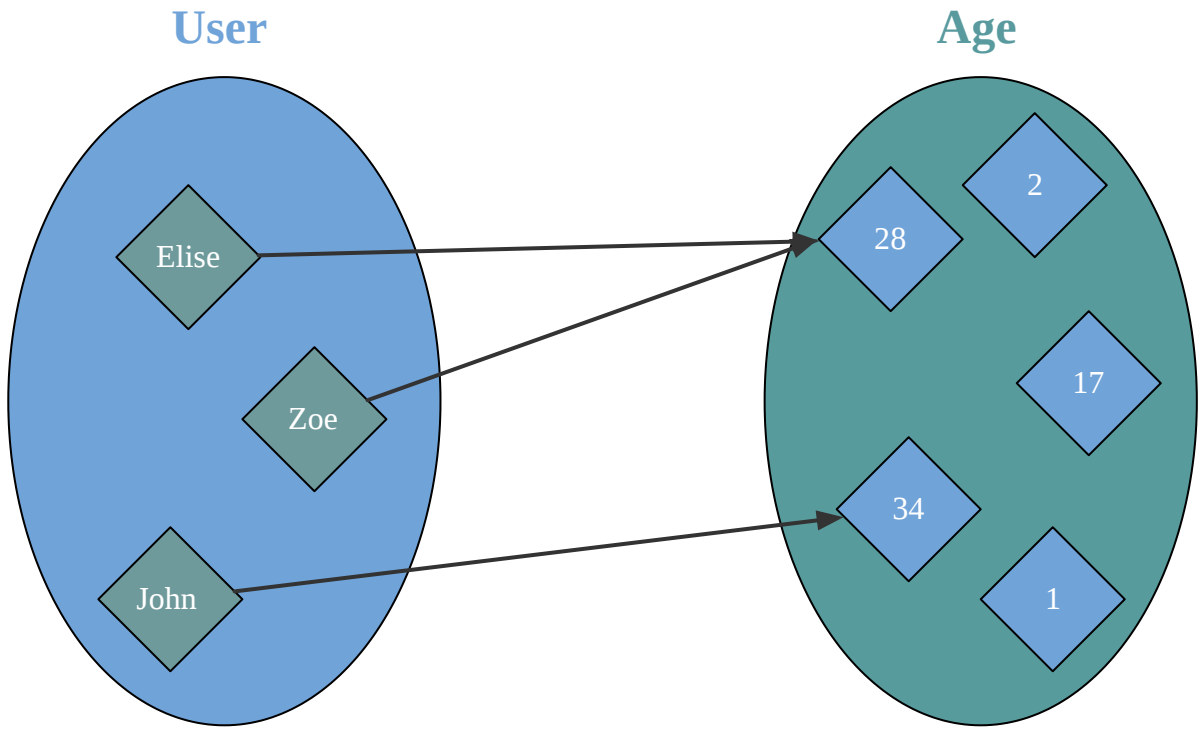
Side Effect

Pure function



How to do something?

- read or write from a file
- save user in database
- send notification to user's phone
- update counter of active users

A pure function cannot DO anything

it can only produce a VALUE

Functional Programming is useless *

Simon Peyton Jones co-author of haskell

What is the solution?

Create a VALUE that describes actions

Create a VALUE that describes actions

INTERPRET the value with side effects in Main

1. Encode Description

```
trait Description[A]
```

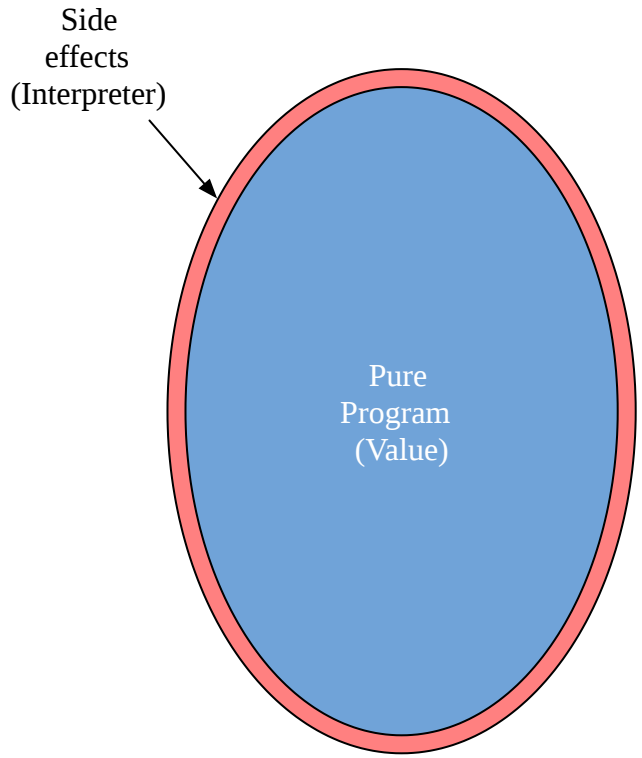
2. Define an unsafe interpreter of Description

```
def unsafeRun[A](fa: Description[A]): A = ??? // execute description, this is not a pure function
```

