

Regaining Control

with Indexed Monads

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Who am I?

- Scala 2.12 Docs Compiler
- Scala 3 Compiler Engineer @ EPFL w/ Martin Odersky
- Software Engineer @ Klarna Bank

Functional State

The Canonical Example

```
type Seed = Long

def rng(seed: Seed): (Seed, Long)

def rng(seed: Seed): (Seed, Boolean) = {
  val (newSeed, rand) = rng(seed)
  (newSeed, rand > 0L)
}
```

Adding Three Random Numbers

```
val s0 = 0L
```

```
val (s1, r0) = rng(s0)
```

```
val (s2, r1) = rng(s1)
```

```
val (_, r2) = rng(s2)
```

```
r0 + r1 + r2
```

```
// res0: Long = 3318706044697439873
```

The Canonical Example

Avoid passing the state?

The Canonical Example

Avoid passing the state?

Get rid of boilerplate?

$$S \Rightarrow (S, A)$$

The State Monad

```
case class State[S, A](run: S ⇒ (S, A)) extends AnyVal
```

The State Monad

```
val nextLong: State[Seed, Long] = State(seed ⇒ rng(seed))
```

The State Monad

```
val nextBool: State[Seed, Boolean] = ???
```

Map

We'd like to implement map in such a way that we do not affect S

$\text{State}[S, A] \Rightarrow \text{State}[S, B]$

The State Monad

```
case class State[S, A](run: S ⇒ (S, A)) extends AnyVal {  
  
  def map[B](f: A ⇒ B): State[S, B] = State {  
    s0 ⇒ {  
      val (s1, a) = run(s0)  
      (s1, f(a))  
    }  
  }  
  
}
```

The State Monad

```
val nextBool: State[Seed, Boolean] = nextLong.map(_ > 0L)
```

The State Monad

How do we get rid of the explicit state passing?

The State Monad

We want to reason about the A value in `State[S, A]`

(without having to worry about S!)

The State Monad

We sort of want to pull the value out, to *bind* it...

The State Monad

```
case class State[S, A](run: S ⇒ (S, A)) extends AnyVal {  
  
  // ...  
  
  def flatMap[B](f: A ⇒ State[S, B]): State[S, B] = State {  
    s0 ⇒ {  
      val (s1, a) = run(s0)  
      f(a).run(s1)  
    }  
  }  
}
```

Adding Three Random Numbers

```
val addition: State[Seed, Long] = for {  
  r0 ← nextLong  
  r1 ← nextLong  
  r2 ← nextLong  
} yield r0 + r1 + r2  
  
addition.run(0L)  
// res1: (Seed, Long) = (-7280499659394350823,3318706044697439873)
```

Cooler stuff

```
case class Customer(id: Long, debt: Long, name: String)
```

```
val randomCustomer: State[Seed, Customer] =  
  for {  
    id      ← nextLong  
    debt    ← nextLong  
    isHuman ← nextBool  
    name    = if (isHuman) "Kim" else "Mark Zuckerberg"  
  } yield Customer(id, debt, name)
```

```
randomCustomer.run(1L)._2
```

```
// res2: Customer = Customer(1,7806831264735756412,Mark Zuckerberg)
```

Are we there yet?

Stack safety?

What about effects?

What about effects?

```
import cats.effect.IO

def getNonce(seed: Seed): IO[(Seed, Long)] =
  IO(rng(seed))

val nextNonce: State[Seed, Long] = State(seed => getNonce(seed))
// <console>:20: error: type mismatch;
//   found   : cats.effect.IO[(Seed, Long)]
//   (which expands to) cats.effect.IO[(Long, Long)]
//   required: (Seed, Long)
//   (which expands to) (Long, Long)
//       val nextNonce: State[Seed, Long] = State(seed => getNonce(seed))
//                                     ^
```


StateT

```
case class StateT[F[_], S, A](val run: S ⇒ F[(S, A)])
```

```
val nextNonce: StateT[IO, Seed, Long] = StateT(seed ⇒ getNonce(seed))
```

Stack Safety

Now depends on $F[_]$

Requirements on F[_]

Functor[F] and FlatMap[F]

for map and flatMap

State in Cats

```
import cats.Eval
```

```
type State[S, A] = StateT[Eval, S, A]
```

Where is my indexed Monad?

