *Rebel* toolchain already makes use of a bounded model checker to check a specification, this could be used to translate an expression and retrieve values for which the condition holds.

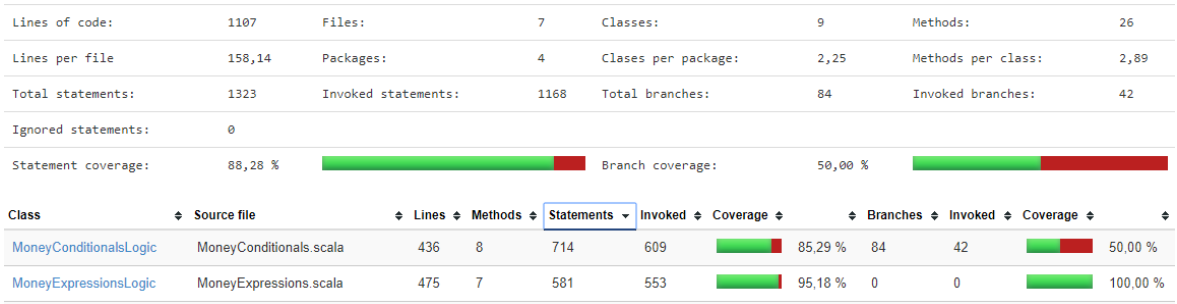
We have looked into this, by using the *Z3* solver. However, the solver always returns the same number when executing it multiple times. Which means that the 100 values that we would ask from the generator, will be exactly the same. A workaround would be to then add the number that was received earlier as an additional constraint, such that 100 unique values are being retrieved. But the problem still remains, as executing the same script multiple times will result in the same values. Another possibility would be to change the seed of the random generator that is being used to generate the values, resulting in different values, however, then a random seed should be used each time the solver is being run to make the generated values unique. In order to integrate the solver with the test framework, the value generator has to be changed.

Checking a *Rebel* specification by using the existing tool chain can already take up some time. Which is probably related to the translations that have to be done and actually running the solver. We have not measured the exact duration of each step in this case, but we expect that generating 100 random input values by using this existing implementation in the tool chain requires some time. Resulting in a overall run time increase for the test framework.

Other solvers might work better for this approach, but these still require an update to the values generation part of the test framework to integrate with such solvers. We stick with our own implementation. The properties that are defined until now can be tested by the test framework automatically with this implementation, as well as additional property definitions in case these are supported by this implementation.

7.4 Evaluation criteria

The coverage in this experiment is almost the same as in the second experiment. The implicative properties are being checked in the same way. In this experiment, additional properties were added. The total test coverage is 88,28% (which is 0,42% lower than the second experiment), shown in Figure 7.1. This shows that adding additional properties do not increase or decrease the test coverage in big amounts. The small percentage loss could be related to the fact that we do not check the *else* clauses of the implicative properties.



Lines of code:	1107	Files:	7	Classes:	9	Methods:	26
Lines per file	158,14	Packages:	4	Clases per package:	2,25	Methods per class:	2,89
Total statements:	1323	Invoked statements:	1168	Total branches:	84	Invoked branches:	42
Ignored statements:	0						
Statement coverage:	88,28 %			Branch coverage:	50,00 %		

Class	Source file	Lines	Methods	Statements	Invoked	Coverage		Branches	Invoked	Coverage	
MoneyConditionalsLogic	MoneyConditionals.scala	436	8	714	609		85,29 %	84	42		50,00 %
MoneyExpressionsLogic	MoneyExpressions.scala	475	7	581	553		95,18 %	0	0		100,00 %

Figure 7.1: Test coverage report of the third experiment

The branch coverage is still reported to be 50%, while the number of branches has been increased. This is correct, as the additional properties are using the implication symbol, which is being translated to if-else statements. This introduces these extra branches. As described before, we do not intend to check the else-clause but are more interested in checking the if-clause.

Unfortunately, no additional bugs have been found in this experiment. Additional properties were being used in this experiment compared to the other experiments, but these did not reveal more bugs. The implicative properties are checked in the same way as in the second experiment, but the values are now generated based on the preconditions of the event definitions in the *Rebel* specification.

The properties that have been added did not require changes in the value generator anymore. Instead, these only had to be written down in the *Rebel* specification. The test framework automatically determines the input values for it. This is an improvement compared to the second experiment, as there it would be required to update the value generator whenever an implicative property is added. There are still some limitations on the value generator, for example, it does not support complex expressions as preconditions. This is also not needed for the current set of property definitions and might or might not be needed in the future. Because of this, we leave the implementation for supporting complex expressions in the value generation as future work.

