Lecture 7 – Lazy Evaluation

SWS121: Secure Programming

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PLRG

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Recall

- Monads
  - Why Monads?
  - Monad in Scala
  - Monad Laws
  - For Comprehensions
  - Examples
- Custom Monads
  - Tree Monad
  - State Monad

Lazy Values

In programming languages, **lazy evaluation** is an evaluation strategy that **delays** the evaluation of an expression until its value is actually **needed**.

Lazy Values

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Scala supports lazy evaluation in different ways:

- Lazy Values
- By-Name Parameters
- Lazy Lists
- Views for Collections

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Lazy Values

Consider the following example:

```scala
val x: Int = {
  println("Initializing x")
  42
}
println("Before accessing x")
println(x)
println("After accessing x")
```

Lazy Values

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The output of the above code is:

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Initializing x
Before accessing x
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After accessing x
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We can delay the initialization of a value by defining it as a `lazy val`.

Lazy Values

The basic form of lazy evaluation in Scala is the `lazy val` declaration.

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Lazy Values

The basic form of lazy evaluation in Scala is the `lazy val` declaration.

```
lazy val x: Int = {
  println("Initializing x")
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}
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println(x)
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```

The output of the above code is:

```
Before accessing x
Initializing x
42
After accessing x
```

Lazy Values

```scala
def f: Int = { println("Evaluating f"); 42 }
println(f)   // First access
println(f)   // Second access
lazy val x: Int = { println("Initializing x"); 42 }
println(x)   // First access
println(x)   // Second access
```

Is it same as the function call?

Lazy Values

```
def f: Int = { println("Evaluating f"); 42 }
println(f)   // First access
println(f)   // Second access
lazy val x: Int = { println("Initializing x"); 42 }
println(x)   // First access
println(x)   // Second access
```

Is it same as the function call? **No!** because the value of a `lazy val` is **cached** after the first evaluation.

The output of the above code is:

```
Evaluating f
42
Evaluating f
42
Initializing x
42
42
```

Call-By-Need Evaluation

We call the evaluation strategy of `lazy val` as **call-by-need**.

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The expression is evaluated **only when needed**.

Call-By-Need Evaluation

We call the evaluation strategy of `lazy val` as **call-by-need**.

In call-by-need evaluation, the expression is evaluated **once** and the result is **cached** for future accesses.

The expression is evaluated **only when needed**.

It supports the following properties at the same time:

1. **Immutability**
2. **On-Demand Evaluation**
3. **Caching for Reuse**

Why Lazy Evaluation?

We can **avoid unnecessary heavy computation**:

```scala
// Heavy computation
lazy val f: Int = {
  Thread.sleep(5000) // sleep for 5 second
  42
}
val x = scala.io.StdIn.readInt
val y = if (x > 0) f else 0
```

Why Lazy Evaluation?

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We can **avoid unnecessary heavy computation**:

```scala
// Heavy computation
lazy val f: Int = {
  Thread.sleep(5000) // sleep for 5 second
  42
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val x = scala.io.StdIn.readInt
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```

The above code will sleep for 5 seconds only if `x` is positive.

Why Lazy Evaluation?

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// Heavy computation
lazy val f: Int = {
  Thread.sleep(5000) // sleep for 5 second
  42
}
val x = scala.io.StdIn.readInt
val y = if (x > 0) f else 0
```

The above code will sleep for 5 seconds only if `x` is positive.

It means that the heavy computation is done only when needed.

Why Lazy Evaluation?

We can **change the evaluation order**:

```scala
lazy val z: Int = y + x
lazy val x: Int = { println("Initializing x"); 1 }
lazy val y: Int = { println("Initializing y"); 2 }
println(z)
```

Why Lazy Evaluation?

We can **change the evaluation order**:

```
lazy val z: Int = y + x
lazy val x: Int = { println("Initializing x"); 1 }
lazy val y: Int = { println("Initializing y"); 2 }
println(z)
```

The output of the above code is:

```
Initializing y
Initializing x
3
```

Why Lazy Evaluation?

We can **change the evaluation order**:

```
lazy val z: Int = y + x
lazy val x: Int = { println("Initializing x"); 1 }
lazy val y: Int = { println("Initializing y"); 2 }
println(z)
```

The output of the above code is:

```
Initializing y
Initializing x
3
```

The evaluation of `z` is done after the evaluation of `y` and `x`.

Contents

By-Name Parameters

Another way to achieve lazy evaluation in Scala is by using **by-name parameters** with the prefix => in the parameter type.

