Bytecode

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Department of Distributed and Dependable Systems

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faculty of mathematics and physics

Bytecode

- Machine code of a JVM
  - stack-based
  - with constructs for manipulation with classes/instances
- The Java™ Virtual Machine Specification
  - http://docs.oracle.com/javase/specs/jvms/se7/html/index.html
- Instructions Overview
  - http://en.wikipedia.org/wiki/Java_bytecode_instruction_listings

Example – Basics

```
void spin() {
  int i;
  for (i = 0; i < 100; i++) {
    ;    // Loop body is empty
  }
}
```

```
Method void spin()
 0 iconst_0       // Push int constant 0
 1 istore_1       // Store into local variable 1 (i=0)
 2 goto 8         // First time don't increment
 5 iinc 1 1       // Increment local variable i by 1
 8 iload_1      // Push local variable 1 (i)
 9 bipush 100   // Push int constant 100
11 if_icmplt 5  // Compare and loop if (i < 100)
14 return       // Return void when done
```

Instruction set – Load and Store

- Load a local variable onto the operand stack
  - *iload, iload_<n>, lload, lload_<n>, fload, fload_<n>, dload, dload_<n>, aload, aload_<n>*
- Store a value from the operand stack into a local variable
  - *istore, istore_<n>, lstore, lstore_<n>, fstore, fstore_<n>, dstore, dstore_<n>, astore, astore_<n>*
- Load a constant onto the operand stack
  - *bipush, sipush, ldc, ldc_w, ldc2_w, aconst_null, iconst_m1, iconst_<i>, lconst_<l>, fconst_<f>, dconst_<d>*
- Gain access to more local variables using a wider index, or to a larger immediate operand
  - *wide*

Example – Constants

```
void useManyNumeric() {
    int i = 100;
    int j = 1000000;
    long l1 = 1;
    long l2 = 0xffffffff;
    double d = 2.2;
    ...do some calculations...
}
```

```
Method void useManyNumeric()
 0 bipush 100  // Push a small int with bipush
 2 istore_1
 3 ldc #1      // Push int constant 1000000
 5 istore_2
 6 lconst_1    // A tiny long value uses short, fast lconst_1
 7 lstore_3
 8 ldc2_w #6   // Push long 0xffffffff (that is, an int -1)
11 lstore 5
13 ldc2_w #8             // Push double constant 2.200000
16 dstore 7
 ...do those calculations...
```

Instruction set – Arithmetics

- Add
  - *iadd, ladd, fadd, dadd*
- Subtract
  - *isub, lsub, fsub, dsub*
- Multiply
  - *imul, lmul, fmul, dmul*
- Divide
  - *idiv, ldiv, fdiv, ddiv*
- Remainder
  - *irem, lrem, frem, drem*
- Negate
  - *ineg, lneg, fneg, dneg*
- Shift
  - *ishl, ishr, iushr, lshl, lshr, lushr*
- Bitwise OR
  - *ior, lor*
- Bitwise AND
  - *iand, land*
- Bitwise exclusive OR
  - *ixor, lxor*
- Local variable increment
  - *iinc*
- Comparison
  - *dcmpg, dcmpl, fcmpg, fcmpl, lcmp*

Example – Arithmetics

```
int align2grain(int i, int grain) {
    return ((i + grain-1) & ~(grain-1));
}
```

```
Method int align2grain(int,int)
 0 iload_1
 1 iload_2
 2 iadd
 3 iconst_1
 4 isub
 5 iload_2
 6 iconst_1
 7 isub
 8 iconst_m1
 9 ixor
10 iand
11 ireturn
```

Instruction set – Execution control

- Conditional branch
  - *ifeq, iflt, ifle, ifne, ifgt, ifge, ifnull, ifnonnull, if_icmpeq, if_icmpne, if_icmplt, if_icmpgt, if_icmple, if_icmpge, if_acmpeq, if_acmpne*
- Compound conditional branch
  - *tableswitch, lookupswitch*
- Unconditional branch
  - *goto, goto_w, jsr, jsr_w, ret*

