Mnemonics – Type-Safe Bytecode Generation in Scala

Johannes Rudolph
CleverSoft GmbH, Munich
Peter Thiemann
Albert-Ludwigs-Universität Freiburg, Germany

Scala Days 2010, Lausanne, 15.04.2010

Existing bytecode generation libraries

- ASM
- CGLIB/BCEL
- Javassist
- Soot

Advantages:

- Proven to work
- well-engineered
- full-featured

Some disadvantages:

- Verbosity
- Complexity
- no particular support for Scala
- user often has to fight with the JVM verifier

What is Mnemonics?

A library which

- is less verbose
- is integrated with Scala
- gives static guarantees

What is Mnemonics?

A library which

- is less verbose
- is integrated with Scala
- gives static guarantees

Focus on

- Runtime generation
- Essential set of bytecodes
- Generation of implementations of scala.Function1

What is Mnemonics?

A library which

- is less verbose
- is integrated with Scala
- gives static guarantees

Focus on

- Runtime generation
- Essential set of bytecodes
- Generation of implementations of scala.Function1

Mnemonics: A dynamic Scala inline bytecode assembler with static guarantees

Example

Let's say we want to optimize formatting Strings:

```
val c1, c2: java.util.Calendar = //...
String.format("%tm/%<te/%<tY", c1) // eg. => "04/15/2010"
String.format("%tm/%<te/%<tY", c2) // eg. => "01/23/1973"
```

Example

Let's say we want to optimize formatting Strings:

```
val c1, c2: java.util.Calendar = //...
String.format("%tm/%<te/%<tY", c1) // eg. => "04/15/2010"
String.format("%tm/%<te/%<tY", c2) // eg. => "01/23/1973"
```

Instead:

```
val formatter = newFormatter("%tm/%<te/%<tY") // generate bytecode
formatter(c1) // eg. => "04/15/2010"
formatter(c2) // eg. => "01/23/1973"
```

Manually writing the formatter

```
val formatter = (cal: Calendar) => (
  (new StringBuilder)
    .append(cal.get(Calendar.MONTH))
    .append("/")
    .append(cal.get(Calendar.DAY_OF_MONTH))
    .append("/")
    .append(cal.get(Calendar.YEAR))
    .toString
)
```

After compiling and javap

```
val formatter = (cal: Calendar) => (
  (new StringBuilder)
    .append(cal.get(Calendar.MONTH))
    .append("/")
    .append(cal.get(Calendar.DAY_OF_MONTH))
    .append("/")
    .append(cal.get(Calendar.YEAR))
    .toString
)
```

```
java.lang.String apply(java.util.Calendar):

new           scala/StringBuilder
dup
invokespecial scala/StringBuilder."<init>":()V

aload         1
iconst        2
invokevirtual java/util/Calendar.get:(I)I
invokevirtual scala/StringBuilder.append:(I)Lscala/StringBuilder;

ldc           String /
invokevirtual scala/StringBuilder.append:(Ljava/lang/String;)Lscala/StringBuilder;

aload         1
iconst        5
invokevirtual java/util/Calendar.get:(I)I
invokevirtual scala/StringBuilder.append:(I)Lscala/StringBuilder;

ldc           String /
invokevirtual scala/StringBuilder.append:(Ljava/lang/String;)Lscala/StringBuilder;

aload         1
iconst        1
invokevirtual java/util/Calendar.get:(I)I
invokevirtual scala/StringBuilder.append:(I)Lscala/StringBuilder;

invokevirtual scala/StringBuilder.toString:()Ljava/lang/String;
areturn
```

Java virtual machine

Runtime data model of the machine: basically stack-based

- Stack: only the top elements can be manipulated
- Local variables: statically-known size, random-accessible

Instruction types:

- Stack-manipulation: `dup, pop, bipush, ...`
- Local-variables: `xload, xstore, iinc, ...`
- Array access: `xaload, xastore`
- Method calling: `invokevirtual, invokestatic, invokespecial`
- Objects: `getfield, getstatic, putfield, putstatic`
- Control-flow: `jmp, ifne, xreturn, ...`
- ...

