Lists
Lists

The list is a fundamental data structure in functional programming.

A list having $x_1, \ldots, x_n$ as elements is written $\text{List}(x_1, \ldots, x_n)$

Example

```scala
val fruit = List("apples", "oranges", "pears")
val nums = List(1, 2, 3, 4)
val diag3 = List(List(1, 0, 0), List(0, 1, 0), List(0, 0, 1))
val empty = List()
```

There are two important differences between lists and arrays.

- Lists are immutable — the elements of a list cannot be changed.
- Lists are recursive, while arrays are flat.
val fruit = List("apples", "oranges", "pears")
val diag3 = List(List(1, 0, 0), List(0, 1, 0), List(0, 0, 1))
The List Type

Like arrays, lists are homogeneous: the elements of a list must all have the same type.

The type of a list with elements of type T is written scala.List[T] or shorter just List[T]

**Example**

```scala
val fruit: List[String] = List("apples", "oranges", "pears")
val nums: List[Int] = List(1, 2, 3, 4)
val diag3: List[List[Int]] = List(List(1, 0, 0), List(0, 1, 0), List(0, 0, 1))
val empty: List[Nothing] = List()
```
Constructors of Lists

All lists are constructed from:

- the empty list Nil, and
- the construction operation :: (pronounced cons):

\[ x :: xs \] gives a new list with the first element \( x \), followed by the elements of \( xs \).

For example:

\[
\begin{align*}
\text{fruit} &= \text{"apples" :: ("oranges" :: ("pears" :: Nil))} \\
\text{nums} &= 1 :: (2 :: (3 :: (4 :: Nil))) \\
\text{empty} &= \text{Nil}
\end{align*}
\]
Right Associativity

Convention: Operators ending in “::” associate to the right.

\[ A :: B :: C \] is interpreted as \[ A :: (B :: C) \].

We can thus omit the parentheses in the definition above.

**Example**

```scala
val nums = 1 :: (2 :: (3 :: (4 :: Nil)))
```

Operators ending in “::” are also different in the they are seen as method calls of the *right-hand* operand.

So the expression above is equivalent to

\[ \text{Nil} :: (4) :: (3) :: (2) :: (1) \]
Operations on Lists

All operations on lists can be expressed in terms of the following three operations:

- head: the first element of the list
- tail: the list composed of all the elements except the first.
- isEmpty: ‘true’ if the list is empty, ‘false’ otherwise.

These operations are defined as methods of objects of type list. For example:

```java
fruit.head == "apples"
fruit.tail.head == "oranges"
diag3.head == List(1, 0, 0)
empty.head == throw new NoSuchElementException("head of empty list")
```
List Patterns

It is also possible to decompose lists with pattern matching.

\[
\begin{align*}
\text{Nil} & \quad \text{The Nil constant} \\
p :: ps & \quad \text{A pattern that matches a list with a head matching } p \text{ and} \\
& \hspace{1cm} \text{a tail matching } ps. \\
\text{List}(p_1, \ldots, p_n) & \quad \text{same as } p_1 :: \ldots :: p_n :: \text{Nil}
\end{align*}
\]

**Example**

\[
\begin{align*}
1 :: 2 :: xs & \quad \text{Lists of that start with 1 and then 2} \\
x :: \text{Nil} & \quad \text{Lists of length 1} \\
\text{List}(x) & \quad \text{Same as } x :: \text{Nil} \\
\text{List}() & \quad \text{The empty list, same as Nil} \\
\text{List}(2 :: xs) & \quad \text{A list that contains as only element another list that starts with 2.}
\end{align*}
\]
Exercise

Consider the pattern `x :: y :: List(xs, ys) :: zs`.

What is the condition that describes most accurately the length `L` of the lists it matches?

<table>
<thead>
<tr>
<th></th>
<th>L == 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>L == 4</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>L == 5</th>
</tr>
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<tbody>
<tr>
<td>0</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>L &gt;= 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>L &gt;= 4</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>L &gt;= 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Exercise

Consider the pattern \( x :: y :: \text{List}(xs, ys) :: zs \).

What is the condition that describes most accurately the length \( L \) of the lists it matches?

- \( 0 \quad L = 3 \)
- \( 0 \quad L = 4 \)
- \( 0 \quad L = 5 \)
- \( 0 \quad L \geq 3 \)
- \( 0 \quad L \geq 4 \)
- \( 0 \quad L \geq 5 \)
Sorting Lists

Suppose we want to sort a list of numbers in ascending order:

- One way to sort the list List(7, 3, 9, 2) is to sort the tail List(3, 9, 2) to obtain List(2, 3, 9).
- The next step is to insert the head 7 in the right place to obtain the result List(2, 3, 7, 9).

This idea describes *Insertion Sort*:

```python
def isort(xs: List[Int]): List[Int] = xs match {
  case List() => List()
  case y :: ys => insert(y, isort(ys))
}
```
Exercise

Complete the definition insertion sort by filling in the ???s in the definition below:

```scala
def insert(x: Int, xs: List[Int]): List[Int] = xs match {
  case List() => ???
  case y :: ys => ???
}
```

What is the worst-case complexity of insertion sort relative to the length of the input list N?

- 0 the sort takes constant time
- 0 proportional to N
- 0 proportional to N log(N)
- 0 proportional to N * N
Exercise

Complete the definition insertion sort by filling in the ???s in the definition below:

```
def insert(x: Int, xs: List[Int]): List[Int] = xs match {
  case List() => ???
  case y :: ys => ???
}
```

What is the worst-case complexity of insertion sort relative to the length of the input list $N$?

0 the sort takes constant time
0 proportional to $N$
0 proportional to $N \log(N)$
0 proportional to $N \times N$
Exercise

Complete the definition insertion sort by filling in the ???s in the definition below:

```haskell
def insert(x: Int, xs: List[Int]): List[Int] = xs match {
  case List() => List(x)
  case y :: ys => if x <= y then x :: xs else y :: insert(x, ys)
}
```

What is the worst-case complexity of insertion sort relative to the length of the input list \( N \)?