7.5 Conclusion

This experiment focused on improving the value generation, such that it is not required to update the test framework whenever an implicative property is being added to the *Rebel* specification. The value generator now uses the statements in the precondition block to determine the input values, which hereby satisfy the preconditions. We have shown that this increased the dynamicallity by adding additional properties. Adding these properties to the test framework was only a matter of translating those property definitions to *events* in the *Rebel* specification.

This experiment did not reveal extra bugs in the generator, but we have shown that adding more property definitions does not require an update to the test framework when it comes to implicative properties. However, there are still some limitations when it comes to the value generation. One of the limitations is that it does not work with complex expressions as preconditions. The value generator will throw an exception when an expression is given that is unsupported.

7.6 Threats to validity

In Chapter 4 and Chapter 6 we described the threat concerning generating incorrect input values. In this experiment we brought changes to the way how these input values are being determined. However, the threat still remains as the current implementation could contain some errors too. When running the test framework, we haven't encountered issues with this, other than the one described in Chapter 6.

Chapter 8

Discussion

In this chapter we discuss the sub research questions.

RQ 1: Which properties are expected to hold on the semantics of the generated code?

There were no existing properties defined for *Rebel* that were expected to hold. We have defined many properties for *Rebel*. With the focus on the *Money* type, which is considered the most important type for a bank.

Many properties have been defined, but are these all the properties? Is each definition correct? Some properties might be considered incorrect or overlapping with others. We have seen this with the definition of *division* that was incorrect, which was encountered in the second experiment. In the third experiment the property definitions for *division* have been updated. Additionally, extra properties were added to the list for the third experiment, *additivity*, *subtraction* and *multiplication*. This showed how additional properties could be added to the test framework to test the generator. In case of incorrect, missing or overlapping property definitions, the current set of property definitions could be updated as we have done with the third experiment. There can be many combinations among the different types of *Rebel* and the supported operators. Therefore, the set of properties that we have defined in Chapter 3 is not the complete set of expected properties in *Rebel*. Although we focused on the *Money* type in *Rebel*, there could be more properties for this. Thus, the set of properties that we have defined is also not complete when only focusing on the *Money* type.

Each property definition is defined as an expression, the test framework is currently limited to checking the generator on these kind of properties. We can also think of other properties that should hold in *Rebel*. For example, the behaviour of sync block: what are the properties of the sync block in *Rebel*? Can these be described in a *Rebel* specification? If so, the current test framework would not support that definition yet because it can currently only cope with expression-based properties.

RQ 2: How can we test each property as automatically as possible to find bugs in the generator?

We have described a way how the generator can be tested by using property-based testing. In order to check the generator, a *Rebel* specification is created containing the property definitions. This specification is used by the test framework to generate tests and run these tests against the generated system.

The initial version of the test framework used random values to test each property. The first experiment showed that this doesn't work for the implicative properties. The if-clause of these implicative properties were not being triggered when using random values. In the second experiment the test framework was improved. The input values where determined such that the condition of the implicative property was being satisfied. Additionally, these values were being mutated by a random

operation, to keep the randomness of the input values. This improvement to the test framework revealed some incorrect property definitions. Also, the implementation of how the input values were determined was not very dynamic. Because every time an implicative property was being added to the specification, an update was required to the test framework.

In the third experiment the input values were determined in a more dynamic way, by using the preconditions to determine the input values. This requires a property definition to define its preconditions. As a result, it was not required to update the test framework when implicative properties were being added. This is shown in the third experiment.

We evaluated the test framework in each experiment by looking at the test coverage and the number of bugs that have been detected. The coverage details showed that in the first experiment the if-clause of the implicative properties was not being triggered. Which lead to an improved version in the second and third experiment. Furthermore the branch coverage reported a consistent 50% over the second and third experiment, which is caused by the implicative properties. The else-clause is not being tested, but that is also not the intention of that property.

The overall test coverage for each experiment was roughly the same (87.80%, 88.87% and 88.28%). This shows that despite of the improvements made to the test framework, the test coverage did not change. However, each experiment is different, some of the differences have an impact on the coverage results:

- The first experiment used random input values for each property. The else-clause of the implicative properties were defined as `true`, resulting that each implicative property was considered correct.
- In the second experiment the else-clause of the implicative properties were set to `false`. The input values are generated such that these satisfy the condition of the if-clause. These values are also being mutated when running the test, to keep the actual values random.
- During the second experiment a fixed version of the generator was being used. This version contains fixes for the issues that were related to the *Money* type. The coverage has been determined with the use of the fixed version of the generator.
- In the third experiment some incorrectly defined properties were updated and additional properties have been added.
- Note that the test framework has been updated throughout the experiments. Meaning that the third experiment contains the changes of the second experiment.

The test coverage of the first experiment would be considerably lower in case the else-clause of the implicative properties would be `false`. This would result in that every test concerning an implicative property would fail. Although the result of this would find many false-positives, because it just returns *false* in its definition.