Appending a calendar field to the string with bytecodes

```
// Convention:
//    - Local variable 1 is the Calendar object
//    - Before this block, StringBuilder is on top of the stack
//    - After this block, StringBuilder is on top of the stack
```

```
ALOAD 1
BIPUSH calField
INVOKEVIRTUAL Calendar.get
INVOKEVIRTUAL StringBuilder.append
```

Appending a calendar field to the string with bytecodes

```
// Convention:
//   - Local variable 1 is the Calendar object
//   - Before this block, StringBuilder is on top of the stack
//   - After this block, StringBuilder is on top of the stack

                                    // Stack contents

                                    // [..., sb]
ALOAD 1                             // [..., sb, cal]
BIPUSH calField                     // [..., sb, cal, calField]
INVOKEVIRTUAL Calendar.get          // [..., sb, calFieldValue]
INVOKEVIRTUAL StringBuilder.append  // [..., sb]
```

Appending a calendar field to the string

with plain ASM

```
def appendCalField(calField: Int, mv: MethodVisitor) {
  // Convention:
  //   - Local variable 1 is the Calendar object
  //   - Before this block, StringBuilder is on top of the stack
  //   - After this block, StringBuilder is on top of the stack

  mv.visitVarInsn(ALOAD, 1)          // ALOAD 1
  mv.visitIntInsn(BIPUSH, calField) // BIPUSH calField
  mv.visitMethodInsn(
    INVOKEVIRTUAL,                   // INVOKEVIRTUAL Calendar.get
    "java/util/Calendar",
    "get",
    "(I)I")
  mv.visitMethodInsn(
    INVOKEVIRTUAL,                   // INVOKEVIRTUAL
    "java/lang/StringBuilder",       //   StringBuilder.append
    "append",
    "(I)Ljava/lang/StringBuilder;")
}
```

Appending a calendar field to the string

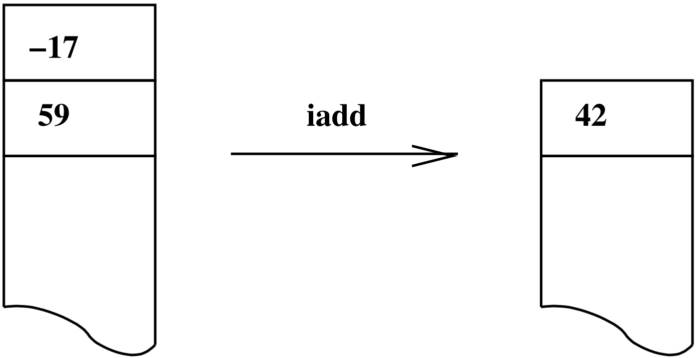
using simple methods and passing methods as closures

```
def appendCalField(calField: Int, mv: MethodVisitor) {
  // Convention:
  //   - Local variable 1 is the Calendar object
  //   - Before this block, StringBuilder is on top of the stack
  //   - After this block, StringBuilder is on top of the stack

  mv.aload(1)
  mv.bipush(calField)
  mv.method2((_: Calendar).get(_: Int))
  mv.method2((_: StringBuilder).append(_: StringBuilder))
}
```

Basic Idea

JVM Instructions are Stack Transformers



See [Jones1998] and [Yelland1999]

Appending a calendar field to the string

the functional way

```
def appendCalField
      (calField: Int)
      (start: F): F = {
  // Convention:
  //   - Local variable 1 is the Calendar object
  //   - Before this block, StringBuilder is on top of the stack
  //   - After this block, StringBuilder is on top of the stack

  start
  aload(1)
  bipush(calField)
  method2((_: Calendar).get(_: Int))
  method2((_: StringBuilder).append(_: StringBuilder))
}
```

Appending a calendar field to the string

by applying frame transformers to a frame in sequence

```
def appendCalField
      (calField: Int)
      (start: F): F = {
  // Convention:
  //    - Local variable 1 is the Calendar object
  //    - Before this block, StringBuilder is on top of the stack
  //    - After this block, StringBuilder is on top of the stack

  start ~
  aload(1) ~
  bipush(calField) ~
  method2((_: Calendar).get(_: Int)) ~
  method2((_: StringBuilder).append(_: StringBuilder))
}

trait F {
  def ~(f: F => F): F
}
```

