



Experiments in Formal Verification of Scala Code

Bachelor thesis

Degree course: Computer Science
Authors: Anna Doukma, Ramon Boss
Tutor: Prof. Dr. Kai Brännler
Date: 2019-06-13

Abstract

In this thesis we try to verify some properties of Bitcoin-S.

First, we look at some theory about formal verification, Stainless – a verification tool and Bitcoin-S – an open source implementation of the Bitcoin protocol.

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

So we verify a less interesting property of Bitcoin-S. There is a datatype Satoshi that represents bitcoins. We verify that the addition of Satoshi with zero results in the same amount of Satoshi. Even this needs many changes in the code that we go through step-by-step.

Finally, we see that software should be written with verification tools in mind, because otherwise the code possibly must be rewritten when it comes to verification.

Contents

Abstract	i
1 Introduction	1
1.1 Formal Verification with Stainless	1
1.2 The Properties to Verify	2
1.2.1 No Inflation Property	2
1.2.2 Addition with Zero Property	3
2 Trying to Verify the No Inflation Property	5
2.1 Creation of a Transaction	5
2.2 Validation of a Transaction	6
2.3 Fixing a Bug in Bitcoin-S	7
2.4 Adjusting No Inflation Property	8
3 Towards Verifying the Addition with Zero Property	9
3.1 Turning Object into Case Object	10
3.2 Getting Rid of Abstract Type Member	11
3.3 Replacing the BigInt Constructor Argument With A String Literal	11
3.4 Getting Rid of Special Generics	12
3.5 Getting Rid of Concrete Type	12
3.6 Replacing the BigInt &-Function With Bound Check	13
3.7 Extracting Private Inner Classes	13
3.8 Removing Second Parameter of Require	13
3.9 Rewriting BigInt Comparison with Long	14
3.10 Writing Specification for the Property	14
3.11 Propagating Require	15
3.12 Result	16
4 Practical Challenges with Stainless	19
4.1 sbt vs JAR	19
4.2 Integration	19
5 Conclusion	21
Declaration of authorship	23

1 Introduction

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. One of them is formal verification. In contrast to testing, where only predefined inputs are tested, with formal verification all possible inputs are covered. 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. We will see an example of a formal specification shortly.

In this work 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 look at the main aspects of formal verification with Stainless and properties of Bitcoin-S we want to verify.

1.1 Formal Verification with 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. The following overview of the framework is taken from the section Introduction of the Stainless documentation [?].

Stainless statically verifies that a program satisfies a given specification and that a program will not crash at runtime. The framework covers 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. *require* specifies, if the parameter of the function hold a certain condition.

With *ensuring*, we define the postcondition of a function. *ensuring* is placed at the end of the function after the body. *ensuring* specifies, if the return value or the result of the function hold a certain condition.

On invoking Stainless, it 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 section Introduction of 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)
```

It 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

Bitcoin-S. Nevertheless, during the analysis of the No Inflation Property we look at a bug in Bitcoin-S found during this work and see the code changes for the bugfix in section 2.3.

1.2.2 Addition with Zero Property

In Bitcoin-S there is a class `Satoshis` representing an amount of bitcoins. We look at the verification of the addition of `Satoshis` with zero `Satoshis`. This operation should result in the same amount of `Satoshis`. Let's call it the Addition with Zero Property.

Using Stainless, we see the successful verification of this property. But the process of the verification with the tool requires many changes in the code, so that Stainless can accept it. We look at all needed modifications in chapter 3.

2 Trying to Verify the No Inflation Property

This chapter describes the part of Bitcoin-S needed to verify the No Inflation Property described before. We are going to create a transaction and show you the relevant parts of the method `checkTransaction`, where transactions are checked against some properties. Then, we will see the bug in Bitcoin-S found during this work and its fix. In the end we see why the No Inflation Property needed to be changed to the Addition with Zero Property.

2.1 Creation of a Transaction

Some code in this section is copied or adapted from Bitcoin-S-Core transaction builder example.[?] Bitcoin-S-Core has a bitcoin transaction builder class with the following constructor:

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

The return type `Future` does not make sense here, since the implementing constructor calls either `Future.successful` or `Future.fromTry` which returns an already resolved `Future`. This might be for future purposes.

Now we create a transaction.

First, we need some money. Thus, we create a fake transaction with one single output. This transaction can be parsed from the bitcoin network, but we create one manually in order to see this process.