The test coverage over the second and third experiment are roughly the same (only 0.59% difference). The third experiment tested 17 more properties than the second experiment. This shows that adding additional properties does not have much impact on the test coverage. The additional properties are being checked automatically by the test framework because these properties are defined in the *Rebel* specification.

RQ 3: What kind of bugs can be found using this approach and how many?

Multiple bugs were found using property-based testing to check the generator. The generator failed to satisfy a total of 8 properties that we have defined. Some properties triggered different kind of bugs. We can categorize the bugs found as follows:

Precision errors: Errors causing an unexpected outcome value when using calculations.

Overflow/underflow errors: Errors happening because of a value limit that has been reached on specific types.

Compilation errors: Errors that make the generated system unable to compile, resulting that the generated system cannot be used.

Despite of the bugs that were found, we also found that two of the initial property definitions were incorrect. This was not found in the first experiment because of the random values. In the second experiment, this finding was the result of using a fixed version of the generator in which the precision errors related to the *Money* type were fixed. This shows that some errors can hide other bugs, this is also known as finding false-negatives. We do not consider the invalid property definitions as bugs. This was not due to an error in the generator, but an error in the property definitions.

The test framework should also be able to find other kind of bugs which did not exist in the generator that we have used. We can think of certain operations that are not correctly implemented. For example, when addition would act like subtraction. This would cause each the test case that use addition to fail.

Also, we perhaps have missed some property definitions that would trigger more bugs in the generator. The use of other types and operators that exist in *Rebel* can lead to more bugs. *Rebel* also supports data structures like *map* and *set* which we did not cover during this thesis. Therefore we cannot conclude that the test framework would only find the kind of bugs that we found. But we can conclude that these kind of bugs can at least be found, which we have shown in the experiments.

Below we provide a discussion about the different kind of bugs that have been found, precision errors, overflow/underflow errors and compilation errors.

Precision errors

As we have seen, the *Money* precision errors both occurred when using *Percentage* values as well as when using *Integer* values to operate with the *Money* type. We were able to reproduce the issue in a clean *REPL* environment and concluded that the problem existed in the open-source library, called *Squants* [21]. This library is being used for the *Money* type. In order to solve this problem, we created an issue on *Github*[1] related to the precision problems on the *Money* type. A contributor responded and fixed the issue within a day, the change will be included in the next version of the library (1.4).

The generator should be updated to use this version of the library in order to fix these precision errors. This is what has been done in the second experiment, where we use the fixed version of the generator. So would updating the library fix all the precision errors that have been found? No, in the first experiment one of the precision errors found was being caused by multiplying a *Percentage* with an *Integer*. This precision error is not related to the precision errors when using the *Money* type and still remains to exist in the generator. There might be more precision errors when using the generator, but then we did not define properties for these cases and thus did not trigger those. Thus, adding more property definitions might lead to more bugs, including precision errors.

Overflow/underflow errors

The overflow/underflow errors are caused by using the *Integer* type. On one hand, this could be prevented by checking the operations beforehand for overflow errors. On the other hand, this could be the expected behaviour when an *Integer* is being used in *Rebel*. As *Integers* are known have such limits that are also dependent on the platform the application is run [33]. However, in *Rebel* there is currently no other type that can be used to hold a bigger number. For example in *Java* there is *Long* for a larger number or *BigDecimal* for even bigger numbers. This would mean that *Rebel* does not support such big numbers or that a custom type must be used for this. Although *Rebel* does support custom types, the generator does not support custom types yet. Meaning that custom types will not

[1] https://github.com/typelevel/squants/issues/265

work with the current implementation.

Considering that *Rebel* does not provide another type for bigger numbers, we conclude that the *Integer* type should also hold bigger numbers. In this case, *Integer* is being used to represent a number value in *Rebel*. Since the specification is about banking products and it probably could happen that a big number is needed. After all, we cannot know this for sure, as *Rebel* does not provide a specification yet of each of type in *Rebel*. Maybe it is not needed or required to support bigger numbers than an integer, resulting in that our conclusion is incorrect. However, what would be the minimum and maximum value it can hold then? Would it be the value of a 32 bit *Integer*, a 64 bit *Integer* or perhaps even arbitrary size numbers? In case our conclusion is incorrect, this should be defined too. The property definition could be updated to describe the actual bounds of the input values.

Compilation errors

In the first experiment, the test framework was initially being terminated because of a compilation error. Although one assumption was that the generated system should be able to compile, another assumption was that the specification was consistent. The specification containing all the properties is consistent, as *Rebel* did not report any syntactic or semantic errors with the type checker. Because of this, it was expected that the generated system could compile and run.

