@AndrzejWasowski@scholar.social

Andrzej Wąsowski
Florian Biermann

Advanced Programming

Laziness and Lazy Lists

IT UNIVERSITY OF COPENHAGEN

SOFTWARE QUALITY RESEARCH

- The idea of **delaying computations**
- **Evaluation strategies**:
  - Call-by-value (strict), call-by-name (non-strict), lazy (also non-strict)
- **Applications** of Call-By-Name and Laziness
- An implementation of **lazy lists**

AGENDA

Functional Programming is Declarative!
Separate the What from the How.

Aside: Making Types Work For You!

```scala
enum EmptyType:
  case E(e : EmptyType)
```

- The `EmptyType` can never be instantiated.
- It is like `Nothing`, except that `Nothing <: T` for all `T`.
- Scala already has `Nothing` - but you can use this in any statically typed language!

```scala
enum AST[+A]:
  case ConstInt(c : Int) extends AST[Nothing]
  case BinOp[A](a : A, op : Op, lhs : AST[A], rhs : AST[A]) extends AST[A]

type ConstInt = AST[Nothing]
type ConstInt = AST[EmptyType]
type Expr = AST[Unit]
```

Strict vs Non-strict Evaluation

- A function is **strict** if it always evaluates all its arguments (typically before evaluating its body)
- A **non-strict** function may choose not to evaluate all of its arguments.

Definition (strictness)

A function $f(x)$ is **strict** iff for every expression x that diverges (does not terminate or fails) the execution of $f(x)$ diverges, too.

- Strictness is a common default in most languages
- Haskell is non-strict, Scala is strict by default
- **Every language has a non-strict construct**
- Typical non-strict constructs: control flow statements, say **if-then-else**, and some operators disjunction, and conjunction
- **Every language needs a strict construct** (otherwise nothing will be computed)
- For example, pattern matching is strict in Haskell (as in Scala).

Any functional language can simulate non-strictness

- In any functional language non-strictness can be **simulated** quite easily
- Use `() => A` , a type of a nullary function returning `A`

```
def if2[A](cond: Boolean, onTrue: () => A, onFalse: () => A): A =
    if cond then onTrue() else onFalse()

val res = if2(a < 22, () => println ("a"), () => println ("b"))
```

- **Mentimeter 5147 6006:** What is the value of `res` if `a == 42` ? (think first, a trick)
- A **delayed computation** is called a **thunk**, executing a thunk is called **forcing** it
- Scala has special syntax to make it slightly nicer (**call-by-name**):

```
def if3[A] (cond:Boolean, onTrue: => A, onFalse: => A): A =
  if cond then onTrue else onFalse

if3(a < 22, println ("a"), println ("b"))
```

- The semantics of both programs are the same, but forcing is automatic, **no caching**

Lazy Evaluation

- A by-name argument of a function is re-evaluated **every single time it is accessed**
- Store it in a `lazy val` if you want to evaluate **only once** and **cache the result**
- A `lazy val` is forced at first access, the value cached, retrieved on later accesses

```
def convoluted (a: => Unit, b: => Unit): Unit =
  lazy val cacheB = b
  lazy val cacheA = a
  cacheA;
  cacheB;
  cacheA;
  cacheB;

convoluted (print ("A"), print ("B"))
```

- Prints `"AB"`
- Laziness interacts badly with **side effects**. Use in pure computations

Evaluation Strategies (Defs)

Definition (Call-by-value Evaluation)

The arguments of a function are evaluated before the function call. Then their **value** is substituted for the formal arguments

Definition (Call-by-name Evaluation)

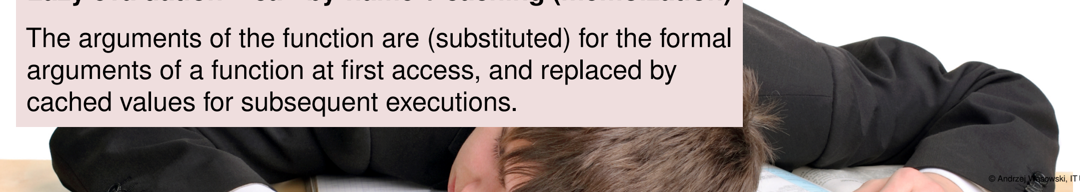
The arguments of a function are not evaluated but **syntactically substituted** for the formal arguments in the body

Definition (Lazy Evaluation)

Lazy evaluation = call-by-name + caching (memoization)

The arguments of the function are (substituted) for the formal arguments of a function at first access, and replaced by cached values for subsequent executions.

- Scala supports **all three** strategies
- In pure programs: **no difference** between these strategies (besides performance and memory usage)
- Impure programs: **perplexing** differences
- This difference allows the compiler and us to **simplify** and optimize pure programs
- For instance, constructing **only needed parts** of data structures



Call-by-name & Laziness: Usage

- Implementing **non-strict-functions**
  - If function **accesses parameters at most once** (simple control-flow like if, or, and, etc.) it can be built with call-by-name only, without memoization; for instance error handling code can be passed as one of parameters
  - We have seen: `getOrElse`, we can implement our own loops, etc.
- Implementing **internal DSLs**
- Handling **large amounts of data**, only accessing necessary parts; especially when it is hard to see which parts need to be accessed/loaded/precomputed
- Implementing **generators of object/value sequences** elegantly (lazy list of naturals, lazy list of prime numbers, lazy list of messages, lazy list of random numbers, etc.)