- 0 the sort takes constant time
- 0 proportional to \( N \)
- 0 proportional to \( N \times \log(N) \)
- 0 proportional to \( N \times N \)
More Functions on Lists
List Methods (1)

Sublists and element access:

- `xs.length` The number of elements of `xs`.
- `xs.last` The list's last element, exception if `xs` is empty.
- `xs.init` A list consisting of all elements of `xs` except the last one, exception if `xs` is empty.
- `xs take n` A list consisting of the first `n` elements of `xs`, or `xs` itself if it is shorter than `n`.
- `xs drop n` The rest of the collection after taking `n` elements.
- `xs(n)` (or, written out, `xs apply n`). The element of `xs` at index `n`.

```
\begin{center}
\begin{tikzpicture}
  \draw[thick] (0,0) -- (4,0) -- (4,2) -- (0,2) -- cycle;
  \draw[thick] (0,0) -- (1,1) -- (3,1) -- (4,0);
  \node at (2,0.5) {head};
  \node at (1,1.5) {init};
  \node at (3.5,1.5) {past};
  \node at (2.5,0.5) {tail};
\end{tikzpicture}
\end{center}
```
List Methods (2)

Creating new lists:

- `xs ++ ys` The list consisting of all elements of `xs` followed by all elements of `ys`.
- `xs.reverse` The list containing the elements of `xs` in reversed order.
- `xs updated (n, x)` The list containing the same elements as `xs`, except at index `n` where it contains `x`.

Finding elements:

- `xs indexOf x` The index of the first element in `xs` equal to `x`, or `-1` if `x` does not appear in `xs`.
- `xs contains x` same as `xs indexOf x >= 0`
Implementation of last

The complexity of head is (small) constant time.

What is the complexity of last?

To find out, let’s write a possible implementation of last as a stand-alone function.

```scala
def last[T](xs: List[T]): T = xs match {
  case List() => throw new Error("last of empty list")
  case List(x) =>
  case y :: ys =>
```
Implementation of \texttt{last}

The complexity of \texttt{head} is (small) constant time.

What is the complexity of \texttt{last}?

To find out, let’s write a possible implementation of \texttt{last} as a stand-alone function.

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  case List(x) => x
  case y :: ys =>
}
```
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}
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def last[T](xs: List[T]): T = xs match {
  case List() => throw new Error("last of empty list")
  case List(x) => x
  case y :: ys => last(ys)
}
```

So, last takes steps proportional to the length of the list xs.
Exercise

Implement `init` as an external function, analogous to `last`.

```python
def init[T](xs: List[T]): List[T] = xs match {
  case List() => throw new Error("init of empty list")
  case List(x) => ???
  case y :: ys => ???
}
```
Implement `init` as an external function, analogous to `last`.

```python
def init[T](xs: List[T]): List[T] = xs match {
  case List() => throw new Error("init of empty list")
  case List(x) =>
  case y :: ys =>
}
```
Implementation of Concatenation

How can concatenation be implemented?
Let’s try by writing a stand-alone function:

```python
def concat[T](xs: List[T], ys: List[T]) =
```
Implementation of Concatenation

How can concatenation be implemented?

Let’s try by writing a stand-alone function:

```python
def concat[T](xs: List[T], ys: List[T]) = xs match {
    case List() =>
    case z :: zs =>
}
```
Implementation of Concatenation

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Let’s try by writing a stand-alone function:

```python
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  case List() => ys
  case z :: zs =>
}
```
Implementation of Concatenation

How can concatenation be implemented?

Let’s try by writing a stand-alone function:

```python
def concat[T](xs: List[T], ys: List[T]) = xs match {
    case List() => ys
    case z :: zs => z :: concat(zs, ys)
}
```
Implementation of Concatenation

How can concatenation be implemented?

Let’s try by writing a stand-alone function:

```python
def concat[T](xs: List[T], ys: List[T]) = xs match {
  case List() => ys
  case z :: zs => z :: concat(zs, ys)
}
```

What is the complexity of `concat` for a list of length `n`?
Implementation of reverse

How can reverse be implemented?

Let’s try by writing a stand-alone function:

def reverse[T](xs: List[T]): List[T] = xs match {
  case List() => xs
  case y :: ys => reverse(ys) ++ list(y)
}

Implementation of reverse

How can reverse be implemented?

Let’s try by writing a stand-alone function:

```python
def reverse[T](xs: List[T]): List[T] = xs match {
  case List() => List()
  case y :: ys => reverse(ys) ++ List(y)
}
```
Implementation of reverse

How can reverse be implemented?

Let’s try by writing a stand-alone function:

```python
def reverse[T](xs: List[T]): List[T] = xs match {
  case List() => List()
  case y :: ys => reverse(ys) ++ List(y)
}
```

What is the complexity of reverse?

*Can we do better?* (to be solved later).
Exercise

Remove the n’th element of a list xs. If n is out of bounds, return xs itself.

```python
def removeAt[T](xs: List[T], n: Int) = ???

Usage example:
```removeAt(1, List('a', 'b', 'c', 'd')) > List(a, c, d)```
Exercise (Harder, Optional)

Flatten a list structure:

```python
def flatten(xs: List[Any]): List[Any] = ???

flatten(List(List(1, 1), 2, List(3, List(5, 8))))
  > res0: List[Any] = List(1, 1, 2, 3, 5, 8)
```
Pairs and Tuples
Sorting Lists Faster

As a non-trivial example, let’s design a function to sort lists that is more efficient than insertion sort.

A good algorithm for this is *merge sort*. The idea is as follows:

If the list consists of zero or one elements, it is already sorted.

