Scala Days

Polymorphic Function Types in Scala 3

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Arteris IP / Scala Center

About me

- 2016-2022: PhD at **EPFL**
- 2022-2023: **Scala Center**
- Since last week: **Arteris IP** + 20% time with the **Scala Center**
  - Arteris develops *interconnects* for System-on-Chips.
  - Hiring Scala engineers (in Nice, France) to research Domain Specific Languages for hardware design!

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What is a method?

A **method** is a member of a scope (class, object, ...) declared using def:

```
def conv(x: Int): String = x.toString
```

What is a function?

A **value** is an instance of a type. The type determines how we can use the value.

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In particular, a **function value** is an instance of a **function type**, for example:

```
val f: Int => String = ...
```

What is a function?

A **value** is an instance of a type. The type determines how we can use the value.

In particular, a **function value** is an instance of a **function type**, for example:

```
val f: Int => String = ...
```

The type `Int => String` is a short-hand for `scala.Function1[Int, String]`:

```
trait Function1[-T, +R]:
  def apply(x: T): R
```

What is a function?

A **value** is an instance of a type. The type determines how we can use the value.

In particular, a **function value** is an instance of a **function type**, for example:

```
val f: Int => String = ...
```

The type `Int => String` is a short-hand for `scala.Function1[Int, String]`:

```
trait Function1[-T, +R]:
  def apply(x: T): R
```

If `f` is a value, then `f(1)` expands to `f.apply(1)`

What is a lambda?

A **lambda** is a convenient way to create an instance of a function type:

```
(x: Int) => x + 1
```

is equivalent to:

```
new Function1[Int, Int]:
  def apply(x: Int): Int = x + 1
```

What is a lambda?

A **lambda** is a convenient way to create an instance of a function type:

```
(x: Int) => x + 1
```

is equivalent to:

```
new Function1[Int, Int]:
  def apply(x: Int): Int = x + 1
```

... which itself expands to:

```
class anon() extends Function1[Int, Int]:
  def apply(x: Int): Int = x + 1
new anon()
```

Method references

A reference to a method is not a value, but it can be automatically converted into one:

```
def inc(x: Int) = x + 1
List(1,2,3).map(inc)
```

Method references

A reference to a method is not a value, but it can be automatically converted into one:

```scala
def inc(x: Int) = x + 1
List(1,2,3).map(x => inc(x))
```

Method references

A reference to a method is not a value, but it can be automatically converted into one:

```
def inc(x: Int) = x + 1
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This process is called eta-expansion.

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The missing square

	Method	**Function**

	`def m(x: Int): List[Int] =`
	`  List(x)`
		`val f: Int => List[Int] =`
		`  x => List(x)`

The missing square

	Method	**Function**

Monomorphic	`def m(x: Int): List[Int] =`
	`  List(x)`
		`val f: Int => List[Int] =`
		`  x => List(x)`

The missing square

	Method	**Function**

Monomorphic	`def m(x: Int): List[Int] =`
	`List(x)`
		`val f: Int => List[Int] =`
		`x => List(x)`

Polymorphic	`def m[T](x: T): List[T] =`
	`List(x)`
		❓

Inventing polymorphic functions

```
def m[T](x: T): List[T] = List(x)
```

```
val f: ... = ... List(x) ...
```

Inventing polymorphic functions

```scala
def m[T](x: T): List[T] = List(x)
```

```scala
val f: ... = ... List(x) ...
```

Inventing polymorphic functions

```scala
def m[T](x: T): List[T] = List(x)
```

```scala
val f: ... = ... List(x) ...
```

The type of `f` needs to have a polymorphic method `apply` as a member so we can call:

```scala
f[Int](1) == List(1)
```

Inventing polymorphic functions

```
def m[T](x: T): List[T] = List(x)
```

```
val f: ... = ... List(x) ...
```

The type of f needs to have a polymorphic method apply as a member so we can call:

```
f.apply[Int](1) == List(1)
```

Manual encoding

```
trait MkList:
  def apply[T](x: T): List[T]

val f: MkList = new MkList:
  def apply[T](x: T): List[T] = List(x)
```

This works, but it requires creating a new trait each time we need a polymorphic function with different parameters.

What if we could use a lambda?