Appending a calendar field to the string

by applying frame transformers to a frame in sequence

```
def appendCalField
      (calField: Int)
      (start: F): F = {
  // Convention:
  //   - Local variable 1 is the Calendar object
  //   - Before this block, StringBuilder is on top of the stack
  //   - After this block, StringBuilder is on top of the stack

  start ~
  aload(1) ~
  bipush(calField) ~
  method2((_: Calendar).get(_: Int)) ~
  method2((_: StringBuilder).append(_: StringBuilder))
}

trait F {
  def ~(f: F => F): F
}


def aload(i: Int): F => F
def bipush: F => F
```

Appending a calendar field to the string

in a typed way

```
def appendCalField[R<:Stack]
      (calField: Int)
      (start: F[R**StringBuilder]): F[R**StringBuilder] = {
  // Convention:
  //   - Local variable 1 is the Calendar object
  //   - Before this block, StringBuilder is on top of the stack
  //   - After this block, StringBuilder is on top of the stack

  start ~
  aload(1) ~
  bipush(calField) ~
  method2((_: Calendar).get(_: Int)) ~
  method2((_: StringBuilder).append(_: StringBuilder))
}

trait F[+ST<:Stack] {
  def ~[ResST<:Stack](f: F[Stack] => F[ResST]): F[ResST]
}


def aload[R<:Stack, X<:AnyRef](i: Int): F[R] => F[R**X]
def bipush[R<:Stack]: F[R] => F[R**Int]
```

Appending a calendar field to the string

explictly passing a local variable token

```
def appendCalField[R<:Stack]
      (calField: Int)
      (cal: Local[Calendar])
      (start: F[R**StringBuilder]): F[R**StringBuilder] = {
  // Convention:
  //   - Local variable 1 is the Calendar object
  //   - Before this block, StringBuilder is on top of the stack
  //   - After this block, StringBuilder is on top of the stack

  start ~
  cal.load ~
  bipush(calField) ~
  method2((_: Calendar).get(_: Int)) ~
  method2((_: StringBuilder).append(_: StringBuilder))
}

trait F[+ST<:Stack] {
  def ~[ResST<:Stack](f: F[Stack] => F[ResST]): F[ResST]
}


trait Local[T] {
  def load[R<:Stack]: F[R] => F[R**T]
}
```

Appending a calendar field to the string

conventions encoded in types

```
def appendCalField[R<:Stack]
      (calField: Int)
      (cal: Local[Calendar])
      (start: F[R**StringBuilder]): F[R**StringBuilder] = {
  start ~
  cal.load ~
  bipush(calField) ~
  method2((_: Calendar).get(_: Int)) ~
  method2((_: StringBuilder).append(_: StringBuilder))
}

trait F[+ST<:Stack] {
  def ~[ResST<:Stack](f: F[Stack] => F[ResST]): F[ResST]
}
```

Appending a calendar field to the string

with more types inferred

```
def appendCalField[R<:Stack]
      (calField: Int)
      (cal: Local[Calendar])
      (start: F[R**StringBuilder]): F[R**StringBuilder] = {
  start ~
  cal.load ~
  bipush(calField) ~
  method2(_.get(_)) ~
  method2(_.append(_))
}

trait F[+ST<:Stack] {
  def ~[ResST<:Stack](f: F[Stack] => F[ResST]): F[ResST]
}
```

Appending a calendar field to the string with Mnemonics

```
def appendCalField[R<:Stack]
      (calField: Int)
      (cal: Local[Calendar])
      (start: F[R**StringBuilder]): F[R**StringBuilder] = {
  start ~
  cal.load ~
  bipush(calField) ~
  method2(_.get(_)) ~
  method2(_.append(_))
}

def appendConstant[R<:Stack]
      (str: String)
      : F[R**StringBuilder] => F[R**StringBuilder] = { f =>
  f ~
  ldc(str) ~
  method2(_.append(_))
}
```

Almost the implementation

```
def generateFormatter: Calendar => String =
  ASMCompiler.compiler(classOf[Calendar], classOf[String]) {
    (param: Local[Calendar]) =>
    (ret  : Return[String])  =>
    (f    : F[Nil])          =>

    f ~
    newInstance(classOf[StringBuilder]) ~
    appendCalField(param)(Calendar.MONTH) ~
    appendConstant("/") ~
    appendCalField(param)(Calendar.DAY_OF_MONTH) ~
    appendConstant("/") ~
    appendCalField(param)(Calendar.YEAR) ~
    method1(_.toString) ~
    ret.jmp
  }
```

Summary (1)

