TastyTruffle: A Subtitle

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Mathematics
in
Computer Science

Waterloo, Ontario, Canada, 2022

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This is the abstract.

Acknowledgements

I would like to thank all the little people who made this thesis possible.

Dedication

This is dedicated to the one I love.

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TASTy Typed Abstract Syntax Tree 2, 5, 17, 18

Chapter 1

Introduction

Chapter 2

Background

In this chapter, we will provide an introduction to the Scala programming language. We will showcase a running example that we will use for the remainder of this thesis which exhibits features commonly present in Scala programs. We will describe Typed Abstract Syntax Tree (TASTy), an intermediate storage format used for separate compilation[**?**] of Scala programs. We will introduce a critical transformation, type erasure, which alters Scala programs so that they may executable on their default platform the Java Virtual Machine (JVM). We will detail GraalVM Just-in-time (JIT) compiler infrastructure, an alternative JVM implementation which we use to implement a runtime for Scala in this thesis.

2.1 Scala

Scala[36] is a objected-oriented, generic and statically typed programming language. Scala uses a *pure* object-oriected programming model[21] and addresses many of the shortcomings[20] in other object-oriented programming languages. Scala can be still considered *Java-like* because of the interoperability between Java and Scala programs. Programs in Scala may contain generic definitions, allowing Scala programs to composable and reusable[38]. We describe the programming paradigms present in Scala in detail:

Object-oriented Every value in Scala is an object and every operation is method invocation on an object. Every object in Scala is an instance of a *class* and their type is determined by their class. Classes[13] are a mechanism for defining state and behaviour for a group of objects.

Generic Classes in Scala may contain *type parameters* and such classes can be considered *polymorphic*[45]. Polymorphic classes may define behavior independent of their state, allowing them to be reused extensively for multiple types of data.

Statically typed Static typing is a discipline where the type information about a program is known *before* it is executed. In order for a Scala program to compile successfully, it must be *well-type*. For our purposes, computation should always produce a value which has a type matching the type declared by the programmer to be considered well-typed. Classes are the primary syntactical mechanism for declaring types in Scala. The properties of classes such as state, in the form of fields, and behaviour, in the form of methods, must be well-typed. Similarly, the uses of these properties in other classes must also be well-typed.

2.2 Case Study: A List in Scala

In this section, we will introduce the running example that will be used for the remainder of this thesis and our motivations for its selection. Figures 2.1, 2.2 and 2.3 contain an abstract singly-linked list class and its two concrete subclass implementations. This set of `List` implementations represent probable real-world use cases as they are a scaled down and simplified version of the list implementation present in the Scala collections library. The `List` definition from the collections library is available by default to all Scala programs.

```
1 abstract class List[+T] {
2     def head: T
3     def tail: List[T]
4     def length: Int
5     def isEmpty: Boolean = length == 0
6     def contains[T1 >: T](elem: T1): Boolean
7 }
```

Figure 2.1: Definition of `List` class

Figure 2.1 is an example which showcases the paradigms discussed in the previous section that are also commonly present real-world Scala programs. Implementations which derive abstract the `List` class will demonstrate *class inheritance*. The `List` class contains both polymorphic and non-polymorphic methods to showcase type specialization. The `head` method is class-polymorphic in that its type is derived from a class parameter

and becomes specialized when the class is specialized. The `contains` method is method-polymorphic and must be specialized after the class is specialized.

```
case class Cons[+T](head: T, tail: List[T]) extends List[T] {
    override def length: Int = 1 + tail.length

    override def contains[T1 >: T](elem: T1): Boolean = {
        var these: List[T] = this
        while (!these.isEmpty)
        if (these.head == elem) return true
        else these = these.tail
        false
    }

    override def hashCode(): Int = {
        var these: List[T] = this
        var hashCode: Int = 0
        while (!these.isEmpty) {
            val headHash = these.head.## // Compute hashcode
            if (these.tail.isEmpty) hashCode = hashCode | headHash
            else hashCode = hashCode | headHash >> 8
            these = these.tail
        }
        hashCode
    }
}
```

Figure 2.2: Implementation of `Con` class

Figure 2.2 contains the implementation of a list node. The `Cons` implementation contains two polymorphic fields, `head` and `tail`. For specialization, we only care about `head` as a field does not change to store a `List[Int]` or `List[Double]`. On the other hand, the layout of the class would change if the head field was meant to store an integer instead of a byte.

```
case object Nil extends List[Nothing] {
    override def head: Nothing = throw new NoSuchElementException("head of empty list")
    override def tail: Nothing = throw new UnsupportedOperationException("tail of empty list")
    override def length: Int = 0
    override def contains[T1 >: Nothing](elem: T1): Boolean = false
    override def hashCode(): Int = 0
}
```

Figure 2.3: Implementation of `Nil` class

Figure 2.3 contains the implementation of the empty list. We provide the implementation of this class for completeness.

2.3 Typed Abstract Syntax Trees

An Intermediate Representation (IR) is a structural abstraction representing a program during compilation or execution. Intermediate representations are more suitable for reasoning about a program than program source code. IR can be used for compilation[31], optimization[31][12], or execution[32][33].

Typed Abstract Syntax Tree (TASTy) is a high-level Intermediate Representation (IR) which is produced and emitted after type checking phase of the Scala compiler (see appendix A). Figure 2.4 gives an overview of TASTy generation in the context of the Scala compilation pipeline, note that TASTy is only generated for Scala program sources. TASTy is a well-typed variation of an Abstract Syntax Tree (AST), an IR which is close to the program source representation. TASty can be considered a *complete* IR of a Scala program before compilation, unlike the other intermediate representations we will examine throughout this thesis. A complete IR is able to capture all information of the original Scala source program, we will expand on why this is significant in section 2.5.

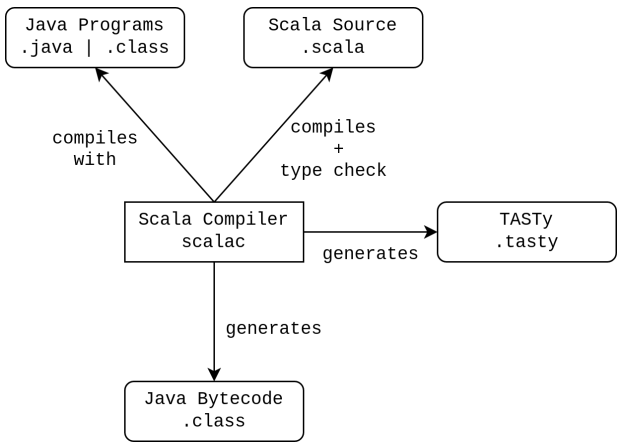


Figure 2.4: TASTy in the context of the Scala compilation pipeline.