Example – Comparison

```
int lessThan100(double d) {
  if (d < 100.0) {
    return 1;
  } else {
    return -1;
  }
}
```

```
Method int lessThan100(double)
 0 dload_1
 1 ldc2_w #4   // Push double constant 100.0
 4 dcmpg       // Push 1 if d is NaN or d \> 100.0;
               // push 0 if d == 100.0
 5 ifge 10     // Branch on 0 or 1
 8 iconst_1
 9 ireturn
10 iconst_m1
11 ireturn
```

Instruction set – Type conversions

- Widening numeric conversions
  - *i2l, i2f, i2d, l2f, l2d, f2d*
- Narrowing numeric conversions
  - *i2b, i2c, i2s, l2i, f2i, f2l, d2i, d2l, d2f*

Example – Type conversion

```
void sspin() {
  short i;
  for (i = 0; i < 100; i++) {
    ;       // Loop body is empty
  }
}
```

```
Method void sspin()
 0 iconst_0
 1 istore_1
 2 goto 10
 5 iload_1      // The short is treated as though an int
 6 iconst_1
 7 iadd
 8 i2s          // Truncate int to short
 9 istore_1
10 iload_1
11 bipush 100
13 if_icmplt 5
16 return
```

Instruction set – Calling a method

- *invokevirtual*
  - invokes an instance method of an object, dispatching on the (virtual) type of the object. This is the normal method dispatch in the Java programming language.
- *invokeinterface*
  - invokes a method that is implemented by an interface, searching the methods implemented by the particular runtime object to find the appropriate method.
- *invokespecial*
  - invokes an instance method requiring special handling, whether an instance initialization method, a private method, or a superclass method.
- *invokestatic*
  - invokes a class (static) method in a named class.
- *invokedynamic*
  - invokes a method obtained by calling a bootstrap method

Example – Calling a virtual method

```
int add12and13() {
  return addTwo(12, 13);
}
```

```
Method int add12and13()
 0 aload_0     // Push local variable 0 (this)
 1 bipush 12   // Push int constant 12
 3 bipush 13   // Push int constant 13
 5 invokevirtual #4  // Method Example.addtwo(II)I
 8 ireturn     // Return int on top of operand stack; it is
               // the int result of addTwo()
```

Type specification

BaseType Character	Type	Interpretation
`B`	`byte`	signed byte
`C`	`char`	Unicode character
`D`	`double`	double-precision floating-point value
`F`	`float`	single-precision floating-point value
`I`	`int`	integer
`J`	`long`	long integer
`L Classname;`	`reference`	an instance of class `<classname>`
`S`	`short`	signed short
`Z`	`boolean`	`true` or `false`
`[`	`reference`	one array dimension

Examples:

- `double d[][][]` ⟹ `[[[D`
- `Object mymethod(int i, double d, Thread t)`
  ⟹ `(IDLjava/lang/Thread;)Ljava/lang/Object;`

Example – Calling a static method

```
int add12and13() {
  return addTwoStatic(12, 13);
}
```

```
Method int add12and13()
 0 bipush 12
 2 bipush 13
 4 invokestatic #3 // Method Example.addTwoStatic(II)I
 7 ireturn
```

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Example – Calling a special method

```
class Near {
  int it;
  public int getItNear() {
    return getIt();
  }
  private int getIt() {
    return it;
  }
}
```

```
class Far extends Near {
  int getItFar() {
    return super.getItNear();
  }
}
```

```
Method int getItNear()
 0 aload_0
 1 invokespecial #5
     // Method Near.getIt()I
 4 ireturn
```

```
Method int getItFar()
 0 aload_0
 1 invokespecial #4
     // Method
     //   Near.getItNear()I
 4 ireturn
```

Invokedynamic

```
static void test() throws Throwable {
    // THE FOLLOWING LINE IS PSEUDOCODE FOR A JVM INSTRUCTION
    InvokeDynamic[#bootstrapDynamic].baz("baz arg", 2, 3.14);
}

private static void printArgs(Object... args) {
  System.out.println(java.util.Arrays.deepToString(args));
}

private static CallSite bootstrapDynamic(MethodHandles.Lookup caller,
                                             String name, MethodType type) {

  MethodHandles.Lookup lookup = MethodHandles.lookup();
  Class thisClass = lookup.lookupClass();  // (who am I?)
  MethodHandle printArgs = lookup.findStatic(thisClass,
      "printArgs", MethodType.methodType(void.class, Object[].class));

  // ignore caller and name, but match the type:
  return new ConstantCallSite(printArgs.asType(type));
}
```