The test framework is able to find such compilation errors, as we have seen in the first experiment. However, the test framework cannot proceed with running the generated tests in this case, thus hiding other bugs that can exist. The test framework does not specifically check for compile errors and whether these are expected or not. This is out of the scope of this thesis, because there can be many causes of compilation errors in the generated system and detecting the actual causes of those is hard, if not impossible.

The cause of the compilation error we found in the first experiment was an implementation error in the open-source library that is being used for the *Money* type called *Squants* [21]. We created a *Github* issue[2] describing this problem. When this issue has been fixed, the generator should be updated in order to fix this compilation error. Since this issue has not been fixed during this thesis, we temporarily disabled the property causing this problem.

[2] https://github.com/typelevel/squants/issues/281

Chapter 9

Conclusion

In this thesis, we have shown a way how the generator can be tested by using property-based testing. This is done by generating tests based on the *Rebel* specification and making use of the generator to generate the tests. The *Rebel* specification is build up based on a set of defined properties of *Rebel*. These property definitions were not defined earlier, thus we defined many expected properties in *Rebel*.

With test framework we have found some bugs in the generated system that were unknown before. This proves that this approach already worked to identify some problems in the generator that were not known before. Additionally, we contributed to an open-source library called *Squants*, by issuing two reports of bugs that existed in the library.

To answer the main research question, we defined and answered the three sub research questions, which have been discussed in Chapter 8. The main research question was as follows:

> How can the generator in the *Rebel* toolchain be tested automatically, by using the generated system, to check whether the implementation works as expected?

A *Rebel* specification is created from the defined properties. Next, the existing generator is being used to generate the generated system and to translate the properties (in the *Rebel* specification) to test cases. When running the test framework, we found some errors by using the generated system. Additionally, we were able to detect a compilation error and incorrectly translated formulas.

We conclude that, by using this approach, the semantics of the generated code can be checked automatically on whether it satisfies the defined properties. With this approach, we have found bugs in the generated code that were unknown before. The full source of our test framework is available on *Github*[1].

9.1 Future work

Complete property definitions

In this thesis, we defined some properties on the *Rebel* language, which we consider to hold when using *Rebel*. This list of property definitions on *Rebel* is not complete, there can be many more properties and there are other types available in *Rebel* which we did not cover. Defining these and adding them to the set of property definitions is left as future work.

Values generation by using solvers

The current value generation works for the properties that we defined throughout this thesis. When additional properties are being added, the value generator might or might not have to be updated. This depends on what preconditions have to be parsed for that property and whether the current

[1] https://github.com/alexkok/master-thesis

implementation supports these operations.

Another way how the value generator could work is to use some tools to determine the random values. As we have discussed in Chapter 7, the *SMT* solver would theoratically be an option. Although in our attempts this resulted in having the same input values every time the test framework is run. To counter this problem, other solvers might be more useful to implement this behaviour, such as *SageMath* [35]. *SageMath* can parse expressions and determine the conditions to which each variable in the expression should hold. When using this, it would mean that the value generator has to be modified such that it integrates with this tool. Another approach could be used for this too, such as concolic testing [36] to determine the input values. We did not use this in this thesis, due to time constraints.

Multiple generators

Throughout this thesis, we have only tested the Scala/Akka generator which is developed by *ING*. Since there are more generators available, the test framework can be improved such that it is compatible with the other systems that can be generated by using one of the other generators that are available within *ING*. By doing this, the same property definitions can be tested on different kind of generated systems. This can be used to detect inequalities among the generated systems. Although the properties will remain the same in this case, generating the test suite requires some modifications for each generator.

Templating is used to generate the test cases. The way how the tests should be written down depends on the generated system. When a generated system uses a different setup or is written in another language then *Scala*, an update is needed for this part of the test framework. The other parts of the test framework can be reused, as the test framework also uses the generator from which the generated system is created.

Mutation testing

Another metric to evaluate the effectiveness of the test framework would be to use mutation testing. The mutation coverage could be used to measure how effective the test framework would be (the number of mutants created and the number of killed mutants). Unfortunately, there is currently a limited support for mutation testing for *Scala* systems. *PIT* for example, cannot meaningfully mutate *Scala* code [31]. Because of this, we did not use this as metric to evaluate the test framework.

Scala compiles to *Java* bytecode, mutating on bytecode level could be used too. However, some mutants might not be relevant in that the modifications would not affect the implementation, which can lead to false-positives.

Other components

Besides completing the set of property definitions, the test framework could also be extended such that it can also support property definitions concerning other components of the system. Such as the sync block definitions, which defines actions that should happen synchronously. Or performance measures when interacting with data in the system. Currently, such components are not being tested and are unsupported, while these components are also important for the bank. This is left as future work.

It might not be possible to check each and every component by using this approach. For example, it might be unable to check how multiple generated systems would integrate with each other and if this is done correctly. The generated system is configured to work with multiple distributions of the system, but is not being tested thoroughly yet.