In this thesis, we will use a limited subset of TASTy which is sufficient to represent the program given in figures 2.1 and **??**. The TASTy trees used in this thesis can be divided

into categories, definitions, terms, and types. We give the pseudo implementations of these trees in figures 2.5, 2.7, and 2.9.

2.3.1 Definitions

```
// Tree representing code written in the source
trait Tree {
    def symbol: Symbol
}
trait Statement extends Tree       // Tree representing a statement in the source code
trait Definition extends Statement // Tree representing a definition in the source code.

// Tree representing a class definition.
case class ClassDef(
    name:        String,
    constructor: DefDef,
    parents:     List[Tree],
    self:        Option[ValDef],
    body:        List[Statement]
) extends Definition
// Tree representing a method definition in the source code
case class DefDef(
    name:      String,
    params:    List[ParamClause],
    returnTpt: TypeTree,
    rhs:       Option[Term]
) extends Definition
// Tree representing a value definition in the source code.
case class ValDef(name: String, tpt: TypeTree, rhs: Option[Term]) extends Definition
// Tree representing a type (parameter or member) definition in the source code
case class TypeDef(name: String, rhs: Tree) extends Definition
```

Figure 2.5: Pseudocode class definitions for a subset of TASTy trees.

A Scala program consists of top level class definition which themselves contain statements. Statements either represent a declaration inside a class, such as a method definition, or executable code, which we discuss in section 2.3.2. Figure 2.5 provides the pseudo implementations of all definitions in our subset of TASTy. Every tree has a symbol, which is a unique reference to a definition. For the use cases in this thesis, most definitions can be translated and be represented by a corresponding implementation in Truffle. A `ClassDef` represents a top level class definition. A `DefDef` tree is the definition of a method inside a class definition. While the trees defined here can be used represent more complex object-oriented and functional abstractions such as nested classes or closures, they are beyond the scope of this thesis.

```
ClassDef(
    // name
    "List",
    // constructor
    DefDef("<init>", List(TypeParams(TypeDef("T", TypeBoundsTree(_, _)), TermParams(Nil)), _, None)),
    // parents
    List(Apply(Select(New(_, "<init>"), Nil))),
    // self
    None,
    // body
    List(
        TypeDef("T", TypeBoundsTree(_, _)),
        DefDef("head", Nil, TypeIdent("T"), None),
        DefDef(
            "tail",
            Nil,
            Applied(TypeIdent("List"), List(TypeIdent("T"))),
            None
        ),
        DefDef("length", Nil, TypeIdent("Int"), None),
        DefDef("isEmpty", Nil, TypeIdent("Boolean"), None),
        DefDef(
            "contains",
            List(
                TypeParams(TypeDef("T1", TypeBoundsTree(TypeIdent("T"), _))),
                TermParams(ValDef("elem", TypeIdent("T1"), None))
            ),
            TypeIdent("Boolean"),
            None
        )
    )
)
```

Figure 2.6: Tree structure for the definition of `List` . For brevity, we use _ to represent inferred[14] type trees by the compiler.

Figure 2.6 is the TASTy structure of the `List` class given in figure 2.1. Recall that `ClassDef` trees has four structural components, the constructor, the list of parent class definitions, the self type, and the body of the definition. In this thesis, we will not discuss the self type as it is an abstraction for composition[8][11] and is not relevant for execution. As result of the self type not being present, the list of parents in a class definition can be assumed to always be a singleton. Note that while the abstract `List` class did not explicit declare a constructor, the compiler autogenerates and inserts the appropriate constructor implementation. Since `List` is polymorphic, it contains an inner type definition of its sole type parameter. This distinction is what makes TASTy distinct from the other intermediate representations we will describe further in this thesis.

Similarly, `DefDef` trees also retain their polymorphic properties. The parameters section of a `DefDef` tree is split into two halves. The type parameter section preserves any polymorphic type parameters in the method definition. The term parameter section contains the normal value paramers found in a method. Term parameters may have types which are derived from the type parameter section.

2.3.2 Terms

```
1  // Tree representing an expression in the source code
2  trait Term extends Statement {
3      def tpe: Type
4  }
5  // Tree representing a reference to definition
6  trait Ref extends Term
7
8  // Tree representing an assignment lhs = rhs in the source code
9  case class Assign(lhs: Term, rhs: Term) extends Term
10 // Tree representing new in the source code
11 case class New(tpt: TypeTree) extends Term
12 // Tree representing a block `{ ... }` in the source code
13 case class Block(statements: List[Statement], expr: Term) extends Term
14 // Tree representing a while loop
15 case class While(cond: Term, body: Term) extends Term
16 // Tree representing a selection of definition with a given name on a given prefix
17 case class Select(qualifier: Term, selector: String) extends Term
18 // Tree representing an application of arguments.
19 case class Apply(applicator: Term, arguments: List[Term]) extends Term
20 // Tree representing an application of type arguments
21 case class TypeApply(fun: Term, args: List[TypeTree]) extends Term
22 // Tree representing a reference to definition with a given name
23 case class Ident(name: String) extends Ref
```

Figure 2.7: Pseudocode class definitions for a subset of TASTy trees.

Figure 2.7 gives the implementation for terms in our subset of TASTy. Terms represent an executable atom of code which return a value. Terms can be thought of as a representation that is analogous to expressions from the abstract syntax trees commonly used for other imperative programming languages. Our term tree subset of TASTy represents a basic language with support for simple imperative programming with control flow constructs such as branching and loops. A basic set of object-oriented features are also encapsulated in the tree definitions given above, these include object creation, instance method invocation, and instance field access. This subset of TASTY is sufficient to represent the creation

of polymorphic classes as well as the invocation of polymorphic methods to showcase the described in this thesis.

Terms in TASTy also retain their types after the type checking by the Scala compiler. A type for a term describes the type of the value produced by the term. Terms with no children, such as `Ident`, retain their types and those types 'flow' upwards to their parent terms. We will describe types in detail in the next section.

2.3.3 Types and Type Trees

```
1  // Type tree representing a type written in the source
2  trait TypeTree extends Tree {
3      def tpe: Type
4  }
5
6  // Type tree representing a reference to definition with a given name
7  case class TypeIdent(name: String) extends TypeTree
8  // Type tree representing a type application
9  case class Applied(tpt: TypeTree, args: List[TypeTree | TypeBoundsTree]) extends TypeTree
10 // Type tree representing a type bound written in the source
11 case class TypeBoundsTree(lo: TypeTree, hi: TypeTree) extends TypeTree
```

Figure 2.8: Pseudocode class definitions for a subset of TASTy type trees.

```
1  // A type, type constructors, type bounds
2  trait Type
```

Figure 2.9: Pseudocode class definitions for a subset of TASTy type trees.

TASTy encodes Scala programs with two kinds of type information, types trees and types. Type trees are a subset of trees which represent types as they are declared in Scala source code. On the other hands, types are the canonical representation of a type after type checking in the Scala compiler. Multiple type trees may share the same underlying type.