Instruction set – Instance manipulation

- Create a new class instance
  - *new*
- Access fields of classes (static fields, known as class variables) and fields of class instances (non-static fields, known as instance variables)
  - *getfield, putfield, getstatic, putstatic*
- Check properties of class instances or arrays
  - *instanceof, checkcast*

Example – Instance creation

```
Object create() {
    return new Object();
}
```

```
Method java.lang.Object create()
 0 new #1 // Class java.lang.Object
 3 dup
 4 invokespecial #4 // Method java.lang.Object.<init>()V
 7 areturn
```

Example – Attribute access

```
void setIt(int value) {
  i = value;
}
int getIt() {
  return i;
}
```

```
Method void setIt(int)
 0 aload_0
 1 iload_1
 2 putfield #4            // Field Example.i I
 5 return
Method int getIt()
 0 aload_0
 1 getfield #4            // Field Example.i I
 4 ireturn
```

Instruction set – Array manipulation

- Create a new array
  - *newarray, anewarray, multianewarray*
- Load an array component onto the operand stack
  - *baload, caload, saload, iaload, laload, faload, daload, aaload*
- Store a value from the operand stack as an array component
  - *bastore, castore, sastore, iastore, lastore, fastore, dastore, aastore*
- Get the length of array
  - *arraylength*

Example – Array (primitive type)

```
void createBuffer() {
  int buffer[];         int bufsz = 100;
  int value = 12;       buffer = new int[bufsz];
  buffer[10] = value;   value = buffer[11];
}
```

```
Method void createBuffer()
 0 bipush 100    // Push int constant 100 (bufsz)
 2 istore_2      // Store bufsz in local variable 2
 3 bipush 12     // Push int constant 12 (value)
 5 istore_3      // Store value in local variable 3
 6 iload_2       // Push bufsz...
 7 newarray int  // ...and create new array of int of that length
 9 astore_1      // Store new array in buffer
10 aload_1       // Push buffer
11 bipush 10     // Push int constant 10
13 iload_3       // Push value
14 iastore       // Store value at buffer[10]
15 aload_1       // Push buffer
16 bipush 11     // Push int constant 11
18 iaload        // Push value at buffer[11]...
19 istore_3      // ...and store it in value
20 return
```

Example – Array (reference)

```
void createThreadArray() {
  Thread threads[];
  int count = 10;
  threads = new Thread[count];
  threads[0] = new Thread();
}
```

```
Method void createThreadArray()
 0 bipush 10            // Push int constant 10
 2 istore_2             // Initialize count to that
 3 iload_2              // Push count, used by anewarray
 4 anewarray class #1   // Create new array of class Thread
 7 astore_1             // Store new array in threads
 8 aload_1              // Push value of threads
 9 iconst_0             // Push int constant 0
10 new #1               // Create instance of class Thread
13 dup                  // Make duplicate reference...
14 invokespecial #5     // ...to pass to instance initialization
                        // method Method java.lang.Thread.<init>()V
17 aastore              // Store new Thread in array at 0
18 return
```

Example – Array (multidimensional)

```
int[][][] create3DArray() {
  int grid[][][];
  grid = new int[10][5][];
  return grid;
}
```

```
Method int create3DArray()[][][]
 0 bipush 10                 // Push int 10 (dimension one)
 2 iconst_5                  // Push int 5 (dimension two)
 3 multianewarray #1 dim #2 // Class [[[I, a three
                             // dimensional int array; only
                             // create first two dimensions
 7 astore_1                  // Store new array...
 8 aload_1                   // ...then prepare to return it
 9 areturn
```

Instruction set – Stack manipulation

- *pop, pop2, dup, dup2, dup_x1, dup2_x1, dup_x2, dup2_x2, swap*

Example – Array (multidimensional)

```
public long nextIndex() {
    return index++;
}
private long index = 0;
```

```
Method long nextIndex()
 0 aload_0   // Push this
 1 dup       // Make a copy of it
 2 getfield #4   // One of the copies of this is consumed
                 // pushing long field index,
                 // above the original this
 5 dup2_x1       // The long on top of the operand stack is
                 // inserted into the operand stack below the
                 // original this
 6 lconst_1      // Push long constant 1
 7 ladd          // The index value is incremented...
 8 putfield #4   // ...and the result stored back in the field
11 lreturn       // The original value of index is left on top
                 // of the operand stack, ready to be returned
```