```
// return y if x is positive, otherwise return 0
def f(x: Int, y: => Int): Int = {
  println(s"Calling f with x = $x")
  val result = if (x > 0) y else 0
  println(s"Returning $result")
  result
}
f(1, { println("Evaluating y"); 42 })
f(-1, { println("Evaluating y"); 42 })
```

By-Name Parameters

Another way to achieve lazy evaluation in Scala is by using **by-name parameters** with the prefix => in the parameter type.

```scala
// return y if x is positive, otherwise return 0
def f(x: Int, y: => Int): Int = {
  println(s"Calling f with x = $x")
  val result = if (x > 0) y else 0
  println(s"Returning $result")
  result
}
f(1, { println("Evaluating y"); 42 })
f(-1, { println("Evaluating y"); 42 })
```

The output of the above code is:

```
Calling f with x = 1
Evaluating y
Returning 42
Calling f with x = -1
Returning 0
```

By-Name Parameters

```scala
def f(x: => Int): Int = {
  println(s"Calling f with x = $x")
  x + x + x
  println(s"Returning $result")
}
f({ println("Evaluating x"); 42 })
```

Is it also **call-by-need** evaluation?

By-Name Parameters

```scala
def f(x: => Int): Int = {
  println(s"Calling f with x = $x")
  x + x + x
  println(s"Returning $result")
}
f({ println("Evaluating x"); 42 })
```

Is it also **call-by-need** evaluation? **No!** because it evaluates the expression **every time** it is used unlike `lazy val`.

The output of the above code is:

```
Calling f with x = 42
Evaluating x
Evaluating x
Evaluating x
Returning 126
```

Call-By-Need vs Call-By-Name

The **call-by-need** evaluation satisfies the following properties:

1. **Immutability**
2. **On-Demand Evaluation**
3. **Caching for Reuse**

The **call-by-name** evaluation evaluates the following properties:

1. **Immutability**
2. **On-Demand Evaluation**
3. **No Caching for Reuse** (evaluate every time it is used)

Examples

The common use case of call-by-name parameters is **short-circuiting**:

```
def myAndNoShortCircuit(left: Boolean, right: Boolean): Boolean =
  if (left) right
  else false
def myAndShortCircuit(left: Boolean, right: => Boolean): Boolean =
  if (left) right
  else false
def left: Boolean = { println("Evaluating left"); false }
def right: Boolean = { println("Evaluating right"); true }
println(myAndNoShortCircuit(left, right))
println(myAndShortCircuit(left, right))
```

Examples

The common use case of call-by-name parameters is **short-circuiting**:

```
def myAndNoShortCircuit(left: Boolean, right: Boolean): Boolean =
  if (left) right
  else false
def myAndShortCircuit(left: Boolean, right: => Boolean): Boolean =
  if (left) right
  else false
def left: Boolean = { println("Evaluating left"); false }
def right: Boolean = { println("Evaluating right"); true }
println(myAndNoShortCircuit(left, right))
println(myAndShortCircuit(left, right))
```

The output of the above code is:

```
Evaluating left
Evaluating right
false
Evaluating left
false
```

Examples

The `getOrElse` method in `Option` is also implemented using call-by-name parameters:

```
def f(opt: Option[Int]): Int = opt.getOrElse {
  println("Evaluating default value"),
  42
}
println(f(Some(10)))
println(f(None))
```

Examples

The `getOrElse` method in `Option` is also implemented using call-by-name parameters:

```
def f(opt: Option[Int]): Int = opt.getOrElse {
  println("Evaluating default value"),
  42
}
println(f(Some(10)))
println(f(None))
```

The output of the above code is:

```
10
Evaluating default value
42
```

By-Name Parameters with Lazy Values

We can combine **call-by-name parameters** with `lazy val` to achieve the properties of both.

```scala
def f(x: Int, y: => Int): Int = {
  println(s"Calling f with x = $x")
  lazy val z = y
  val result = if (x > 0) z + z + z else 0
  println(s"Returning $result")
}
f(1, { println("Evaluating y"); 42 })
f(-1, { println("Evaluating y"); 42 })
```

By-Name Parameters with Lazy Values

We can combine **call-by-name parameters** with `lazy val` to achieve the properties of both.