Figure 2.8 gives the subset of type trees which we will use in this thesis. For our purposes, there are only three ways to refer to types. A `TypeIdent` type tree is a reference to a type which is a `ClassDef`. An `Applied` type tree represents type constructor, which

accept type arguments and produce a new type. For example, the `Cons[T]` would be represented as an applied type tree, where `Cons` would the constructor and `T` would be the type argument. A `TypeBounds` tree represents the type expression `Lo <: T <: Hi`, a constraint where `T` must be a subtype of type `Hi` and supertype of type `Lo`. In the context of this thesis, we can use subtype to mean *subclass of* and supertype of to mean *superclass of*.

We will go over each tree and their relevance for execution in our interpeter in chapter 3. As part of normal Scala compilation pipeline, TASTy is eventually consumed by the Scala compiler and the approriate Java bytecode is emitted.

2.4 Java Bytecode

Java bytecode is a portable and compact intermediate language and instruction set used by the Java Virtual Machine to execute programs. Java bytecode can be considered similar to an assembly language, where programs are represented as sequences of atomic instructions which manipulate a stack or registers. The type system in Java bytecode can describe primitive values such as `int` and references to objects such as `String`. As bytecode is intended to be simple for execution, it is not possible to represent polymorphic programs fully in Java bytecode.

Types in TASTy are not immediately compatible with types available in Java bytecode. Scala's type semantics must be eliminated from programs by the compiler before Java bytecode of the program can be emitted. The resulting Java bytecode is considered an *incomplete* IR of Scala source programs, as the type information found in the program source or inferred from compilation is no longer present. This becomes a particular drawback for executing Scala programs on the JVM because speculative optimizations are unable to incorporate source level semantics.

Figure 2.10 is the Java bytecode of the `contains` defined at line 4 in figure 2.2. Typical control flow elements of Scala programs such as if terms and while terms have been converted into branch and jump instructions. Notice that there are no polymorphic type parameters in the description of classes nor in the invocation of polymorphic methods present in the bytecode. In particular, notice the equality comparison in line 7 of figure 2.2 is actually a method invocation (line 14 in figure 2.10). As the Scala compiler is unable to determine the type of a polymorphic type parameters during complilation time, it is unable to select a Java bytecode instruction which implements polymorphic comparison. Instead, a bridge method part of the Scala standard library is responsible for handling polymorphic

```
0:  aload_0
1:  astore_2
2:  aload_2
3:  invokevirtual #44 // List.isEmpty:()Z
6:  ifne          30
9:  aload_2
10: invokevirtual #46 // List.head:()Ljava/lang/Object;
13: aload_1
14: invokestatic  #52 // Method scala/runtime/BoxesRunTime.equals:(Ljava/lang/Object;Ljava/lang/Object;)Z
17: ifeq          22
20: iconst_1
21: ireturn
22: aload_2
23: invokevirtual #53 // List.tail:()LList;
26: astore_2
27: goto          2
30: iconst_0
31: ireturn
```

Figure 2.10: Java bytecode of `Cons.contains`

operations which operate on both reference and primitive types during runtime. In the next section, we describe the process which transforms Scala programs to a reprensentation amenable for Java bytecode generation and the necessary additional runtime overhead associated with this transformation.

2.5 Type Erasure

Type erasure[35] is a transformation which converts polymorphic classes methods in Scala to monomorphic classes and methods. This conversion is necessary because the JVM does not support polymorphic classes during runtime. Erasure ensures that any given polymorphic class and method has a single representation in practice. Type erasure is a crucial part of the Scala compilation which renders TASTy incomplete. Figure 2.11 shows the `Cons` class after type erasure.

The polymorphic `Cons` class has all type parameters in its class definition *erased* and replaced by the `Any` type. The `Any` type is a Scala platform-independent[36] abstract type representing the super type of primitive and reference types. In Java bytecode, the Any type resolves to the `Object` type, the super type of all reference types on the JVM.

While type erasure simplifies classes for runtime, the Scala compiler must resolve the incompatibility of operations between primitives types and reference types on the JVM[32],

```
case class Cons(head: Any, tail: List) extends List {
    override def length: Int = 1 + tail.length

    override def contains(elem: Any): Boolean = {
        var these: List = this
        while (!these.isEmpty)
        if (these.head == elem) return true
        else these = these.tail
        false
    }

    override def hashCode(): Int = {
        var these: List = this
        var hashCode: Int = 0
        while (!these.isEmpty) {
            val headHash = these.head.##
            if (these.tail.isEmpty) hashCode = hashCode | headHash
            else hashCode = hashCode | headHash >> 8
            these = these.tail
        }
        hashCode
    }
}
```

Figure 2.11: `Cons` class after type erasure

The set of operations introduced by the compiler whenever a primitive value is accessed under a polymorphic context is known as *autoboxing*[1]. Autoboxing can be divided into two operations. *Boxing* occurs when a primitive value must be used where a generic value is expected. *Unboxing* occurs when a generic value must be used where a primitive value is expected. Figure 2.12 shows a simple example of inserted autoboxing operations when using the polymorphic `Cons` class after type erasure.

```
// Before type erasure
val lst: List[Int] = Cons(1, Nil)
val head: Int = lst.head
// After type erasure
val lst: List = Cons(box(1), Nil)
val head: Int = unbox(lst.head)
```

Figure 2.12: Example of autoboxing introduced for a list

The `head0` field inside the `Cons` class after erasure is no longer polymorphic and instead has the type `Any`. The integer value of `1` which is passed into the class constructor for the

list is boxed and the primitive value is wrapped as a instance of its boxed class. Similarly, when the `head0` field of the instance is read and stored into a local variable, an unboxing operation occurs which extracts the primitive value out of its wrapper instance. In the Scala collections library, a set of commonly used polymorphic data structures, autoboxing operations are frequent and necessary. The computational overheads of autoboxing operations on programs which make substantial use of polymorphic collections, especially the Scala standard library, is significant[40]. The elimination of this overhead through optimizing autoboxing operations is one of the central goals of this thesis.

2.6 GraalVM

GraalVM[49] is an implementation of a JVM. Traditionally, the JVM is responsible for the majority of the performance optimizations in Java programs[39] through Just-in-time (JIT) compilation. JIT compilation is an adaptive optimization which occurs during program execution. JIT compilation is concerned with optimizing and eliminating *hotspots* or portions of the program which are the slowest. JIT compilers[19][2] employ a range of *speculative* techniques to transform the program under optimization. Speculative optimizations use information collected during program execution, otherwise known as *profiling*. Assumptions are then made about gathered profiling data in order to generate high-performance native machine code.