Instruction set – Monitors

- *monitorenter*
- *monitorexit*

Example – Exceptions (throw)

```
void cantBeZero(int i) throws TestExc {
  if (i == 0) {
    throw new TestExc();
  }
}
```

```
Method void cantBeZero(int)
 0 iload_1          // Push argument 1 (i)
 1 ifne 12          // If i==0, allocate instance and throw
 4 new #1           // Create instance of TestExc
 7 dup              // One reference goes to the constructor
 8 invokespecial #7  // Method TestExc.<init>()V
11 athrow           // Second reference is thrown
12 return           // Never get here if we threw TestExc
```

Example – Exceptions (catch)

```
void catchOne() {
  try {
    tryItOut();
  } catch (TestExc e) {
    handleExc(e);
  }
}
```

```
Method void catchOne()
 0 aload_0              // Beginning of try block
 1 invokevirtual #6     // Method Example.tryItOut()V
 4 return               // End of try block; normal return
 5 astore_1             // Store thrown value in local variable 1
 6 aload_0              // Push this
 7 aload_1              // Push thrown value
 8 invokevirtual #5     // Invoke handler method:
                        // Example.handleExc(LTestExc;)V
 11 return              // Return after handling TestExc

Exception table:
     From   To     Target   Type
     0      4      5        Class TestExc
```

Example – Exceptions (nested)

```
void nestedCatch() {
  try {
    try {
      tryItOut();
    } catch (TestExc1 e) {
      handleExc1(e);
    }
  } catch (TestExc2 e) {
    handleExc2(e);
  }
}
```

```
Method void nestedCatch()
  .....
  .....

Exception table:
     From    To     Target    Type
     0       4      5         Class TestExc1
     0       11     12        Class TestExc2
```

Instruction set – Exceptions

- Throwing an exception
  - *athrow*
- Try-catch declaration
  - Via special *exception table* associated with a method
- Finally
  - Implemented by the compiler

Example – Monitors

```
void onlyMe(Foo f) {
  synchronized(f) {
    doSomething();
  }
}
```

```
Method void onlyMe(Foo)
 0 aload_1            // Push f
 1 astore_2           // Store it in local variable 2
 2 aload_2            // Push local variable 2 (f)
 3 monitorenter       // Enter the monitor associated with f
 4 aload_0            // Holding the monitor, pass this and...
 5 invokevirtual #5 // ...call Example.doSomething()V
 8 aload_2            // Push local variable 2 (f)
 9 monitorexit        // Exit the monitor associated with f
10 return             // Return normally
11 aload_2            // In case of any throw, end up here
12 monitorexit        // Be sure to exit monitor...
13 athrow             // ...then rethrow the value to the invoker

Exception table:
     From   To     Target   Type
     4      8      11       any
```

Statically-typed Class-based languages (Scala)

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Scala

- Statically-typed language
- Compiles to bytecode
- Modern concepts

- Example: E01

Semicolon inference

- A line ending is treated as a semicolon unless one of the following conditions is true:
  - The line in question ends in a word that would not be legal as the end of a statement, such as a period or an infix operator.
  - The next line begins with a word that cannot start a statement.
  - The line ends while inside parentheses (...) or brackets [...], because these cannot contain multiple statements anyway.

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Static vs. dynamic typing

- Target function is determined
  - at compile time – static typing
  - at runtime – dynamic typing

- Example: E02

Classes vs. objects

- Scala does not have static method
- Instead it features a singleton object
  - Defines a class and a singleton instance