```
def f(x: Int, y: => Int): Int = {
  println(s"Calling f with x = $x")
  lazy val z = y
  val result = if (x > 0) z + z + z else 0
  println(s"Returning $result")
}
f(1, { println("Evaluating y"); 42 })
f(-1, { println("Evaluating y"); 42 })
```

The output of the above code is:

```
Calling f with x = 1
Evaluating y
Returning 126
Calling f with x = -1
Returning 0
```

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Lazy Lists

In Scala, a `LazyList` is a **lazy** version of a `List` that evaluates elements **only when needed**.

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We can create a `LazyList` using the `#::` operator.

```
def create(n: Int): LazyList[Int] = {
  println(s"Creating lazy list with $n")
  n #:: create(n + 1)
}
lazy val xs: LazyList[Int] = create(0)
println(xs(0))
println(xs(2))
```

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  println(s"Creating lazy list with $n")
  n #:: create(n + 1)
}
lazy val xs: LazyList[Int] = create(0)
println(xs(0))
println(xs(2))
```

The output of the above code is:

```
Creating lazy list with 0
0
Creating lazy list with 1
Creating lazy list with 2
2
```

Example: Natural Numbers

Using the `LazyList`, we can create **infinite** lists.

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The following code creates a `LazyList` of all **natural numbers**:

nat ----...

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```scala
lazy val nat: LazyList[Int] = 0 #:: nat.map(_ + 1)
```

Example: Natural Numbers

Using the `LazyList`, we can create **infinite** lists.

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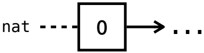

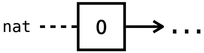


```
lazy val nat: LazyList[Int] = 0 #:: nat.map(_ + 1)
println(nat(0))    // 0
```

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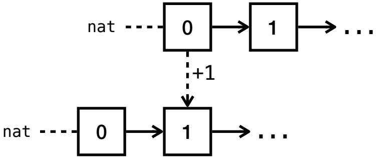


```
lazy val nat: LazyList[Int] = 0 #:: nat.map(_ + 1)
println(nat(0))    // 0
println(nat(1))    // 1
```

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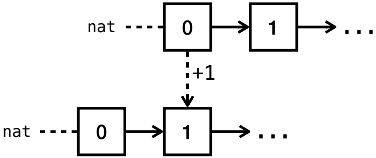


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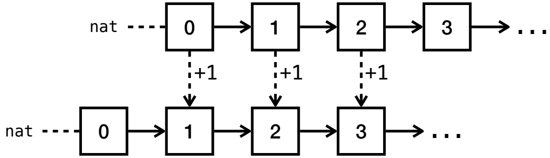


```scala
lazy val nat: LazyList[Int] = 0 #:: nat.map(_ + 1)
println(nat(0))    // 0
println(nat(1))    // 1
println(nat(0))    // 0
println(nat(3))    // 3
```

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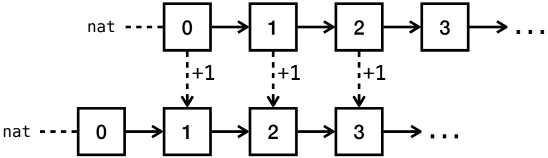


```
lazy val nat: LazyList[Int] = 0 #:: nat.map(_ + 1)
println(nat(0))    // 0
println(nat(1))    // 1
println(nat(0))    // 0
println(nat(3))    // 3
println(nat(2))    // 2
```

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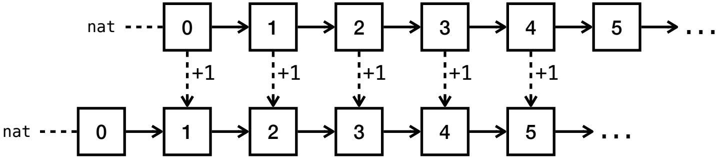


```
lazy val nat: LazyList[Int] = 0 #:: nat.map(_ + 1)
println(nat(0))    // 0
println(nat(1))    // 1
println(nat(0))    // 0
println(nat(3))    // 3
println(nat(2))    // 2
println(nat(5))    // 5
```

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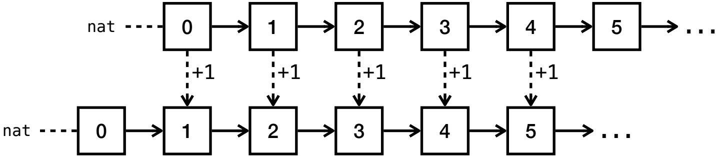