```
def m[T](x: T): List[T] = List[T](x)

val f: T => List[T] =
   (x: T) => List[T](x)
```

What if we could use a lambda?

```
def m[T](x: T): List[T] = List[T](x)

val f: T => List[T] =
  (x: T) => List[T](x)
```

What if we could use a lambda?

```
def m[T](x: T): List[T] = List[T](x)

val f: [T] => T => List[T] =
  [T] => (x: T) => List[T](x)
```

What if we could use a lambda?

```
def m[T](x: T): List[T] = List[T](x)

val f: [T] => T => List[T] =
  [T] => (x: T) => List[T](x)
```

`f` is a **polymorphic function value** with a **polymorphic function type**!

Example usecase

In Scala 3, all tuples extend `scala.Tuple` which defines:

```scala
def map[F[_]](f: [T] => T => F[T]): Map[this.type, F]
```

Example usecase

In Scala 3, all tuples extend `scala.Tuple` which defines:

```
def map[F[_]](f: [T] => T => F[T]): Map[this.type, F]
```

```
val x: (Int, String) = (1, "")
val y: (List[Int], List[String]) =
  x.map([T] => (x: T) => List(x))
```

The Function Zoo

	From Term	From Type
To Term	`val f: Int => Int`	`val f: [T] => T => List[T]`

The Function Zoo

	From Term	**From Type**
To Term	`val f: Int => Int`	`val f: [T] => T => List[T]`
To Type		`type F[T] = List[T]`

The Function Zoo

	From Term	**From Type**
To Term	`val f: Int => Int`	`val f: [T] => T => List[T]`

To Type		`type F[T] = List[T]`
		`type F = [T] =>> List[T]`

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How do we implement this?

Source code	Desugared form
`Int => List[Int]`	`Function1[Int, List[Int]]`
`[T] => T => List[T]`	🤔

First attempt

```
val f: [T] => T => List[T] =
  [T] => (x: T) => List[T](x)
```

First attempt

```scala
val f: [T] => T => List[T] =
  [T] => (x: T) => List[T](x)
```

```scala
trait PolyFunction1[-Param[_], +Result[_]]:
  def apply[T](x: Param[T]): Result[T]

val f = new PolyFunction1[[X] =>> X, List]:
  def apply[T](x: T): List[T] = List[T](x)
```

First attempt

```
val f: [T] => T => List[T] =
  [T] => (x: T) => List[T](x)
```

```
trait PolyFunction1[-Param[_], +Result[_]]:
  def apply[T](x: Param[T]): Result[T]

val f = new PolyFunction1[[X] =>> X, List]:
  def apply[T](x: T): List[T] = List[T](x)
```

What if we want to **bound** T?

First attempt

```
val f: [T] => T => List[T] =
  [T] => (x: T) => List[T](x)
```

```
trait PolyFunction1[-Param[_], +Result[_]]:
  def apply[T](x: Param[T]): Result[T]

val f = new PolyFunction1[[X] =>> X, List]:
  def apply[T](x: T): List[T] = List[T](x)
```

What if we want to **bound** T? E.g. `[T <: AnyRef] => T => List[T]`

Getting complicated!

```scala
trait PolyFunction1[
    -Bound[_],
    -Param[x <: Bound[x]],
    +Result[x <: Bound[x]]
]:
  def apply[T <: Bound[T]](x: Param[T]): Result[T]
```

Getting complicated!

```
trait PolyFunction1[
    -Bound[_],
    -Param[x <: Bound[x]],
    +Result[x <: Bound[x]]
]:
  def apply[T <: Bound[T]](x: Param[T]): Result[T]
```

What about multiple type parameters? Multiple term parameters?

Taking a step back

Can we use **structural typing** to avoid having to define all these traits?

Taking a step back

Can we use **structural typing** to avoid having to define all these traits?

