

Formal verification of Scala programs with Stainless

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About me

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- MSc in Computer Science from EPFL
- ~2 years as an engineer at LARA

Outline

- Stainless: Verification framework for Scala
- What Stainless verifies
- Termination checker
- Case study: Verifying typeclasses
- More case studies
- Bonus
- Coming soon / further work

Stainless: Verification framework for Scala

Stainless is a verification framework for higher-order programs written in a subset of Scala, named *PureScala*:

- Traits, abstract classes, case classes, implicit classes, methods
- Higher-order functions, lambdas
- Any, Nothing, co-/contra-variant type parameters
- Single inheritance
- Anonymous and local classes, inner functions

- Type members, type aliases
- GADTs
- PartialFunctions
- Set, Bag, List, Map, Array, Byte, Short, Int, Long, BigInt
- Local state, while, traits/classes with vars, and more...

Currently supports Scala 2.12.x.

Some Dotty-specific features:

- Intersection and union types
- Dependent function types
- Extension methods
- Opaque types

Currently only supports Dotty 0.12.0, will try to catch up.

What Stainless verifies

- **Assertions** which should hold at the place where they are stated, **checked statically**
- **Postconditions** using `ensuring` function: assertions for return values of functions
- **Preconditions** using `require` function: assertions on function parameters
- **Loop invariants**: inductive assertions that hold in each loop iteration after the while condition check passes
- **ADT/Class invariants**: assertions on constructors parameters (which remain true for all constructed values)

Stainless also automatically performs **automatic checks for the absence of runtime failures**:

- Exhaustiveness of pattern matching (taking guards into account)
- Division by zero, array bounds checks
- Map domain checks

Moreover, Stainless also prevents *PureScala* programs from:

- Creating null values or uninitialized local variables or fields
- Explicitly throwing an exception
- Overflows and underflows on sized integer types

Termination checker

A *verified* function in stainless is guaranteed to never crash, however, it can still lead to an infinite evaluation.

Stainless therefore provides a termination checker that complements the verification of safety properties.

Pipeline

TODO: Image

- Scala/Dotty compiler
- Extraction
- Lowering
- Inox
- SMT solver

Case study: Verifying typeclasses

```
Seq(1, 2, 3, 4).par.fold(10)(_ - _)
```

```
// (((((10 - 1) - 2) - 3) - 4) => 0
```

```
// (10 - 1) - (2 - (3 - 4))    => 6
```

```
Seq(1, 2, 3, 4).par.fold(0)(_ + _)
```

```
// (((((10 + 1) + 2) + 3) + 4) => 10
```

```
// (10 + 1) + (2 + (3 + 4))    => 10
```

```
abstract class Semigroup[A] {  
  def combine(x: A, y: A): A  
  
  @law def law_assoc(x: A, y: A, z: A) =  
    combine(x, combine(y, z)) == combine(combine(x, y), z)  
}
```

```
abstract class Monoid[A]
  extends Semigroup[A] {

  def empty: A

  @law def law_leftIdentity(x: A) =
    combine(empty, x) == x

  @law def law_rightIdentity(x: A) =
    combine(x, empty) == x
}
```

```
case class Sum(get: BigInt)
```

```
implicit def sumMonoid = new Monoid[Sum] {  
  def empty = Sum(0)  
  def combine(x: Sum, y: Sum) = Sum(x.get + y.get)  
}
```



```
val A: (Object) => Boolean = (x: Object) => x is Sum
val x: { x: Object | @unchecked A(x) } = Sum(x)
val y: { x: Object | @unchecked A(x) } = Sum(y)
val z: { x: Object | @unchecked A(x) } = Sum(z)

val res: Boolean = {
  combine(A, thiss, x, combine(A, thiss, y, z)) ==
  combine(A, thiss, combine(A, thiss, x, y), z)
}

assume(res == law_assoc(thiss, x, y, z))

res
```

stainless summary

law_leftIdentity	law	valid	nativez3	0.223
law_rightIdentity	law	valid	nativez3	0.407
law_assoc	law	valid	nativez3	0.944