3. Combine everything in Main

```
object Main extends App {

  val description: Description[Unit] = ???

  unsafeRun(description)

}
```

Run side effects at the edges



Examples of description / evaluation

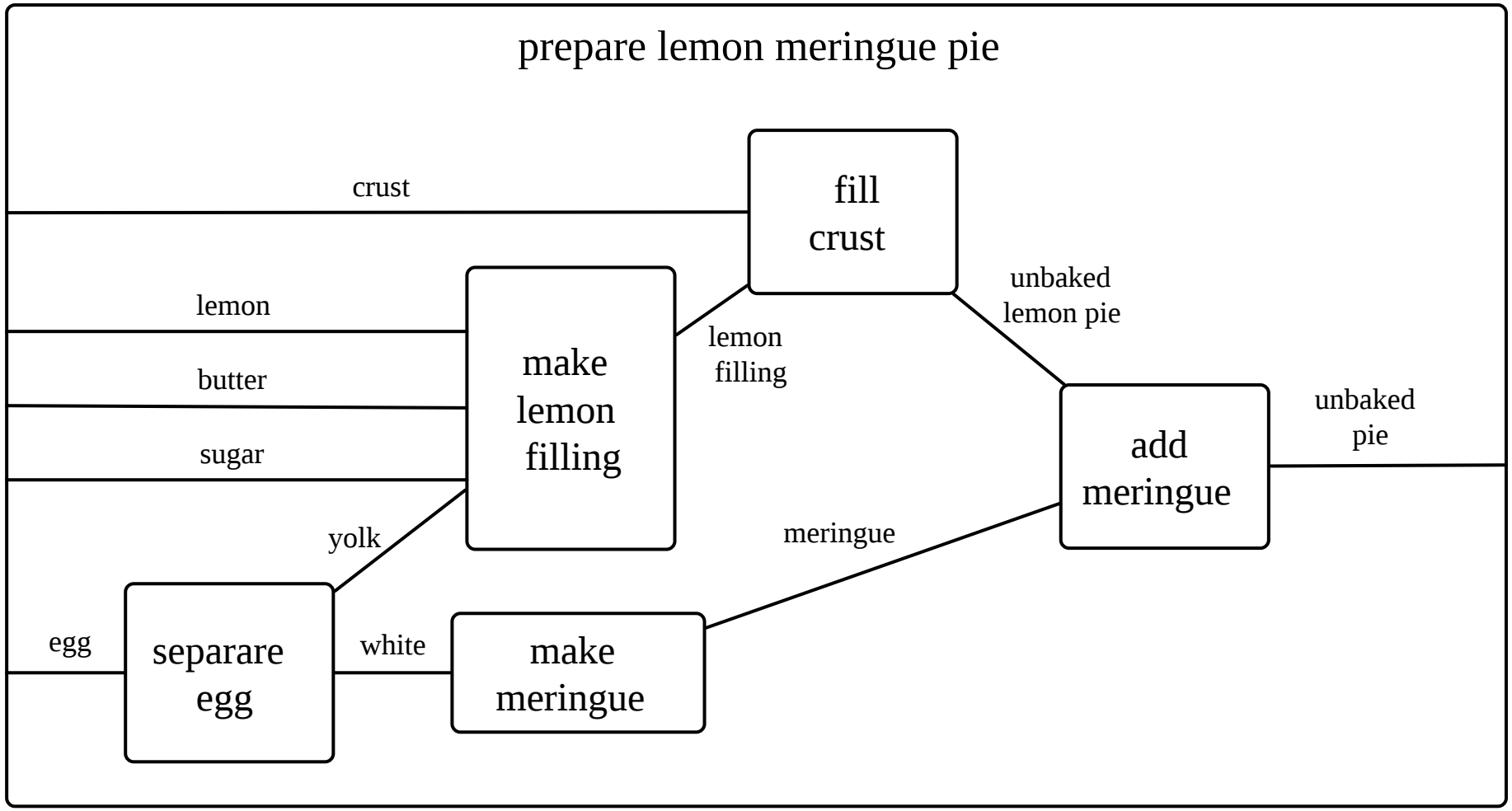
Cooking

1. Secret pasta recipe (Description)

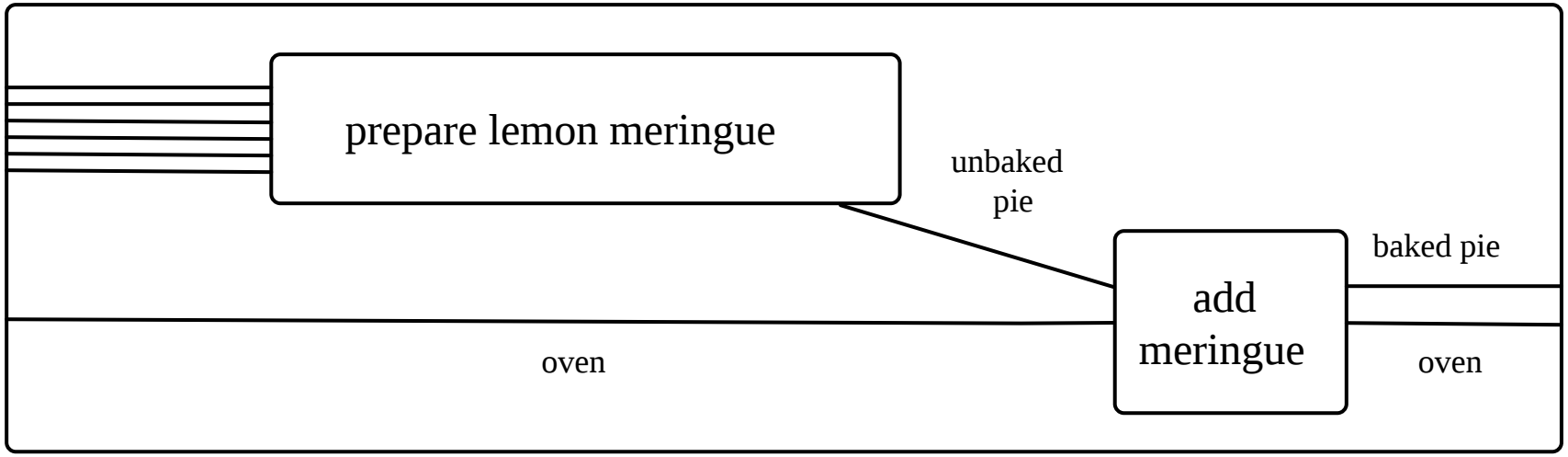
1. Boil 200 ml of water
2. Add 250 g of dry pasta
3. Wait 11 minutes
4. Drain the pasta

2. Cook (Unsafe evaluation)

Take the recipe and do it at home


prepare lemon meringue pie
crust
fill crust
lemon
butter
sugar
make lemon filling
lemon filling
unbaked lemon pie
add meringue
unbaked pie
yolk
meringue
egg
separare egg
white
make meringue