```
val s: scala.Selectable { def foo(): Int } = ...
val x: Int = s.foo()
```

Putting it all together

Source code	Desugared form
`Int => List[Int]`	`Function1[Int, List[Int]]`

`[T] => T => List[T]`	`scala.PolyFunction {`
	`  def apply[T](x: T): List[T]`
	`}`

`scala.PolyFunction` is an empty trait which is allowed to have a polymorphic apply refinement.

Putting it all together

Source code	Desugared form
`Int => List[Int]`	`Function1[Int, List[Int]]`

`[T <: Int] => T => List[T]`	`scala.PolyFunction {`
	`  def apply[T <: Int](x: T): List[T]`
	`}`

`scala.PolyFunction` is an empty trait which is allowed to have a polymorphic apply refinement.

Type erasure (1/2)

When compiling to Java bytecode, we need to **erase** type parameters:

```
// Scala
trait Function1[-T, +R]:
  def apply(x: T): R

val f: String => List[String] = …
f("").head
```

```
// Java bytecode
interface Function1:
  def apply(x: Object): Object

val f: Function1 = …
f.apply("").asInstanceOf[List]
 .head.asInstanceOf[String]
```

Type erasure (2/2)

```scala
val g: [T] => (x: T) => List[T] =
  [T] => (x: T) => List(x)
g[String]("").head
```

We could use any compilation scheme we want, but if we want to be efficient, we need a class with an apply method!

Type erasure (2/2)

```
val g: [T] => (x: T) => List[T] =
  [T] => (x: T) => List(x)
g[String]("").head
```

We could use any compilation scheme we want, but if we want to be efficient, we need a class with an apply method!

```
val g: Function1 =
  (x: Object) => List.apply(x)
g.apply("").asInstanceOf[List].head.asInstanceOf[String]
```

Type erasure (2/2)

```
val g: [T] => (x: T) => List[T] =
  [T] => (x: T) => List(x)
g[String]("").head
```

We could use any compilation scheme we want, but if we want to be efficient, we need a class with an apply method!

```
val g: Function1 =
  (x: Object) => List.apply(x)
g.apply("").asInstanceOf[List].head.asInstanceOf[String]
```

We erase a polymorphic function with N term arguments like a monomorphic function with N term arguments.

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Example 1: Generic programming

```
trait Order[A]:
  def lessOrEqual(x: A, y: A): Boolean
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```
trait Order[A]:
  def lessOrEqual(x: A, y: A): Boolean
```

```
given Order[Int] with
  def lessOrEqual(x: Int, y: Int) = x <= y
given Order[String] with
  def lessOrEqual(x: String, y: String) = x <= y
```

Example 1: Generic programming

```
trait Order[A]:
  def lessOrEqual(x: A, y: A): Boolean
```

```
case class Foo(a: Int, b: String)

given Order[Foo] with
  def lessOrEqual(x: Foo, y: Foo) =
```

Example 1: Generic programming

```
trait Order[A]:
  def lessOrEqual(x: A, y: A): Boolean
```

```
case class Foo(a: Int, b: String)

given Order[Foo] with
  def lessOrEqual(x: Foo, y: Foo) =
    summon[Order[Int]].lessOrEqual(x.a, y.a)
    && summon[Order[String]].lessOrEqual(x.b, y.b)
```

Example 1: Generic programming

```
trait Order[A]:
  def lessOrEqual(x: A, y: A): Boolean
```

```
case class Foo(a: Int, b: String)

given Order[Foo] with
  def lessOrEqual(x: Foo, y: Foo) =
    val inst = summon[ProductInstances[Order, Foo]]
    inst.foldLeft2(x, y)(true)(


    )
```

Example 1: Generic programming

```
trait Order[A]:
  def lessOrEqual(x: A, y: A): Boolean
```

```
case class Foo(a: Int, b: String)

given Order[Foo] with
  def lessOrEqual(x: Foo, y: Foo) =
    val inst = summon[ProductInstances[Order, Foo]]
    inst.foldLeft2(x, y)(true)(
      [T] => (acc: Boolean, order: Order[T], x1: T, y1: T) =>
        acc && order.lessOrEqual(x1, y1)
    )
```

Example 2: Preserving type information

```
enum SList:
  case SNil
  case SCons(head: String, tail: SList)

  def foldRight[B](z: B)(op: (String, B) => B): B = ...
```

Example 2: Preserving type information

```
enum SList:
  case SNil
  case SCons(head: String, tail: SList)

  def foldRight[B](z: B)(op: (String, B) => B): B = ...


  def appended(elem: Int): SList =
    val newTail: SList = SCons(elem, SNil)
    foldRight(newTail)(SCons(_, _))
```

Example 2: Preserving type information