total: 3 valid: 3 invalid: 0 unknown: 0 time: 1.574

```
implicit def optionMonoid[A](implicit S: Semigroup[A]) =  
  new Monoid[Option[A]] {  
    def empty: Option[A] = None()  
  
    def combine(x: Option[A], y: Option[A]) =  
      x match {  
        case None()    => y  
        case Some(xv) => y match {  
          case None()    => x  
          case Some(yv) => Some(S.combine(xv, yv))  
        }  
      }  
  }  
}
```

```
implicit def optionMonoid[A](implicit val S: Semigroup[A]) =
  new Monoid[Option[A]] {
    // ...

    override def law_assoc(@induct x: Option[A], y: Option[A],
      super.law_assoc(x, y, z) because {
        (x, y, z) match {
          case (Some(xv), Some(yv), Some(zv)) =>
            S.law_assoc(xv, yv, zv)

          case _ => true
        }
      }
  }
```

```
val A: (Object) => Boolean = (x: Object) =>
  x is Option && isOption[Object](x.value, A)
```

```
val x: { x: Object | @unchecked A(x) } = Option(x)
val y: { x: Object | @unchecked A(x) } = Option(y)
val z: { x: Object | @unchecked A(x) } = Option(z)
```

```
x is Some ==> {
  (x, y, z) match {
    case (Some(xv), Some(yv), Some(zv)) =>
      law_assoc(A, this.S, xv, yv, zv)
    case _ =>
      true
  } && {
    val res: Boolean = {
      combine(A, this, x, combine(A, this, y, z)) ==
      combine(A, this, combine(A, this, x, y), z)
    }
    assume(res == law_assoc(this, x, y, z))
  }
}
```

```
x$569 is None$0 ==> {  
  // snip...  
}
```

```
def foldMap[M, A](xs: List[A])(f: A => M)(implicit M: Monoid[A])  
  xs.map(f).fold(M.empty)(M.append)
```

@extern

```
def parFoldMap[M, A](xs: List[A])(f: A => M)(implicit M: Monoid[A])  
  xs.toScala.par.map(f).fold(M.empty)(M.append)  
} ensuring { res =>  
  res == foldMap(xs, f)  
}
```

More case studies

Conc-Rope

Verified data-structure which provides

- Worst-case $O(\log n)$ time lookup, update, split and concatenation operations
- Amortized $O(1)$ time append and prepend operations

Very useful for efficient data-parallel operations!

[ConcRope] TODO: Ref

Parellel Map-Reduce pipeline

Fully verified implementation of the previous running example, using a Conc-Rope under the hood instead of Scala's 'par' operator.

Built by Lucien Iseli, BSc student, as a semester project. TODO:
Benchmarks

Actor systems

```
case class Primary(backup: ActorRef, counter: BigInt) extends
  def processMsg(msg: Msg): Behavior = msg match {
    case Inc =>
      backup ! Inc
      PrimBehav(backup, counter + 1)

    case _ => this
  }
}
```

```
case class Backup(counter: BigInt) extends Behavior {  
  def processMsg(msg: Msg): Behavior = msg match {  
    case Inc => BackBehav(counter + 1)  
    case _   => this  
  }  
}
```

```
def invariant(s: ActorSystem): Boolean =  
  val primary = s.behaviors(PrimaryRef)  
  val backup  = s.behaviors(BackupRef)  
  val pending = s.inboxes(PrimaryRef -> BackupRef).length  
  
  primary.counter == backup.counter + pending  
}
```

```
def preserveInv(s: ActorSystem, n: ActorRef, m: ActorRef) = {  
  require(invariant(s))  
  
  val next = s.step(n, m)  
  
  invariant(next)  
}.holds
```

Smart contracts

We also maintain a fork of Stainless, called *Smart* which supports:

- Writing smart contracts in Scala
- Specifying and proving properties of such programs, including precise reasoning about the `Uint256` data type
- Generating Solidity source code from Scala, which can then be compiled and deployed using the usual tools for the Ethereum software ecosystem

[0] <https://github.com/epfl-lara/smart>

Bonus: Refinement types

```
type Nat = { n: BigInt => n >= BigInt(0) }
```



```
def sortedInsert(  
  xs: { List[Int] => xs.nonEmpty },  
  x: { Int => x <= xs.head }  
): { res: List[Int] => isSorted(res) } = {  
  x :: xs // VALID  
}
```

Bonus: Dependent function types

```
trait Entry {  
  type Key  
  val key: Key  
}
```

```
def extractKey(e: Entry): e.Key = e.key
```

```
def extractor: (e: Entry) => e.Key = extractKey(_)
```

```
case class IntEntry() extends Entry {  
  type Key = Int  
  val key: Int = 42  
}
```

```
assert(extractor(entry) == 42) // VALID
```

There is more!

- sbt plugin + metals integration
- Ghost context (think Dotty's erased terms but more general)
- Partial evaluation

Coming soon(ish)

- Higher-kinded types
- Better support for refinement types and type members
- VC generation via type-checking

Coming later

- Scala 2.13 / latest Dotty support
- WebAssembly backend
- and more...

Learn more

- Installation
- Tutorial
- Ghost context
- Imperative features
- Working with existing code
- Proving theorems
- Stainless library
- and more...

=> stainless.epfl.ch

Acknowledgments

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References I