```
lazy val nat: LazyList[Int] = 0 #:: nat.map(_ + 1)
println(nat(0))    // 0
println(nat(1))    // 1
println(nat(0))    // 0
println(nat(3))    // 3
println(nat(2))    // 2
println(nat(5))    // 5
println(nat(4))    // 4
```

Example: Even Numbers

We can create other infinite lists using `LazyList`.

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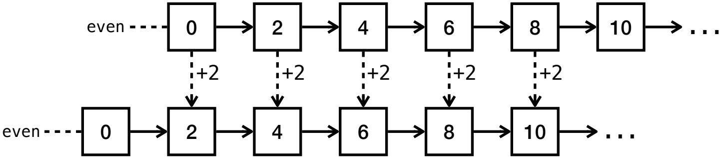
We can create other infinite lists using `LazyList`.

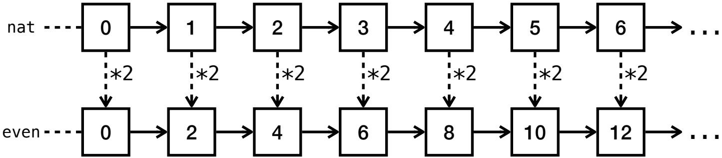
For example, we can create a `LazyList` of all **even numbers**:



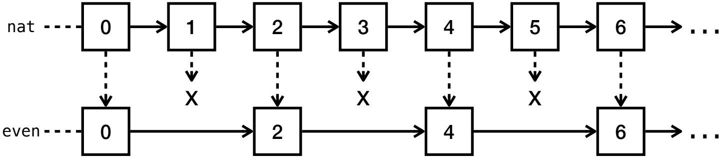

```scala
lazy val even: LazyList[Int] = 0 #:: even.map(_ + 2)
```

Example: Even Numbers

We can utilize the `map` or `filter` methods to create even numbers.



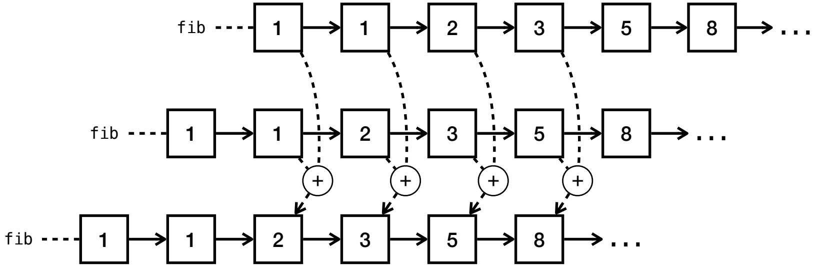

```
lazy val even: LazyList[Int] = nat.map(_ * 2)
```




```
lazy val even: LazyList[Int] = nat.filter(_ % 2 == 0)
```

Example: Fibonacci Numbers

We can utilize the `zip` method to create the **Fibonacci numbers**.




```
lazy val fib: LazyList[Int] = 1 #:: 1 #:: (fib zip fib.tail).map(_ + _)
```

where `fib.tail` takes all elements except the first element.

Example: Prime Numbers

We can create the natural numbers starting from a specific number using `LazyList.from` method:

```
lazy val nats: LazyList[Int] = LazyList.from(3)
// 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, ...
```

Example: Prime Numbers

We can create the natural numbers starting from a specific number using `LazyList.from` method:

```
lazy val nats: LazyList[Int] = LazyList.from(3)
// 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, ...
```

Besides the Fibonacci numbers, we can also create the **prime numbers**:

```
lazy val primes: LazyList[Int] = 2 #:: LazyList
  .from(3)
  .filter {
    i => primes
      .takeWhile(p => p * p <= i)
      .forall(p => i % p != 0)
  }
```

where the `takeWhile` method returns elements until the condition is satisfied, and the `forall` method checks if all elements satisfy the condition.

Contents

Views for Collections

```scala
def inc(x: Int): Int = {
  println(s"inc: $x -> ${x + 1}")
  x + 1
}
def double(x: Int): Int = {
  println(s"double: $x -> ${x * 2}")
  x * 2
}
(1 to 100).map(inc).map(double)(5)
```

Views for Collections

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  println(s"double: $x -> ${x * 2}")
  x * 2
}
(1 to 100).map(inc).map(double)(5)
```

The output of the above code is:

```
inc: 1 -> 2
inc: 2 -> 3
...
double: 2 -> 4
double: 3 -> 6
...
14
```

Views for Collections

The `view` method creates a **view** of the collection that **computes elements on demand**.

```
def inc(x: Int): Int = {
  println(s"inc: $x -> ${x + 1}")
  x + 1
}
def double(x: Int): Int = {
  println(s"double: $x -> ${x * 2}")
  x * 2
}
(1 to 100).view.map(inc).map(double)(5)
```

The output of the above code is:

```
inc: 6 -> 7
double: 7 -> 14
14
```

Views for Collections

The `view` method creates a **view** of the collection that **computes elements on demand**.