While other implementations of Java virtuals machines were designed specifically for Java, GraalVM was designed from the onset to be *language-independent*. GraalVM can be divided into two components. The first is *Truffle*, a framework for translating the semantics of a source language, also called a *guest language*, to take advantage of the Graal infrastrucure. The second is *Graal*, a language-agnostic JIT compilation infrastructure which handles speculative optimizations and generation of high-performance machine code.

This thesis makes substantial of both components of GraalVM to create a runtime for Scala programs using TASTy. The runtime is able to incorporate source level information for speculative optimizations.

2.6.1 Graal

GraalVM incorporates an existing implementation of a JVM[39] for the actual execution of programs. Graal is *only* the general-purpose just-in-time compilation infrastructure which optimizes the programs to be executed. Graal is general-purpose in that conducts

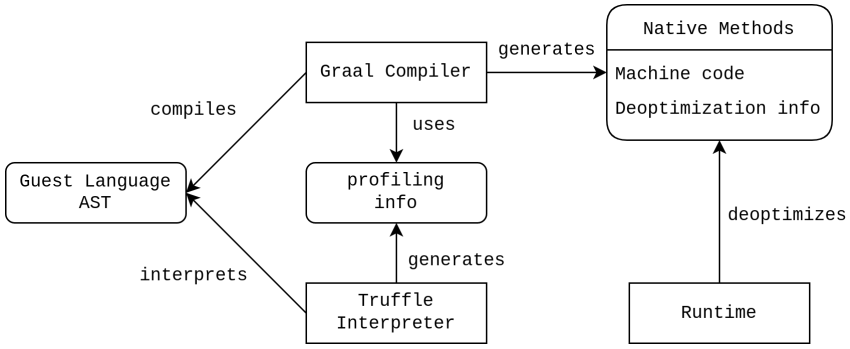


Figure 2.13: GraalVM overview[16].

analysis and optimization on the same intermediate representation, *Graal IR*, regardless of the original source language.

Graal IR[16][1] is an IR which is suitable for speculative optimizations while still retaining information from the Truffle guest language AST. Graal IR is based on the *sea of nodes* concept[10] and sastifies the *static single-assignment*[12] property. A sea of nodes is an abstraction based on a directed graph structure which relate the control flow graph[5] of the program to its data flow graph[4]. An intermediate representation is in single-static assignment form when each variable is declared once and every use of a variable occurs immediately after its declaration[27].

GraalIR enables Graal to speculatively compile only the *hot* branches[17], or branches that are most frequently taken, in the control flow portion of the IR and their transitive data dependencies. When a compiled program enters an unexpected state, execution is *deoptimized*[24] and control of the program is transferred back to the interpreter. Deoptimization occurs when the compiled program is no longer considered stable and therefore is invalid. Graal automatically inserts *guard nodes* into the IR, which are conditional checks which validate that speculative assumptions used to compile the program still hold. Deoptimization is part of an execution loop between Graal and Truffle which allows GraalVM to aggressively adapt and speculate to find the best optimization in a dynamic environment.

2.6.2 Truffle

Truffle is a Domain Specific Language (DSL) framework for guest language implementation embedded in GraalVM. A guest language is a language which is expected to run on Graal

[1]Given the number of intermediate representations introduced thus far, we promise this is the last one

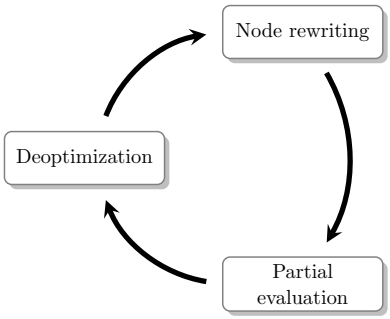


Figure 2.14: Adaptive optimization loop of GraalVM

and requires an implementation in the *host language*, which provides the Truffle DSL. In this thesis, the guest language is TASTy (which represents Scala) and the host language is Java, the implementation language of Truffle. A guest language implementation always takes the form of an executable Truffle AST.

During execution of the AST, profiling information collected from the interpreter is used to drive *node rewriting*. While Graal is language-agnostic, Truffle is able exploit guest language semantics for dynamic optimizations. This process of replacing nodes in the AST with better, specialized guest language counterparts in Truffle is called node rewriting. Node rewriting serves two purposes. The first is to dynamically incorporate guest language semantics into the executing program. The second is to augment the AST for JIT compilation. In this thesis, we will focus heavily on node rewriting the execution of TASTy trees in a Truffle interpreter to augment JIT compilation.

```
1 abstract class EqualsNode extends BinaryOpNode {
2     @Specialization
3     def equalsInt(lhs: Int, rhs: Int): Boolean = lhs == rhs
4
5     @Specialization(replaces="equalsInt")
6     def equals(lhs: Any, rhs: Any): Boolean = if (lhs == null) rhs == null else lhs.equals(rhs)
7 }
```

Figure 2.15: Pseudocode for a Truffle node implementation of an equality which supports node rewriting.

Figure 2.15 demonstrates an example of a node which can be rewritten. The node declares semantics of the equality operation between Integers and as well as values of type `Any`. The `Any` is the super type of every type in Scala, as such, this equality node has

semantics for every case. The node starts off in the uninitialized state. When both the left and right hand side operands are integers, the node is rewritten to `equalsInt`. When arguments of any other combination of types are detected, either in the uninitialized state or the `equalsInt` state, the node is rewritten to the `equals` state.

After node rewriting, Graal JIT compiles Truffle ASTs into native machine code using *partial evaluation*. Partial evaluation is a program optimization technique for specializing an a program (code) for a given input (data)[18]. In the context of Truffle, this means combining a method (code) with a sequence of arguments (data)[48]. When a Truffle AST is submitted for compilation to Graal, it is considered *stable*, or no longer suitable for node rewriting. These arguments, previously considered dynamic input supplied to the method can now be considered static data in the method itself. We can say that the partial evaluation of a method with a set of arguments will produce a specialized method that always execute with those arguments. In Truffle, the results of partial evaluation produce Graal IR which is ready for JIT compilation.

Chapter 3

Implementation

This chapter is divided into two parts. The first half of this chapter will describe the methods used to execute TASTy in a Truffle interpreter. In particular, we will cover how to tranform the semantics of TASTy to Truffle AST nodes. The second half of this chapter covers the techniques we will use to eliminate autoboxing Truffle itself is unable to eliminate.

3.1 Execution

Scala programs in TASTy format are unsuitable for execution in a Truffle interpreter. Programs in must be parsed and transformed into an executable representation in TastyTruffle. As TASTy represents a Scala program close to its equivalent source representation, canonicalization compiler passes (see appendix A) that would otherwise normalize the IR are not present. Instead, we implement TastyTruffle IR to represent a canonicalized executable intermediate representation which can be specialized on demand.

In the following sections, we will describe the individual types of TASTy nodes and why some are directly unsuitable for execution and how to simplify their semantics for execution. We will begin with a explanation of how data is encoded and defined in TASTy.