```
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 create a new keypair to sign the next transaction and have a `scriptPubKey` where the bitcoins are. This is our keypair. So the money is transferred to our public key. Line four specifies the amount of satoshis we have 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 where we want to spend them.

First, we need some out points. They point to outputs of previous transactions. We use the index zero, because the previous transaction has only one output that becomes the first index zero. If there were two previous outputs, the second output would become the index 1 and so on.

```
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)

```

This utxos are the inputs of our transaction.

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 random public key.

Finally, we define the fee rate in satoshis per one byte transaction size as well as some bitcoin network parameters. The bitcoin network parameters are not important, so we use some static values for testing purpose.

```

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

```

Now lets build the transaction with those data.

```

1  val txBuilderF: Future[BitcoinTxBuilder] = BitcoinTxBuilder(
2    destinations = destinations, // where to send the money
3    utxos = utxos,              // unspent transaction outputs
4    feeRate = feeRate,          // fee rate per byte
5    changeSPK = creditingSPK,   // where to send the change
6    network = networkParams     // bitcoin network information
7  )
8
9  val signedTxF: Future[Transaction] = txBuilderF
10   .flatMap(_._sign)              // call sign on the transaction builder
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 ten. We can now use our transaction object on line twelve. For example, after calling *hex* on it, we can send the returned string to the bitcoin network.

2.2 Validation of a Transaction

Bitcoin-S offers a function called *checkTransaction* located in the *ScriptInterpreter* object. 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 transaction built before the returned value would be true, because it's a valid transaction. It might not be accepted by the bitcoin network but for a transaction on its own its valid. We can not check context with it, because we can only pass one transaction.

There are several checks in *checkTransaction*. For example, it checks if there is either no input or no output. In this case we get 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 we call *distinct* on the returned list, we get a list with duplicate removed. If the size of the new list is the same as the size of the old, we know that there was no duplicate transaction id, because, as said, *distinct* removes the duplicates.

2.3 Fixing a Bug in Bitcoin-S

We can see that there is a bug in the `checkTransaction` function from before, recognized and fixed through this work.

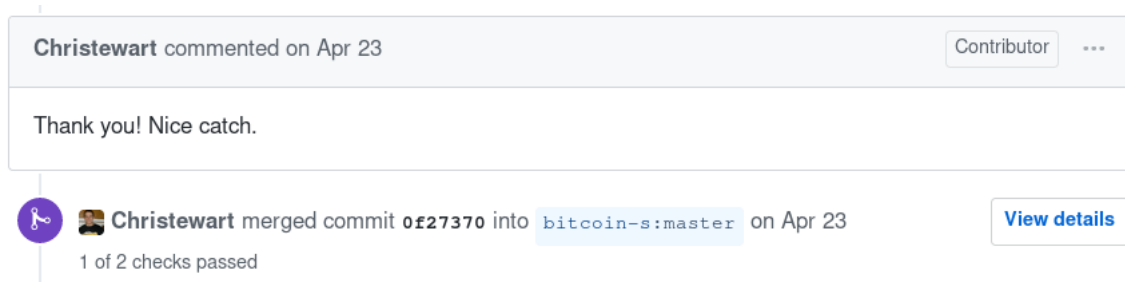


Figure 2.1: Nice catch comment on our PR #435 on GitHub

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 we have two `TransactionOutPoints` (previousOutputs) with a different index but referencing the same Transaction ID (txId)?

According to the Bitcoin protocol this is possible. A transaction can have multiple outputs that should be referenceable by the next transaction. So this is clearly a bug.

What should not be possible is a transaction referencing the same output twice. This bug occurred 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 the same transaction twice. The fix is, to check on `TransactionOutPoint` instead of `TransactionOutPoint.txId`, because `TransactionOutPoint` contains the txId as well as the output index it references. So in pseudo code, we check on the tuple (tx, index) instead of (tx). The fixed code:

```
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	294	@@ -294,6 +294,12 @@ class TransactionTest extends FlatSpec with MustMatchers {
295	295	}
296	296	}
297	297	+ it must "check transaction with two out point referencing the same tx with different indexes" in {
298	298	+ val hex = "0200000002924942b0b7c12ece0dc8100d74a1cd29acd6cfc60698bfc3f07d83890eec20b6000000006a47304402202831
299	299	+ val btx = BaseTransaction.fromHex(hex)
300	300	+ ScriptInterpreter.checkTransaction(btx) must be(true)
301	301	+ }
302	302	+ }
297	303	private def findInput(
298	304	tx: Transaction,
299	305	outPoint: TransactionOutPoint): Option[(TransactionInput, Int)] = {
303	303	}
4	core/src/main/scala/org/bitcoins/core/script/interpreter/ScriptInterpreter.scala	...
779	779	@@ -779,8 +779,8 @@ sealed abstract class ScriptInterpreter {
780	780	val totalSpentByOutputs: CurrencyUnit =
781	781	outputValues.fold(CurrencyUnits.zero) (_ + _)
782	782	val allOutputsValidMoneyRange = validMoneyRange(totalSpentByOutputs)
783	783	- val prevOutputTxIds = transaction.inputs.map(_.previousOutput.txId)
784	784	- val noDuplicateInputs = prevOutputTxIds.distinct.size == prevOutputTxIds.size
785	785	+ val prevOutputs = transaction.inputs.map(_.previousOutput)
786	786	+ val noDuplicateInputs = prevOutputs.distinct.size == prevOutputs.size
787	787	
788	788	val isValidScriptSigForCoinbaseTx = transaction.isCoinbase match {
789	789	case true =>
790	790	
791	791	
792	792	
793	793	
794	794	
795	795	
796	796	
797	797	
798	798	
799	799	
800	800	
801	801	
802	802	
803	803	
804	804	
805	805	
806	806	
807	807	
808	808	
809	809	
810	810	
811	811	
812	812	
813	813	
814	814	
815	815	
816	816	
817	817	
818	818	
819	819	
820	820	
821	821	
822	822	
823	823	
824	824	
825	825	
826	826	
827	827	
828	828	
829	829	
830	830	
831	831	
832	832	
833	833	
834	834	
835	835	
836	836	
837	837	
838	838	
839	839	
840	840	
841	841	
842	842	
843	843	
844	844	
845	845	
846	846	
847	847	
848	848	
849	849	
850	850	
851	851	
852	852	
853	853	
854	854	
855	855	
856	856	
857	857	
858	858	
859	859	
860	860	
861	861	
862	862	
863	863	
864	864	
865	865	
866	866	
867	867	
868	868	
869	869	
870	870	
871	871	
872	872	
873	873	
874	874	
875	875	
876	876	
877	877	
878	878	
879	879	
880	880	
881	881	
882	882	
883	883	
884	884	
885	885	
886	886	
887	887	
888	888	
889	889	
890	890	
891	891	
892	892	
893	893	
894	894	
895	895	
896	896	
897	897	
898	898	
899	899	
900	900	
901	901	
902	902	
903	903	
904	904	
905	905	
906	906	
907	907	
908	908	
909	909	
910	910	
911	911	
912	912	
913	913	
914	914	
915	915	
916	916	
917	917	
918	918	
919	919	
920	920	
921	921	
922	922	
923	923	
924	924	
925	925	
926	926	
927	927	
928	928	
929	929	
930	930	
931	931	
932	932	
933	933	
934	934	
935	935	
936	936	
937	937	
938	938	
939	939	
940	940	
941	941	
942	942	
943	943	
944	944	
945	945	
946	946	
947	947	
948	948	
949	949	
950	950	
951	951	
952	952	
953	953	
954	954	
955	955	
956	956	
957	957	
958	958	
959	959	
960	960	
961	961	
962	962	
963	963	
964	964	
965	965	
966	966	
967	967	
968	968	
969	969	
970	970	
971	971	
972	972	
973	973	
974	974	
975	975	
976	976	
977	977	
978	978	
979	979	
980	980	
981	981	
982	982	
983	983	
984	984	
985	985	
986	986	
987	987	
988	988	
989	989	
990	990	
991	991	
992	992	
993	993	
994	994	
995	995	
996	996	
997	997	
998	998	
999	999	
1000	1000	