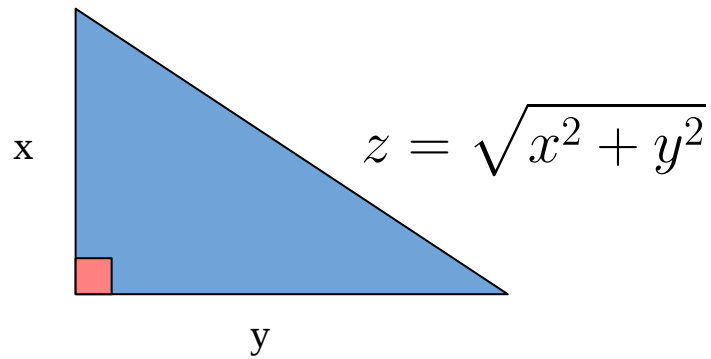
Cooking compose



Seven Sketches in Compositionality: An Invitation to Applied Category Theory

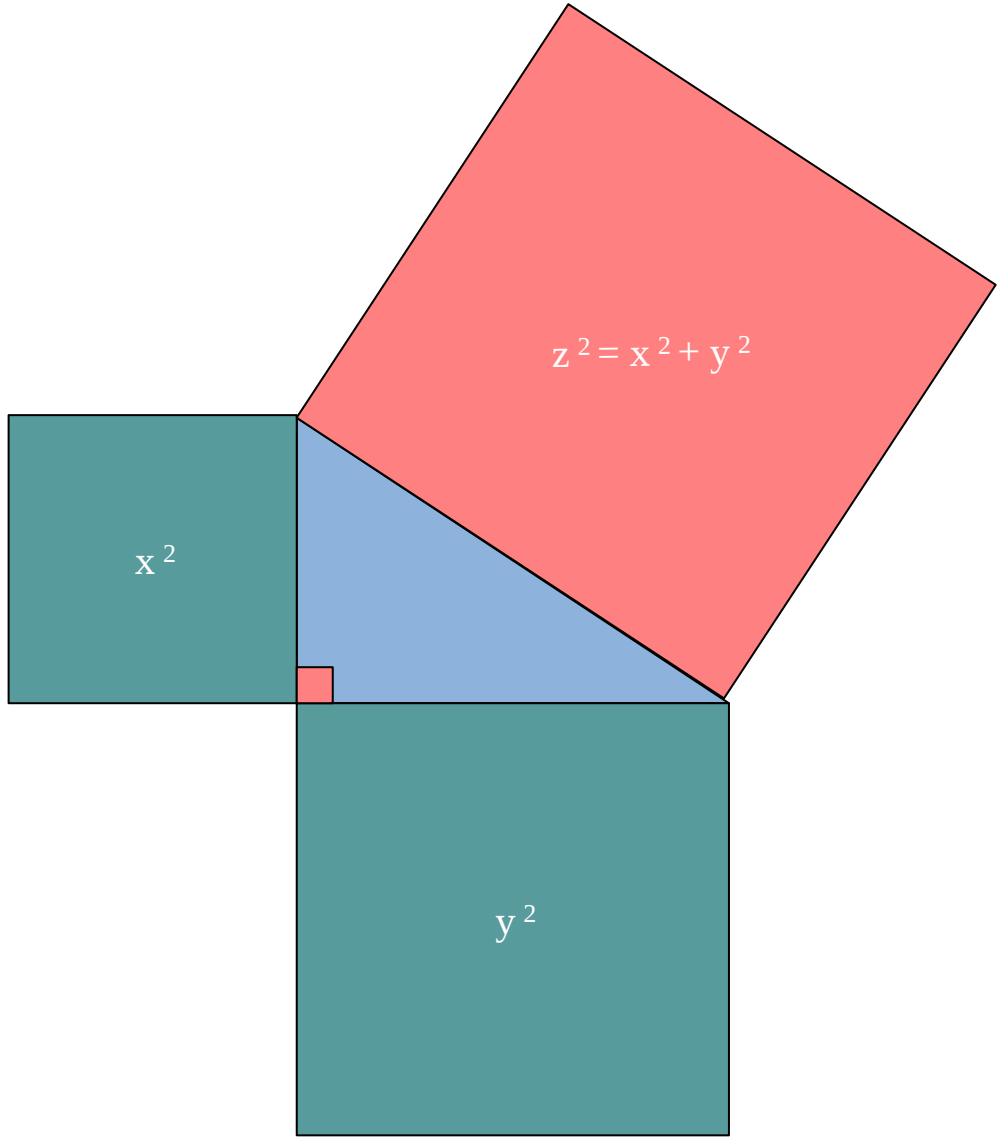
Mathematical formula

```
scala> val x = 2
x: Int = 2

scala> val y = 3
y: Int = 3

scala> val x2 = Math.pow(x, 2)
x2: Double = 4.0

scala> val y2 = Math.pow(y, 2)
y2: Double = 9.0

scala> val z  = Math.sqrt(x2 + y2)
z: Double = 3.605551275463989
```



Mathematical formula

```
scala> val x2 = Math.pow(x, 2)
x2: Double = 4.0

scala> val y2 = Math.pow(y, 2)
y2: Double = 9.0

scala> val z  = Math.sqrt(x2 + y2)
z: Double = 3.605551275463989

scala> Math.pow(z, 2)
res0: Double = 12.999999999999998

scala> x2 + y2
res1: Double = 13.0
```



How to encode description?