3.1.1 Generating Frame Slots from `ValDef` trees

The `ValDef` tree is a multi-purpose node which represents value definitions in many contexts. This section will only cover the `ValDef` tree in the context of local variables. Sections

3.1.2 and 3.1.3 will cover the remaining contexts where `ValDef` trees appear.

Local variables are variables which are bound to a *scope*. A scope represents the lifetime in which a variable can refer to an entity. Similarly, uses of variables are only valid when used under the appropriate scope. Local variables and their use sites are represented in intermediate representations through a myriad of methods. In abstract syntax trees, local variables and their used are represented as nodes *dominated* by their scopes (which are themselves nodes). Unlike more simplified IR, abstract syntax trees do not encode any data dependence between definitions and uses[12]. In order to execute the tree, name binding must be resolved when ???

In TASTy, a local variable is represented by the `ValDef` tree node:

```
1    case class ValDef(name: String, tpt: TypeTree, rhs: Option[Term]) extends Tree
```

Figure 3.1: Simplified `ValDef` tree

The `ValDef` tree represents the site of a local variable declaration when the node is dominated by a `Block` node. A `ValDef` contains the simple, unqualified name of the declaration, the type as represented in the source program and the intializer. When a `ValDef` is dominated by a `Block`, the initializer will always be non-empty.

Each unique variable declaration has a corresponding frame slot in the frame descriptor of its root node. Truffle permits each frame slot in a frame descriptor be described by a *frame slot kind*. At the time of writing, a frame slot kind can be implemented as:

```
1    object FrameSlotKind extends Enumeration {
2        type FrameSlotKind = Value
3        val Object, Long, Int, Double, Float, Boolean, Byte = Value
4    }
```

Figure 3.2: Simplified implementation of `FrameSlotKind`

There is a corresponding frame slot kind for reference types and each JVM primitive type. We determine the frame slot kind of a type using the following method:

```
def getFrameSlotKind(tpe: Type): Option[FrameSlotKind] = {
    if (tpe.isMonomorphic && tpe.isPrimitive)
        Some(primitiveSlotKindOf(tpe))
    else if (tpe.isParameter)
        None
    else
        Some(FrameSlotKind.Object)
}
```

Figure 3.3: Pseudocode for determining the frame slot kind of a type.

Truffle specializes local variable access based on the variable's type during partial evaluation[48]. To eliminate the need to specialize read and writes of variables where types are monomorphic and statically refer to a primitive type, the primitive frame slot kind is matched in the frame descriptor. In all other cases, including when the type is not resolvable through a single type parameter, e.g. `val x: T`, we assign the frame slot the `Object` frame slot kind. We will defer discussion of variable declarations which have polymorphic types that cannot be resolved statically until section 3.2.

3.1.2 Converting the `DefDef` tree into a Truffle Root Node

In this section, we describe the conversion of a `DefDef` tree to *root nodes* Root nodes represent the root of an executable Truffle AST. Each root node has a corresponding *call target*, which is used for invocation. A root node is automatically instrumented[42] to profile its number of invocations. When a limit on the number of invocations inside the interpreter is reached, the call target is submitted for compilation.

```
abstract class RootNode(desc: FrameDescriptor) {
    def execute(frame: Frame): Object
}
```

Figure 3.4: Pseudocode of a root node.

Figure 3.4 gives a simplified implementation of a root node. Each root node in Truffle has a *frame descriptor* and execution semantics. A frame descriptor describes the guest language variables which are in the scope of the root node. The `execute` method in a root

```
class DefDef(_: String, params: List[ParamClause], _: TypeTree, rhs: Option[Term]) extends Definition
```

node is implemented by its guest language subclass encapsulating its method invocation semantics.

3.1.3 Deriving Shapes from the `ClassDef` Tree

The storage layout of an object in a Truffle interpreter is managed by a *Shape*.

```
private ClassShape(
    symbol:  Symbol,
    parents: Array[Symbol],
    fields:  Array[Field] ,
    methods: Map[MethodSignature, RootCallTarget]
    vtable:  Map[Signature, Symbol]
)
```

Figure 3.5: Simplified implementation of a shape.

3.1.4 Data mutation with the `Assign` tree

3.1.5 Initializing Objects with the `New` Tree

Escape Analysis

Escape analysis[28] reasons about the dynamic scope of object allocations. Compiler implementations often exploit the observations of escape analysis to enable optimizations such:

Region Allocation[7][47] The substitution of heap allocations with stack allocations to eliminate unnecessary garbage collection.

Scalar Replacement[29] The complete elimination of an object allocation, where the fields of the replaced object are substituted by local variables.

GraalVM employs *Partial Escape Analysis*[44], a path-sensitive variant of escape analysis which is particularly effective when combined with optimizations described above as well other compiler optimization such as inlining. Truffle offers guest language implementations the `VirtualFrame` abstraction to allow guest language semantics to take advantage of partial escape analysis and subsequent optimizations.

3.1.6 The `Block` tree

3.1.7 The `While` tree

3.1.8 The `Select` tree

3.1.9 Resolving `Apply` tree

As previously mentioned, method invocations exists in multiple forms because tree canocalization happens immediately after the TASTy picking phase in the compilation pipeline. The result is that TASTy trees retain some syntactic elements from their Scala sources. For example, Truffle provides two abstractions for call nodes, the *direct call node* is used when the call target can be statically resolved. In TASTy, this includes the set of methods with private or final modifiers[22] and class constructors. Otherwise, the *indirect call node* is used for calls which have dynamically resolved call targets. TastyTruffle uses a singular call node implementation for both monomorphic and polymorhic calls. we utilize a polymorphic inline cache[23] to eliminate the overhead of resolving polymorphic calls for JIT compilation. Figure 3.6 shows a simplified Truffle call node in TastyTruffle which implements a polymorphic inline cache.

The Truffle DSL emits a cache which is searched linearly based on the type of receiver. When the type of receiver has not been seen in the inline cache, an additional cache entry is generated and appended to the cache for the next call. The size of an polymorphic inline cache must be kept reasonable ???. The generated inline cache can be used to inline code and JIT optimized based on the type of the receiver seen at a call site.

```
1  class ApplyNode(sig: Signature, receiver: TermNode, args: Array[TermNode]) extends TermNode {
2
3      final val INLINE_CACHE_SIZE: Int = 5;
4
5      @Specialization(guards = "inst.type == tpe", limit = "INLINE_CACHE_SIZE")
6      def cached(
7          frame: VirtualFrame,
8          inst: ClassInstance,
9          @Cached("inst.type") tpe: Type,
10         @Cached("create(resolveCall(instance, sig)") callNode: DirectCallNode
11     ): Object = callNode.call(evalArgs(frame, inst));
12
13     @Specialization(replaces = "cached")
14     def virtual(
15         frame: VirtualFrame,
16         inst: ClassInstance,
17         @Cached callNode: IndirectCallNode
18     ): Object = {
19         val callTarget = resolveCall(instance, sig);
20         callNode.call(callTarget, evalArgs(frame, inst))
21     }
22 }
```

Figure 3.6: Simplified implementation of the call node with a polymorphic inline cache used in TastyTruffle.