Acknowledgements

First of all I would like to thank my supervisor, Jurgen Vinju, for his help and guidance throughout the thesis. Despite of his busy schedule, he always found a way to help, to discussing about the topic and to provide feedback throughout my thesis.

Also I would like to thank my company supervisor, Jorryt-Jan Dijkstra, for his help, discussions and feedback throughout this thesis. Thanks to my colleagues at the *ING* and my co-intern on the same topic, Thanusijan Tharumarajah for the discussions we had and for the feedback throughout this thesis.

I would like to thank my fellow students of the master Software Engineering at the University of Amsterdam, for the great times, support and insights throughout past year. The teachers of this masters programme for the interesting and informative courses. Thanks to Ana Oprescu, whom was always available during this master programme for questions, discussions and information about the master programme.

Bibliography

[1] J. Stoel, T. V. D. Storm, J. Vinju, and J. Bosman, "Solving the bank with rebel: on the design of the rebel specification language and its application inside a bank," *Proceedings of the 1st Industry Track on Software Language Engineering - ITSLE 2016*, 2016.

[2] J. Stoel, "A case for rebel, a dsl for product specifications," in *Proceedings of Domain-specific Language Design and Implementation 2015 (DSLDI 2015)*, pp. 9–11, arXiv, 2015.

[3] R. Ramler and K. Wolfmaier, "Economic perspectives in test automation: balancing automated and manual testing with opportunity cost," in *Proceedings of the 2006 international workshop on Automation of software test*, pp. 85–91, ACM, 2006.

[4] G. Fink and M. Bishop, "Property-based testing: a new approach to testing for assurance," *ACM SIGSOFT Software Engineering Notes*, vol. 22, no. 4, pp. 74–80, 1997.

[5] G. Fink and K. Levitt, "Property-based testing of privileged programs," in *Computer Security Applications Conference, 1994. Proceedings., 10th Annual*, pp. 154–163, IEEE, 1994.

[6] K. Claessen and J. Hughes, "Quickcheck: a lightweight tool for random testing of haskell programs," *Acm sigplan notices*, vol. 46, no. 4, pp. 53–64, 2011.

[7] T. Arts, J. Hughes, J. Johansson, and U. Wiger, "Testing telecoms software with quviq quickcheck," in *Proceedings of the 2006 ACM SIGPLAN workshop on Erlang*, pp. 2–10, ACM, 2006.

[8] J. Gannon, P. McMullin, and R. Hamlet, "Data abstraction, implementation, specification, and testing," *ACM Transactions on Programming Languages and Systems (TOPLAS)*, vol. 3, no. 3, pp. 211–223, 1981.

[9] R.-K. Doong and P. G. Frankl, "The astoot approach to testing object-oriented programs," *ACM Transactions on Software Engineering and Methodology (TOSEM)*, vol. 3, no. 2, pp. 101–130, 1994.

[10] A. H. Bagge, V. David, and M. Haveraaen, "The axioms strike back: testing with concepts and axioms in c++," *ACM Sigplan Notices*, vol. 45, no. 2, pp. 15–24, 2010.

[11] C. Pacheco and M. D. Ernst, "Randoop: feedback-directed random testing for java," in *Companion to the 22nd ACM SIGPLAN conference on Object-oriented programming systems and applications companion*, pp. 815–816, ACM, 2007.

[12] M. Boussaa, O. Barais, B. Baudry, and G. Sunyé, "Automatic non-functional testing of code generators families," in *Proceedings of the 2016 ACM SIGPLAN International Conference on Generative Programming: Concepts and Experiences*, pp. 202–212, ACM, 2016.

[13] M. Makki, D. Van Landuyt, and W. Joosen, "Automated regression testing of bpmn 2.0 processes: a capture and replay framework for continuous delivery," in *Proceedings of the 2016 ACM SIGPLAN International Conference on Generative Programming: Concepts and Experiences*, pp. 178–189, ACM, 2016.

[14] M. Al-Hajjaji, S. Krieter, T. Thüm, M. Lochau, and G. Saake, "Incling: efficient product-line testing using incremental pairwise sampling," in *Proceedings of the 2016 ACM SIGPLAN International Conference on Generative Programming: Concepts and Experiences*, pp. 144–155, ACM, 2016.

[15] M. F. Johansen, Ø. Haugen, and F. Fleurey, "An algorithm for generating t-wise covering arrays from large feature models," in *Proceedings of the 16th International Software Product Line Conference-Volume 1*, pp. 46–55, ACM, 2012.

[16] S. R. Dalal, A. Jain, N. Karunanithi, J. Leaton, C. M. Lott, G. C. Patton, and B. M. Horowitz, "Model-based testing in practice," in *Proceedings of the 21st international conference on Software engineering*, pp. 285–294, ACM, 1999.