- Example: E03

Type inference

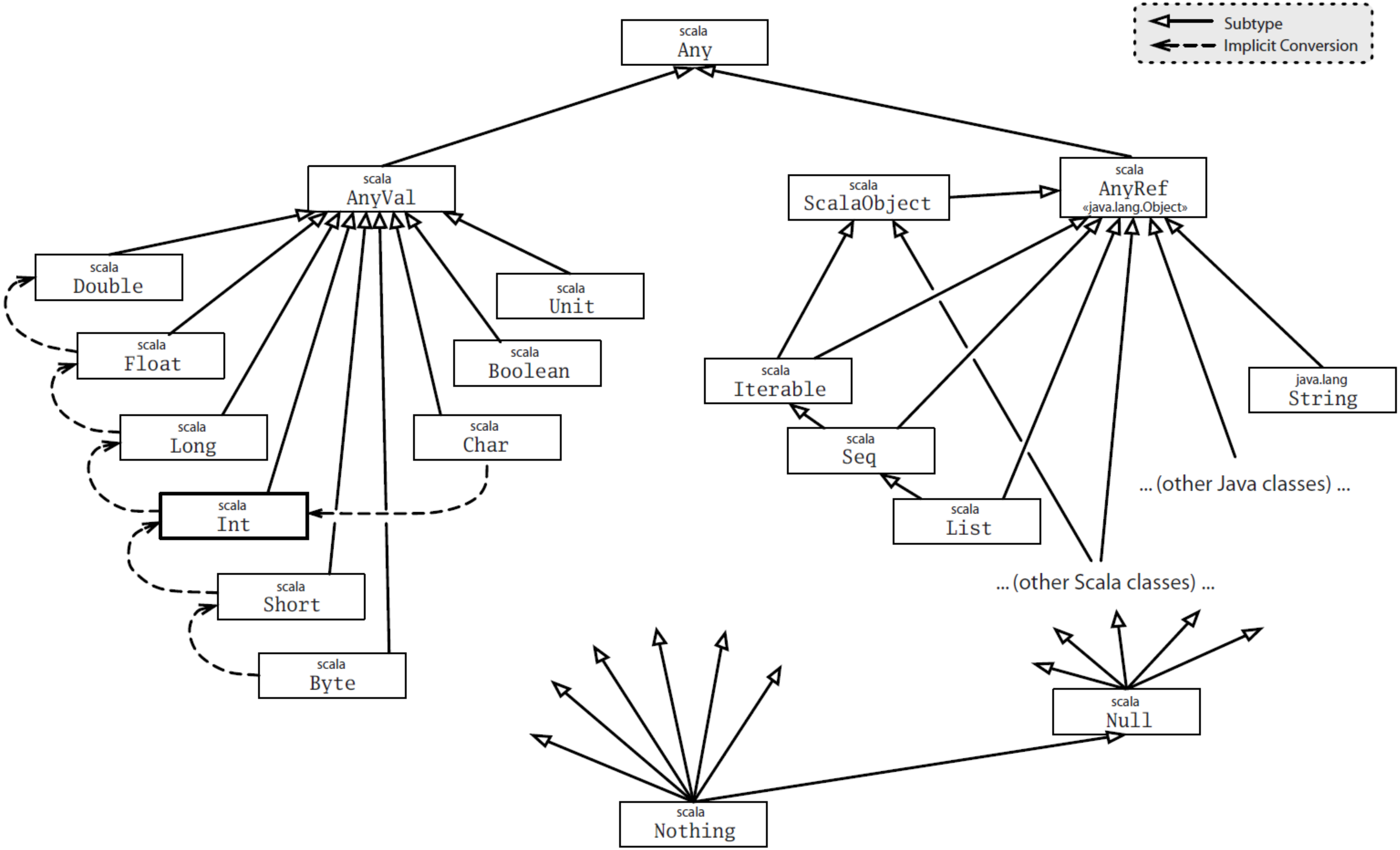
- Types can be omitted – they are inferred automatically
    - At compile time

- Example: E04

Type Hierarchy

- Everything is an object
  - primitive data types behind the scene (boxing/unboxing)
- Compiler optimizes the use of primitive types
  - a primitive type is used if possible
- Null and Nothing types

Type Hierarchy



Null and Nothing types

- **null** is singleton instance of Null
  - can be assigned to any AnyRef

- Nothing is a subtype of everything
  - Can be assigned to anything, but does not have any instance

```
def doesNotReturn(): Nothing = {
  throw new Exception
}
```

Companion object

- A class and object may have the same name
  - Must be defined in the same source