Figure 2.2: Line changes for PR #435 from GitHub

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

2.4 Adjusting No Inflation Property

Trying to integrate Stainless in Bitcoin-S caused a lot of troubles, mainly because of version conflicts. You can find more about it in chapter 4.

After integrating Stainless in Bitcoin-S, there were many errors. It takes too much time to fix them all so it should be easier to extract the classes needed for checkTransaction.

The extracted code has more than 1500 lines. After running Stainless on it, it still throws a huge bunch of errors about what Stainless can not reason about. After fixing some of those errors, there appear new ones. So this would require changing nearly everything of the extracted code.

Let's adjust the property from the No Inflation Property to the Addition with Zero Property, because there is not enough time to fix all these errors and write the verification. This is way less interesting to verify but gives still many insights in what needs to be done to verify some parts of Bitcoin-S and other source code.

So let's look at the Addition with Zero Property.

3 Towards Verifying the Addition with Zero Property

After realizing, that it would consume too much time to rewrite the Bitcoin-S code and even the extracted part with `checkTransaction`, the smallest unit in Bitcoin-S-Core that is worthwhile to verify was extracted. This could be the addition of two `CurrencyUnits`. To make it even easier, the addition of `CurrencyUnits` with zero. `CurrencyUnits` is an abstract class in Bitcoin-S, representing currencies like Satoshis.

Here we can see the extracted code needed for the addition of `CurrencyUnits`:

```
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 }
```

```

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: Satoshi
63
64   def ==(c: CurrencyUnit): Boolean = satoshis == c.satoshis
65
66   override def +(c: CurrencyUnit): CurrencyUnit =
67     Satoshi(satoshis.underlying + c.satoshis.underlying)
68
69   protected def underlying: A
70 }
71
72 sealed abstract class Satoshi extends CurrencyUnit {
73   override type A = Int64
74
75   override def satoshis: Satoshi = this
76
77   def toBigInt: BigInt = BigInt(toLong)
78
79   def toLong: Long = underlying.toLong
80
81   def ==(satoshis: Satoshi): Boolean = underlying == satoshis.underlying
82 }
83
84 object Satoshi extends BaseNumbers[Satoshi] {
85   val zero = Satoshi(Int64.zero)
86   val one = Satoshi(Int64.one)
87
88   def apply(int64: Int64): Satoshi = SatoshiImpl(int64)
89
90   private case class SatoshiImpl(underlying: Int64) extends Satoshi
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 Satoshi extends BaseNumbers[Satoshi] {
        .....
[ Info ] Shutting down executor service.

```

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

3.1 Turning 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 Satoshi extends BaseNumbers[Satoshi] {
      .....

```

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. 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 gives some thoughts if you want to know more.

3.2 Getting 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 `Satoshi`.

Simplified code.