```
import scala.compiletime.ops.int.*

enum SList[N <: Int]:
  case SNil extends SList[0]
  case SCons[M <: Int](head: String, tail: SList[M]) extends SList[M+1]

  def foldRight[B](z: B)(op: (String, B) => B): B = ...


  def appended(elem: Int): SList[N+1] =
    val newTail: SList[1] = SCons(elem, SNil)
    foldRight(newTail)(SCons(_, _))
```

Example 2: Preserving type information

```
import scala.compiletime.ops.int.*

enum SList[N <: Int]:
  case SNil extends SList[0]
  case SCons[M <: Int](head: String, tail: SList[M]) extends SList[M+1]

  def foldRight[B](z: B)(op: (String, B) => B): B = ...
  def foldRightN[B[_ <: Int]](z: B[0])
    (op: [M <: Int] => (String, B[M]) => B[M+1]): B[N] = ...
  def appended(elem: Int): SList[N+1] =
    val newTail: SList[1] = SCons(elem, SNil)
    foldRightN[[X] =>> SList[X+1]](newTail)([M <: Int] => SCons(_, _))
```

Example 3: Encapsulation

```
trait Base[A]:
  extension (x: A) def base: A
```

```
def test[A](a: A)(using Base[A]) =
  a.base
```

Example 3: Encapsulation

```
trait Base[A]:
  extension (x: A) def base: A
```

```
trait Derived[A] extends Base[A]:
  extension (x: A) def dangerous: A
  /** `f` is allowed to call `base`
   *  but not `dangerous` on its input. */
  def compute(f: A => A): A
```

```
def test[A](a: A)(using d: Derived[A]) =
  d.compute(a => a.dangerous)
```

Example 3: Encapsulation

```
trait Base[A]:
  extension (x: A) def base: A
```

```
trait Derived[A] extends Base[A]:
  extension (x: A) def dangerous: A
  /** `f` is allowed to call `base`
   *  but not `dangerous` on its input. */
  def compute(f: A => A): A
  def computeSafe(f:         ): A
```

```
def test[A](a: A)(using d: Derived[A]) =
  d.compute(a => a.dangerous)
```

Example 3: Encapsulation

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trait Base[A]:
  extension (x: A) def base: A
```

```
trait Derived[A] extends Base[A]:
  extension (x: A) def dangerous: A
  /** `f` is allowed to call `base`
   *  but not `dangerous` on its input. */
  def compute(f: A => A): A
  def computeSafe(f: Any => A): A
```

```
def test[A](a: A)(using d: Derived[A]) =
  d.compute(a => a.dangerous)
```

Example 3: Encapsulation

```
trait Base[A]:
  extension (x: A) def base: A
```

```
trait Derived[A] extends Base[A]:
  extension (x: A) def dangerous: A
  /** `f` is allowed to call `base`
   *  but not `dangerous` on its input. */
  def compute(f: A => A): A
  def computeSafe(f: [T] => T => T): A
```

```
def test[A](a: A)(using d: Derived[A]) =
  d.compute(a => a.dangerous)
```

Example 3: Encapsulation

```
trait Base[A]:
  extension (x: A) def base: A
```

```
trait Derived[A] extends Base[A]:
  extension (x: A) def dangerous: A
  /** `f` is allowed to call `base`
   *  but not `dangerous` on its input. */
  def compute(f: A => A): A
  def computeSafe(f: [T] => T => T): A
```

```
def test[A](a: A)(using d: Derived[A]) =
  d.compute(a => a.dangerous)
  d.computeSafe(a => a.base)
```

Example 3: Encapsulation

```
trait Base[A]:
  extension (x: A) def base: A
```

```
trait Derived[A] extends Base[A]:
  extension (x: A) def dangerous: A
  /** `f` is allowed to call `base`
   *  but not `dangerous` on its input. */
  def compute(f: A => A): A
  def computeSafe(f: [T] => T => Base[T] ?=> T): A
```

```
def test[A](a: A)(using d: Derived[A]) =
  d.compute(a => a.dangerous)
  d.computeSafe(a => a.base)
```

Example 3: Encapsulation

This technique is used in **cats-effect** to keep Async#cont safe, see https://typelevel.org/cats-effect/docs/typeclasses/async.