- Bytecode instructions are represented as Scala functions which change a stack value
- Instructions are composed using the ~ operator
- A block of code has a type which describes its effect on the stack as `F[X] => F[Y]`
- A block of code can ignore parts of the stack when defined as a function with a polymorphic type (here: `R<:Stack`) for the rest of the stack
- Local variables are represented by tokens of type `Local[X]`

Summary (2)

- Entry-point `ASMCompiler.compiler` takes a block of code, generates bytecode, loads and instantiates the new class and returns a function value `X => Y`
- When called, `compile` supplies to the block of code:
  1. a token to access the parameter value, `Local[X]`
  2. a token to return a value, `Return[Y]`
  3. a frame representing the empty stack `F[Nil]`
- Instructions and code blocks are treated equally: Both are functions that transform a stack value

Mnemonics

- Goal: Typed generator $\Rightarrow$ verifiable bytecode
- Values on the stack must always have the correct type depending on the instruction
- Need to model
  - Types on the stack at every point in the program
  - Effect of instructions on the stack values' types

Instruction encoding

An instruction is defined as a function from one state of the stack to another.

```
def iadd[R<:Stack]:
  F[R**Int**Int] => F[R**Int]
```

Instruction encoding

An instruction is defined as a function from one state of the stack to another.

```
def iadd[R<:Stack]:
  F[R**Int**Int] => F[R**Int]
```

Instruction encoding

An instruction is defined as a function from one state of the stack to another.

```
def iadd[R<:Stack]:
  F[R**Int**Int] => F[R**Int]
```

Most instructions polymorphic over `R<:Stack`, the rest of the run-time stack $\Rightarrow$ ensures that `R` is not touched

The stack type

```
trait Stack

trait Nil extends Stack
case class Cons[+R<:Stack,+T] extends Stack
```

Infix type alias

```
type ** [x<:Stack,y] = Cons[x,y]
```

Examples

- Nil
- Cons[Nil,String]
- Cons[Cons[Nil,String],Int]
- Nil**String**Int

The Frame state type

```
trait F[+ST<:Stack] {
  def ~[X](f: F[ST] => X): X = f(this)
}
```

More instructions

```
def ldc[R<:Stack](str: String)
  : F[R]                       => F[R**String]

def aload[R<:Stack, T]
  : F[R**Array[T]**Int] => F[R**T]

def checkcast[R<:Stack, T, U](cl: Class[U])
  : F[R**T]                    => F[R**U]
```

Method invocation

- Type of invocation instruction depends on method called
- How to achieve type-safety?

Method invocation

- Type of invocation instruction depends on method called
- How to achieve type-safety?

Two types of method invocation:

- Method statically-known before generation

```
method1((x: Integer) => x.intValue)
```

Method invocation

- Type of invocation instruction depends on method called
- How to achieve type-safety?

Two types of method invocation:

- Method statically-known before generation

```
method1((x: Integer) => x.intValue)
```

- Method dynamically-chosen when generating

```
val m: java.lang.reflect.Method = ...
methodHandle(m, classOf[Integer], classOf[Integer])
```

Statically-known method invocation

```
method1((x: Integer) => x.intValue)
```

- Method is known and available in the compile-time namespace of the *generator*
- Use first-class function to reference method

```
def method1[T, U]
    (code:T => U)
    :Method1[T, U]
```

Statically-known method invocation

```
method1((x: Integer) => x.intValue)
```

- Method is known and available in the compile-time namespace of the *generator*
- Use first-class function to reference method
- Use `scala.reflect.Code` to lift AST to run-time
- Must be abstraction of a method invocation (checked at generation time)

```
def method1[T, U]
    (code:scala.reflect.Code[T => U])
    :Method1[T, U]
```

Statically-known method invocation

```
method1((x: Integer) => x.intValue)
```

- Method is known and available in the compile-time namespace of the *generator*
- Use first-class function to reference method
- Use `scala.reflect.Code` to lift AST to run-time
- Must be abstraction of a method invocation (checked at generation time)

```
def method1[T, U]
    (code:scala.reflect.Code[T => U])
    :Method1[T, U]
```

- Convert to frame transformer with implicits

Parameter and local variable access

Access to Parameters and local variables via *typed storage capabilities* that map transparently to JVM local variables

