Experiments in Formal Verification of Scala Code

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Bachelor thesis

[Insert short text (abstract) if desired]
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Abstract

In this thesis we experiment in formal verification of Bitcoin-S.

First, we show you some theory about formal verification, Stainless – a verification tool and Bitcoin-S.

Then, we try to verify that a non-coinbase transaction should not generate new coins. We explain how to create a transaction and how to check it in Bitcoin-S. After some time we realize that it is not possible with the current tools and the time we have. But because we familiarized us with the Bitcoin-S code we find a bug and send a bug fix to Bitcoin-S.

So we verify a smaller part of Bitcoin-S. The addition of Satoshis with zero. This needs a loot of changes in the code that we go through step-by-step.

Finally, we see that you should write software with verification tools in mind, because otherwise you possibly must rewrite the whole code when it comes to verification.

Contents

1. Introduction

In this work we experiment in formal verification of Scala code. We use the verification framework Stainless to verify parts of the code of Bitcoin-S, a Scala implementation of the Bitcoin protocol. In the following we describe the main aspects of formal verification, Stainless and Bitcoin-S.

1.1. What is formal verification

The longer and more complex a source code is, the more difficult it is to verify its correctness. There are different approaches to show the correctness of a program.

A powerful method to check whether a program works correctly is formal verification. This is a systematic process based on mathematical modeling. With formal verification all possible inputs are explored algorithmically and exhaustively. This is in contrast to testing, where only predefined inputs are tested. The correctness of a program is analyzed relative to its formal specification. Formal specification is a mathematical description of a software behavior that can be used by the verification tool to verify the code. [**?**]

One of such tools is Stainless which we use in our work.

1.2. Overview of Stainless

Stainless is developed by "Lab for Automated Reasoning and Analysis" (LARA) at EPFL's School of Computer and Communication Sciences. Using this framework we can verify the correctness of Scala programs. Stainless statically verifies that a program satisfies a given specification and that a program will not crash at runtime. The framework explores all possible inputs and finds a counter examples for possible failures in a program which violate the given specification. [**?**]

The main functions used to write a specification are *require* and *ensuring*. With *require* we define a precondition of a function, which we want to verify. *require* is placed at the beginning of the function body. We pass a constraint for the inputs of a function as an argument to *require* in the form of a Boolean expression.

With *ensuring* we provide a postcondition which is a condition on an output of the function. *ensuring* is called after the function body.

On invoking, Stainless tries to prove that the postcondition always holds, assuming the given precondition does hold. [**?**]

The following example demonstrates a simple formal specification for the function calculating factorial. This is a modified example from the Stainless documentation, so Stainless reports an error verifying it.

```
1 def factorial(n: Int): Int = {
2     require(n >= 0)
3     if (n == 0) {
4       1
5     } else {
6       n * factorial(n - 1)
7     }
8 } ensuring(res => res >= 0)
```

The function recursively calculates factorial of an integer number. The input of the function is constrained with *require* to a non-negative value. The result should also be non-negative. Thus, Stainless will verify whether the result of the factorial calculation is non-negative for all non-negative inputs.

Stainless can produce 3 outcomes of postcondition verification: *valid*, *invalid* and *unknown*. If the postcondition is *valid* Stainless could prove that for any inputs constrained in the precondition, the postcondition always holds. Reporting the postcondition as *invalid* the framework could find at least one counterexample which satisfies the precondition but violates the postcondition. If Stainless is unable to prove the postcondition or find a counterexample it reports the outcome *unknown*. In this case a timeout or an internal error occurred. Furthermore, Stainless checks for calls in the code to the function with invalid arguments violating the precondition. For example if we invoke factorial with a negative number it reports *invalid*. [**?**]

Let's return back to our incorrect example with factorial. Stainless reports the following result for the factorial verification from our example:

```
[Warning ] The Z3 native interface is not available. Falling back onto smt-z3.
[  Info  ]  - Checking cache: 'postcondition' VC for factorial @10:3...
[  Info  ]  - Checking cache: 'precond. (call factorial(n - 1))' VC for factorial @15:11...
[  Info  ]  - Checking cache: 'postcondition' VC for factorial @10:3...
[  Info  ] Cache miss: 'postcondition' VC for factorial @10:3...
[  Info  ] Cache hit: 'precond. (call factorial(n - 1))' VC for factorial @15:11...
[  Info  ] Cache hit: 'postcondition' VC for factorial @10:3...
[  Info  ]  - Now solving 'postcondition' VC for factorial @10:3...
[  Info  ]  - Result for 'postcondition' VC for factorial @10:3:
[Warning ]  => INVALID
[Warning ] Found counter-example:
[Warning ]   n: Int -> 17
[  Info  ]   ┌─────────────────┐
[  Info  ] ╔═╡ stainless summary ╞═══════════════════════════════════════════════════════════════════════════════════════════════════════╗
[  Info  ] ╟ └─────────────────┘                                                                                                         ╢
[  Info  ] ╟ factorial  postcondition                  valid from cache           src/TestFactorial.scala:10:3   1.055 ╢
[  Info  ] ╟ factorial  postcondition                  invalid          U:smt-z3  src/TestFactorial.scala:10:3   7.861 ╢
[  Info  ] ╟ factorial  precond. (call factorial(n - 1))  valid from cache           src/TestFactorial.scala:15:11  1.054 ╢
[  Info  ] ╠═══════════════════════════════════════════════════════════════════════════════════════════════════════════════════════════╣
[  Info  ] ╟ total: 3    valid: 2    (2 from cache) invalid: 1    unknown: 0    time:   9.970                                        ╢
[  Info  ] ╚═══════════════════════════════════════════════════════════════════════════════════════════════════════════════════════════╝
[  Info  ] Shutting down executor service.
```

Figure 1.1.: Output of Stainless verification for calculating factorial of Int number

Stainless disproves the postcondition and gives the number 17 as a counterexample. Due to an overflow in the 32 bit Int the result becomes a negative value. The program would work correct by changing the type from Int to BigInt.