[17] T. Tharumarajah, "Runtime testing generated systems from rebel specifications," Master's thesis, Universiteit van Amsterdam, the Netherlands, 2017.

[18] L. De Moura and N. Bjørner, "Z3: An efficient smt solver," *Tools and Algorithms for the Construction and Analysis of Systems*, pp. 337–340, 2008.

[19] L. Inc., "Akka — akka." http://akka.io/, 2017.

[20] T. A. S. Foundation, "Apache cassandra." http://cassandra.apache.org/, 2016.

[21] Typelevel, "Squants." http://www.squants.com/, 2017.

[22] S. Kang and S. Ryu, "Fortresscheck: automatic testing for generic properties," in *Proceedings of the 2011 ACM Symposium on Applied Computing*, pp. 1290–1296, ACM, 2011.

[23] R. Nilsson, "Scalacheck." https://www.scalacheck.org/, 2015.

[24] J. K. Baumgart, "Axioms in algebra where did they come from?," *The Mathematics Teacher*, vol. 54, no. 3, pp. 155–160, 1961.

[25] J. G. Raftery, "A perspective on the algebra of logic," *Quaestiones Mathematicae*, vol. 34, no. 3, pp. 275–325, 2011.

[26] T. M. Apostol, *Calculus, volume I*, vol. 1. John Wiley & Sons, 2007.

[27] D. Goldberg, "What every computer scientist should know about floating-point arithmetic," *ACM Computing Surveys (CSUR)*, vol. 23, no. 1, pp. 5–48, 1991.

[28] M. Fowler, *Patterns of enterprise application architecture*. Addison-Wesley Longman Publishing Co., Inc., 2002.

[29] "Scoverage." http://scoverage.org/, 2017.

[30] "Jacoco." http://www.eclemma.org/jacoco/, 2017.

[31] "sbt-pit." https://github.com/pitest/sbt-pit, 2017.

[32] D. Brumley, T.-c. Chiueh, R. Johnson, H. Lin, and D. Song, "Rich: Automatically protecting against integer-based vulnerabilities," *Department of Electrical and Computing Engineering*, p. 28, 2007.

[33] T. Wang, T. Wei, Z. Lin, and W. Zou, "Intscope: Automatically detecting integer overflow vulnerability in x86 binary using symbolic execution.," in *NDSS*, 2009.

[34] M. F. Cowlishaw, "Decimal floating-point: Algorism for computers," in *Computer Arithmetic, 2003. Proceedings. 16th IEEE Symposium on*, pp. 104–111, IEEE, 2003.

[35] "Sagemath." http://doc.sagemath.org/html/en/index.html, 2017.

[36] K. Sen and G. Agha, "Cute and jcute: Concolic unit testing and explicit path model-checking tools," in *CAV*, vol. 6, pp. 419–423, Springer, 2006.

Appendix A

Property definitions in Rebel

```
1  event reflexiveEquality(x: Money) {
2      postconditions {
3          new this.result == ( x == x );
4      }
5  }
6
7  event reflexiveInequalityLET(x: Money) {
8      postconditions {
9          new this.result == ( x <= x );
10     }
11 }
12
13 event reflexiveInequalityGET(x: Money) {
14     postconditions {
15         new this.result == ( x >= x );
16     }
17 }
18
19 event symmetric(x: Money, y:Money) {
20     postconditions {
21         new this.result == ( (x == y) ? y == x : True );
22     }
23 }
24
25 event transitiveEquality(x: Money, y: Money, z: Money) {
26     postconditions {
27         new this.result == ( (x == y && y == z) ? x == z : True );
28     }
29 }
30
31 event transitiveInequalityLT(x: Money, y: Money, z: Money) {
32     postconditions {
33         new this.result == ( (x < y && y < z) ? x < z : True );
34     }
35 }
36
37 event transitiveInequalityGT(x: Money, y: Money, z: Money) {
38     postconditions {
39         new this.result == ( (x > y && y > z) ? x > z : True );
40     }
41 }
```

