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Advanced Programming

Laziness and Streams

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S SOFTWARE
Q QUALITY
R 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
- **Reactive Extensions:** A Motivating application of Streams (push)
- An implementation of **lazy streams** (pull)



AGENDA

I use imperative code (print) to demonstrate differences between call-by-value and call-by-name

We still disallow imperative code in home works, unless asked for it explicitly

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 (and so it is 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) onTrue () else onFalse ()  
val res = if2 (a < 22, () => println ("a"), () => println ("b"))
```

- **Mentimeter:** 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 if2[A] (cond:Boolean, onTrue: => A, onFalse: => A): A =  
  if (cond) onTrue else onFalse  
  
if2 (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**
- 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: `getOrNull`, we can implement our own loops, etc.

■ Implementing **internal DSLs** [more next semester]

- 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 (stream of naturals, stream of prime numbers, stream of messages, stream of random numbers, etc.)

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

In Apache Spark's implementation

```
/**
 * 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**.

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

In Apache Spark's implementation

```
/**
 * 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

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]

```
} 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

Lazy Streams (Pull Streams)

- Reactive programming streams are **push-streams** (react when a new event arrives)
- We now develop **pull-streams** (ask for data when needed)

```
sealed trait Stream [+A] {  
  def headOption[A] = this match {  
    case Empty => None  
    case Cons(h,t) => Some (h())  
  }  
}  
case object Empty extends Stream[Nothing]  
case class Cons[+A] (h: () => A, t: () => Stream[A]) extends Stream[A]
```

- Lazy streams are **isomorphic to lists** (capture the same structures/shapes)
- But evaluate the head and tail arguments **lazily**
- Case classes cannot take by-name args in Scala, so we use the trick from if2
- Add a **convenience constructor** to work around this limitation:

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

Examples with Lazy Streams

- An infinite stream of ones:

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

- We can implement similar methods as on lists.

- Chop n elements from a prefix of a stream:

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

- Take a finite prefix from a stream (exercises):

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

- Convert a finite stream to a list (exercises)

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

- Two streams of random numbers:

```
val random1: Stream[Double] = Cons(() => Math.random, () => random1)
```

```
val random2: Stream[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 Streams?

- 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 stream of random numbers than precisely 1000
 - The generator (stream) 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
 - “stream map f map g” runs one iteration over a stream
- **Streams 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.)