Stainless supports only a subset of Scala. They call is Pure Scala. You can find the specification of Pure Scala on the Stainless website[1].

In addition, Stainless has its own library with annotations, reimplementaion of some core data types, collections and input-output functions and more. Some of them are described on the website[2]. There are more details about library in the source code of Stainless on GitHub in the folder *frontends/library/stainless*[3].

Stainless verifies Scala programs using SMT (satisfiability modulo theories) solvers. The framework transforms a program code to the Pure Scala fragment supported by Inox solver. This solver was also developed by LARA-Group and allows usage of different SMT solvers such as Z3, CVC4 and Princess, adding support of other higher-level features. Thus, preconditions, postconditions and assertions are translated into SMT formulas, so an SMT solver can determine if all properties hold.[**?**][**?**]

[1] https://epfl-lara.github.io/stainless/purescala.html
[2] https://epfl-lara.github.io/stainless/library.html
[3] https://github.com/epfl-lara/stainless

1.3. Overview of Bitcoin-S

In the work some fragments of the code of Bitcoin-S has to be verified. Bitcoin-S is an open source Scala implementation of the Bitcoin protocol. There are different projects belonging to Bitcoin-S. Protocol data structures are defined in the package **bitcoin-s-core**. This package is the main target to be verified because it specifies the base of Bitcoin protocol, and it is crucial for correct protocol functionality. There is also the package **bitcoind-rpc** which is an RPC client implementation to communicate with *bitcoind*, daemon of Bitcoin Core running on a machine. Developers of Bitcoin-S are working on the implementation of a lightweight bitcoin client in the package **bitcoin-s-spv-node**. The whole list of packages can be found on GitHub[4].

Bitcoin-S is a large project implementing many functionalities. In this work one of them is going to be examined and worked on, namely the property of the Bitcoin that a non-coinbase transaction can not generate new coins. Thus, the code of Bitcoin-S should be analyzed, and fragments implementing this feature should be identified. Afterwards, the fragments should be rewritten, so that Stainless can accept it. After that a formal specification for functions should be defined and annotated according Stainless libraries, so that Stainless can verify correctness of the code.

[4] `https://github.com/bitcoin-s`

2. Trying to Verify checkTransaction

This chapter describes some parts of Bitcoin-S needed to verify our property. We are going to create a transaction and show you the relevant parts of checkTransaction, where transactions are checked against some properties. Then we see some troubles occurred during this work. In the end you will see how we fixed a bug in Bitcoin-S.

2.1. Creation of a Transaction

Some of the code in this section are copied or modified parts of Bitcoin-S-Core transaction builder example.[**?**] Bitcoin-S-Core has a bitcoin transaction builder class with the following signature:

```
1 BitcoinTxBuilder(
2   destinations: Seq[TransactionOutput], // where we send money
3   utxos: BitcoinTxBuilder.UTXOMap,      // unspent transaction outputs
4   feeRate: FeeUnit,                     // fee rate per byte
5   changeSPK: ScriptPubKey,              // public key
6   network: BitcoinNetwork               // bitcoin network information
7 ): Future[BitcoinTxBuilder]             // sign TxBuilder to get tx
```

Here is how those parameters are generated.

First, we need a some bitcoins/satoshis. Thus, we create a transaction with one single output. This transaction can also be parsed from the real bitcoin network but to show the progression we create one.

```
1 val privKey = ECPrivateKey.freshPrivateKey
2 val creditingSPK = P2PKHScriptPubKey(pubKey = privKey.publicKey)
3
4 val amount = Satoshis(Int64(10000))
5
6 val utxo = TransactionOutput(currencyUnit = amount, scriptPubKey = creditingSPK)
7
8 val prevTx = BaseTransaction(
9   version = Int32.one,
10  inputs = List.empty,
11  outputs = List(utxo),
12  lockTime = UInt32.zero
13 )
```

On line one and two we are creating a new keypair to sign the next transaction and have a scriptPubKey where the bitcoins are. Line four specifies the amount of satoshis we are having in the transaction. Then we create the actual transaction from line 6 to 13.

Now that we have some bitcoins, we create the new transaction to spend them.

First, we need some out points. This are pointers to previous transactions' outputs. We use the index zero, because the previous transaction has only one output that becomes the first index zero.

```
1 val outPoint = TransactionOutPoint(prevTx.txId, UInt32.zero)
2
3 val utxoSpendingInfo = BitcoinUTXOSpendingInfo(
4   outPoint = outPoint,
5   output = utxo,
6   signers = List(privKey),
7   redeemScriptOpt = None,
8   scriptWitnessOpt = None,
9   hashType = HashType.sigHashAll
10 )
11
12 val utxos = List(utxoSpendingInfo)
```

Second, we need destinations to spend the bitcoins to. For the sake of convenience we create only one.

```
1 val destinationAmount = Satoshis(Int64(5000))
2
3 val destinationSPK = P2PKHScriptPubKey(pubKey = ECPrivateKey.freshPrivateKey.publicKey)
4
5 val destinations = List(
6   TransactionOutput(currencyUnit = destinationAmount, scriptPubKey = destinationSPK)
7 )
```

We spend 5000 satoshis to the newly created script public key.