Otherwise,

- Separate the list into two sub-lists, each containing around half of the elements of the original list.
- Sort the two sub-lists.
- Merge the two sorted sub-lists into a single sorted list.
Here is the implementation of that algorithm in Scala:

```scala
def msort(xs: List[Int]): List[Int] = {
  val n = xs.length/2
  if (n == 0) xs
  else {
    def merge(xs: List[Int], ys: List[Int]) = ???
    val (fst, snd) = xs splitAt n
    merge(msort(fst), msort(snd))
  }
}
```
Definition of Merge

Here is a definition of the merge function:

```scala
def merge(xs: List[Int], ys: List[Int]) =
  xs match {
    case Nil =>
      ys
    case x :: xs1 =>
      ys match {
        case Nil =>
          xs
        case y :: ys1 =>
          if (x < y) x :: merge(xs1, ys)
          else y :: merge(xs, ys1)
      }
  }
```
The SplitAt Function

The `splitAt` function on lists returns two sublists

- the elements up to the given index
- the elements from that index

The lists are returned in a *pair*. 
Detour: Pair and Tuples

The pair consisting of x and y is written \((x, y)\) in Scala.

**Example**

```scala
val pair = ("answer", 42)  // pair : (String, Int) = (answer,42)
```

The type of pair above is \((\text{String}, \text{Int})\).

Pairs can also be used as patterns:

```scala
val (label, value) = pair  // label : String = answer
                        | value : Int = 42
```

This works analogously for tuples with more than two elements.
Translation of Tuples

A tuple type \((T_1, \ldots, T_n)\) is an abbreviation of the parameterized type

\[
\text{scala.Tuple}_n[T_1, \ldots, T_n]
\]

A tuple expression \((e_1, \ldots, e_n)\) is equivalent to the function application

\[
\text{scala.Tuple}_n(e_1, \ldots, e_n)
\]

A tuple pattern \((p_1, \ldots, p_n)\) is equivalent to the constructor pattern

\[
\text{scala.Tuple}_n(p_1, \ldots, p_n)
\]
The Tuple class

Here, all Tuple\(_n\) classes are modeled after the following pattern:

```scala
case class Tuple2[T1, T2](_1: +T1, _2: +T2) {
    override def toString = "(" + _1 + "," + _2 + ")"
}
```

The fields of a tuple can be accessed with names \_1, \_2, ... 
So instead of the pattern binding

```scala
val (label, value) = pair
```

one could also have written:

```scala
val label = pair._1
val value = pair._2
```

But the pattern matching form is generally preferred.
Exercise

The `merge` function as given uses a nested pattern match. This does not reflect the inherent symmetry of the merge algorithm. Rewrite `merge` using a pattern matching over pairs.

```python
def merge(xs: List[Int], ys: List[Int]): List[Int] =
  (xs, ys) match {
    ???
  }
```
Implicit Parameters
Making Sort more General

Problem: How to parameterize msort so that it can also be used for lists with elements other than Int?

```python
def msort[T](xs: List[T]): List[T] = ...
```

does not work, because the comparison `<` in `merge` is not defined for arbitrary types T.

Idea: Parameterize `merge` with the necessary comparison function.
Parameterization of Sort

The most flexible design is to make the function sort polymorphic and to pass the comparison operation as an additional parameter:

```python
def msort[T](xs: List[T])(lt: (T, T) => Boolean) = {
    ...
    merge(msort(fst)(lt), msort(snd)(lt))
}
```

Merge then needs to be adapted as follows:

```python
def merge(xs: List[T], ys: List[T]) = (xs, ys) match {
    ...
    case (x :: xs1, y :: ys1) =>
        if (lt(x, y)) ...
        else ...
    }
```
Calling Parameterized Sort

We can now call msort as follows:

```scala
val xs = List(-5, 6, 3, 2, 7)
val fruit = List(”apple”, ”pear”, ”orange”, ”pineapple”)

merge(xs)((x: Int, y: Int) => x < y)
merge(fruit)((x: String, y: String) => x.compareTo(y) < 0)
```

Or, since parameter types can be inferred from the call `merge(xs):

merge(xs)((x, y) => x < y)
Parametrization with Ordered

There is already a class in the standard library that represents orderings.

    scala.math.Ordering[T]

provides ways to compare elements of type T. So instead of parameterizing with the `lt` operation directly, we could parameterize with `Ordering` instead:

    def msort[T](xs: List[T])(ord: Ordering) =

    def merge(xs: List[T], ys: List[T]) =
        ... if (ord.lt(x, y)) ...

        ... merge(msort(fst)(ord), msort(snd)(ord)) ...
Ordered Instances:

Calling the new `msort` can be done like this:

```scala
import math.Ordering

msort(nums)(Ordering.Int)
msort(fruits)(Ordering.String)
```

This makes use of the values `Int` and `String` defined in the `scala.math.Ordering` object, which produce the right orderings on integers and strings.
Aside: Implicit Parameters

Problem: Passing around lt or ord values is cumbersome. We can avoid this by making ord an implicit parameter.

```
def msort[T](xs: List[T])(implicit ord: Ordering) =

  def merge(xs: List[T], ys: List[T]) =
  ... if (ord.lt(x, y)) ...

  ... merge(msort(fst), msort(snd)) ...
```

Then calls to msort can avoid the ordering parameters:

```
msort(nums)
msort(fruits)
```

The compiler will figure out the right implicit to pass based on the demanded type.
Rules for Implicit Parameters

Say, a function takes an implicit parameter of type T.
The compiler will search an implicit definition that

- is marked implicit
- has a type compatible with T
- is visible at the point of the function call, or is defined in a companion object associated with T.

If there is a single (most specific) definition, it will be taken as actual argument for the implicit parameter.
Otherwise it’s an error.
Exercise: Implicit Parameters

Consider the following line of the definition of msort:

... merge(msort(fst), msort(snd)) ...

Which implicit argument is inserted?

0 Ordering.Int
0 Ordering.String
0 the "ord" parameter of "msort"
Higher-order List Functions
Recurring Patterns for Computations on Lists

The examples have shown that functions on lists often have similar structures.

We can identify several recurring patterns, like,

- transforming each element in a list in a certain way,
- retrieving a list of all elements satisfying a criterion,
- combining the elements of a list using an operator.

Functional languages allow programmers to write generic functions that implement patterns such as these using higher-order functions.
Applying a Function to Elements of a List

A common operation is to transform each element of a list and then return the list of results.