Parameter and local variable access

Access to Parameters and local variables via *typed storage capabilities* that map transparently to JVM local variables

```
trait Local[T] {
  def load[R<:Stack]  :F[R]    => F[R**T]
  def store[R<:Stack] :F[R**T] => F[R]
}
```

Parameter and local variable access

Access to Parameters and local variables via *typed storage capabilities* that map transparently to JVM local variables

```
trait Local[T] {
  def load[R<:Stack]  :F[R]    => F[R**T]
  def store[R<:Stack] :F[R**T] => F[R]
}
```

Introduce variable scope

```
def withLocal[ST1<:Stack, ST2<:Stack, T]
    (body: Local[T] => F[ST1] => F[ST2])
    :F[ST1**T] => F[ST2]
```

Parameter and local variable access

Access to Parameters and local variables via *typed storage capabilities* that map transparently to JVM local variables

```
trait Local[T] {
  def load[R<:Stack]  :F[R]    => F[R**T]
  def store[R<:Stack] :F[R**T] => F[R]
}
```

Introduce variable scope

```
def withLocal[ST1<:Stack, ST2<:Stack, T]
    (body: Local[T] => F[ST1] => F[ST2])
    :F[ST1**T] => F[ST2]
```

Usage

```
bipush(5) ~
withLocal(i => f => f ~
  i.load ~ dup ~ iadd ~ i.store // i = i + i
  // etc
)
```

Category 2 Types

Further uses of implicits

- Two categories of JVM types
  - Category 1 (one word): Int, Float, Ref, . . .
  - Category 2 (two words): Double, Long
- Mostly transparent on the stack
- Some instructions require special treatment

```
trait Category1
def swap[R<:Stack, T1<%Category1, T2<%Category1]()
    :F[R**T2**T1]   => F[R**T1**T2]

implicit def cat1any:AnyRef=>Category1 = null
implicit def cat1int:Int=>Category1 = null
implicit def cat1float:Float=>Category1 = null
/* and so on, seven definitions in total */
```

Composite instructions

- Construct typed high-level instructions by composing primitives
- Example: `foldArray`

```
def foldArray[R<:Stack, T, U]
     (array: Local[Array[T]])
     (func : Local[Int] => F[R**U**T] => F[R**U])
      : F[R**U] => F[R**U]
```

Conclusions

- Convenient, type-safe bytecode generation at run time
- Typed generator $\Rightarrow$ verifiable bytecode
- Many instructions directly available
- Type-safe patterns for method invocation, local variables, return instructions, structured control transfers, instance creation
- Vital Scala ingredients: type inference with bounded polymorphism, variance, implicit parameters, overloading, and reflection

Current state of codebase

Unfortunately...

- Original implementation for Scala 2.7.7
- Some improvements with Scala 2.8.0
- But: Unfortunately code doesn't work with Scala 2.8.0.Beta1, only trunk
- Tests don't work with Scala trunk
- $\Rightarrow$ No stable version right now

Further information

Thanks for listening! Questions?

At `http://github.com/jrudolph/bytecode` you'll find

- Code under BSD license
- The PEPM '10 paper and the original thesis
- A tutorial (soon)

Framework

Mnemonics has only a minimal framework:

- No support for “full” class generation
- Only generation of subclasses of `scala.Function1`
- Support for several backends: `ASMCompiler`, interpreter

Framework

Mnemonics has only a minimal framework:

- No support for “full” class generation
- Only generation of subclasses of `scala.Function1`
- Support for several backends: `ASMCompiler`, interpreter

```
class ASMCompiler {
  def compile[T1<:AnyRef, Ret<:AnyRef]
      (param1Cl: Class[T1], returnCl: Class[Ret])
      (code: Local[T1] => Return[Ret] => F[Nil] => Nothing)
      : T1 => Ret = // implementation
}
```

Applicability

- DSLs describing operations or transformations, i.e. an operation representable by a function `T => U`
- Candidates
  - XPath
  - Regular expressions
  - Parser combinators
  - Functional reactive programming

Branching, jumping, and returning

Low-level:

- Unconditional jump: `withTargetHere` and `target.jmp`
- Conditional jump: `ifne`

High-level:

- Conditional: `ifne2`
- Looping: `tailRecursive`

Return via *typed return capability*:

```
trait Return[U<:AnyRef] {
  def jmp:F[Nil**U] => Nothing }
```