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def inc(x: Int): Int = {
  println(s"inc: $x -> ${x + 1}")
  x + 1
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def double(x: Int): Int = {
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  x * 2
}
(1 to 100).view.map(inc).map(double)(5)
```

The output of the above code is:

```
inc: 6 -> 7
double: 7 -> 14
14
```

We can optimize the computation using `view` method.

Views for Collections

```scala
val xs: IndexedSeqView[Int] = (1 to 100).view
```

Views for Collections

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The `view` type supports the same operations as the original collection (e.g., `IndexedSeqView` supports similar operations as `IndexedSeq`).

```scala
val ys = xs.view.map(_ + 1).filter(_ % 2 == 0).take(5)
```

Views for Collections

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(e.g., `IndexedSeqView` supports similar operations as `IndexedSeq`).

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val ys = xs.view.map(_ + 1).filter(_ % 2 == 0).take(5)
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We can force to perform the computation using the `to` method or `to*` method (e.g., `toVector`, etc.).

```
ys.to(Vector) // Vector(2, 4, 6, 8, 10)
ys.toVector   // Vector(2, 4, 6, 8, 10)
```

Views for Collections

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```
ys.to(Vector) // Vector(2, 4, 6, 8, 10)
ys.toVector   // Vector(2, 4, 6, 8, 10)
```

It computes elements **in need** but **not caches** the results. (**call-by-name**).

```
val zs = xs.view.map(x => { println(x); x + 1 })
zs(42)  // prints 42
zs(42)  // prints 42
```

Find Palindromes

Consider the following huge list of words:

```scala
val words: List[String] = // a huge list of words
```

Find Palindromes

Consider the following huge list of words:

```
val words: List[String] = // a huge list of words
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Let's implement a code to find the first palindrome word in the first 10,000 words, or return `None` if no palindrome word is found.

Find Palindromes

Consider the following huge list of words:

```
val words: List[String] = // a huge list of words
```

Let's implement a code to find the first palindrome word in the first 10,000 words, or return `None` if no palindrome word is found.

The possible basic implementation is:

```
def isPalin(s: String): Boolean = s == s.reverse
def findPalin(words: List[String]): Option[String] = words.find(isPalin)
findPlain(words.take(10_000))
```

However, it always requires to create a new list of the first 10,000 words.

Find Palindromes

Consider the following huge list of words:

```
val words: List[String] = // a huge list of words
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def isPalin(s: String): Boolean = s == s.reverse
def findPalin(words: List[String]): Option[String] = words.find(isPalin)
findPlain(words.take(10_000))
```

However, it always requires to create a new list of the first 10,000 words.

To avoid creating a new list, we can use the `view` method.

```
findPalin(words.view.take(10_000))
```

Find Palindromes

PLRG

Consider the following huge list of words:

```
val words: List[String] = // a huge list of words
```

Let's implement a code to find the first palindrome word in the first 10,000 words, or return `None` if no palindrome word is found.

The possible basic implementation is:

```
def isPalin(s: String): Boolean = s == s.reverse
def findPalin(words: List[String]): Option[String] = words.find(isPalin)
findPlain(words.take(10_000))
```

However, it always requires to create a new list of the first 10,000 words.

To avoid creating a new list, we can use the `view` method.

```
findPalin(words.view.take(10_000))
```

The `view` method helps to **optimize** the computation in diverse ways.

Summary

1. Lazy Values (`lazy val`)
   - Call-By-Need Evaluation
   - Why Lazy Values?
2. By-Name Parameters
   - Call-By-Need vs Call-By-Name
   - Examples
   - By-Name Parameters with Lazy Values
3. Lazy Lists
   - Example: Natural Numbers
   - Example: Even Numbers
   - Example: Fibonacci Numbers
   - Example: Prime Numbers
4. Views for Collections
   - Example: Find Palindromes

Next Lecture

- Generics

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