Example of Call-by-name [1/4]

In Apache Spark's implementation

```scala
/**
 * Return a new RDD by applying a function to all elements of this RDD.
 */
def map[U: ClassTag](f: T => U): RDD[U] = withScope {
  val cleanF = sc.clean(f)
  new MapPartitionsRDD[U, T](this, (context, pid, iter) => iter.map(cleanF))
}
```

How do we implement a function like withScope?

With **call-by-value** the body of the block would always be executed.

But we can use **call-by-name**.

`https://github.com/apache/spark/blob/master/core/src/main/scala/org/apache/spark/rdd/RDD.scala`, captured 2022/09

Example of Call-by-name [2/4]

In Apache Spark's implementation

```scala
  /**
   * Execute a block of code in a scope such that all new RDDs created in this body will
   * be part of the same scope. For more detail, see {{org.apache.spark.rdd.RDDOperationScope}}.
   *
   * Note: Return statements are NOT allowed in the given body.
   */
  private[spark] def withScope[U](body: => U): U = RDDOperationScope.withScope[U](sc)(body)
```

The body (U) is passed by-name and then

Forwarded to a similar method in another class, also by-name

No forcing happens

`https://github.com/apache/spark/blob/master/core/src/main/scala/org/apache/spark/rdd/RDD.scala`, captured 2022/09

Example of Call-by-name [3/4]

In RDDOperationScope ...

```
private[spark] def withScope[T](
    sc: SparkContext,
    name: String,
    allowNesting: Boolean,
    ignoreParent: Boolean)(body: => T): T = {
  // Save the old scope to restore it later
  val scopeKey = SparkContext.RDD_SCOPE_KEY
  val noOverrideKey = SparkContext.RDD_SCOPE_NO_OVERRIDE_KEY
  val oldScopeJson = sc.getLocalProperty(scopeKey)
  val oldScope = Option(oldScopeJson).map(RDDOperationScope.fromJson)
  val oldNoOverride = sc.getLocalProperty(noOverrideKey)
  try {
    if (ignoreParent) {
      // Ignore all parent settings and scopes and start afresh with our own root scope
      sc.setLocalProperty(scopeKey, new RDDOperationScope(name).toJson)
    } else if (sc.getLocalProperty(noOverrideKey) == null) {
      // Otherwise, set the scope only if the higher level caller allows us to do so
```

Example of Call-by-name [4/4]

```scala
} else if (sc.getLocalProperty(noOverrideKey) == null) {
  // Otherwise, set the scope only if the higher level caller allows us to do so
  sc.setLocalProperty(scopeKey, new RDDOperationScope(name, oldScope).toJson)
}
// Optionally disallow the child body to override our scope
if (!allowNesting) {
  sc.setLocalProperty(noOverrideKey, "true")
}
body
```

The body is executed if the control flow reaches the last line above
(in here: no exceptions thrown)
Otherwise the body will never be executed

`https://github.com/apache/spark/blob/master/core/src/main/scala/org/apache/spark/rdd/RDDOperationScope.scala`, 2022/09

Lazy Lists (Pull Streams)

- Lazy lists (**pull-streams**, ask for data when needed)

```
enum LazyList[+A]:
  case Empty
  case Cons(h: () => A, t: () => LazyList[A])

  def headOption[A] = this match
    case Empty => None
    case Cons(h, t) => Some(h())
```

- Lazy lists capture the same structures as lists. We call this **isomorphic!**
- Difference: evaluate the head and tail arguments **lazily**
- Enum cases cannot have by-name args in Scala, so we use the trick from `if3`
- Add a **convenience constructor** to work around this limitation:

```
def cons[A](hd: => A, tl: => LazyList[A]): LazyList[A] =
  lazy val head = hd
  lazy val tail = tl
  Cons(() => head, () => tail)
```

Examples with Lazy Lists

- An infinite lazy list of ones:

```
val ones: LazyList[Int] = cons(1, ones)
```

- We can implement similar methods as on lists.
- Chop `n` elements from a prefix of a lazy list:

```
def drop (n: Int): LazyList[A] = ???
```

- Take a finite prefix from a lazy list (exercises):

```
def take (n: Int): LazyList[A] = ???
```

- Convert a finite lazy list to a list (exercises)

```
def toList: List[A] = ???
```

- Two lazy lists of random numbers:

```
val random1: LazyList[Double] = Cons(() => Math.random, () => random1)
val random2: LazyList[Double] = cons (Math.random, random2)
random1.take (5).toList      // try several times
random2.take (5).toList      // try several times
```

- `random1` always gives a new list of values, `random2` always the same list. Why?
- We see a difference because `random1` is **not referentially transparent**

Why Lazy Lists?

- Separate the **description of computation** from running it
- **Run only what you need**
  - Describe a larger expression, **evaluate only a portion** of it
  - Easier to program an infinite lazy list of random numbers than precisely 1000
  - The generator (lazy list) can be separated from the context of use: sometimes need 42 sometimes 1000 numbers, **generate them the same way**
  - Work with data **incrementally** as if everything loaded into memory
- **Fusion**: cache/memory locality
  - "`list map f map g`" runs two iterations over a list
  - "`lazyList map f map g`" runs zero iterations over a lazy list (why?)
- **Lazy lists are functional iterators.** In OO an "iterator" is an example of laziness. Forcing is explicit, usually called `next`
- Conceptual basis for **reactive programming** (+real time, push, etc.)