For example, to multiply each element of a list by the same factor, you could write:

```scala
def scaleList(xs: List[Double], factor: Double): List[Double] = xs match {
  case Nil => xs
  case y :: ys => y * factor :: scaleList(ys, factor)
}
```
Map

This scheme can be generalized to the method `map` of the `List` class.
A simple way to define `map` is as follows:

```scala
abstract class List[T] { ... 
  def map[U](f: T => U): List[U] = this match { 
    case Nil => this 
    case x :: xs => f(x) :: xs.map(f) 
  }

  (in fact, the actual definition of `map` is a bit more complicated, 
  because it is tail-recursive, and also because it works for arbitrary 
  collections, not just lists).

  Using `map`, `scaleList` can be written more concisely.

  def scaleList(xs: List[Double], factor: Double) = 
    xs map (x => x * factor)
```
Exercise

Consider a function to square each element of a list, and return the result. Complete the two following equivalent definitions of squareList.

```python
def squareList(xs: List[Int]): List[Int] = xs match {
  case Nil => ???
  case y :: ys => ???
}

def squareList(xs: List[Int]): List[Int] =
  xs map ???
```
Exercise

Consider a function to square each element of a list, and return the result. Complete the two following equivalent definitions of squareList.

```scala
def squareList(xs: List[Int]): List[Int] = xs match {
  case Nil => Nil
  case y :: ys => y * y :: squareList(ys)
}

def squareList(xs: List[Int]): List[Int] = 
  xs map (x => x * x)
```
Filtering

Another common operation on lists is the selection of all elements satisfying a given condition. For example:

def posElems(xs: List[Int]): List[Int] = xs match {
  case Nil => xs
  case y :: ys => if (y > 0) y :: posElems(ys) else posElems(ys)
}
This pattern is generalized by the method filter of the List class:

```scala
abstract class List[T] {
  ...
  def filter(p: T => Boolean): List[T] = this match {
    case Nil => this
    case x :: xs => if (p(x)) x :: xs.filter(p) else xs.filter(p)
  }
}
```

Using filter, posElems can be written more concisely.

```scala
def posElems(xs: List[Int]): List[Int] =
  xs filter (x => x > 0)
```
Variations of Filter

Besides filter, there are also the following methods that extract sublists based on a predicate:

- \(xs\) filterNot \(p\)  
  Same as \(xs\) filter \((x \Rightarrow !p(x))\); The list consisting of those elements of \(xs\) that do not satisfy the predicate \(p\).

- \(xs\) partition \(p\)  
  Same as \((xs\) filter \(p\), \(xs\) filterNot \(p\))\), but computed in a single traversal of the list \(xs\).

- \(xs\) takeWhile \(p\)  
  The longest prefix of list \(xs\) consisting of elements that all satisfy the predicate \(p\).

- \(xs\) dropWhile \(p\)  
  The remainder of the list \(xs\) after any leading elements satisfying \(p\) have been removed.

- \(xs\) span \(p\)  
  Same as \((xs\) takeWhile \(p\), \(xs\) dropWhile \(p\))\) but computed in a single traversal of the list \(xs\).
### Exercise

Write a function `pack` that packs consecutive duplicates of list elements into sublists. For instance,

```
pack(List("a", "a", "a", "b", "c", "c", "a"))
```

should give

```
List(List("a", "a", "a"), List("b"), List("c", "c"), List("a"));
```

You can use the following template:

```python
def pack[T](xs: List[T]): List[List[T]] = xs match {
  case Nil => Nil
  case x :: xs1 => ???
}
```
Exercise

Using pack, write a function encode that produces the run-length encoding of a list.

The idea is to encode \( n \) consecutive duplicates of an element \( x \) as a pair \((x, n)\). For instance,

\[
\text{encode(List("a", "a", "a", "b", "c", "c", "a"))}
\]

should give

\[
\text{List(("a", 3), ("b", 1), ("c", 2), ("a", 1)).}
\]
Reduction of Lists
Reduction of Lists

Another common operation on lists is to combine the elements of a list using a given operator.

For example:

$$\text{sum} (\text{List}(x_1, \ldots, x_n)) = 0 + x_1 + \ldots + x_n$$
$$\text{product} (\text{List}(x_1, \ldots, x_n)) = 1 * x_1 * \ldots * x_n$$

We can implement this with the usual recursive schema:

```python
def sum(xs: List[Int]): Int = xs match {
  case Nil => 0
  case y :: ys => y + sum(ys)
}
```
ReduceLeft

This pattern can be abstracted out using the generic method reduceLeft:

reduceLeft inserts a given binary operator between adjacent elements of a list:

\[
\text{List}(x_1, \ldots, x_n) \text{reduceLeft} \text{ op } = ((\ldots(x_1 \text{ op } x_2) \text{ op } \ldots) \text{ op } x_n)
\]

Using reduceLeft, we can simplify:

\[
\text{def } \text{sum}(xs: \text{List[Int]}) = (0 :: xs) \text{reduceLeft} ((x, y) => x + y) \\
\text{def } \text{product}(xs: \text{List[Int]}) = (1 :: xs) \text{reduceLeft} ((x, y) => x * y)
\]
A Shorter Way to Write Functions

Instead of \(((x, y) \Rightarrow x \times y)\), one can also write shorter:

\[
(_ \times \_)
\]

\[
((x,y) \Rightarrow (x \times y))
\]

Every \_ represents a new parameter, going from left to right.

The parameters are defined at the next outer pair of parentheses (or the whole expression if there are no enclosing parentheses).

So, sum and product can also be expressed like this:

```scala
def sum(xs: List[Int]) = (0 :: xs) reduceLeft (_ + _)
def product(xs: List[Int]) = (1 :: xs) reduceLeft (_ * _)
```
FoldLeft

The function reduceLeft is defined in terms of a more general function, foldLeft.

foldLeft is like reduceLeft but takes an accumulator, z, as an additional parameter, which is returned when foldLeft is called on an empty list.

$$(\text{List}(x_1, \ldots, x_n) \text{ foldLeft } z)(\text{op}) = (\ldots(z \text{ op } x_1) \text{ op } \ldots) \text{ op } x_n$$

So, sum and product can also be defined as follows:

```scala
def sum(xs: List[Int]) = (xs foldLeft 0)(_ + _)
def product(xs: List[Int]) = (xs foldLeft 1)(_ * _)
```
Implementations of ReduceLeft and FoldLeft

foldLeft and reduceLeft can be implemented in class List as follows.

```scala
abstract class List[T] { ... 
  def reduceLeft(op: (T, T) => T): T = this match {
    case Nil => throw new Error("Nil.reduceLeft")
    case x :: xs => (xs foldLeft x)(op)
  }
  def foldLeft[U](z: U)(op: (U, T) => U): U = this match {
    case Nil => z
    case x :: xs => (xs foldLeft op(z, x))(op)
  }
}
```
FoldRight and ReduceRight

Applications of foldLeft and reduceLeft unfold on trees that lean to the left.