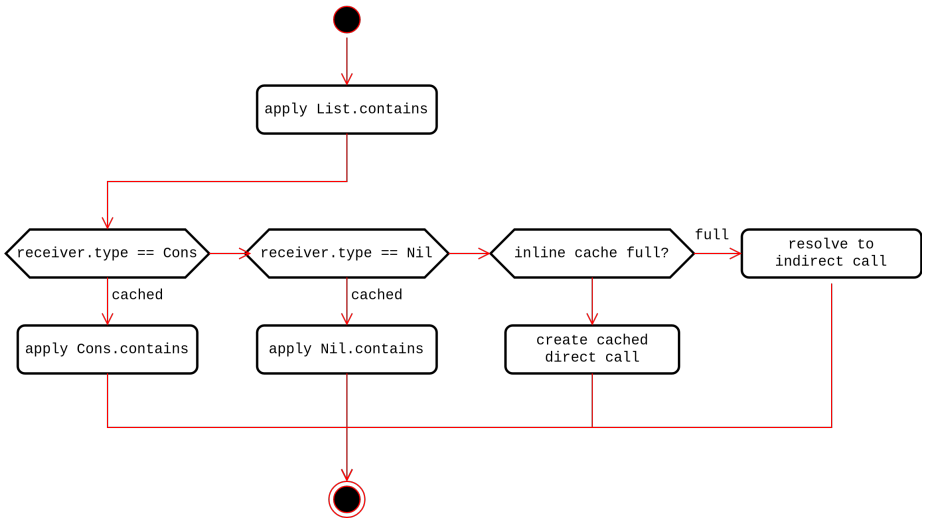


Figure 3.7: A possible polymorphic inline cache for a `List.contains` callsite.

When the polymorphic inline cache is applied to a monomorphic call site, it simplifies to a single element inline cache[15]. Because the type of the receiver at the call site remains stable, the cache look up of the call target based on the type always succeeds and the call site never fallbacks to using an indirect call node.

Unary and Binary Expressions

Unary and Binary operations in Scala are syntactic sugar for function invocation. For example, the following addition `1 + 2` is desugared to `1.+(2)`. That is, the binary operator `+` is represented as the invocation of the instance function `Int.+` on the receiver with value `1` and type `Int` with a single argument `2`. Normally in the Scala compilation pipeline, methods which operate on primtive types and have an underlying implementation on the JVM[32], e.g. in a bytecode instruction, are replaced by those instructions in compiled program bytecode. Similarly, TastyTruffle avoids implementing methods of primitive types with actual call semantcs as primitive operations are frequently used and simple to optimize as instrinsic implementations exist on many Java virtual machines.[**?**]

3.1.10 The `Ident` tree

3.2 Specialization

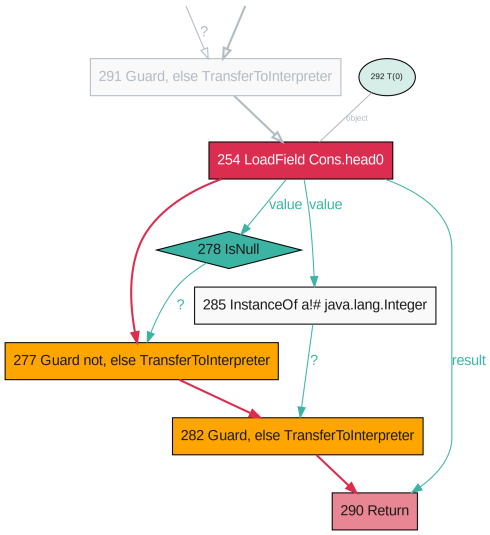
3.2.1 Specializing Object Layout with `Applied` type trees

```
1 trait PolymorphicTermNode extends TermNode {
2     def resolveType: ClassType
3     override def execute(frame: VirtualFrame): Object =
4         throw new UnsupportOperationException("generic code cannot be executed!")
5 }
```

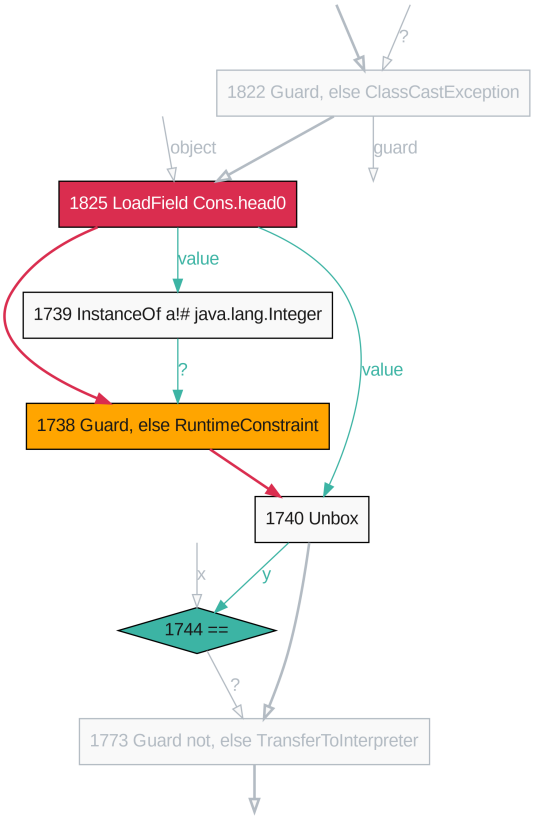
Figure 3.8: A placeholder node for polymorphic code in TastyTruffle

3.2.2 Specializing Call Sites with `TypeApply` trees

Generic methods in Scala can be polymorphic under class type parameters, method type parameters, or both. In the latter two cases, polymorphic methods contain additional



(a) Graal IR of `Cons.head` focused on field access of `head0`



(b) Graal IR of `Cons.head` after being inlined into `Cons.contains`

reified type parameters. In addition to the polymorphic terms present in the method body discussed in the previous section, the type of method term parameters may be polymorphic. The following components of a generic method must specialized:

- Polymorphic method parameters.
- Polymorphic terms inside the method body.