Also, what are indexed Monads?

$$S \Rightarrow (S, A)$$

$$\mathbf{I} \Rightarrow (0, A)$$

Chaining State Transitions

$(S1 \Rightarrow (S2, A)) \Rightarrow$
 $(S2 \Rightarrow (S3, A)) \Rightarrow$
 $(S3 \Rightarrow (S4, A)) \dots$

Indexed State Monad

```
case class IxState[I, O, A](run: I  $\Rightarrow$  (O, A))
```

Yet Another Naive Implementation

```
case class IxState[I, O, A](run: I  $\Rightarrow$  (O, A)) {  
  
  def map[B](f: A  $\Rightarrow$  B): IxState[I, O, B] = IxState {  
    i  $\Rightarrow$  {  
      val (o, a) = run(i)  
      (o, f(a))  
    }  
  }  
}
```

Yet Another Naive Implementation

```
case class IxState[I, O, A](run: I  $\Rightarrow$  (O, A)) {  
  
  // ...  
  
  def flatMap[OO, B](f: A  $\Rightarrow$  IxState[O, OO, B]): IxState[I, OO, B] =  
    IxState {  
      i  $\Rightarrow$  {  
        val (o, a) = run(i)  
        f(a).run(o)  
      }  
    }  
}
```

Chained State Transitions

`IxState[S1, S2, A] ⇒`
`IxState[S2, S3, B] ⇒`
`IxState[S3, S4, C] ...`

Now we can model state transitions!

```
sealed trait OrderStatus
case class Initiated() extends OrderStatus
case class Received() extends OrderStatus
case class Packed() extends OrderStatus
case class Shipped() extends OrderStatus
case class Delivered() extends OrderStatus
```

Helper Functions

```
object IxState {  
  def set[I, O](o: O): IxState[I, O, Unit] =  
    IxState(_ => (o, ()))  
}
```

Helper Functions

```
def received: IxState[Initiated, Received, Unit] =  
    IxState.set(Received())
```

```
def packed: IxState[Received, Packed, Unit] =  
    IxState.set(Packed())
```

```
def shipped: IxState[Packed, Shipped, Unit] =  
    IxState.set(Shipped())
```

```
def delivered: IxState[Shipped, Delivered, Unit] =  
    IxState.set(Delivered())
```


Usage

```
val order = for {  
  _ ← received  
  _ ← packed  
  _ ← shipped  
  _ ← delivered  
} yield ()  
  
order.run(Initiated())  
// res3: (Delivered, Unit) = (Delivered(),())
```

Static errors!

```
for {  
  _ ← delivered  
  _ ← packed  
} yield ()  
// <console>:22: error: type mismatch;  
//   found   : IxState[Received,Packed,Unit]  
//   required: IxState[Delivered,?,?]  
//           _ ← packed  
//           ^
```

Cats

```
class IndexedStateT[F[_], SA, SB, A](val runF: F[SA  $\Rightarrow$  F[(SB, A)]])
```

Wait a minute, this looks familiar...

StateT in Cats

```
import cats.data.IndexedStateT
```

```
type StateT[F[_], S, A] = IndexedStateT[F, S, S, A]
```

The Epiphany

The Epiphany

Passing state explicitly



The Epiphany

$$S \Rightarrow (S, A)$$



The Epiphany

State[S, A]



The Epiphany

StateT[F[_], S, A]



The Epiphany

**State[S, A] =
StateT[Eval, S, A]**



The Epiphany

IndexedStateT[F[_], SA, SB, A]



The Epiphany

**StateT[F[_], S, A] =
IndexedStateT[F, S, S, A]**



Designing APIs Using IndexedStateT

Our Order Status API

```
sealed trait OrderStatus
case class Initiated() extends OrderStatus
case class Received() extends OrderStatus
case class Packed() extends OrderStatus
case class Shipped() extends OrderStatus
case class Delivered() extends OrderStatus
```