They have two dual functions, foldRight and reduceRight, which produce trees which lean to the right, i.e.,

$$\text{List}(x_1, \ldots, x_{n-1}, x_n) \text{ reduceRight } \text{op} \ = \ x_1 \ \text{op} \ (\ldots (x_{n-1} \ \text{op} \ x_n) \ldots )$$

$$(\text{List}(x_1, \ldots, x_n) \ \text{foldRight } \text{acc})(\text{op}) \ = \ x_1 \ \text{op} \ (\ldots (x_n \ \text{op} \ \text{acc}) \ldots )$$
Implementation of FoldRight and ReduceRight

They are defined as follows

```python
def reduceRight(op: (T, T) => T): T = this match {
  case Nil => throw new Error("Nil.reduceRight")
  case x :: Nil => x
  case x :: xs => op(x, xs.reduceRight(op))
}
def foldRight(z: U)(op: (T, U) => U): U = this match {
  case Nil => z
  case x :: xs => op(x, (xs foldRight z)(op))
}
```

Difference between `foldLeft` and `foldRight`

For operators that are associative and commutative, `foldLeft` and `foldRight` are equivalent (even though there may be a difference in efficiency).

But sometimes, only one of the two operators is appropriate.
Exercise

Here is another formulation of concat:

```python
def concat[T](xs: List[T], ys: List[T]): List[T] =
    (xs foldRight ys) (_ :: _)  
```

Here, it isn’t possible to replace `foldRight` by `foldLeft`. Why?

0  The types would not work out
0  The resulting function would not terminate
0  The result would be reversed
Back to Reversing Lists

We now develop a function for reversing lists which has a linear cost.

The idea is to use the operation foldLeft:

```scala
def reverse[T](xs: List[T]): List[T] = (xs foldLeft z?)(op?)
```

All that remains is to replace the parts z? and op?.

Let's try to *compute* them from examples.
Deduction of Reverse (1)

To start computing z?, let’s consider reverse(Nil).

We know reverse(Nil) == Nil, so we can compute as follows:

Nil
Deduction of Reverse (1)

To start computing $z?$, let’s consider $\text{reverse}(\text{Nil})$.

We know $\text{reverse}(\text{Nil}) == \text{Nil}$, so we can compute as follows:

\[
\text{Nil}
\]

\[
= \text{reverse}(\text{Nil})
\]
Deduction of Reverse (1)

To start computing z?, let’s consider reverse(Nil).

We know reverse(Nil) == Nil, so we can compute as follows:

\[
\text{Nil} \\
= \quad \text{reverse(Nil)} \\
= \quad \text{(Nil foldLeft z?)(op)}
\]
Deduction of Reverse (1)

To start computing $z\uparrow$, let’s consider $\text{reverse}(\text{Nil})$.

We know $\text{reverse}(\text{Nil}) = \text{Nil}$, so we can compute as follows:

\[
\text{Nil} \\
\quad = \quad \text{reverse}(\text{Nil}) \\
\quad = \quad (\text{Nil} \ \text{foldLeft} \ z\uparrow)(\text{op}) \\
\quad = \quad z\uparrow
\]

Consequently, $z\uparrow = \text{List()}$
Deduction of Reverse (2)

We still need to compute $o_\rho?$. To do that let's plug in the next simplest list after $\text{Nil}$ into our equation for reverse:

$$\text{List}(x)$$
Deduction of Reverse (2)

We still need to compute \( op? \). To do that let’s plug in the next simplest list after \( \text{Nil} \) into our equation for \( \text{reverse} \):

\[
\text{List}(x) = \text{reverse}(\text{List}(x))
\]
Deduction of Reverse (2)

We still need to compute \( \text{op?} \). To do that let’s plug in the next simplest list after \( \text{Nil} \) into our equation for \( \text{reverse} \):

\[
\text{List}(x) = \text{reverse}(\text{List}(x)) = (\text{List}(x) \ \text{foldLeft} \ \text{Nil})(\text{op?})
\]
Deduction of Reverse (2)

We still need to compute \( \text{op?} \). To do that let’s plug in the next simplest list after \( \text{Nil} \) into our equation for \( \text{reverse} \):

\[
\text{List}(x)
\]

\[
= \text{reverse}(\text{List}(x))
\]

\[
= (\text{List}(x) \text{ foldLeft} \text{ Nil})(\text{op?})
\]

\[
= \text{op?}(\text{Nil}, x)
\]

Consequently, \( \text{op?}(\text{Nil}, x) = \text{List}(x) = x :: \text{List}() \).

This suggests to take for \( \text{op?} \) the operator \( :: \) but with its operands swapped.
Deduction of Reverse(3)

We thus arrive at the following implementation of reverse.

```scala
def reverse[a](xs: List[T]): List[T] =
  (xs foldLeft List[T]())((xs, x) => x :: xs)
```

Remark: the type parameter in `List[T]()` is necessary for type inference.

**Question**: What is the complexity of this implementation of reverse?
Exercise

Complete the following definitions of the basic functions map and length on lists, such that their implementation uses foldRight:

```python
def mapFun[T, U](xs: List[T], f: T => U): List[U] =
    (xs foldRight List[U]())( ??? )

def lengthFun[T](xs: List[T]): Int =
    (xs foldRight 0)( ??? )
```
Reasoning About Lists
Laws of Concat

Recall the concatenation operation ++ on lists.

We would like to verify that concatenation is associative, and that it admits the empty list Nil as neutral element to the left and to the right:

\[(xs \ ++ \ ys) \ ++ \ zs \ = \ xs \ ++ \ (ys \ ++ \ zs)\]
\[xs \ ++ \ Nil \ = \ xs\]
\[Nil \ ++ \ xs \ = \ xs\]

_Q: How can we prove properties like these?_
Laws of Concat

Recall the concatenation operation ++ on lists.

We would like to verify that concatenation is associative, and that it admits the empty list Nil as neutral element to the left and to the right:

\[(xs ++ ys) ++ zs = xs ++ (ys ++ zs)\]
\[xs ++ Nil = xs\]
\[Nil ++ xs = xs\]

Q: How can we prove properties like these?

A: By *structural induction* on lists.
Reminder: Natural Induction

Recall the principle of proof by *natural induction*:

To show a property $P(n)$ for all the integers $n \geq b$,

- Show that we have $P(b)$ (*base case*),
- for all integers $n \geq b$ show the *induction step*:

  *if one has $P(n)$, then one also has $P(n + 1)$.*
Example

Given:

```python
def factorial(n: Int): Int =
    if (n == 0) 1  // 1st clause
    else n * factorial(n-1)  // 2nd clause
```

Show that, for all \( n \geq 4 \)

\[
factorial(n) \geq power(2, n)  \quad 2^n
\]
Base Case

**Base case:** 4

This case is established by simple calculations:

\[ \text{factorial}(4) = 24 \geq 16 = \text{power}(2, 4) \]
Induction Step

**Induction step:** \( n+1 \)

We have for \( n \geq 4 \):

\[
\text{factorial}(n + 1) \geq 2^n
\]
Induction Step

**Induction step:** \( n+1 \)

We have for \( n \geq 4 \):

\[
\text{factorial}(n + 1) \\
\geq (n + 1) \times \text{factorial}(n) \quad // \text{by 2nd clause in factorial}
\]
Induction Step

**Induction step:** \( n + 1 \)

We have for \( n \geq 4 \):

\[
\text{factorial}(n + 1) \\
\geq (n + 1) \times \text{factorial}(n) \quad // \text{by 2nd clause in factorial}
\]

\[
> 2 \times \text{factorial}(n) \quad // \text{by calculating}
\]
**Induction Step**

**Induction step: n+1**

We have for $n \geq 4$:

\[
\text{factorial}(n + 1) \\
\geq (n + 1) \times \text{factorial}(n) \quad \text{// by 2nd clause in factorial} \\
> 2 \times \text{factorial}(n) \quad \text{// by calculating} \\
\geq 2 \times \text{power}(2, n) \quad \text{// by induction hypothesis}
\]
**Induction Step**

**Induction step: n+1**

We have for $n \geq 4$:

\[
\text{factorial}(n + 1)
\]

\[
\geq (n + 1) \times \text{factorial}(n) \quad // \text{by 2nd clause in factorial}
\]

\[
> 2 \times \text{factorial}(n) \quad // \text{by calculating}
\]

\[
\geq 2 \times \text{power}(2, n) \quad // \text{by induction hypothesis}
\]

\[
= \text{power}(2, n + 1) \quad // \text{by definition of power}
\]

\[
2 \times 2^n = 2^{n+1}
\]
Referential Transparency

Note that a proof can freely apply reduction steps as equalities to some part of a term.

That works because pure functional programs don’t have side effects; so that a term is equivalent to the term to which it reduces.

This principle is called *referential transparency*. 
Structural Induction

The principle of structural induction is analogous to natural induction:

To prove a property $P(xs)$ for all lists $xs$,

- show that $P(Nil)$ holds (base case),
- for a list $xs$ and some element $x$, show the induction step:
  
  \[ \text{if } P(xs) \text{ holds, then } P(x :: xs) \text{ also holds.} \]
Example

Let's show that, for lists \( \text{xs}, \text{ys}, \text{zs} \):

\[
(\text{xs} \; ++ \; \text{ys}) \; ++ \; \text{zs} \; = \; \text{xs} \; ++ \; (\text{ys} \; ++ \; \text{zs})
\]

To do this, use structural induction on \( \text{xs} \). From the previous implementation of \texttt{concat},

\[
\text{def} \ \text{concat}[T](\text{xs}: \text{List}[T], \text{ys}: \text{List}[T]) = \text{xs} \; \text{match} \ \{ \\
\text{case} \ \text{List}() \Rightarrow \text{ys} \\
\text{case} \ \text{x} :: \text{xs1} \Rightarrow \text{x} :: \text{concat}(\text{xs1}, \text{ys}) \\
\} 
\]

distill two \textit{defining clauses} of \( ++ \):

\[
\begin{align*}
\text{Nil} \; ++ \; \text{ys} & \; = \; \text{ys} & \text{// 1st clause} \\
(\text{x} :: \text{xs1}) \; ++ \; \text{ys} & \; = \; \text{x} :: (\text{xs1} \; ++ \; \text{ys}) & \text{// 2nd clause}
\end{align*}
\]
**Base Case**

**Base case:** Nil

For the left-hand side we have:

\[(\text{Nil } ++ \text{ ys}) ++ \text{ zs}\]
Base Case

**Base case:** Nil

For the left-hand side we have:

\[(\text{Nil} \ ++ \ ys) \ ++ \ zs\]

\[= \ ys \ ++ \ zs \quad \quad \quad \text{// by 1st clause of } ++\]
Base Case

**Base case:** \text{Nil}

For the left-hand side we have:

\[(\text{Nil} \ ++ \ ys) \ ++ \ zs\]

\[= \quad ys \ ++ \ zs \quad // \text{by 1st clause of ++}\]

For the right-hand side, we have:

\[\text{Nil} \ ++ \ (ys \ ++ \ zs)\]
Base Case

**Base case:** Nil

For the left-hand side we have:

\[(\text{Nil} \mathbin{++} \text{ys}) \mathbin{++} \text{zs}\]

\[= \text{ys} \mathbin{++} \text{zs} \quad \text{// by 1st clause of ++}\]

For the right-hand side, we have:

\[\text{Nil} \mathbin{++} (\text{ys} \mathbin{++} \text{zs})\]

\[= \text{ys} \mathbin{++} \text{zs} \quad \text{// by 1st clause of ++}\]

This case is therefore established.
Induction Step: LHS

**Induction step:** \( x :: xs \)

For the left-hand side, we have:

\[((x :: xs) ++ ys) ++ zs\]
Induction Step: LHS

**Induction step:** \( x :: xs \)

For the left-hand side, we have:

\[
((x :: xs) ++ ys) ++ zs
\]

\[
= (x :: (xs ++ ys)) ++ zs \quad \text{// by 2nd clause of ++}
\]
Induction Step: LHS

**Induction step:** \( x :: xs \)

For the left-hand side, we have:

\[
\begin{align*}
((x :: xs) ++ ys) ++ zs \\
= & (x :: (xs ++ ys)) ++ zs \quad // \text{by 2nd clause of ++} \\
= & x :: ((xs ++ ys) ++ zs) \quad // \text{by 2nd clause of ++}
\end{align*}
\]
Induction Step: LHS

**Induction step:** \( x :: xs \)

For the left-hand side, we have:

\[ ((x :: xs) ++ ys) ++ zs \]

\[ = (x :: (xs ++ ys)) ++ zs \]  // by 2nd clause of ++

\[ = x :: ((xs ++ ys) ++ zs) \]  // by 2nd clause of ++

\[ = x :: (xs ++ (ys ++ zs)) \]  // by induction hypothesis
Induction Step: RHS

For the right hand side we have:

\[(x :: xs) ++ (ys ++ zs)\]
Induction Step: RHS

For the right hand side we have:

\[(x :: xs) ++ (ys ++ zs)\]

= \[x :: (xs ++ (ys ++ zs))\] // by 2nd clause of ++

So this case (and with it, the property) is established.
Exercise

Show by induction on \( \text{xs} \) that \( \text{xs} ++ \text{Nil} = \text{xs} \).

How many equations do you need for the inductive step?

\[
\begin{align*}
\text{Base case: } & \quad \text{xs} = \text{Nil} \\
& \quad \text{Nil} ++ \text{Nil} \\
& \quad = \text{Nil} \quad \text{by 1st clause} \\
\text{Induction step: } & \quad \text{xs} \quad \text{xs} \\
& \quad (\text{x} :: \text{xs} ) ++ \text{Nil} \\
& \quad = \text{x} :: (\text{xs} ++ \text{Nil} ) \quad \text{by 2nd clause} \\
& \quad = \text{x} :: \text{xs} \quad \text{by eq. i.h.}
\end{align*}
\]
A Larger Equational Proof on Lists
A Law of Reverse

For a more difficult example, let’s consider the reverse function.

We pick its inefficient definition, because its more amenable to equational proofs:

\[
\begin{align*}
\text{Nil}.\text{reverse} &= \text{Nil} \quad \text{ // 1st clause} \\
(x :: xs).\text{reverse} &= xs.\text{reverse} ++ \text{List}(x) \quad \text{ // 2nd clause}
\end{align*}
\]

We’d like to prove the following proposition

\[
xs.\text{reverse}.\text{reverse} = xs
\]
Proof

By induction on \(xs\). The base case is easy:

\[
\begin{align*}
\text{Nil.reverse.reverse} &= \text{Nil.reverse} & \text{// by 1st clause of reverse} \\
&= \text{Nil} & \text{// by 1st clause of reverse}
\end{align*}
\]
Proof

By induction on \( xs \). The base case is easy:

\[
\begin{align*}
\text{Nil.reverse.reverse} &= \text{Nil.reverse} \quad \text{// by 1st clause of reverse} \\
&= \text{Nil} \quad \text{// by 1st clause of reverse}
\end{align*}
\]

For the induction step, let's try:

\[
\begin{align*}
(x :: xs).\text{reverse.reverse} &= (xs.\text{reverse} ++ \text{List}(x)).\text{reverse} \quad \text{// by 2nd clause of reverse}
\end{align*}
\]
Proof

By induction on \(xs\). The base case is easy:

\[
\begin{align*}
\text{Nil.reverse.reverse} &= \text{Nil.reverse} \quad \text{// by 1st clause of reverse} \\
&= \text{Nil} \quad \text{// by 1st clause of reverse}
\end{align*}
\]

For the induction step, let’s try:

\[
\begin{align*}
(x :: xs).\text{reverse.reverse} &= (xs.\text{reverse ++ List}(x)).\text{reverse} \quad \text{// by 2nd clause of reverse}
\end{align*}
\]

We can’t do anything more with this expression, therefore we turn to the right-hand side:

\[
\begin{align*}
x :: xs &= x :: xs.\text{reverse.reverse} \quad \text{// by induction hypothesis}
\end{align*}
\]

Both sides are simplified in different expressions.
To Do

We still need to show:

\[(\text{reverse}(\text{xs}) + \text{List}(x)).\text{reverse} = x :: \text{reverse}(\text{reverse}(\text{xs}))\]

Trying to prove it directly by induction doesn’t work.

We must instead try to generalize the equation. For any list \(y\),

\[(\text{reverse}(\text{reverse}(\text{ys}) + \text{List}(x))).\text{reverse} = x :: \text{reverse}(\text{reverse}(\text{ys}))\]

This equation can be proved by a second induction argument on \(y\).
Auxiliary Equation, Base Case

\[ y_s = \text{Nil} \]

\((\text{Nil} ++ \text{List}(x)).\text{reverse} \quad \text{// to show: } = \ x :: \text{Nil}.\text{reverse}\)
Auxiliary Equation, Base Case

\[(\text{Nil} \, \text{++} \, \text{List(x))}.\text{reverse} \quad \text{// to show: } = \quad x \, :: \, \text{Nil}.\text{reverse}\]

\[= \quad \text{List(x)}\text{.reverse} \quad \text{// by 1st clause of \text{++}}\]
Auxiliary Equation, Base Case

\[(\text{Nil} + \text{List}(x)).\text{reverse} \quad \text{// to show: } = \quad x :: \text{Nil}.\text{reverse}\]

\[= \quad \text{List}(x).\text{reverse} \quad \text{// by 1st clause of } + \]

\[= \quad (x :: \text{Nil}).\text{reverse} \quad \text{// by definition of List}\]
Auxiliary Equation, Base Case

\[
\text{Nil} \ ++ \ \text{List}(x).\text{reverse} \quad // \text{to show: } = \ x :: \text{Nil}.\text{reverse}
\]

\[
= \ \text{List}(x).\text{reverse} \quad // \text{by 1st clause of ++}
\]

\[
= \ (x :: \text{Nil}).\text{reverse} \quad // \text{by definition of List}
\]

\[
= \ \text{Nil} \ .\text{reverse} + \ \text{List}(x) \quad // \text{by 2nd clause of reverse}
\]

\[
= \ \text{Nil} \ ++ \ (x :: \text{Nil}) \quad // \text{by 2nd clause of reverse}
\]
Auxiliary Equation, Base Case

\[
(\text{Nil} ++ \text{List}(x)).\text{reverse} \quad \text{// to show: } = x :: \text{Nil}\.\text{reverse}
\]

\[= \text{List}(x).\text{reverse} \quad \text{// by 1st clause of ++}\]

\[= (x :: \text{Nil}).\text{reverse} \quad \text{// by definition of List}\]

\[= \text{Nil} ++ (x :: \text{Nil}) \quad \text{// by 2nd clause of reverse}\]

\[= x :: \text{Nil} \quad \text{// by 1st clause of ++}\]
Auxiliary Equation, Base Case

\[(\text{Nil} \ ++ \ \text{List}(x)).\text{reverse} \quad // \text{to show: } = \ x :: \text{Nil}.\text{reverse}\]

\[= \ \text{List}(x).\text{reverse} \quad // \text{by 1st clause of } ++\]

\[= \ (x :: \text{Nil}).\text{reverse} \quad // \text{by definition of } \text{List}\]

\[= \ \text{Nil} \ ++ \ (x :: \text{Nil}) \quad // \text{by 2nd clause of } \text{reverse}\]

\[= \ x :: \text{Nil} \quad // \text{by 1st clause of } ++\]

\[= \ x :: \text{Nil}.\text{reverse} \quad // \text{by 1st clause of } \text{reverse}\]
Auxiliary Equation, Inductive Step

\[(y :: ys) ++ \text{List}(x)).\text{reverse} \quad \text{// to show: } = \quad x :: (y :: ys).\text{reverse}\]
Auxiliary Equation, Inductive Step

\[(y :: ys) ++ \text{List}(x)).\text{reverse} \quad \text{// to show: } = x :: (y :: ys).\text{reverse}

= (y :: (ys ++ \text{List}(x))).\text{reverse} \quad \text{// by 2nd clause of ++}
Auxiliary Equation, Inductive Step

\[
((y :: ys) ++ \text{List}(x)).\text{reverse} \quad \text{\textit{// to show: } } x :: (y :: ys).\text{reverse}
\]

\[
= \quad (y :: (ys ++ \text{List}(x))).\text{reverse} \quad \text{\textit{// by 2nd clause of ++}}
\]

\[
= \quad (ys ++ \text{List}(x)).\text{reverse} ++ \text{List}(y) \quad \text{\textit{// by 2nd clause of reverse}}
\]
Auxiliary Equation, Inductive Step

\[(y :: ys) ++ \text{List}(x)).\text{reverse} \quad \text{// to show: } = x :: (y :: ys).\text{reverse}\]

\[= (y :: (ys ++ \text{List}(x))).\text{reverse} \quad \text{// by 2nd clause of ++}\]

\[= (ys ++ \text{List}(x)).\text{reverse} ++ \text{List}(y) \quad \text{// by 2nd clause of reverse}\]

\[= (x :: ys.\text{reverse}) ++ \text{List}(y) \quad \text{// by the induction hypothesis}\]
**Auxiliary Equation, Inductive Step**

\[
\begin{align*}
((y :: ys) ++ \text{List}(x)).\text{reverse} & \quad \text{// to show: } = x :: (y :: ys).\text{reverse} \\
= (y :: (ys ++ \text{List}(x))).\text{reverse} & \quad \text{// by 2nd clause of ++} \\
= (ys ++ \text{List}(x)).\text{reverse} ++ \text{List}(y) & \quad \text{// by 2nd clause of reverse} \\
= (x :: ys.\text{reverse}) ++ \text{List}(y) & \quad \text{// by the induction hypothesis} \\
= x :: (ys.\text{reverse} ++ \text{List}(y)) & \quad \text{// by 1st clause of ++}
\end{align*}
\]
Auxiliary Equation, Inductive Step

\[(y :: ys) ++ \text{List}(x)).reverse\]  \hspace{1cm} // to show: = \(x :: (y :: ys).reverse\)

\[= (y :: (ys ++ \text{List}(x))).reverse\]  \hspace{1cm} // by 2nd clause of ++

\[= (ys ++ \text{List}(x)).\text{reverse} ++ \text{List}(y)\]  \hspace{1cm} // by 2nd clause of reverse

\[= (x :: ys.\text{reverse}) ++ \text{List}(y)\]  \hspace{1cm} // by the induction hypothesis

\[= x :: (ys.\text{reverse} ++ \text{List}(y))\]  \hspace{1cm} // by 1st clause of ++

\[= x :: (y :: ys).\text{reverse}\]  \hspace{1cm} // by 2nd clause of reverse

This establishes the auxiliary equation, and with it the main proposition.
Exercise (Open-Ended, Harder)

Prove the following distribution law for map over concatenation.

For any lists `xs`, `ys`, function `f`:

\[(xs ++ ys) \text{map } f = (xs \text{ map } f) ++ (ys \text{ map } f)\]

You will need the clauses of `++` as well as the following clauses for `map`:

\[
\begin{align*}
\text{Nil map } f & = \text{Nil} \\
(x :: xs) \text{map } f & = f(x) :: (xs \text{ map } f)
\end{align*}
\]