Finally, we define the fee rate in satoshis per one byte transaction size as well as some bitcoin network parameters.

```
1 val feeRate = SatoshisPerByte(Satoshis.one)
2
3 val networkParams = RegTest // soem static values for testing
```

Now lets build the transaction with those data.

```
1 val txBuilder: Future[BitcoinTxBuilder] = BitcoinTxBuilder(
2   destinations = destinations,
3   utxos = utxos,
4   feeRate = feeRate,
5   changeSPK = creditingSPK,
6   network = networkParams
7 )
8
9 val signedTxF: Future[Transaction] = txBuilder
10   .flatMap(_.sign)
11   .map {
12     (tx: Transaction) => println(tx.hex) // transaction in hex for the bitcoin network
13   }
```

Line one to seven creates a transaction builder which is then signed on line nine to thirteen. On line twelve we can now use our transaction object. For example, after calling the *hex* function on it, we can send the returned string to the real bitcoin network.

2.2. Validation of a Transaction

Bitcoin-S-Core offers a function called *checkTransaction*. This is its type signature.

```
1 checkTransaction(transaction: Transaction): Boolean
```

We can pass a transaction and it returns a Boolean whether the transaction is valid or not. So for example when we pass the built transaction from above to it the returned value would be true, because it's a valid transaction.

There are several checks in checkTransaction. For example, it checks if there is either no input or no output. In this case it returns false.

The relevant part for the bug we found.

```
1 val prevOutputTxIds = transaction.inputs.map(_.previousOutput.txId)
2 val noDuplicateInputs = prevOutputTxIds.distinct.size == prevOutputTxIds.size
```

It gathers all transaction ids referenced by the out points. When calling *distinct* on the returned list, it returns a list where duplicated are removed. Is the size of the new list is the same as the size of the old, we know that there was no duplicate transaction id.

There is a bug, because checkTransaction checks on the transaction id that we are going to explain the next section.

2.3. Fixing a Bug in Bitcoin-S

During the examination of the checkTransaction function, we found a bug in Bitcoin-S.

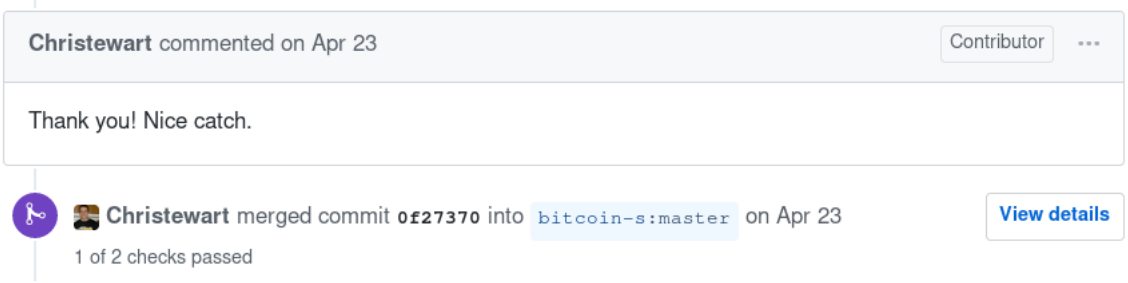


Figure 2.1.: Nice catch comment on our PR #435 on GitHub

Here the relevant code of checkTransaction again:

```
1 val prevOutputTxIds = transaction.inputs.map(_.previousOutput.txId)
2 val noDuplicateInputs = prevOutputTxIds.distinct.size == prevOutputTxIds.size
```

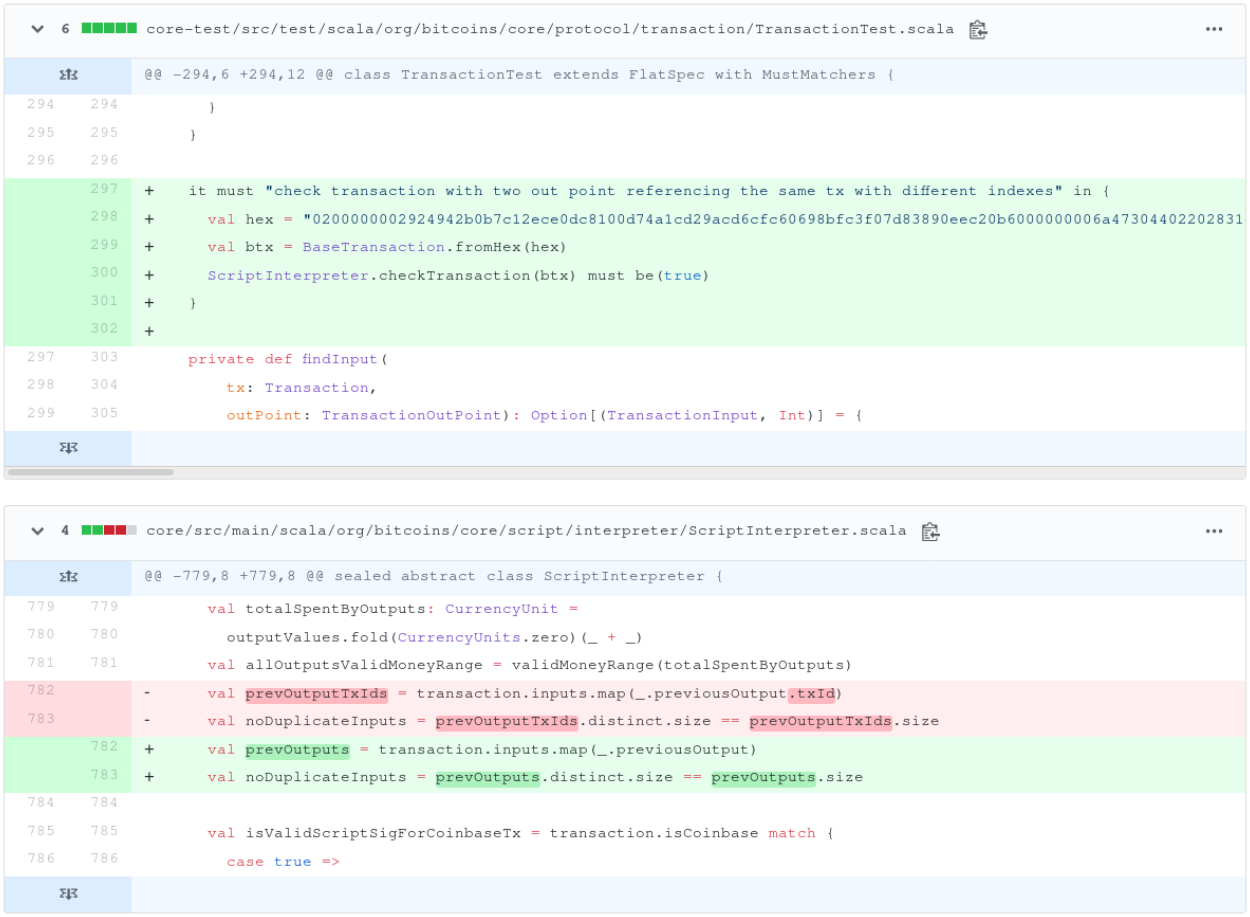
What happens, if a TransactionOutPoint (previousOutput) references the same Transaction ID (txId) another does?