A Vanilla API

```
HttpService[IO] {  
  case GET → Root / "status" / IntVar(id) ⇒  
    orderStatus(id).flatMap(Ok(_))  
  
  case POST → Root / "status" / IntVar(id) ⇒  
    createOrder(id) *> Ok()  
  
  case PATCH → Root / "status" / "packAndShip" / IntVar(id) ⇒  
    ship(id) *> pack(id) *> Ok()  
}
```


Designing APIs Using IndexedStateT

```
def createOrder(init: OrderInit): IndexedStateT[IO, Initiated, Received, OrderId] =  
  IndexedStateT(_ => persist(init).map(id => (Received(), id)))
```

```
def packed(id: OrderId): IndexedStateT[IO, Received, Packed, Unit] =  
  IndexedStateT.setF(persist(Packed()), id))
```

```
def shipped(id: OrderId): IndexedStateT[IO, Packed, Shipped, Unit] =  
  IndexedStateT.setF(persist(Shipped()), id))
```

```
def delivered(id: OrderId): IndexedStateT[IO, Shipped, Delivered, Unit] =  
  IndexedStateT.setF(persist(Delivered()), id))
```

Using the API

```
val orderId = 1L

val packAndShip = for {
  _ ← packed(orderId)
  _ ← shipped(orderId)
} yield ()

packAndShip.runS(Received()).unsafeRunSync()
// res6: Shipped = Shipped()
```

The non-vanilla API

```
HttpService[IO] {  
  case GET → Root / "status" / IntVar(id) ⇒  
    getState(id).flatMap(Ok(_))  
  
  case POST → Root / "status" / IntVar(id) ⇒  
    createOrder(OrderInit(id)).run(Initiated()) *> Ok()  
  
  case PATCH → Root / "status" / "packAndShip" / LongVar(id) ⇒  
    for {  
      r ← state[Received](id)  
      _ ← packAndShip.run(r)  
      res ← Ok()  
    } yield res  
}
```

Encode Any Protocol

- File Protocols

```
def writeHeader(header: String): IxState[NoHeader, HeaderWritten, Array[Byte]]
```

- Session types

```
def initSSL(ch: ClientHello): IxState[NoSession, ClientHello, Unit]
```

Downsides to using IndexedStateT?

Downsides

```
scala> for {  
  |   _ ← packed(orderId)  
  |   _ ← IndexedStateT.set[IO, Unrelated0, Unrelated1](Unrelated1())  
  | } yield ()  
<console>:52: error: type mismatch;  
found   : cats.data.IndexedStateT[cats.effect.IO,Unrelated0,Unrelated1,Unit]  
required: cats.data.IndexedStateT[cats.effect.IO,Packed,?,?]  
  _ ← IndexedStateT.set[IO, Unrelated0, Unrelated1](Unrelated1())  
    ^
```

Shapeless: “Hold my beer”

HLists

HLists

`State[S1 :: R1 :: HNil] ⇒`

`State[S2 :: R1 :: HNil] ⇒`

`State[S2 :: R2 :: HNil]`

HLists

```
def packed[I <: HList, O <: HList](id: OrderId)(  
  implicit  
    I: Input[I, Received],  
    O: Output[O, Received, Packed],  
): IndexedStateT[IO, I, O, Unit] = IndexedStateT.set(O.out)  
  
packed(0L).run(Received() :: HNil)  
// res9: cats.effect.IO[(Packed :: shapeless.HNil, Unit)] = IO$2117376236
```

Should you do this?

Probably not.

Abstracting over F[_]

These structures allow you to stay generic. Don't commit too early.

- `F = Id`
- `F = Option`
- `F = OptionT[IO, ?]`
- `F = EitherT[IO, Throwable, ?]`
- `F = MonadError[Throwable, ?]`

References

- Cats State - Typelevel Cats Documentation
- Control.Monad.State - Hackage
- pandoc-include-code - Oskar Wickström // @owickstrom
- tut - doc/tutorial generator for scala // @tpolecat

Thank You!