Method Parameters

Typed Dispatch Chains

Dispatch chains[**?**]

```
1  class TypeDispatchNode(parent: RootNode) extends TermNode {
2
3      type TypeArguments: Array[Type]
4      @CompilerDirectives.CompilationFinal
5      var cache: Map[TypeArguments, DirectCallNode]
6
7      override def execute(frame: VirtualFrame): Object = {
8          val types: TypeArguments = resolveTypeParameters(frame)
9          dispatch(frame, args);
10     }
11
12     def dispatch(frame: VirtualFrame, types: TypeArguments): Object = cache.get(types) match {
13         case Some(callNode) => callNode.call(frame.getArguments)
14         case None           => createAndDispatch(frame, types)
15     }
16
17     def createAndDispatch(frame: VirtualFrame, types: TypeArguments): Object = {
18         CompilerDirectives.transferToInterpreterAndInvalidate()
19         val specialization = parent.specialize(types)
20         val callNode = DirectCallNode.create(specialization)
21         cache = cache.updated(types, callNode)
22         callNode.call(frame.getArguments)
23     }
24 }
```

Figure 3.10: Simplified implementation of generic dispatch node based on reified type arguments.

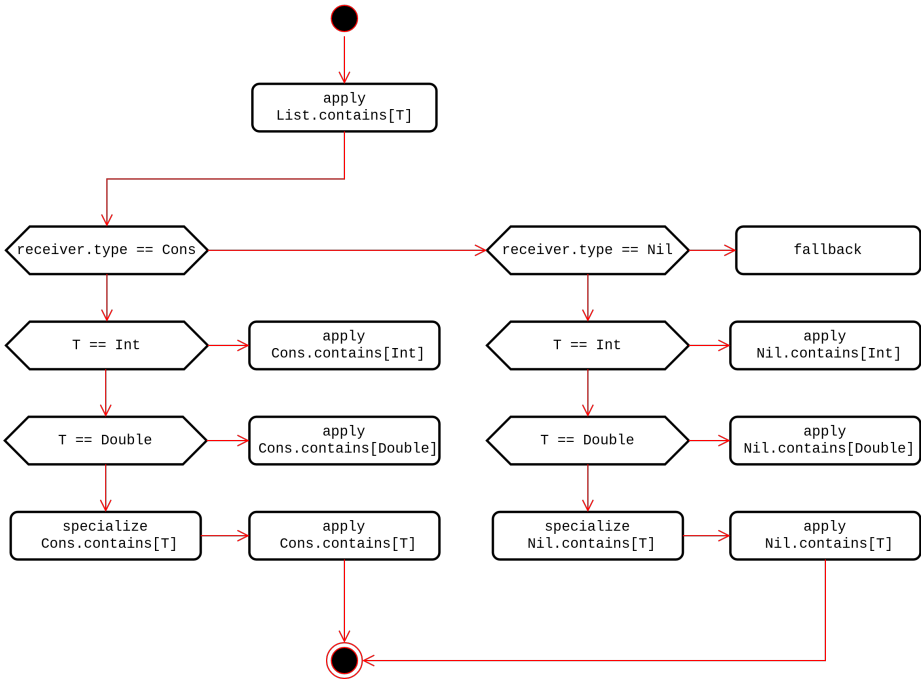


Figure 3.11: The typed dispatch chain for a `List.contains` call site

Code Duplication

Partial Evaluation

3.2.3 Specializing Terms

The basic polymorphic unit of code in Scala are terms whose types are derived directly from a type parameter `T` or indirectly from a type constructor such as `Array[T]`. Polymorphic terms can be divided into the following categories:

Polymorphic local access

Polymorphic field access

Polymorphic method call

Polymorphic instantiation

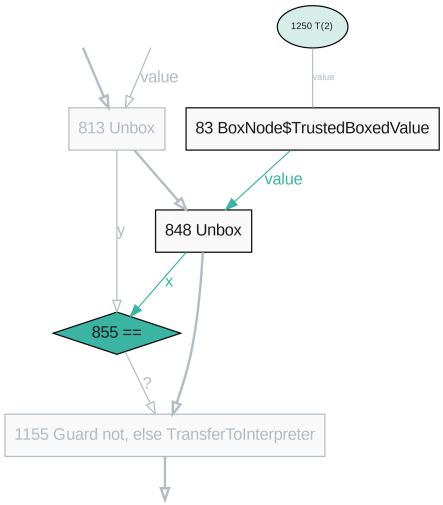
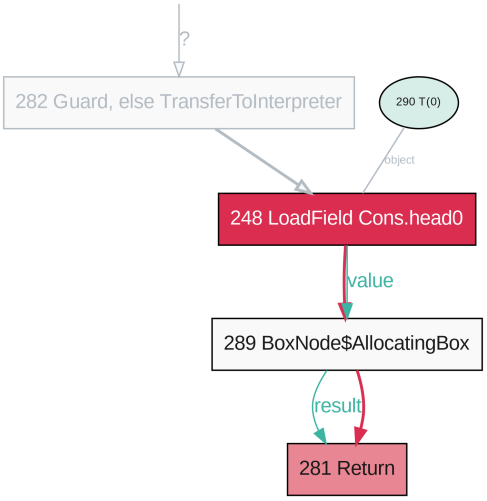
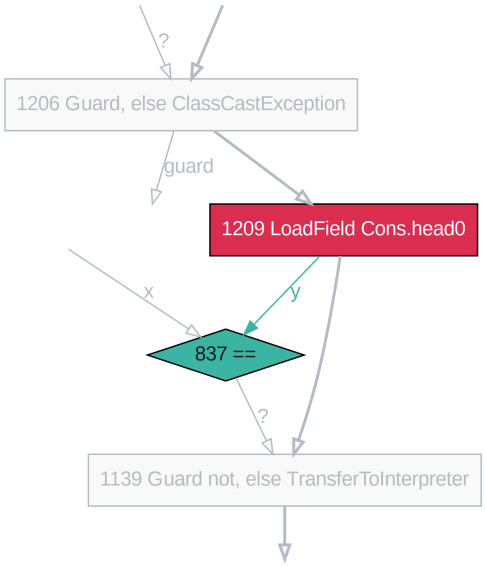


Figure 3.12: Graal IR of `List.head` after field read of `head0` is specialized.



(a) Graal IR of `List.head` after field read of `head0` is specialized.