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SIP-49: Polymorphic Eta-Expansion (by Quentin Bernet)

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6. The SIP committee members vote on accepting it as **stable**.

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1. Have an idea! 💡
2. Discuss it on contributors.scala-lang.org
3. Write a SIP proposal with a formal specification.
4. The SIP committee members vote on accepting it as **experimental**.
5. Implement the SIP in the compiler as experimental, gather feedback.
6. The SIP committee members vote on accepting it as **stable**.
7. The feature is marked as stable in the compiler.

Idea 1: Polymorphic eta-expansion (2/2)

Adapt **polymorphic method references** by eta-expansion:

```
def singleton[T](x: T): List[T] = List(x)
(1, "").map(singleton)
```

Idea 1: Polymorphic eta-expansion (2/2)

Adapt **polymorphic method references** by eta-expansion:

```
def singleton[T](x: T): List[T] = List(x)
(1, "").map([T] => (x: T) => singleton[T](x))
```

What about regular lambdas?

If we only adapt method references, this will work:

```
(1, "").map(List.apply)
```

… but this won’t work:

```
(1, "").map(List(_))
```

What about regular lambdas?

If we only adapt method references, this will work:

```
(1, "").map(List.apply)
```

... but this won’t work:

```
(1, "").map(List(_))

(1, "").map(_.toString)
```

Idea 2: type parameter clause inference

Instead, we could adapt regular lambdas into polymorphic lambdas by type parameter clause inference combined with the usual type inference.

```
val f: [T] => T => String =
              x => x.toString
```

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```
val f: [T] => T => String =
       [T] => x => x.toString
```

Idea 2: type parameter clause inference

Instead, we could adapt regular lambdas into polymorphic lambdas by type parameter clause inference combined with the usual type inference.

```
val f: [T] => T => String =
       [T] => (x: T) => x.toString
```

Idea 2: type parameter clause inference

Regular eta-expansion can also be combined with type parameter clause inference and type inference.

```
def singleton[T](x: T): List[T] = List(x)

val f: [T] => T => List[T] =
  singleton
```

Idea 2: type parameter clause inference

Regular eta-expansion can also be combined with type parameter clause inference and type inference.

```
def singleton[T](x: T): List[T] = List(x)

val f: [T] => T => List[T] =
  x => singleton(x)
```

Idea 2: type parameter clause inference

Regular eta-expansion can also be combined with type parameter clause inference and type inference.

```
def singleton[T](x: T): List[T] = List(x)

val f: [T] => T => List[T] =
  [T] => x => singleton(x)
```

Idea 2: type parameter clause inference

Regular eta-expansion can also be combined with type parameter clause inference and type inference.

```
def singleton[T](x: T): List[T] = List(x)

val f: [T] => T => List[T] =
  [T] => (x: T) => singleton(x)
```

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```
def singleton[T](x: T): List[T] = List(x)

val f: [T] => T => List[T] =
  [T] => (x: T) => singleton[T](x)
```

```
val g: [T, S] => (T, S) => List[(T, S)] =
   singleton
```

Idea 2: type parameter clause inference

Regular eta-expansion can also be combined with type parameter clause inference and type inference.

```
def singleton[T](x: T): List[T] = List(x)

val f: [T] => T => List[T] =
  [T] => (x: T) => singleton[T](x)
```

```
val g: [T, S] => (T, S) => List[(T, S)] =
  [T, S] => (x: (T, S)) => singleton[(T, S)](x)
```

Idea 3: Better subtyping

For regular function types:

```
Any => Int    <:   Any =>
```

Idea 3: Better subtyping

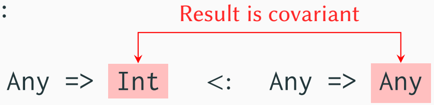
For regular function types:

Result is covariant

```
Any => Int   <:   Any => Any
```

Idea 3: Better subtyping

For regular function types:



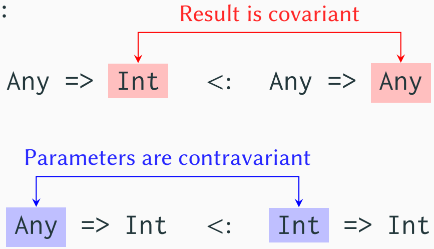
Result is covariant

```
Any => Int    <:   Any => Any
```

```
Any => Int    <:         => Int
```