```
1 sealed abstract class CurrencyUnit {
2   type A
3
4   def +(c: CurrencyUnit): CurrencyUnit =
5     Satoshi(satoshi.underlying + c.satoshi.underlying)
6
7   protected def underlying: A
8 }
9
10 sealed abstract class Satoshi extends CurrencyUnit {
11   override type A = Int64
12 }

```

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

`Satoshi` extends `CurrencyUnit` with type `Int64`, so it would be of type `CurrencyUnit[Int64]`. That's too specific, because the return type of the addition is then `CurrencyUnit[Int64]` not `CurrencyUnit[A]`. Maybe the Bitcoin-S developers should reimplement this part and not use `Satoshi` directly.

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 set it to `Int64`. This limits the verification a bit, but as we only want to verify the addition in `satoshi`, that's OK.

3.3 Replacing the BigInt Constructor Argument With A String Literal

Stainless output:

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

```

As described before, Stainless supports only a subset of Scala. The `BigInt` from the Stainless library is a bit restricted. One such restriction is, that `BigInt` does not support dynamic `BigInt` construction. Thus, the constructor parameter of `BigInt` must be a literal arguments.

Again, a simplified code version.

```
1 sealed abstract class Satoshi 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. Maybe it would even be impossible, because they need to parse dynamic values from the bitcoin network.

Luckily, we can use `toBigInt` on `underlying` directly instead of going over `toLong`. So, instead of converting the `underlying` to `Long` and and back to `BigInt` we convert `underlying` directly to `BigInt`.

After fixing all Stainless errors, a new error appears.

3.4 Getting 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, issue #519 was created on GitHub during this work.

```
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`. `Int64`, because Satoshi uses only `Int64`. There are other number types like `UInt16` but for our property we don't need them.

Now, there are two new errors.

3.5 Getting Rid of Concrete 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 occurrence of `A` with `BigInt`, since `A` is not overrode in an implementing class. This is not exact the same code, because an implementing class can not override `A` anymore but that's fine for our verification.

This was a missing feature in Stainless that was fixed on Mai 28, 2019 with pull request #470 on GitHub. Now it should work without this change.

3.6 Replacing the 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 either. Simplified code:

```
1 sealed abstract class Number extends BasicArithmetic[Int64] {
2   def andMask: BigInt
3
4   override def +(num: Int64): Int64 = apply(checkResult(underlying + num.underlying))
5
6   private def checkResult(result: BigInt): BigInt = {
7     require((result & andMask) == result, "Result was out of bounds, got: " + result)
8     result
9   }
10 }
```

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, because Int64 has the same 64-bit range as Long. 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 Extracting Private Inner Classes

Stainless output:

```
[Warning ] Code.scala:90:3: Could not extract tree in class: case private
      class SatoshiImpl extends Satoshi 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:

```
1 object Int64 extends BaseNumbers[Int64] {
2   private case class Int64Impl(underlying: BigInt) extends Int64
3 }
```

This is easy to fix. We just extract the private class out of the object. This is not exactly the same code, because other classes in the same file could now access the private class. But for our property it does not change anything.

Now we get some weird warnings about require.

3.8 Removing 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 safely remove the string parameters from the `requires`, since they only serve as error message.

A new error appears.

3.9 Rewriting 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 Long values in the code.

```
1 private case class Int64Impl(underlying: BigInt) extends Int64 {
2   require(underlying >= -9223372036854775808L)
3   require(underlying <= 9223372036854775807L)
4 }
```

Looks like it can not compare a BigInt with a Long value. We can easily convert this Long value to a BigInt with string literal parameter by passing this numbers as strings to the BigInt constructor.

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 ] + precondition. (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 counterexample for it.

Let's ignore this for a moment and write the specification for the Addition with Zero Property.

3.10 Writing Specification for the Property

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

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

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

```
1 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:

```
1 override def +(c: CurrencyUnit): CurrencyUnit = {
2   require(c.satoshis == Satoshis.zero)
3   Satoshis(satoshis.underlying + c.satoshis.underlying)
4 } 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 Propagating 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 ]   this: { 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 ]   this: { 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.