(b) Graal IR of `Cons.head` after being inlined into `Cons.contains`

Chapter 4

Evaluation

Chapter 5

Related Work

5.1 Truffle Interpreters

5.2 Specializing Scala

5.3 Specializing Other Languages

Chapter 6

Future Work

Chapter 7

Conclusions

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APPENDICES

Appendix A

Scala 3 Compiler Phases

```
/** Phases dealing with the frontend up to trees ready for TASTY pickling */
protected def frontendPhases: List[List[Phase]] =
    List(new Parser) ::                       // scanner, parser
    List(new TyperPhase) ::                   // namer, typer
    List(new YCheckPositions) ::              // YCheck positions
    List(new sbt.ExtractDependencies) ::      // Sends information on classes' dependencies to sbt via callbacks
    List(new semanticdb.ExtractSemanticDB) :: // Extract info into .semanticdb files
    List(new PostTyper) ::                    // Additional checks and cleanups after type checking
    List(new sjs.PrepJSInterop) ::            // Additional checks and transformations for Scala.js (Scala.js only)
    List(new Staging) ::                      // Check PCP, heal quoted types and expand macros
    List(new sbt.ExtractAPI) ::               // Sends a representation of the API of classes to sbt via callbacks
    List(new SetRootTree) ::                  // Set the `rootTreeOrProvider` on class symbols
    Nil
```

```
/** Phases dealing with TASTY tree pickling and unpickling */
protected def picklerPhases: List[List[Phase]] =
    List(new Pickler) ::            // Generate TASTY info
    List(new PickleQuotes) ::       // Turn quoted trees into explicit run-time data structures
    Nil
```

```
/** Phases dealing with the transformation from pickled trees to backend trees */
protected def transformPhases: List[List[Phase]] =
    List(
        new FirstTransform,         // Some transformations to put trees into a canonical form
        new CheckReentrant,         // Internal use only: Check that compiled program has no data races involving global va
        new ElimPackagePrefixes,    // Eliminate references to package prefixes in Select nodes
        new CookComments,           // Cook the comments: expand variables, doc, etc.
```

```
8         new CheckStatic,            // Check restrictions that apply to @static members
9         new BetaReduce,             // Reduce closure applications
10        new init.Checker) ::        // Check initialization of objects
11    List(
12        new ElimRepeated,           // Rewrite vararg parameters and arguments
13        new ExpandSAMs,             // Expand single abstract method closures to anonymous classes
14        new ProtectedAccessors,     // Add accessors for protected members
15        new ExtensionMethods,       // Expand methods of value classes with extension methods
16        new UncacheGivenAliases,    // Avoid caching RHS of simple parameterless given aliases
17        new ByNameClosures,         // Expand arguments to by-name parameters to closures
18        new HoistSuperArgs,         // Hoist complex arguments of supercalls to enclosing scope
19        new SpecializeApplyMethods, // Adds specialized methods to FunctionN
20        new RefChecks) ::           // Various checks mostly related to abstract members and overriding
21    List(
22        // Turn opaque into normal aliases
23        new ElimOpaque,
24        // Compile cases in try/catch
25        new TryCatchPatterns,
26        // Compile pattern matches
27        new PatternMatcher,
28        // Make all JS classes explicit (Scala.js only)
29        new sjs.ExplicitJSClasses,
30        // Add accessors to outer classes from nested ones.
31        new ExplicitOuter,
32        // Make references to non-trivial self types explicit as casts
33        new ExplicitSelf,
34        // Expand by-name parameter references
35        new ElimByName,
36        // Optimizes raw and s string interpolators by rewriting them to string concatentations
37        new StringInterpolatorOpt) ::
38    List(
39        new PruneErasedDefs,        // Drop erased definitions from scopes and simplify erased expressions
40        new InlinePatterns,         // Remove placeholders of inlined patterns
41        new VCInlineMethods,        // Inlines calls to value class methods
42        new SeqLiterals,            // Express vararg arguments as arrays
43        new InterceptedMethods,     // Special handling of `==`, `|=`, `getClass` methods
44        new Getters,                // Replace non-private vals and vars with getter defs (fields are added later)
45        new SpecializeFunctions,    // Specialized Function{0,1,2} by replacing super with specialized super
46        new LiftTry,                // Put try expressions that might execute on non-empty stacks into their own methods
47        new CollectNullableFields,  // Collect fields that can be nulled out after use in lazy initialization
48        new ElimOuterSelect,        // Expand outer selections
49        new ResolveSuper,           // Implement super accessors
50        new FunctionXXLForwarders,  // Add forwarders for FunctionXXL apply method
51        new ParamForwarding,        // Add forwarders for aliases of superclass parameters
52        new TupleOptimizations,     // Optimize generic operations on tuples
53        new LetOverApply,           // Lift blocks from receivers of applications
54        new ArrayConstructors) ::   // Intercept creation of (non-generic) arrays and intrinsify.
55    List(new Erasure) ::            // Rewrite types to JVM model, erasing all type parameters, abstract types and refineme
56    List(
57        new ElimErasedValueType,    // Expand erased value types to their underlying implmementation types
58        new PureStats,              // Remove pure stats from blocks
59        new VCElideAllocations,     // Peep-hole optimization to eliminate unnecessary value class allocations
60        new ArrayApply,             // Optimize `scala.Array.apply([....])` and `scala.Array.apply(..., [....])` into `[..
61        new sjs.AddLocalJSFakeNews, // Adds fake new invocations to local JS classes in calls to `createLocalJSClass`
62        new ElimPolyFunction,       // Rewrite PolyFunction subclasses to FunctionN subclasses
63        new TailRec,                // Rewrite tail recursion to loops
64        new CompleteJavaEnums,      // Fill in constructors for Java enums
```

```
65          new Mixin,                  // Expand trait fields and trait initializers
66          // Expand lazy vals
67          new LazyVals,
68          // Add private fields to getters and setters
69          new Memoize,
70           // Expand non-local returns
71          new NonLocalReturns,
72          // Represent vars captured by closures as heap objects
73          new CapturedVars) ::
74      List(
75          new Constructors,           // Collect initialization code in primary constructors
76          // Note: constructors changes decls in transformTemplate, no InfoTransformers should be added after it
77          new Instrumentation) ::     // Count calls and allocations under -Yinstrument
78      List(
79          // Lifts out nested functions to class scope, storing free variables in environments
80          new LambdaLift,
81          // Note: in this mini-phase block scopes are incorrect. No phases that rely on scopes should be here
82          // Replace `this` references to static objects by global identifiers
83          new ElimStaticThis,
84          // Identify outer accessors that can be dropped
85          new CountOuterAccesses) ::
86      List(
87          // Drop unused outer accessors
88          new DropOuterAccessors,
89          // Lift all inner classes to package scope
90          new Flatten,
91          // Renames lifted classes to local numbering scheme
92          new RenameLifted,
93          // Replace wildcards with default values
94          new TransformWildcards,
95           // Move static methods from companion to the class itself
96          new MoveStatics,
97          // Widen private definitions accessed from nested classes
98          new ExpandPrivate,
99           // Repair scopes rendered invalid by moving definitions in prior phases of the group
100         new RestoreScopes,
101         // get rid of selects that would be compiled into GetStatic
102         new SelectStatic,
103         // Generate JUnit-specific bootstrapper classes for Scala.js (not enabled by default)
104         new sjs.JUnitBootstrappers,
105         // Find classes that are called with super
106         new CollectSuperCalls) ::
107     Nil
```

```
1  /** Generate the output of the compilation */
2  protected def backendPhases: List[List[Phase]] =
3      List(new backend.sjs.GenSJSIR) :: // Generate .sjsir files for Scala.js (not enabled by default)
4      List(new GenBCode) ::             // Generate JVM bytecode
5      Nil
```