Listing A.18: The property definitions as *Rebel* specification

```
event transitiveInequalityLET(x: Money, y: Money, z: Money) {
    postconditions {
        new this.result == ( (x <= y && y <= z) ? x <= z : True );
    }
}

event transitiveInequalityGET(x: Money, y: Money, z: Money) {
    postconditions {
        new this.result == ( (x >= y && y >= z) ? x >= z : True );
    }
}

event additive(x: Money, y: Money, z: Money) {
    postconditions {
         new this.result == ( (x==y) ? x+z == y+z : True );
    }
}

event additive4params(x: Money, y: Money, z: Money, a: Money) {
    postconditions {
        new this.result == ( (x == y && z == a) ? x+z == y+a : True );
    }
}

event commutativeAddition(x: Money, y: Money) {
    postconditions {
        new this.result == ( x+y == y+x );
    }
}

event commutativeMultiplicationInteger1(x: Integer, y: Money) {
    postconditions {
        new this.result == ( x*y == y*x );
    }
}

event commutativeMultiplicationInteger2(x: Money, y: Integer) {
    postconditions {
        new this.result == ( x*y == y*x );
    }
}

event commutativeMultiplicationPercentage1(x: Percentage, y: Money) {
    postconditions {
        new this.result == ( x*y == y*x );
    }
}

event commutativeMultiplicationPercentage2(x: Money, y: Percentage) {
    postconditions {
        new this.result == ( x*y == y*x );
    }
}

event associativeAddition(x: Money, y: Money, z: Money) {
    postconditions {
        new this.result == ( (x+y)+z == x+(y+z) );
    }
}

event associativeMultiplicationInteger1(x: Integer, y: Integer, z: Money) {
    postconditions {
        new this.result == ( (x*y)*z == x*(y*z) );
    }
}
```

Listing A.19: The property definitions as *Rebel* specification (continued)

```
event associativeMultiplicationInteger2(x: Money, y: Integer, z: Integer) {
    postconditions {
        new this.result == ( (x*y)*z == x*(y*z) );
    }
}

event associativeMultiplicationPercentage1(x: Money, y: Percentage, z: Integer) {
    postconditions {
        new this.result == ( (x*y)*z == x*(y*z) );
    }
}

event associativeMultiplicationPercentage2(x: Integer, y: Money, z: Percentage) {
    postconditions {
        new this.result == ( (x*y)*z == x*(y*z) );
    }
}

event distributiveInteger1(x: Money, y: Integer, z: Integer) {
    postconditions {
        new this.result == ( x*(y+z) == x*y + x*z );
    }
}

event distributiveInteger2(x: Integer, y: Money, z: Money) {
    postconditions {
        new this.result == ( (y+z)*x == y*x + z*x );
    }
}

event distributivePercentage1(x: Percentage, y: Money, z: Money) {
    postconditions {
        new this.result == ( x*(y+z) == x*y + x*z );
    }
}

event distributivePercentage2(x: Percentage, y: Money, z: Money) {
    postconditions {
        new this.result == ( (y+z)*x == y*x + z*x );
    }
}

event additiveIdentity1(x: Money) {
    postconditions {
        new this.result == ( x + EUR 0.00 == x );
    }
}

event additiveIdentity2(x: Money) {
    postconditions {
        new this.result == ( EUR 0.00 + x == x );
    }
}

event multiplicativeIdentity1(x: Money) {
    postconditions {
        new this.result == ( x*1 == x );
    }
}
event multiplicativeIdentity2(x: Money) {
    postconditions {
        new this.result == ( 1*x == x );
    }
}
```

Listing A.20: The property definitions as *Rebel* specification (continued)

```
event additiveInverse1(x: Money) {
    postconditions {
        new this.result == ( x+(−x) == EUR 0.00 );
    }
}

event additiveInverse2(x: Money) {
    postconditions {
        new this.result == ( (−x)+x == EUR 0.00 );
    }
}

event antisymmetryLET(x: Money, y: Money) {
    postconditions {
        new this.result == ( (x <= y && y <= x) ? x == y : True );
    }
}

event antisymmetryGET(x: Money, y: Money) {
    postconditions {
        new this.result == ( (x >= y && y >= x) ? x == y : True );
    }
}

event division1(x: Money, y: Integer, z: Money) {
    postconditions {
        new this.result == ( (x∗y == z) ? (x == z/y) : True );
    }
}

event division2(x: Money, y: Integer, z: Money) {
    postconditions {
        new this.result == ( (x == z∗y) ? (x/y == z) : True );
    }
}

event multiplicativeZeroProperty1(x: Money) {
    postconditions {
        new this.result == ( x∗0 == EUR 0.00 );
    }
}

event multiplicativeZeroProperty2(x: Money) {
    postconditions {
        new this.result == ( 0∗x == EUR 0.00 );
    }
}

event anticommutativity(x: Money, y: Money) {
    postconditions {
        new this.result == ( x−y == −(y−x) );
    }
}

event nonassociativity(x: Money, y: Money, z: Money) {
    postconditions {
        new this.result == ( (x−y)−z != x−(y−z) );
    }
}

event trichotomy(x: Money, y: Money) {
    postconditions {
        new this.result == ( x < y || x == y || x > y );
    }
}
```

Listing A.21: The property definitions as *Rebel* specification (continued)