Idea 3: Better subtyping

For regular function types:



Result is covariant

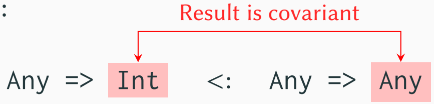
`Any => Int <: Any => Any`

Parameters are contravariant

`Any => Int <: Int => Int`

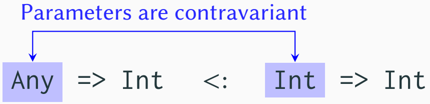
Idea 3: Better subtyping

For regular function types:



Result is covariant

```
Any => Int   <:   Any => Any
```



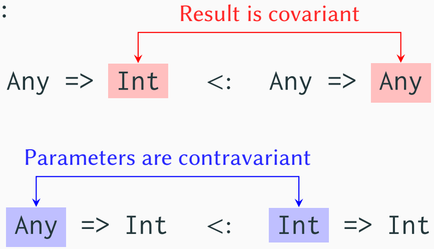
Parameters are contravariant

```
Any => Int   <:   Int => Int
```

For polymorphic function types everything is invariant currently, but ideally:

Idea 3: Better subtyping

For regular function types:



Result is covariant

```
Any => Int   <:   Any => Any
```

Parameters are contravariant

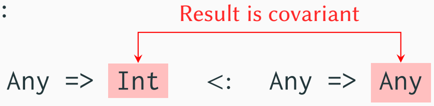
```
Any => Int   <:   Int => Int
```

For polymorphic function types everything is invariant currently, but ideally:

```
[T <: Any] => Seq[T] => Option[T] <: [T <:     ] =>           =>     
```

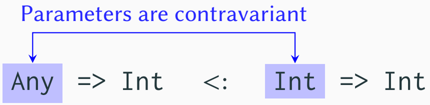
Idea 3: Better subtyping

For regular function types:



Result is covariant

```
Any => Int   <:   Any => Any
```



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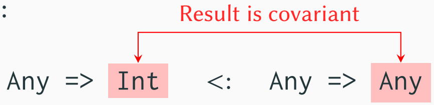
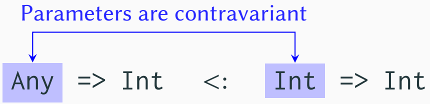
Idea 3: Better subtyping

For regular function types:



Result is covariant

`Any => Int   <:   Any => Any`



Parameters are contravariant

`Any => Int   <:   Int => Int`

For polymorphic function types everything is invariant currently, but ideally:

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[T <: Any ] => Seq[T] => Option[T] <: [T <:     ] =>          => Any
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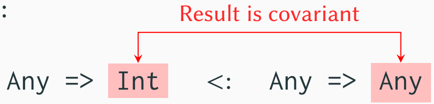
Idea 3: Better subtyping

For regular function types:


Result is covariant

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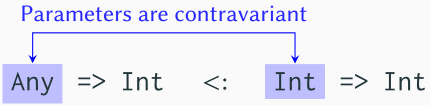
Any => Int   <:   Any => Any
```


Parameters are contravariant

```
Any => Int   <:   Int => Int
```

For polymorphic function types everything is invariant currently, but ideally:

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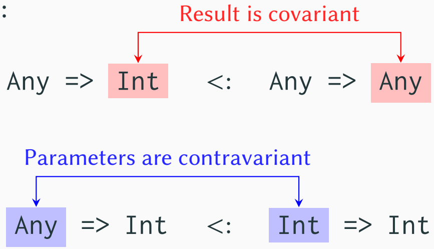
Idea 3: Better subtyping

For regular function types:



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Any => Int   <:   Any => Any
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Parameters are contravariant

```
Any => Int   <:   Int => Int
```

For polymorphic function types everything is invariant currently, but ideally:

```
[T <: Any] => Seq[T] => Option[T] <: [T <: Int] => List[T] => Any
```

Thank you!

Come to the Scala Spree this Friday! https://github.com/scalacenter/sprees

Resources:

- Slides for this talk: http://guillaume.martres.me/talks/scaladays23-madrid.pdf
- Scala 3 Compiler Academy on Youtube.
- `#scala-contributors` on the Scala Discord.