According to the Bitcoin protocol this is possible. A transaction can have multiple outputs that should be referenceable by the next transaction. What should not be possible is a transaction referencing the same output twice. This was a bug in Bitcoin Core known as CVE-201817144 which was patched on September 18, 2018. [**?**]

Here, Bitcoin-S did a bit too much and marked all transaction as invalid, if they referenced a transaction twice in the next transaction. The fix is, to check on TransactionOutPoint instead of TransactionOutPoint.txId, because TransactionOutPoint contains the txId as well as the output index it references.

```
1 val prevOutputs = transaction.inputs.map(_.previousOutput)
2 val noDuplicateInputs = prevOutputs.distinct.size == prevOutputs.size
```

Since TransactionOutPoint is a case class and Scala has a built in == for case classes there is no need to implement TransactionOutPoint.==.



```
6 core-test/src/test/scala/org/bitcoins/core/protocol/transaction/TransactionTest.scala
@@ -294,6 +294,12 @@ class TransactionTest extends FlatSpec with MustMatchers {
294 294         }
295 295       }
296 296
297     +   it must "check transaction with two out point referencing the same tx with different indexes" in {
298     +     val hex = "0200000002924942b0b7c12ece0dc8100d74a1cd29acd6cfc60698bfc3f07d83890eec20b6000000006a47304402202831
299     +     val btx = BaseTransaction.fromHex(hex)
300     +     ScriptInterpreter.checkTransaction(btx) must be(true)
301     +   }
302     +
297 303     private def findInput(
298 304         tx: Transaction,
299 305         outPoint: TransactionOutPoint): Option[(TransactionInput, Int)] = {

4 core/src/main/scala/org/bitcoins/core/script/interpreter/ScriptInterpreter.scala
@@ -779,8 +779,8 @@ sealed abstract class ScriptInterpreter {
779 779       val totalSpentByOutputs: CurrencyUnit =
780 780         outputValues.fold(CurrencyUnits.zero)(_ + _)
781 781       val allOutputsValidMoneyRange = validMoneyRange(totalSpentByOutputs)
782     -     val prevOutputTxIds = transaction.inputs.map(_.previousOutput.txId)
783     -     val noDuplicateInputs = prevOutputTxIds.distinct.size == prevOutputTxIds.size
782     +     val prevOutputs = transaction.inputs.map(_.previousOutput)
783     +     val noDuplicateInputs = prevOutputs.distinct.size == prevOutputs.size
784 784
785 785       val isValidScriptSigForCoinbaseTx = transaction.isCoinbase match {
786 786         case true =>
```

Figure 2.2.: Line changes for PR #435 from GitHub

This was fixed in pull request #435 on GitHub[1] at April 23, 2019 by us along a unit test to prevent this bug from appearing again in the future.

2.4. Adjusting Property

Trying to integrate Stainless in Bitcoin-S caused a lot of troubles, because of version conflicts. If you are interested in it you can read more in the appendix A.

It takes too much time to do it and after some discussion, we decided to extract only the parts of the code that are needed for checkTransaction.

The extracted code has more than 1500 lines. After running Stainless on it, it throws a really huge bunch of errors about what Stainless can not reason about. And after fixing some of those errors there appear new ones as we can see in the next chapter. This would require to change nearly everything of the extracted code.

We arrived at the decision that we need a smaller part to verify. We have chosen to verify the addition with zero of Bitcoin-Ss CurrencyUnit class as described in the next chapter.

[1] https://github.com/bitcoin-s/bitcoin-s/pull/435

3. Towards Verifying Addition with Zero

After realizing, that it would consume to much time to rewrite the Bitcoin-S code and even the extracted part with checkTransaction, we decided to extract the smallest unit in Bitcoin-S-Core that is worthwhile to verify. We found the addition of two Satoshis would be a good candidate. To make it even easier, we decided to verify only the addition of some satoshis with zero.

The initial code is this:

```
1 package code.initial
2
3 trait BasicArithmetic[N] {
4   def +(n: N): N
5 }
6
7 sealed abstract class Number[T <: Number[T]]
8     extends BasicArithmetic[T] {
9   type A = BigInt
10
11  protected def underlying: A
12
13  def toLong: Long = toBigInt.longValue()
14  def toBigInt: BigInt = underlying
15
16  def andMask: BigInt
17
18  def apply: A => T
19
20  override def +(num: T): T = apply(checkResult(underlying + num.underlying))
21
22  private def checkResult(result: BigInt): A = {
23    require((result & andMask) == result,
24      "Result was out of bounds, got: " + result)
25    result
26  }
27 }
28
29 sealed abstract class SignedNumber[T <: Number[T]] extends Number[T]
30
31 sealed abstract class Int64 extends SignedNumber[Int64] {
32   override def apply: A => Int64 = Int64(_)
33   override def andMask = 0xffffffffffffffffL
34 }
35
36 trait BaseNumbers[T] {
37   def zero: T
38   def one: T
39 }
40
41 object Int64 extends BaseNumbers[Int64] {
42   private case class Int64Impl(underlying: BigInt) extends Int64 {
43     require(underlying >= -9223372036854775808L,
44       "Number was too small for a int64, got: " + underlying)
45     require(underlying <= 9223372036854775807L,
46       "Number was too big for a int64, got: " + underlying)
47   }
48
49   lazy val zero = Int64(0)
50   lazy val one = Int64(1)
51
52   def apply(long: Long): Int64 = Int64(BigInt(long))
53
54   def apply(bigInt: BigInt): Int64 = Int64Impl(bigInt)
55 }
```

```
56
57
58 sealed abstract class CurrencyUnit
59   extends BasicArithmetic[CurrencyUnit] {
60   type A
61
62   def satoshis: Satoshis
63
64   def ==(c: CurrencyUnit): Boolean = satoshis == c.satoshis
65
66   override def +(c: CurrencyUnit): CurrencyUnit =
67     Satoshis(satoshis.underlying + c.satoshis.underlying)
68
69   protected def underlying: A
70 }
71
72 sealed abstract class Satoshis extends CurrencyUnit {
73   override type A = Int64
74
75   override def satoshis: Satoshis = this
76
77   def toBigInt: BigInt = BigInt(toLong)
78
79   def toLong: Long = underlying.toLong
80
81   def ==(satoshis: Satoshis): Boolean = underlying == satoshis.underlying
82 }
83
84 object Satoshis extends BaseNumbers[Satoshis] {
85   val zero = Satoshis(Int64.zero)
86   val one = Satoshis(Int64.one)
87
88   def apply(int64: Int64): Satoshis = SatoshisImpl(int64)
89
90   private case class SatoshisImpl(underlying: Int64) extends Satoshis
91 }
```

The additions signature looks like this:

```
1 +(c: CurrencyUnit): CurrencyUnit
```

When we run Stainless on it, it throws the following errors:

```
[ Error  ] Code.scala:41:1: Objects cannot extend classes or implement traits,
           use a case object instead
         object Int64 extends BaseNumbers[Int64] {
         ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^...
[ Error  ] Code.scala:60:3: Stainless doesn't support abstract type members
             type A
             ^^^^^^
[ Error  ] Code.scala:77:33: Only literal arguments are allowed for BigInt.
             def toBigInt: BigInt = BigInt(toLong)
                                    ^^^^^^
[ Error  ] Code.scala:84:1: Objects cannot extend classes or implement traits,
           use a case object instead
         object Satoshis extends BaseNumbers[Satoshis] {
         ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^...
[  Info  ] Shutting down executor service.
```

So let's see how we can fix those errors.

3.1. Turn object Into case object

Stainless output:

```
[ Error  ] Code.scala:41:1: Objects cannot extend classes or implement traits,
           use a case object instead
         object Int64 extends BaseNumbers[Int64] {
         ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^...
[ Error  ] Code.scala:84:1: Objects cannot extend classes or implement traits,
          use a case object instead
          object Satoshis extends BaseNumbers[Satoshis] {
          ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^...
```

Here, we can just change the objects from object to case object. Stainless recommendation is to use objects for modules and case objects as algebraic data type.

This is, due to the internal design of Scala and Java. It's possible to reason about case object but not about object. This needs a fundamental knowledge of Scala and some functional paradigms that should not be part of this thesis. The issue #520 on Stainless GitHub[1] gives some thoughts if you want to know more.

3.2. Get Rid of Abstract Type Member

Stainless output:

```
[ Error  ] Code.scala:60:3: Stainless doesn't support abstract type members
             type A
             ^^^^^^
```

This should be easy to rewrite by using generics instead of an abstract type, right? Unfortunately not. The problem is, CurrencyUnit uses one of its implementing class Satoshis.

Simplified code.

```
1 sealed abstract class CurrencyUnit {
2   type A
3
4   def +(c: CurrencyUnit): CurrencyUnit =
5     Satoshis(satoshis.underlying + c.satoshis.underlying)
6
7   protected def underlying: A
8 }
9
10 sealed abstract class Satoshis extends CurrencyUnit
```

What happens, if we typify CurrencyUnit with A, meaning to make it generic with type A?

Satoshis extends CurrencyUnit with type Int64, so it is of type CurrencyUnit[Int64]. That's too specific, because the addition would require CurrencyUnits of type CurrencyUnit[A] not CurrencyUnit[Int64].

Since there is no easy way to fix it and the code should stay as much as possible the original, we just remove the abstract type and fixed it to Int64. This limits the verification a bit, but as we only want to verify the addition in satoshis, thats OK.

3.3. Replace BigInt Constructor Argument With String Literal

Stainless output:

```
[ Error  ] Code.scala:77:33: Only literal arguments are allowed for BigInt.
             def toBigInt: BigInt = BigInt(toLong)
                                    ^^^^^^^^^^^^^^
```

[1] https://github.com/epfl-lara/stainless/issues/520

As described before, Stainless supports only a subset of Scala. The BigInt from the Stainless library is a bit restricted. It does not support dynamic BigInt construction. Only from literal arguments.

Again, a simplified code version.

```
1 sealed abstract class Satoshis extends CurrencyUnit {
2   def toBigInt: BigInt = BigInt(toLong)
3   def toLong: Long = underlying.toLong
4 }
```

This would be really hard to refactor, because Bitcoin-S tries to be as much dynamic as possible so it can be used with other cryptocurrencies than bitcoins too. Maybe it would even be impossible, because they need to parse a lot from the bitcoin network.