Appendix B

Additional property definitions

```
1  event divisionEquality1(x: Money, y: Integer, z: Money) {
2      preconditions {
3          round((x*y)) == round((z));
4      }
5      postconditions {
6          new this.result == ( (round(x*y) == round(z)) ? (round(x) == round(z/y)) : False );
7      }
8  }
9
10 event divisionEquality2(x: Money, y: Integer, z: Money) {
11     preconditions {
12         round((x)) == round((z*y));
13     }
14     postconditions {
15         new this.result == ( (round(x) == round(z*y)) ? (round(x/y) == round(z)) : False );
16     }
17 }
18
19 event divisionEquality3(x: Money, y: Money, z: Integer) {
20     preconditions {
21         x == y;
22         z != 0;
23     }
24     postconditions {
25         new this.result == ( (x == y && z != 0) ? (x/z == y/z) : False );
26     }
27 }
28
29 event divisionInequalityLT1(x: Money, y: Money, z: Integer) {
30     preconditions {
31         x < y;
32         z > 0;
33     }
34     postconditions {
35         new this.result == ( (x < y && z > 0) ? (x/z < y/z) : False );
36     }
37 }
```

Listing B.22: Additional property definitions as *Rebel* specification

```
event divisionInequalityLT2(x: Money, y: Money, z: Integer) {
    preconditions {
        x < y;
        z < 0;
    }
    postconditions {
        new this.result == ( (x < y && z < 0) ? (x/z > y/z) : False );
    }
}

event divisionInequalityLGT1(x: Money, y: Money, z: Integer) {
    preconditions {
        x > y;
        z > 0;
    }
    postconditions {
        new this.result == ( (x > y && z > 0) ? (x/z > y/z) : False );
    }
}

event divisionInequalityLGT2(x: Money, y: Money, z: Integer) {
    preconditions {
        x > y;
        z < 0;
    }
    postconditions {
        new this.result == ( (x > y && z < 0) ? (x/z < y/z) : False );
    }
}

event additiveEquality(x: Money, y: Money, z: Money) {
    preconditions {
        x == y;
    }
    postconditions {
         new this.result == ( (x==y) ? x+z == y+z : False );
    }
}

event additiveEquality4params(x: Money, y: Money, z: Money, a: Money) {
    preconditions {
        x == y;
        z == a;
    }
    postconditions {
        new this.result == ( (x == y && z == a) ? x+z == y+a : False );
    }
}

event additiveInequalityLT(x: Money, y: Money, z: Money) {
    preconditions {
        x < y;
    }
    postconditions {
         new this.result == ( (x<y) ? x+z < y+z : False );
    }
}

event additiveInequalityGT(x: Money, y: Money, z: Money) {
    preconditions {
        x > y;
    }
    postconditions {
         new this.result == ( (x>y) ? x+z > y+z : False );
    }
}
```

Listing B.23: Additional property definitions as *Rebel* specification (continued)

```
event subtractiveEquality(x: Money, y: Money, z: Money) {
    preconditions {
        x == y;
    }
    postconditions {
        new this.result == ( (x==y) ? (x−z == y−z) : False );
    }
}

event subtractiveInequalityLT(x: Money, y: Money, z: Money) {
    preconditions {
        x < y;
    }
    postconditions {
        new this.result == ( (x<y) ? (x−z < y−z) : False );
    }
}

event subtractiveInequalityGT(x: Money, y: Money, z: Money) {
    preconditions {
        x > y;
    }
    postconditions {
        new this.result == ( (x>y) ? (x−z > y−z) : False );
    }
}

event multiplicativeEquality(x: Money, y: Money, z: Integer) {
    preconditions {
        x == y;
    }
    postconditions {
        new this.result == ( (x==y) ? (x∗z == y∗z) : False );
    }
}

event multiplicativeInequalityLT1(x: Money, y: Money, z: Integer) {
    preconditions {
        x < y;
        z > 0;
    }
    postconditions {
        new this.result == ( (x<y && z > 0) ? (x∗z < y∗z) : False );
    }
}

event multiplicativeInequalityLT2(x: Money, y: Money, z: Integer) {
    preconditions {
        x < y;
        z < 0;
    }
    postconditions {
        new this.result == ( (x<y && z < 0) ? (x∗z > y∗z) : False );
    }
}

event multiplicativeInequalityGT1(x: Money, y: Money, z: Integer) {
    preconditions {
        x > y;
        z > 0;
    }
    postconditions {
        new this.result == ( (x>y && z > 0) ? (x∗z > y∗z) : False );
    }
}
```

Listing B.24: Additional property definitions as *Rebel* specification (continued)

```
event multiplicativeInequalityGT2(x: Money, y: Money, z: Integer) {
    preconditions {
        x > y;
        z < 0;
    }
    postconditions {
        new this.result == ( (x>y && z < 0) ? (x*z < y*z) : False );
    }
}
```

Listing B.25: Additional property definitions as *Rebel* specification (continued)