- Then the class and object may access each others private fields

- Example: E05

Constructors

- One primary constructor
  - class parameters
  - can invoke superclass constructor

- Auxiliary constructors
  - must invoke the primary constructor (as the first one)
  - must not invoke superclass constructor

Operators

- Scala allows almost arbitrary method names (including operators)
- A method may be called without a dot
- Prefix operators have special names

- Example: E06

Flexibility in Identifiers and Operators

- Alphanumeric identifier
  - starts with letter or underscore
- Operator identifier
  - an operator character belongs to the Unicode set of mathematical symbols(Sm) or other symbols(So), or to the 7-bit ASCII characters that are not letters, digits
  - any sequence of them
- Mixed identifier
  - e.g. unary_- to denote a prefix operator
- Literal identifier
  - with backticks (e.g. \`class\`) to avoid clashes with reserved words, etc.

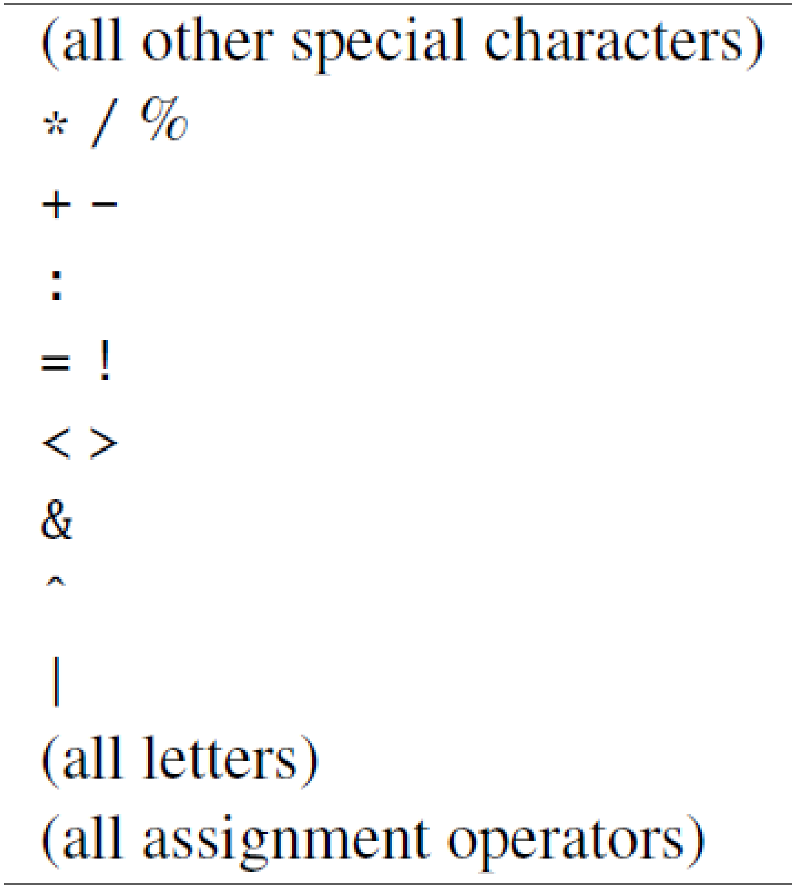
Implicit conversions

- Scala allows specifying functions that are applied automatically to make the code correct
  - conversion to the type of the argument or to the type of the receiver
  - must be in current scope or source or target type scope
  - scalac -Xprint:typer mocha.scala
    - program after implicits added and fully-qualified types substituted

- Example: E07

Operator precedences

- Operator precedence determined by the first character
  - Only if the operator ends with “=“, the last character is used