Luckily, we can use toBigInt on underlying directly instead of going over toLong.

After fixing all Stainless errors, a new error appears.

3.4. Get Rid of Special Generics

Stainless output:

```
[ Error  ] Code.scala:7:30: Unknown type parameter type T
           sealed abstract class Number[T <: Number[T]]
                                        ^^^^^^^^^^^^^^
```

This is a missing feature in Stainless. It does not support upper type bound on the class itself. To track this, there is the issue #519 on GitHub[2].

```
1 sealed abstract class Number[T <: Number[T]] extends BasicArithmetic[T]
```

For the sake of convenience we make this a concrete type by replacing T with Int64.

Now, there are two new errors.

3.5. Get Rid of Concret Type

Stainless output:

```
[Warning ] Code.scala:9:3: Could not extract tree in class: type A =
           BigInt (class scala.reflect.internal.Trees$TypeDef)
           type A = BigInt
           ^^^^^^^^^^^^^^
```

This is easy. We just replace all occurence of A with BigInt, since A is not overrided in an implementing class. This is not exact the same code, because an implementing class could not override A anymore but thats fine for our verification.

This was a missing feature of Stainless that was fixed on Mai 28, 2019 with pull request #470 on GitHub[3].

[2] https://github.com/epfl-lara/stainless/issues/519
[3] https://github.com/epfl-lara/stainless/pull/470

3.6. Replace BigInt &-Function With Bound Check

Stainless output:

```
[ Error  ] Code.scala:22:14: Unknown call to & on result (BigInt) with arguments
            List(Number.this.andMask) of type List(BigInt)
           require((result & andMask) == result,
                   ^^^^^^^^^^^^^^^^
```

Due to the restrictions on BigInt, we can not use the & function on. Simplified code:

```
sealed abstract class Number extends BasicArithmetic[Int64] {
  def andMask: BigInt

  override def +(num: Int64): Int64 = apply(checkResult(underlying + num.underlying))

  private def checkResult(result: BigInt): BigInt = {
    require((result & andMask) == result, "Result was out of bounds, got: " + result)
    result
  }
}
```

This is a bound check. It checks, if the result of the addition is in range of the specified type, which is now the hard coded Int64.

So, we can replace the & mask with a bound check whether the result is in range of Long.MinValue and Long.MaxValue. Again the code gets a bit more static and it's not the exact same code anymore.

Running Stainless produces again new errors.

3.7. Extract Private Inner Classes

Stainless output:

```
[Warning ] Code.scala:90:3: Could not extract tree in class: case private
            class SatoshisImpl extends Satoshis with Product with Serializable {
```

Stainless can not extract the private class inside the object. Bitcoin-S uses this a lot, because they separate the class from its implementation. Simplified:

```
object Int64 extends BaseNumbers[Int64] {
  private case class Int64Impl(underlying: BigInt) extends Int64
}
```

This is an easy to fix. We just extract the private class out of the object. This is not exactly the same code but since the class is still private it can not be extended outside of the file.

Now we get som weird warnings about require.

3.8. Remove Second Parameter of require

Stainless output:

```
[Warning ] Code.scala:51:3: Could not extract tree in class: scala.this.Predef
            .require(Int64Impl.this.underlying.>=(math.this.BigInt.long2bigInt(
            -9223372036854775808L)), "Number was too small for a int64, got: "
            .+(Int64Impl.this.underlying)) (class scala.reflect.internal.Trees$Apply)
           require(underlying >= -9223372036854775808L,
           ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^...
[Warning ] Code.scala:53:3: Could not extract tree in class: scala.this.Predef
            .require(Int64Impl.this.underlying.<=(math.this.BigInt.long2bigInt(
            9223372036854775807L)), "Number was too big for a int64, got: "
```

```
            .+(Int64Impl.this.underlying)) (class scala.reflect.internal.Trees$Apply)
           require(underlying <= 9223372036854775807L,
           ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^...
  [ Error  ] checkResult$0 depends on missing dependencies: require$1.
```

Seems like Stainless does not support the second string parameter of require or at least it throws a warning about it. We can saftly remove it.

A new error apperas.

3.9. Rewrite BigInt Comparison with Long

Stainless output:

```
  [ Error  ] inv$4 depends on missing dependencies: long2bigInt$0.
```

This error is hard to understand but we can see that there is a missing Long to BigInt conversion. So we search for all longs in the code.

```
private case class Int64Impl(underlying: BigInt) extends Int64 {
  require(underlying >= -9223372036854775808L)
  require(underlying <= 9223372036854775807L)
}
```

Looks like it can not compare a BigInt with a Long value. We can easily convert this Long value to a BigInt with string literals parameter.

Finally, we get some output from Stainless about the verification in the code.

```
[...]
[Warning ]  => INVALID
[Warning ] Found counter-example:
[Warning ]   thiss: { x: Object | @unchecked isNumber(x) } -> Int64Impl(0)
[Warning ]   num: { x: Object | @unchecked isInt64(x) }    -> Int64Impl(9223372036854775808)
[...]
[  Info  ] +  precond. (call checkResult(thiss, underlying(thiss) + u ...)  invalid  Code.scala:16:45
[...]
[  Info  ] total: 5  valid: 4  (4 from cache) invalid: 1  unknown: 0  time:  1.317
```

This show, that there is an invalid specification in checkResult and Stainless prints a counter example for it.

Let's ignore this for a moment and write the verification for our addition with zero.

3.10. Write Specification for Verification

As specified, our verification must only support addition with zero. So we restrict the parameter to be zero in the precondition.

```
require(c.satoshis == Satoshis.zero)
```

We ensure the result is the same value as *this* in the postcondition.

```
ensuring(res => res.satoshis == this.satoshis)
```

We can use equals (==) directly on Satoshis, because it is a case class. The addition will now look like this:

```
override def +(c: CurrencyUnit): CurrencyUnit = {
  require(c.satoshis == Satoshis.zero)
  Satoshis(satoshis.underlying + c.satoshis.underlying)
} ensuring(res => res.satoshis == this.satoshis)
```

That's all we need to verify our addition.

Now we will look into the previous error.

3.11. Propagate require

There is another problem with Bitcoin-S. Bitcoin-S-Core uses require as a fail-fast method whereas Stainless needs it to verify the code.

The Stainless output again:

```
[Warning ] Found counter-example:
[Warning ]   thiss: { x: Object | @unchecked isNumber(x) } -> Int64Impl(0)
[Warning ]   num: { x: Object | @unchecked isInt64(x) }    -> Int64Impl(9223372036854775808)
```

Corresponding code:

```
1 sealed abstract class Number extends BasicArithmetic[Int64] {
2   override def +(num: Int64): Int64 = apply(checkResult(underlying + num.underlying))
3
4   private def checkResult(result: BigInt): BigInt = {
5     require(
6       result <= BigInt("9223372036854775807")
7       && result >= BigInt("-9223372036854775808")
8     )
9     result
10  }
11 }
```

But how does Stainless find a counter example ignoring the require in checkResult? Since Stainless is a static verification tool, it tests every possibility. So it can use a number bigger than the maximum Int64 and pass it to the addition. The require in checkResult fails.

Thus, we need to add the restriction from checkResult to the addition too.

```
1 override def +(num: Int64): Int64 = {
2   require(
3         num.underlying <= BigInt("9223372036854775807")
4     &&  num.underlying >= BigInt("-9223372036854775808")
5     && this.underlying <= BigInt("9223372036854775807")
6     && this.underlying >= BigInt("-9223372036854775808")
7   )
8   apply(checkResult(underlying + num.underlying))
9 }
```

Stainless finds another counter example:

```
[Warning ] Found counter-example:
[Warning ]   num: { x: Object | @unchecked isInt64(x) }    -> Int64Impl(1)
[Warning ]   thiss: { x: Object | @unchecked isNumber(x) } ->
               Int64Impl(9223372036854775807)
```

Sure, when adding one to the maximum Int64 the require does not hold anymore. Since we do only allow zero as a parameter the easiest way is to restrict it to zero here too.

3.12. Result

Finally, everything is green and correctly verified.

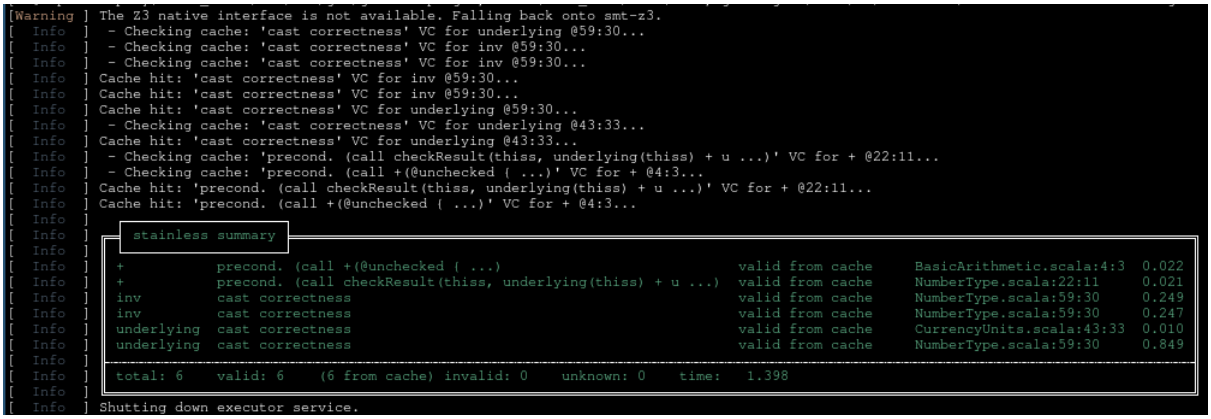


Figure 3.1.: Output of Stainless verification for addition with 0 of Bitcoin-S-Cores CurrencyUnit

The verified code.

```
1 package code.end
2
3 trait BasicArithmetic[N] {
4   def +(n: N): N
5 }
6
7 sealed abstract class Number
8     extends BasicArithmetic[Int64] {
9
10  protected def underlying: BigInt
11
12  def toBigInt: BigInt = underlying
13
14  def apply: BigInt => Int64
15
16  override def +(num: Int64): Int64 = {
17    require(
18          num.underlying <= BigInt(0)
19      && this.underlying <= BigInt("9223372036854775807")
20      && this.underlying >= BigInt("-9223372036854775808")
21    )
22    apply(checkResult(underlying + num.underlying))
23  }
24
25  private def checkResult(result: BigInt): BigInt = {
26    require(
27         result <= BigInt("9223372036854775807")
28      && result >= BigInt("-9223372036854775808")
29    )
30    result
31  }
32 }
33
34 sealed abstract class SignedNumber extends Number
35
36 sealed abstract class Int64 extends SignedNumber {
37   override def apply: BigInt => Int64 = Int64(_)
38 }
39
40 trait BaseNumbers[T] {
41   def zero: T
42   def one: T
43 }
44
45 case object Int64 extends BaseNumbers[Int64] {
46   lazy val zero = Int64(0)
47   lazy val one = Int64(1)
48
49   def apply(bigInt: BigInt): Int64 = Int64Impl(bigInt)
50 }
```

```
51
52 private case class Int64Impl(underlying: BigInt) extends Int64 {
53   require(underlying >= BigInt("-9223372036854775808"))
54   require(underlying <= BigInt("9223372036854775807"))
55 }
56
57 sealed abstract class CurrencyUnit
58     extends BasicArithmetic[CurrencyUnit] {
59   def satoshis: Satoshis
60
61   def ==(c: CurrencyUnit): Boolean = satoshis == c.satoshis
62
63   override def +(c: CurrencyUnit): CurrencyUnit = {
64     require(
65         c.satoshis == Satoshis.zero
66       && this.underlying.toBigInt <= BigInt("9223372036854775807")
67       && this.underlying.toBigInt >= BigInt("-9223372036854775808")
68     )
69     Satoshis(satoshis.underlying + c.satoshis.underlying)
70   } ensuring(res => res.satoshis == this.satoshis)
71
72   protected def underlying: Int64
73 }
74
75 sealed abstract class Satoshis extends CurrencyUnit {
76   override def satoshis: Satoshis = this
77
78   def toBigInt: BigInt = underlying.toBigInt
79
80   def ==(satoshis: Satoshis): Boolean = underlying == satoshis.underlying
81 }
82
83 case object Satoshis extends BaseNumbers[Satoshis] {
84   val zero = Satoshis(Int64.zero)
85   val one = Satoshis(Int64.one)
86
87   def apply(int64: Int64): Satoshis = SatoshisImpl(int64)
88 }
89
90 private case class SatoshisImpl(underlying: Int64) extends Satoshis
```

But is it really the original code that we verified? And why did we have to change that much? This and other questions will be answered in the next chapter.

4. Conclusion

As we saw, it is really hard to verify a software not written with verification in mind. It needs a loot of changes in the software because verification is mathematical and the current software is written mostly in Object-oriented style. A functional programmed software would be much easier to reason about.

Thus either Stainless must find ways to translate more of built-in object-oriented patterns of Scala to their verification tool or developers must invest more in functional programming.

The code we verified in the previous chapter is not the original code from Bitcoin-S. So we can not guarantee the correctness of the addition of Satoshis with zero in Bitcoin-S. There are changes that stays the same like the change from object to case object but there are other changes where we can not say if they are the same or not like the bound check in section 3.6.

Declaration of primary authorship

We hereby confirm that we have written this thesis independently and without using other sources and resources than those specified in the bibliography. All text passages which were not written by me are marked as quotations and provided with the exact indication of its origin.

Place, Date:	Biel, TODO fix this	
Last Names, First Names:	Doukmak Anna	Boss Ramon
Signatures:	.....	.....

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APPENDICES

A. Practical Challenges with Stainless

A.1. Integration

During this work, Stainless bumped the sbt plugin from version 0.13.17 to 1.2.8 and Scala from 2.11.12 to 2.12.8. So this section might be out of date now.

There are two ways to integrate Stainless in a Scala project, the Scala build tool (sbt) plugin or a command line tool. Both, when run, analyses the code passed and report warnings to the console about the given code. Stainless requires and Scala recommends Java SE Development Kit 8. Newer Java versions won't work.

To use the latest version of the sbt tool you have to build it locally. You can run `sbt universal:stage` in the cloned Stainless git repository. This generates *frontends/scalac/target/universal/stage/bin/stainless-scalac*.

Bitcoin-S-Core uses sbt 1.2.8 and Scala 2.12.8, while Stainless sbt plugin is on sbt 0.13.17 and Scala 2.11.12.

Sbt introduced new features in the 1.x release used by Bitcoin-S. Most of them can be written the sbt 0.13.17 way.

The bigger problem is, due to the different Scala and sbt versions, the error message, after trying to go in a sbt shell.

```
[warn] There may be incompatibilities among your library dependencies; run 'evicted'
       to see detailed eviction warnings.
[error] java.lang.NoClassDefFoundError: sbt/SourcePosition
...
Project loading failed: (r)etry, (q)uit, (l)ast, or (i)gnore?
```

Downgrading Bitcoin-S sbt version to 0.13.17 fixes the error but then it can not load some libraries only compiled for newer versions. So this would take too much time to fix and changes the Bitcoin-S code unwantingly.

The next approach is to use stainless cli instead of sbt. Running stainless on all source files does not work, because the dependencies are missing. The parameter *-classpath* can resolve it but the value of this parameter must be the paths to all the dependencies separated by a ':'. Finally, *core* depends on *secp256k1jni*, another package of Bitcoin-S written in Java. So this needs to be in the source files to.

The final command looks like this in *core* folder of Bitcoin-S:

```
1 $ stainless
2   -classpath ".:$(find ~/.ivy2/ -type f -name *.jar | tr '\n' ':')"
3   $(find . -type f -name *.scala | tr '\n' ' ')
4   $(find ../secp256k1jni -type f -name *.java | tr '\n' ' ')
```

The output was some Stainless error.

```
[Internal] Error: object scala.reflect.macros.internal.macroImpl in compiler mirror
           not found.. Trace:
[Internal] - scala.reflect.internal.MissingRequirementError$.signal
           (MissingRequirementError.scala:17)
...
[Internal] object scala.reflect.macros.internal.macroImpl in compiler mirror not found.
[Internal] Please inform the authors of Inox about this message
```

After some discussion, we decided to go another way, because the errors may take too much time and it might lead to a next error. Let's extract the code needed to verify a transaction mainly the class Transaction and ScriptInterpreter with many other classes their depending on.

After this extraction Stainless was successfully integrated with both, sbt and JAR. This leads us to another finding as described in the next section.

A.2. Error Reporting with sbt and JAR

Running `sbt compile` in the project with Stainless ended without error. But it also ended with no output. So we were not able to change the code so Stainless would accept it.

After running the JAR file on the code there were many errors as described in chapter 3.

So the sbt plugin does not complain always but the JAR file did. The open issue #484 on GitHub[1] might describe this error.

[1] urlhttps://github.com/epfl-lara/stainless/issues/484