```
[Warning] The Z3 native interface is not available. Falling back onto smt-z3.
[ Info ] - Checking cache: 'cast correctness' VC for underlying @59:30...
[ Info ] - Checking cache: 'cast correctness' VC for inv @59:30...
[ Info ] - Checking cache: 'cast correctness' VC for inv @59:30...
[ Info ] Cache hit: 'cast correctness' VC for inv @59:30...
[ Info ] Cache hit: 'cast correctness' VC for inv @59:30...
[ Info ] Cache hit: 'cast correctness' VC for underlying @59:30...
[ Info ] - Checking cache: 'cast correctness' VC for underlying @43:33...
[ Info ] Cache hit: 'cast correctness' VC for underlying @43:33...
[ Info ] - Checking cache: 'precond. (call checkResult(thiss, underlying(thiss) + u ...)' VC for + @22:11...
[ Info ] - Checking cache: 'precond. (call +(@unchecked ( ...)' VC for + @4:3...
[ Info ] Cache hit: 'precond. (call checkResult(thiss, underlying(thiss) + u ...)' VC for + @22:11...
[ Info ] Cache hit: 'precond. (call +(@unchecked ( ...)' VC for + @4:3...
[ Info ]
[ Info ] stainless summary
[ Info ]
[ Info ] +      precondition. (call +(@unchecked ( ...))      valid from cache      BasicArithmetic.scala:4:3  0.022
[ Info ] +      precondition. (call checkResult(thiss, underlying(thiss) + u ...) valid from cache      NumberType.scala:22:11  0.021
[ Info ] inv      cast correctness      valid from cache      NumberType.scala:59:30  0.249
[ Info ] inv      cast correctness      valid from cache      NumberType.scala:59:30  0.247
[ Info ] underlying cast correctness      valid from cache      CurrencyUnits.scala:43:33 0.010
[ Info ] underlying cast correctness      valid from cache      NumberType.scala:59:30  0.849
[ Info ]
[ Info ] total: 6      valid: 6      (6 from cache) invalid: 0      unknown: 0      time: 1.398
[ Info ]
[ Info ] Shutting down executor service.
```

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

```

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 Practical Challenges with Stainless

In this chapter we look at the practical challenges that could occur by using Stainless. Since Stainless is still in development and there is no 1.x release there might still be breaking changes and improvements fixing problems described now.

4.1 sbt vs JAR

We can either use the sbt plugin or a JAR file to check the code with Stainless.

Invoking the JAR on our source code Stainless will verify it. If we have a bigger project, this becomes really tricky, because we must pass all files needed including the dependencies. This is in contrast to the sbt plugin, where we can integrate Stainless in our compilation process. When we call `compile`, Stainless verifies the code and stops the compilation if the verification fails.

Having a fixed version configured in the sbt build file, every developer has the same Stainless features available. This should prevent incompatibility with new or deprecated features when we use different plugins.

So the sbt plugin has clear advantages over the JAR file since its integrated directly. We do not have to download it manually and find the right version and if we bump the version we can just edit it in the build file and every developer is on the same version again.

However, there are some drawbacks currently. For example the sbt plugin does not always report errors. We will read more about that shortly.

4.2 Integration

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

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 inadvertent.

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' '\n ')
4 $(find ../secp256k1jni -type f -name *.java | tr '\n' '\n ')
```

`.ivy2` is the dependency cache of sbt. The `tr` replaces the first char with the second so `'` `n` with either `:` or `'`.

With this command, Stainless throws the next 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
```

So we can not know how many errors will face us. Let's go another way, because the errors may take too much time and it might lead to a next error. We 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.

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

So the sbt plugin does not always complain where the JAR file did. The open issue #484 on GitHub might describe exactly this error.

Now we can finally run Stainless on our code. But this leads us to the next findings. We must rewrite most of the code, as described in the previous chapters.

5 Conclusion

As we saw, it is really hard to verify a software not written with verification in mind. It needs a lot 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 as 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, 2019-06-13	
Last Names, First Names:	Doukmak Anna	Boss Ramon
Signatures:

