Functional programming in Scala
A practical introduction

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Goals

At the end of this training session, you will:

- Be able to write complete Scala programs on your own
- Have a solid understanding of some of the most important concepts surrounding functional programming
- Be able to handle asynchronous communication on TCP sockets

What we will build

- A command-line Tic Tac Toe game that can be played both locally and on the local network
- We'll follow a *purely functional* style (no mutable state, strict encapsulation of side-effects)
- The game logic will be properly tested
- We'll use common Scala libraries

What is Scala?

- Scala was born in 2003 at the EPFL
- It's a programming language that mixes ideas from strongly typed functional programming langauges such as Haskell and object-oriented languages such as Java
- It runs mostly on the JVM but also in the browser through Scala.js and natively through Scala Native
- On the JVM, it is completely interoperable with Java and its massive ecosystem

Scala in the wild

- Scala is a general purpose language. Its main use cases are
  - Web development
  - Data engineering
  - Highly concurrent applications more generally
- It is the most widely used functional programming language today
- It is used in production by Twitter, Zalando, Netflix, Disney, Fortnite, Linkedin …

Installing your development environment

To productive in Scala you'll need two things :

- sbt, which you can install through Homebrew or Sdkman
  - `sdk install sbt`
- A Scala IDE : Either Intellij IDEA or a text editor with the *Metals* extension
  - To use *Metals* you'll also need a JDK 8 installed

Meet sbt

Sbt is the *de facto* build tool for Scala.

- It defines the metadata of your Scala project
- It fetches your external dependencies
- It leverages the Scala compiler to build your sources into .class files
- It runs your tests
- It allows you to define custom tasks and run them

It's time to open your first Scala project

Checkout the `exercises` branch and open the project

Hello, World!

- In Scala, the simplest Hello World is written as follows:

```
object Main extends App {
  println(“Hello world”)
}
```

- To run the project, we do

```
sbt run
```

Functions and expressions

Functions.scala

Expressions

- An expression is a combination of terms that can be reduced to a value, e.g.:
  - `45 + 3`
  - `"Foo Bar Baz"`
  - `"Hello" + " " + "World"`
- Named values are defined using the `val` keyword
  - `val a = 12`
- Named values are immutable
- Every value has a type

Typing

- All values have a type, including functions
- Types in Scala are organized into a hierarchy
  - Children of `AnyVal` : primitive value types such as `Boolean`, `Unit`, `String`, `Int`…
  - Children of `AnyRef` : object types such as `List`, `Option` and user-defined classes
  - Any is the root of all types

Type inference

- The type of a value can in many cases be inferred ("guessed") by the compiler, meaning:
  - You can define it explicitly:
    `val name: String = "George"`
  - Or let the compiler do its work:
    `val name = "George"

Complex expressions

- Scala is an expressive language : it doesn't make a distinction between expressions and statements that imperative languages make
- In other words : every construct in Scala yields a value, including control structure such as if/else
- Curly braces are use to delimitate complex expressions
- The effective value of a complex expression is the last line of the block

Functions

- Methods in Scala are defined with the `def` keyword like so:

```
def square(value: Int) = value * value
```

- The return type of a method can be defined explicitly:

```
def square(value: Int): Int = value * value
```

Methods and *functions* are slightly different things in Scala, but for now we'll use them interchangeably.

Different evaluation strategies

Evaluation is the process by which *expressions* are reduced to *values*

Scala supports different evaluation strategies for named values, methods, and methods arguments.

`val` vs `def`

- `val`s are evaluated the moment they are defined
- `def`s are evaluated every time they are accessed
- `lazy val`s are evaluated when they are first accessed and then memoized for later use

`val` vs `def`, an example

- This would crash immediately:

```
val a: String = throw new Exception(“BOOM”)
println(“Hello”)
println(a)
```

- This would print "Hello" then crash:

```
def a: String = throw new Exception(“BOOM”)
println(“Hello”)
println(a)
```

Call-by-name, call-by-value

- By default, method arguments are evaluated before the body of the function. We call it *call-by-value*
- *Call-by-name* arguments are evaluated only when accessed within the body of the function, not before
  - It means we can partially evaluate the body of a function without evaluating its arguments
  - They are defined with a fat arrow like so

    ```
    def greet(name: => String) = println("Hello " + name)
    ```


What is the billion dollar mistake? 💰

I call it my billion-dollar mistake. It was the invention of the null reference in 1965. [...] This has led to innumerable errors, vulnerabilities, and system crashes, which have probably caused a billion dollars of pain and damage in the last forty years.

– Sir Tony Hoare

Options

- Options are designed to avoid the infamous `NullPointerException`
- Options can be one of two things : Some or None
- They make the code more explicit, remove the need to search in documentation for possible nulls and prevents runtime exceptions in many cases
- They are explicitly checked by the compiler

Building options

- To build an empty option, use the None constructor:

```
val batmanFather: Option[String] = None
```

- To build an option from a value, use the Some constructor:

```
val batgirlFather: Option[String] = Some("Jim Gordon")
```

Working with options

- `map`
  - If you have `Option[A]` and `A => B`, then you get `Option[B]`
- `flatMap`
  - If you have `Option[A]` and `A => Option[B]`, then you get `Option[B]`
- `flatten`
  - If you have `Option[Option[A]]`, then you get `Option[A]`
- `getOrElse`
- `isEmpty`

Case classes

Case classes are used to create immutable values out of multiple named fields. Think of them as immutable structs.

```
case class Position(x: Int, y: Int)
```

One the case class is defined, instances can be created like so :

```
val playerPosition = Position(18, 4)
```

- Case classes fields are public:

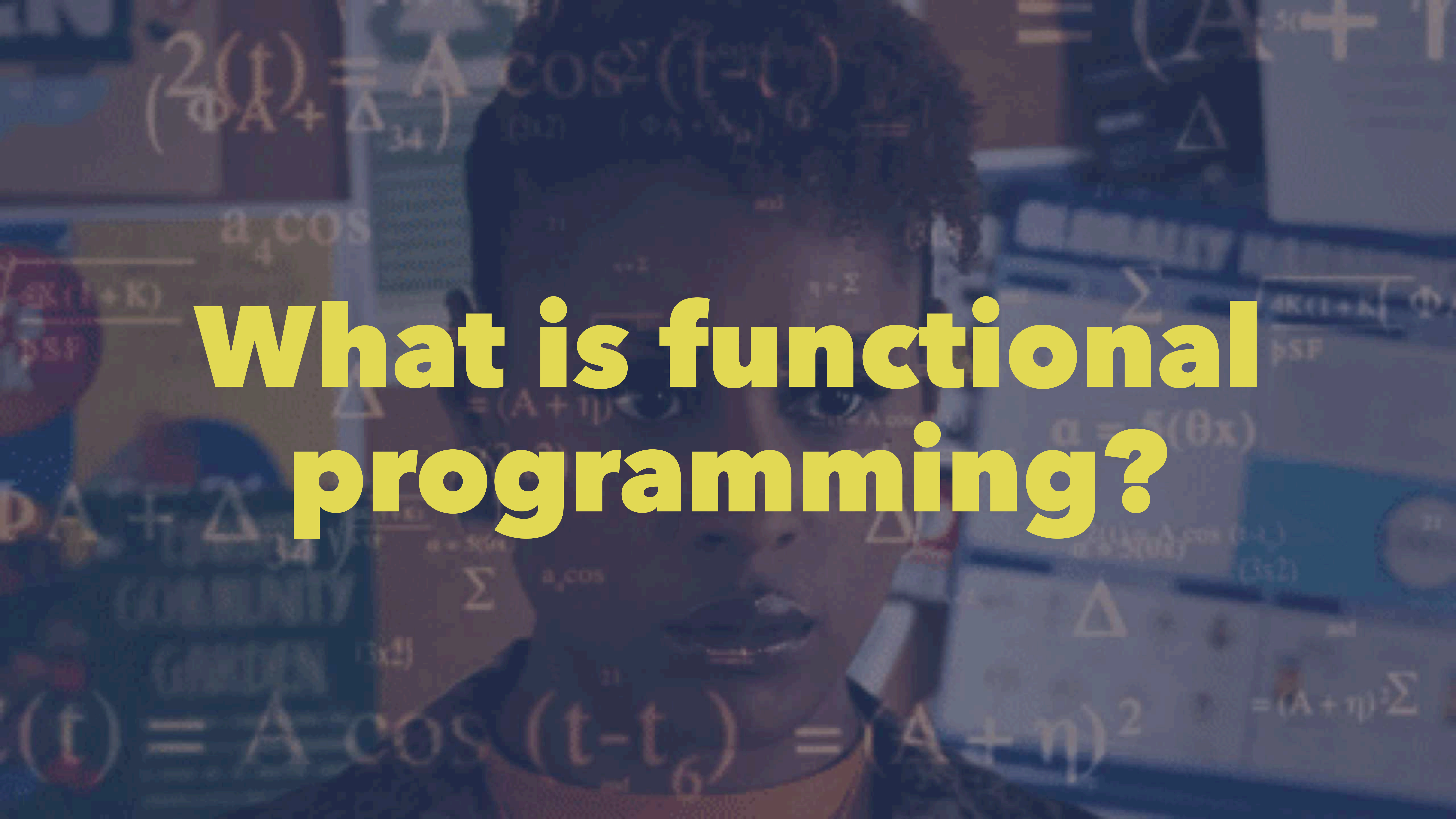
```
println(playerPosition.x)
```

- Case classes can be copied

```
val nextPosition =
  playerPosition.copy(y = playerPosition.y + 1)
```

- They can be structurally compared

```
playerPosition == Position(18, 4) // => true
```

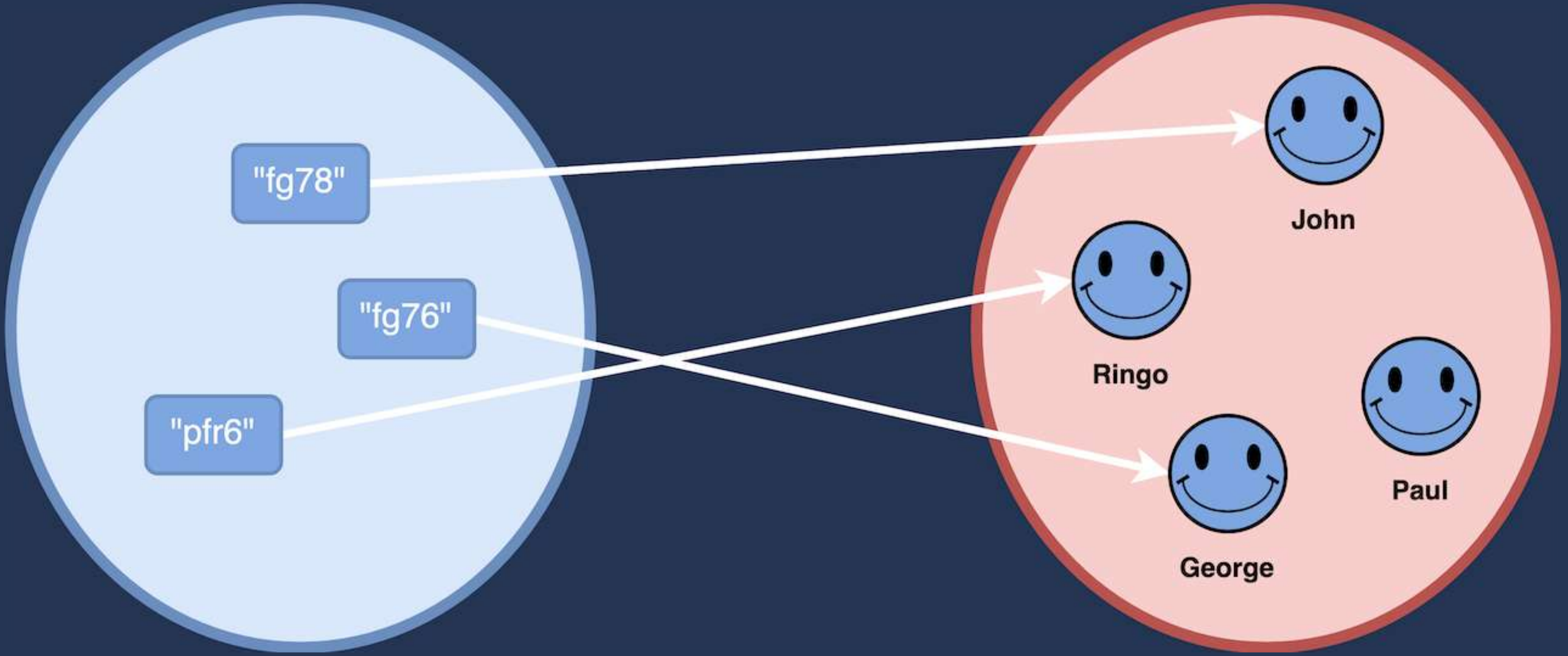

What is functional programming?

Functional programming is a *programming paradigm* that treats computation as the *evaluation* of *pure functions*.

(Or, as we call them, functions)

What are functions?

- In procedural programming, the term *function* is often wrongfully used to mean *procedure*, a way of binding a set of instructions to name and some arguments
- In FP, we treat functions as mere arrows between values of two sets
- Functions are first-class citizens: they can be passed around as arguments, returned from other functions and composed


"fg78"
"fg76"
"pfr6"
John
Ringo
Paul
George

A bit of history : Lambda-calculus

Lambda-calculus is the foundation of all functional languages. It can be described as the *most simple, universal programming language*

Lambda-calculus doest not care about the computer. It abstracts away the computation steps under a purely expressive form, much like FP languages

Everything that can be computed by a Turing machine can be expressed in Lambda-calculus form[1].

---

[1] Look at the Church-Turing thesis

The syntax of λ-calculus

$$
\begin{array}{llr}
\mathit{expression} := & \mid \mathit{variable} & \text{(identifier)} \\
& \mid \mathit{expression}\ \mathit{expression} & \text{(application)} \\
& \mid \lambda \mathit{variable}.\ \mathit{expression} & \text{(abtraction)} \\
& \mid (\mathit{expression}) & \text{(grouping)}
\end{array}
$$

λ-calculus is tiny symbol manipulation framework.
It is entirely *expression-oriented*.

How does it work?

Consider this function:

$$f(x) = x^2$$

We can implement it in Scala like so:

```scala
def f(x: Int) = x * x
```

And expressed in λ-calculus a:

$$\lambda x.\, x^2$$

Abstractions in λ-calculus don't need to be named.

Lambda calculus introduced anonymous functions as values for the first time. I

In some programming languages, anonymous functions are still called lambda expressions today.

Abstractions in λ-calculus are mappings from one expression to another. They are *unary* (only one argument)

How would one write functions of two arguments in λ-calculus?

$$f(x, y) = xy$$

would become

$$\lambda x.\,\lambda y.\,xy$$

A function of two arguments *x* and *y* can be expressed as a function of a single argument *x*, itself returning a function of a single argument *y*. This is called *currying*.

Most importantly, λ-calculus introduced *higher-order functions* : functions that can take return other functions or take them as argument. `map`, `filter`, `reduce` ... you already know some of them!

Some definitions

- α-conversion : λx.x = λy.y (any variable can be renamed given it isn’t free)
- B-reduction : lambda-terms may be reduced to a simpler form through a succession of conversions, until we reach a form we cannot further simplify (β-normal form)
- This is the foundation of program *evaluation*

⚠ Some terms cannot be reduced (halting problem)

Why do we care about Lambda-Calculus?

A story of abstractions

Turing machines are hypothetical devices that perform state-based computation on an infinite strip. Turing machines work *imperatively*.

On the other hand, Lambda-calculus is a purely abstract symbol rewriting framework. It's *expressive*.

Modern computers are built on the foundation of Turing machines.

One can usually categorize a programming language based on the level of abstraction it provides over the computer

- Modern computers (Turing-machine-inspired)
- Machine code
- Assembly languages
- Higher-level machine-centric languages (C),
- Higher-level imperative and object-oriented languages (C#, Java ...)
- Functional languages (LISP, Ocaml ...)
- Purely functional languages (Haskell, Idris ...)

Thinking beyond the machine

- Computers work imperatively. They execute instructions that change their state over time
- Functional programming languages operate on a higher level of abstraction : They don't care about the computer, they care very little for state, let alone time ... and it's great!
- Modern computers are more than capable of supporting these abstractions. Functional languages open up more possibilities for software engineering and developer productivity

Programming concepts that come from Lambda-calculus

- Lazy evaluation
- Lexical scoping and shadowing
- **Referential transparency**
- **Recursion**
- **Higher-order functions**
- Currying
- Closures

…

Defining pure functions

How to identify *pure functions* in an impure language such as Scala?

Referential transparency

- Referential transparency is one of the two key properties of pure functions
- A functions is *referentially transparent* if you can substitute its *application* for its return value without changing the program's behavior

Example

```
def square(a: Int) = a * a
val result = square(6)
```

And

```
val result = 36
```

are equivalent programs, which means that square is referentially transparent

We can also say it has no *side effects*.

Example

```
def square(a: Int) = {
  println("Hi!")
  a * a
}
val result = square(6)
```

is not equivalent to

```
val result = 36
```

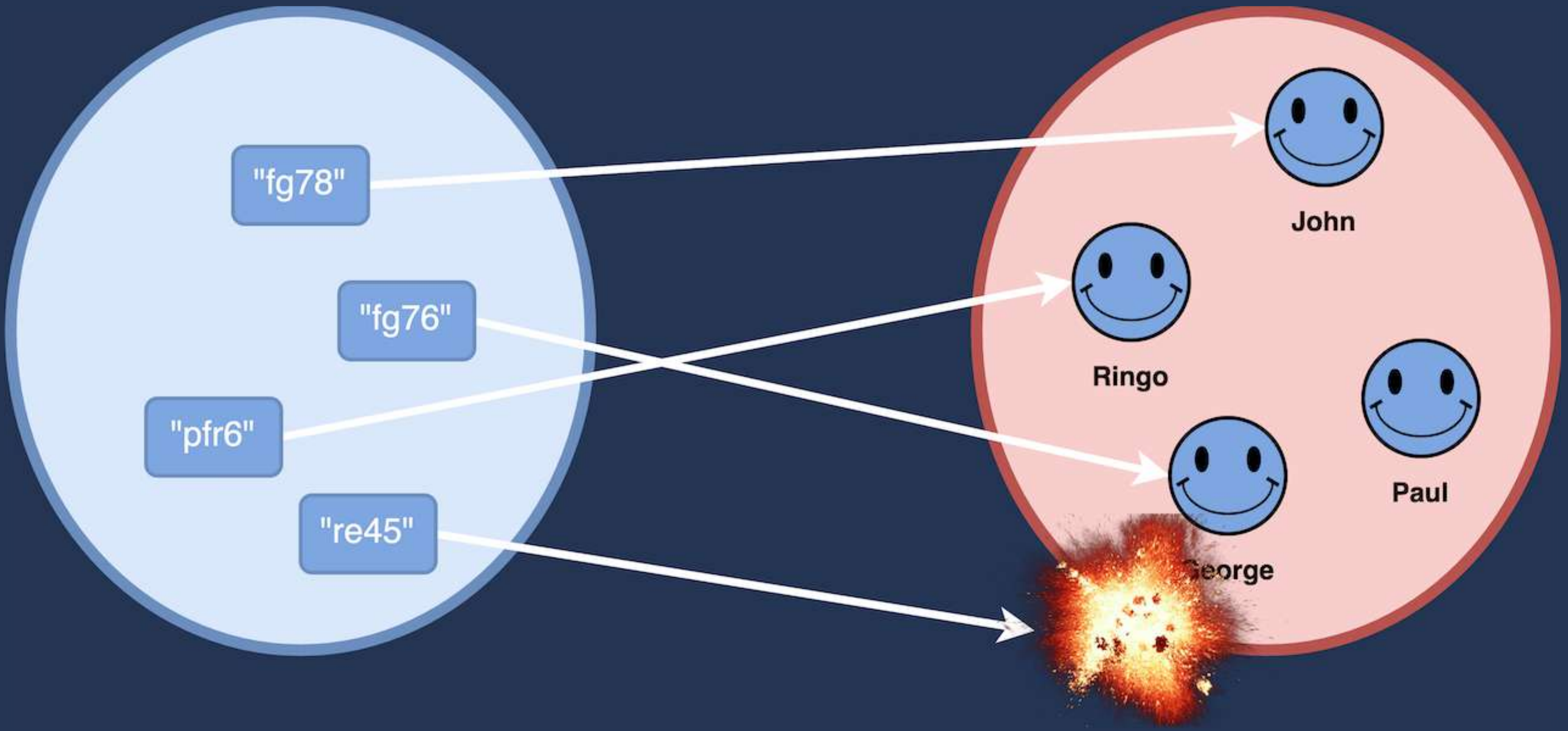
While the value of `result` is the same in both cases, the runtime behaviors of the two programs is not the same.

Why should I care? Benefits of referential transparency

- Referentially transparent functions are trivial to test
- They are easy to execute in parallel
- Predictability! You know exactly how your program will run
- Memoization : if a function is guaranteed to return always the same result for some input, it can be memoized (cached) without risks

Totality

- Totality is the other key characteristic of pure functions
- A function `A => B` must absolutely yield a value of B for *any* value A
- Partial functions (functions that operate on a subset of A) are unsafe
- As a rule of thumb, *if it compiles, it must always work*
    - Exceptions break totality and should be avoided im most cases


"fg78"
"fg76"
"pfr6"
"re45"
John
Ringo
Paul
George

A short definition for pure functions

A function is pure if, and only if, it is both total and referentially transparent

Spotting impure functions in the wild

Is this function pure?

```
def max(a: Int, b: Int) =
    if (b >= a) b
  else a
```

Remember to ask yourself:

- Does it have side effects?
- Does it return a value for every possible argument?
- Is the return value defined by the arguments only?

What about this one?

```
var counter = 0
def getName: String = {
    counter += 1
    ”Jessica”
}
```

And this one?

```
def mean(numbers: List[Int]): Float = {
  println(“Computing mean”)
  numbers.sum.toFloat / numbers.length
}
```

This one is trickier

```
def mean(numbers: List[Int]): Float = {
  numbers.sum.toFloat / numbers.length
}
```

- Sometimes, identifying an impure function isn't as straightforward.
- How could we make it safer?

What bout his last one?

```
def getSecret(user: User): Secret =
  if (user.isAdmin()) {
        secret
    }
  else {
      throw new Exception(“You don’t have access”)
  }
```

From now on, we will only use pure functions

Wait, how am I supposed to *do* stuff if everything is forbidden?

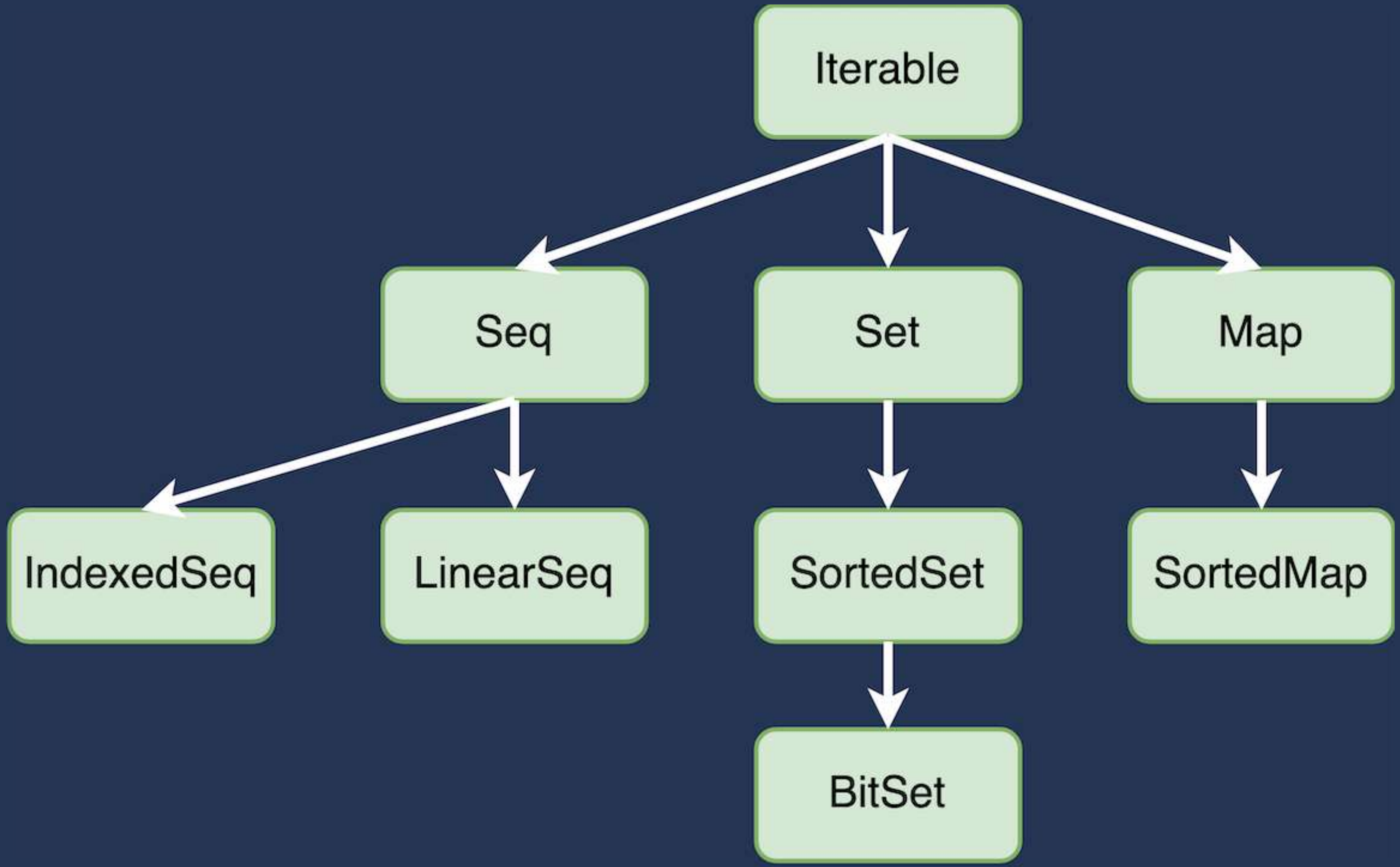
Functional programmers have strategies

- Persistent Data Structures
- Algebraic Data Types
- Pattern matching
- IO monads

Scala collections

Collections.scala

- Scala provides several collections that can model lists of elements, ranges, sets of unique elements, maps ...
- Scala's collections are persistent by default, which means you can't modify them in place
- Scala's collections are organized into a hierarchy. Different concrete data structures can be manipulated through common interfaces


Iterable
Seq
Set
Map
IndexedSeq
LinearSeq
SortedSet
SortedMap
BitSet

Which do I need?

- Is your code's performance critical?
  - Yes: check performance characteristics of all data structures in the documentation
  - No:
  - If you need a list of possibly duplicated elements, use `List`
  - If you need a list of unique elements, use `Set`
  - If you need to identify elements using a key, use a `Map`
  - If you're writing a library, it's a good idea to abstract over the collection type using an interface

Working with Lists

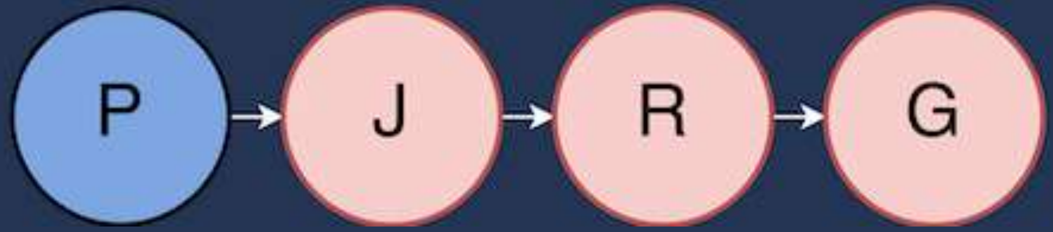
- `map`: If you have `List[A]` and `A => B`, you get `List[B]`
- `flatMap`: If you have `List[A]` and `A => List[B]`, you get `List[B]`
- `filter`: If you have `List[A]` and `A => Boolean`, you get a subset of your original list
- `flatten`: If you have `List[List[A]]`, then you get `List[A]`
- `headOption` : A safe way of retrieving the first element
- `lift` : A safe way of retrieving any element
- sum (on a numerical list only)

Structural sharing

```scala
val a = List[User](john, ringo, george)
```


```scala
val paul = User("Paul", "McCartney")
```


```scala
val fabFour = paul :: a
```



A couple things to remember

- Lists are good at prepending (constant time) but no so much at appending (linear time)
- Persistent data structures are space efficient : since every value is reputed immutable, they can be shared by reference across multiple structures

Building new types

Domain modeling using Algebraic Data Types

ADT.scala

Product Types

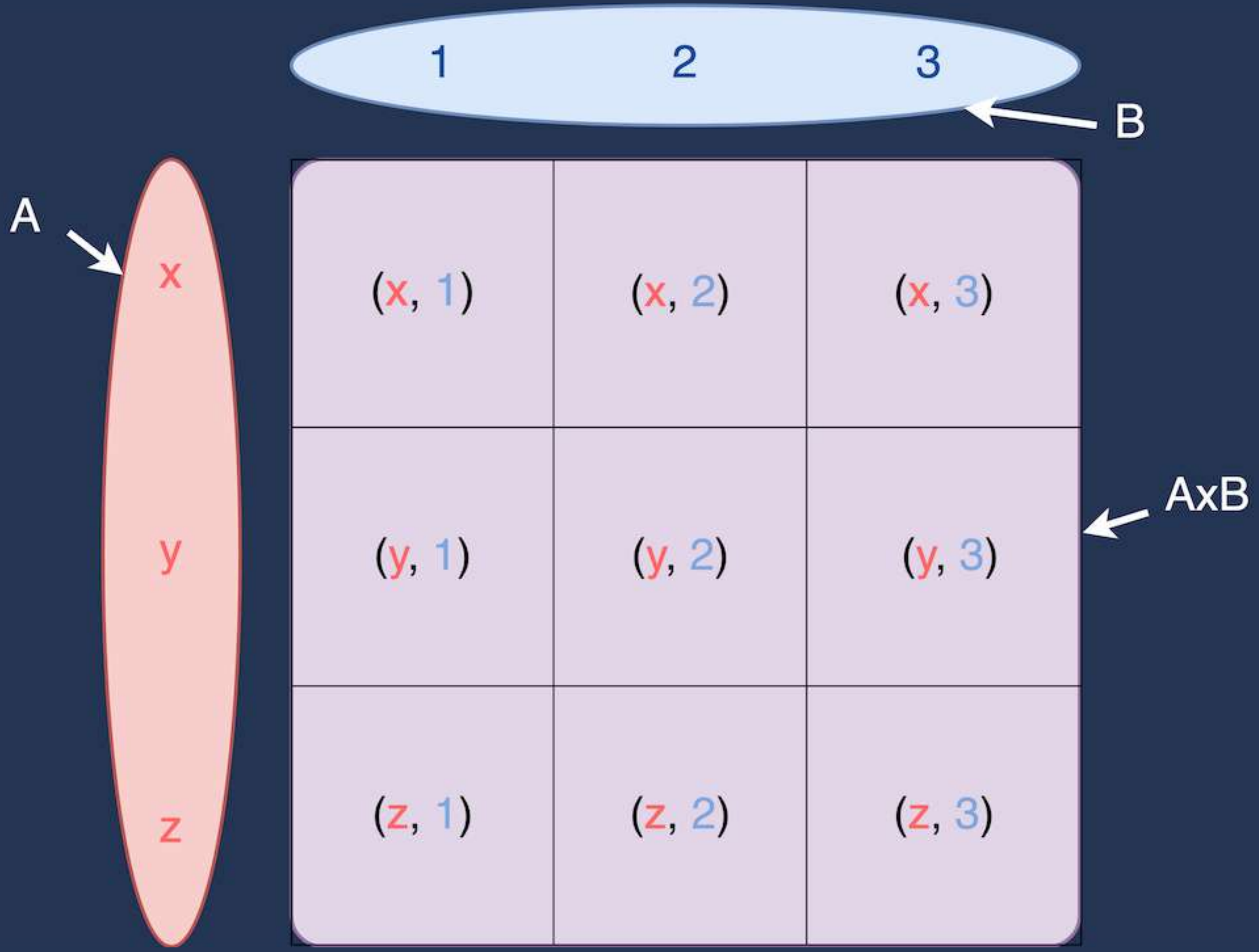
Tuples and case classes can encapsulate the values of several types into one single value :

```
val cathy: (String, Int, Role) =
  ("Cathy", 38, Role.Manager)
```

The cartesian product

Product types are called that way because they can be seen as the cartesian product of several sets :

- Types, such as `Int` and `Boolean` are sets
- A tuple `(Int, Boolean)` can match any `Int` with any `Boolean`
- The total number of distinct values this tuple can have will be
  - The number of values `Int` can take
  - Multiplied by the number of values `Boolean` can take (2)


1
2
3
B
A
x
y
z
AxB
(x, 1)
(x, 2)
(x, 3)
(y, 1)
(y, 2)
(y, 3)
(z, 1)
(z, 2)
(z, 3)

Case classes are product types

Case classes can be seen as tuples with labels

```scala
case class User(
  firstName: String,
  lastName: String
)
```

can be expressed as

```scala
type User = (String, String)
```

However, tuples are ambiguous. Which is the `firstName` in that case ?
Keep tuples for very simple values and internal use only.

Sum types

- Sum types can hold values coming from exactly one of several fixed types
- They are sometimes called *variants*, *disjoint unions* or *discriminated unions*
- They can be recursive

Common subtypes you might already know

- `Option[A]`: One of `Some[A]` or `None`
- `Either[L, R]`: One of `Left[L]` or `Right[R]`
- `List[A]` : One of `Nil` or `::(A, List[A])`

Lists are recursive sum types!

The `List` structure, a linked list, is sum type of two *terms* :

```
sealed trait List[+A]
// A Nil term representing an empty list
case object Nil extends List[Nothing]

// A :: term representing an element
//and a pointer to the rest of the list
case class ::[A](head: A, tail: List[A]) extends List[A]
```

This is how we would build lists using that encoding:

```
Nil                               // An empty List
::(1, Nil)                        // A List of one element
::(1, ::(2, Nil))                 // A list of two elements
::(1, ::(2, ::(3, Nil)))          // And so on ...
```

Luckily, Scala provides some syntactic sugar for us:

```
val nb = 1 :: 2 :: 3 :: 4 :: Nil
```

Algebraic Data Types are the main tool for data modeling in Scala

A sum type for our Tic Tac Toe

We can model a *move* in the Tic Tac Toe game using a sum type

```
sealed trait Move
case object X extends Move
case object O extends Move
```

NB: Case objects are singleton objects. You can see them as sets of exactly one element

Pattern matching

PatternMatching.scala

Pattern matching

- Pattern matching is a pure mapping between a *pattern of expressions* on the left side, and an expression on the right side.
- It can deconstruct case classes and match their individual fields
- It can have arbitrary guards (if statements)
- Exhaustivity can be enforced at compile tile

How does that help us?

- Persistent data structures give us
  - Complex data transformations without the need for shared mutable state and its risk
- ADTs coupled with pattern matching give us
  - Powerful data modeling
  - Total functions
  - Safety from the most common runtime exceptions

General strategies for building total functions

In order to make a function total, you generally have two possible approaches:

- Restrict the input of the function (or *domain*) so that your function can't be called with input you can't deal with
- Expand the output of the function (or *codomain*) so that you can produce a result in every case

Expanding the output

Expanding the output generally means turning your return type from A to `Option[A]`, `Either[Error, A]` or another structure.

Instead of returning values from the smaller set A, you operate on a bigger set, the set of *A + all the possible edge-cases*.

You essentially force your caller to deal with the edge cases somewhere outside.

Restricting the input

You can also change the types of your arguments to accept a smaller set of values. This way, you ensure your function cannot be called with values you can't handle.

For instance, instead of accepting any `String`, you can use a sum type as your input type.

Summing up

Scala let's you perform the most common computing tasks without relying on side-effects.

Writing total functions means you don't need Exceptions to deal with edge-cases, hence no crashes at runtime.

Writing referentially transparent functions means you can refactor your code safely. It also means *no lies* : your types should always tell the truth


Friends don't lie.

But still,
what if I *need* that side-effect?

Introducing IO monads

SideEffects.scala

IO monads

- The `IO` monad comes from Haskell, a purely functional language where side effects are strictly forbidden
- An `IO[A]` represents a *lazy* computation that has some side effects and eventually yields a value of type `A`
- IOs can be transformed with `map` and composed with `flatMap` just like `Option` and `List`

Why do we care?

- The #1 reason: _*functions signatures are contract_. When you perform a side-effect without signaling it, you break the contract. (aka. _Friends don't lie_)
- `IO`s reduce the need for further documentation and the risk of forgetting to catch an exception
- They are referentially transparent, so you can define them in any order
- In a FP team, other functions should be assumed to be pure

Daniel Brice
@fried_brice

Show me your implementations and conceal your types, and I shall continue to be mystified. Show me your types, and I won’t usually need your implementations; they'll be obvious.

Traduire le Tweet

12:29 AM · 3 sept. 2019 · Twitter Web App

4 Retweets **31** J'aime

Other benefits from `IO`

- They can raise and recover exceptions
- They can easily be executed in parallel
- They form a large ecosystem that makes concurrent applications easier
  - Concurrency constructs from Cats Effect such as `Ref`, `MVar`…
  - Reactive streams with fs2
  - Purely functional database access with Doobie
  - Highly performant HTTP APIs with Http4s

  …

IO is a Monad. What is that?

A Monad `M[A]` is an immutable data structure used to describe the computation of one or more values of type `A`

- Values of type `A` can be turned into *monadic values* `M[A]`
- Monads can chain subsequent computations (i.e solve big problems out of smaller problems)
- They describe some *functional effect*: `Option` describes optionality, `Either` describes failure ...

Monads `M[A]` have essentially four elements:

- A `pure` method that wraps `A` into the type constructor `M[A]`
- A `map` method of the form `M[A] => (A => B) => M[B]`, which is the definition of a *functor*
- A `flatMap` method of the form `M[A] => (A => M[B]) => M[B]`
- Laws called *identities*

You already know how to use them

	pure	the functor	flatMap
M[A]	A => M[A]	M[A] => (A => B) => `M[B]	M[A] => (A => M[B]) => M[B]
Option[String]	Some("Hello")	Some("Hello") .map(_.toUpperCase) // Some("HELLO")	Some("Hello") .flatMap(_ => Some("World")) // Some("World")
List[String]	List("foo", "bar")	List("Foo", "Bar") .map(_.length) // List(3, 3)	List("ab", "cd") .flatMap(_.toList) // List('a', 'b', 'c', 'd')
Either[A, B] IO[A] Reader State ...	They all have the same shape		

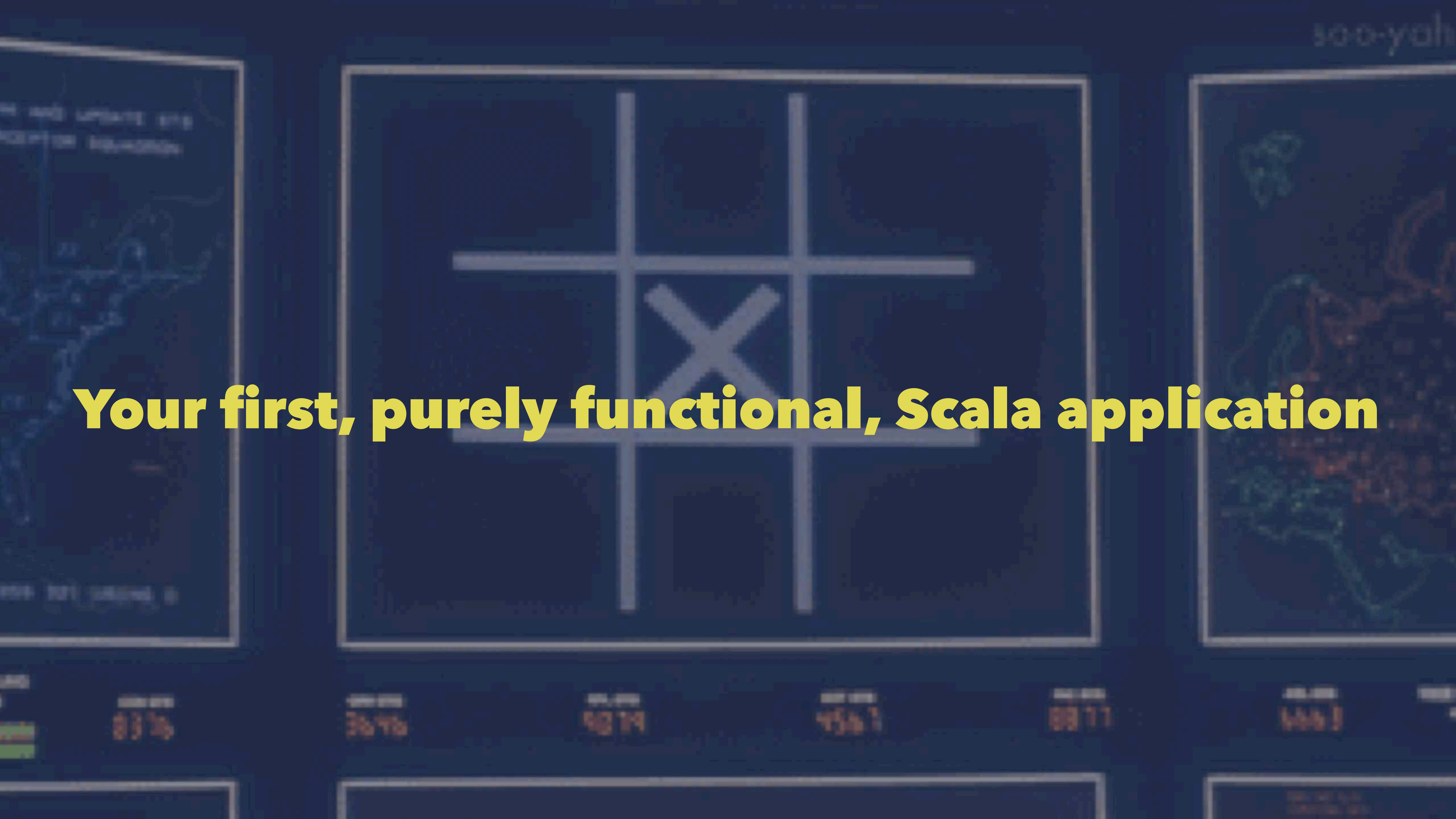
Why monads?

- Monads are used to encode *functional effects* such as optionality or failure, in a way that **makes the effect appear in the signature**
(Remember, signatures must always tell the truth)
- The essence of a monad is *composition*, the ability to chain dependent computations
    - All monads can be used in a *for-comprehension*

Because they can encode all sorts of effects using the same signatures, monads can encode features that would otherwise require specific syntax at the language level.

Diogo (f a) Castro
@dfacastro

Welcome to Haskell, we got list comprehensions (>>=), optional chaining (>>=) , async/await (>>=), if err != nil (>>=), function composition(>>=), mutable state (>>=),



Your first, purely functional, Scala application

Building a functional Tic Tac Toe

Let's use what we've learn to build a command-line Tic Tac Toe that can be played on the network!

- Tic Tac Toe can be modeled as a *finite state machine*
- Possible states = a `State` ADT
- State transitions = pure function of `State => State`
- The board will be a matrix of *moves*, modeled as a two-dimensional `List`
- The user interface and server can be separated from the core logic using higher-order functions and IO monads