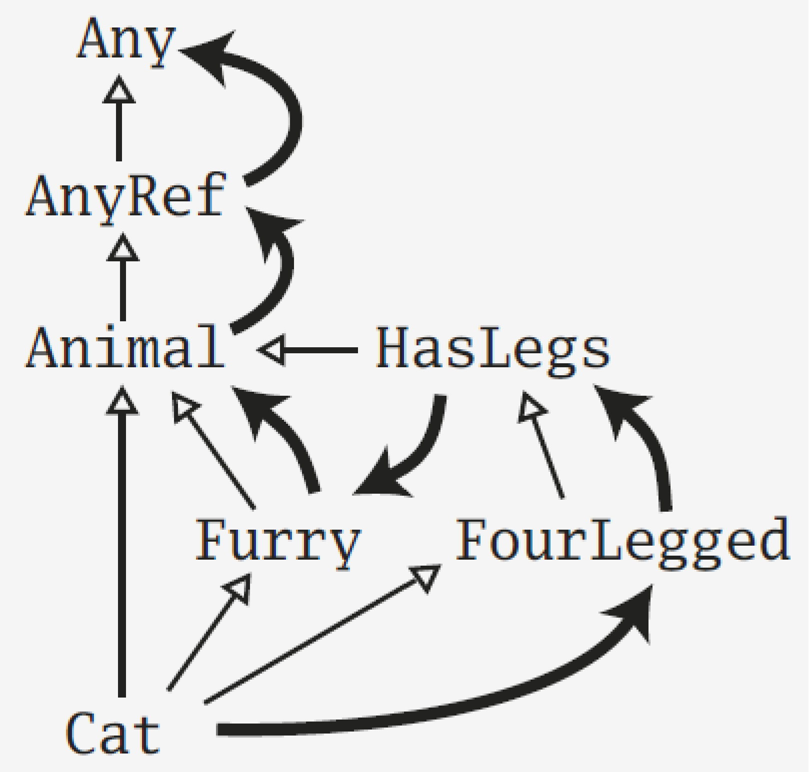
(all other special characters)
* / %
+ -
:
= !
< >
&
^
|
(all letters)
(all assignment operators)

Traits

- Scala does not have interfaces
  - It has something stronger – mixins (called traits)
- A trait is like an interface, but allows for defining methods and variables
- Example: E08

Linearization

- As opposed to multiple inheritance, traits do not suffer from the diamond problem
- This is because the semantics of super is determined only when the final type is defined
- Example: E09



Scala – Java interoperability

- trait T
  - interface T – method declarations
  - class T$class – method implementations
- class C extends T
  - instance methods of C
  - delegate methods to methods of T$class
- object C
  - static methods in C
    - delegate to methods of C$.MODULE
  - class C$
    - instance methods of C
    - static field C$.MODULE of type C (the singleton instance)

- Example: E10

Type parameterization

- Each class and method may be parameterized by a type

- Lower and upper bounds

- Example: E11

Instance private data

- The mutable state in a class typically prevents the covariance/contravariance
- Why?
- Example (covariance): E12
- Example (contravariance): E13

Abstract types

- What about if we want methods in a subclass to specialize method parameters?

- Example: E14

Structural subtyping

- It is possible to specify only properties of a type

- Example: E15

First-class functions

- Functions are first-class citizens
- May be passed as parameters
- Anonymous functions, …
- Anonymous functions are instances of classes
  - Function1, Function2, …

- Example: E16

Tail recursion

- The compiler can do simple tail recursion
  - If the return value of a function is a recursive call to the function itself
- Example: E17

For-comprehension

- Generalized for-loops
  - generators, definitions, filters
- Translated to operations over collections
  - map, flatMap, withFilter, foreach
- Example: E18

New control structures

- Currying – function that returns function
- By-name parameters
  - omitting empty parameter list in an anonymous function

- Example: E19

Behavior Driven Development

- Unit test as a specification
- Human readable style
- Still executable

- Example: E20

Case-classes, pattern matching

- Scala allows for simple pattern matching (similar to Prolog terms)
- Case-classes
  - factory method (no new necessary)
  - all parameters are vals

- Example: E21

Case sequences & Partial functions

- Functions may be defined as case sequences
  - It’s like a function with more entry points

- Since the case sequence does not have to cover all cases, it yields a partial function
  - Partial function may be queried if a given value is in its domain
  - or it throws a runtime exception if called with an unsupported input argument

- Example: E22 + H2

Delayed init

- If a class extends the DelayedInit trait
  - the compiler turns the class initializer to a function
  - and calls delayedInit function on the class instance giving it the initializer function
- Example: E23

XML

- Scala has native support for parsing XML
- XML can be included where expression is expected
- It gets transformed to a runtime structure

- Example: E24

Lift

- Web-framework written in Scala
- Utilizes advanced Scala concepts
  - DSL, functions, XML