How to encode description?

```
trait Description[A]


def unsafeRun[A](fa: Description[A]): A = ???
```

Method 1: Thunk

```
type Thunk[A] = () => A  // Unit => A

def unsafeRun[A](fa: Thunk[A]): A = fa()
```

Method 1: Thunk

```
type Thunk[A] = () => A  // Unit => A

def unsafeRun[A](fa: Thunk[A]): A = fa()
```

```
import java.time.LocalDate
import scala.io.Source

def writeLine(message: String): Thunk[Unit] =
  () => println(message)

val today: Thunk[LocalDate] =
  () => LocalDate.now()

def fetch(url: String): Thunk[Iterator[String]] =
  () => Source.fromURL(url)("ISO-8859-1").getLines
```

Method 1: IO

```
class IO[A](thunk: () => A) {
  def unsafeRun(): A = thunk()
}

def writeLine(message: String): IO[Unit] =
  new IO(() => println(message))

val today: IO[LocalDate] =
  new IO(() => LocalDate.now())

def fetch(url: String): IO[Iterator[String]] =
  new IO(() => Source.fromURL(url)("ISO-8859-1").getLines)
```

```
scala> val google = fetch("http://google.com")
google: IO[Iterator[String]] = IO@557d2ac2

scala> google.unsafeRun().take(1).toList
res2: List[String] = List(<!doctype html><html itemscope="" itemtype="http://schema.org/WebPage" lang="en"><head><me
```

IO Exercises

`exercises.sideeffect.IOExercises.scala`

IO Summary

- An `IO` is a thunk of potentially impure code
- Composing `IO` is referentially transparent, nothing get executed
- It is easier to test `IO` if they are defined in a interface (see `Console` and `Clock` trait in `IOExercises`)

IO Execution

IO execution

```
case class UserId (value: String)
case class OrderId(value: String)

case class User(userId: UserId, name: String, orderIds: List[OrderId])
```

```
def getUser(userId: UserId): IO[User] =
  IO.effect{
    val response = httpClient.get(s"http://foo.com/user/${userId.value}")
    if(response.status == 200) parseJson[User](response.body)
    else throw new Exception(s"Invalid status ${response.status}")
  }

def deleteOrder(orderId: OrderId): IO[Unit] =
  IO.effect{
    val response = httpClient.delete(s"http://foo.com/order/${orderId.value}")
    if(response.status == 200) () else throw new Exception(s"Invalid status ${response.status}")
  }
```

How is it executed?

```
def deleteAllUserOrders(userId: UserId): IO[Unit] =
  for {
    user <- getUser(userId)
    _    <- traverse(user.orderIds)(deleteOrder)
  } yield ()

object Main extends App {

  deleteAllUserOrders(UserId("1234")).unsafeRun()

}
```

How is it executed?

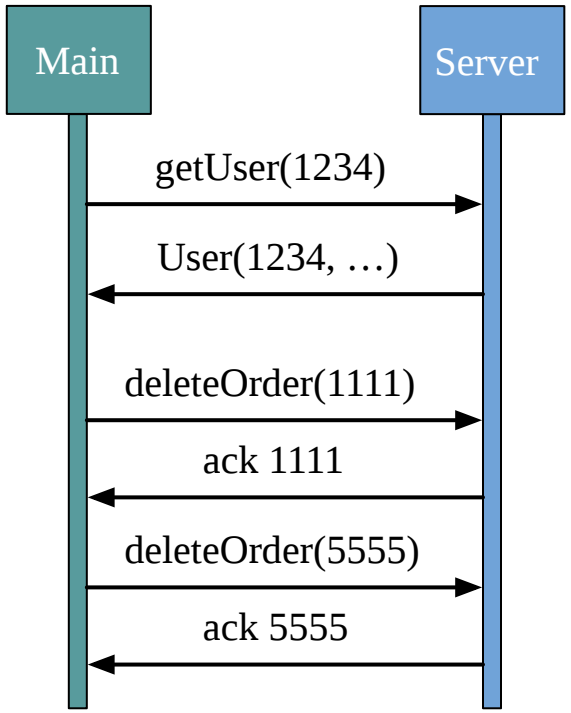
```
def deleteAllUserOrders(userId: UserId): IO[Unit] =
  for {
    user    <- getUser(userId)
    deletes  = user.orderIds.map(deleteOrder): List[IO[Unit]]
    _       <- sequence(deletes)             : IO[List[Unit]]
  } yield ()

object Main extends App {

  deleteAllUserOrders(UserId("1234")).unsafeRun()

}
```

How is it executed?

```
def deleteAllUserOrders(userId: UserId): IO[Unit] =
  for {
    user <- getUser(userId)
    // User("1234", "Rob", List("1111", "5555"))
    _    <- deleteOrder(user.orderIds(0)) // 1111
    _    <- deleteOrder(user.orderIds(1)) // 5555
  } yield ()

object Main extends App {

  deleteAllUserOrders(UserId("1234")).unsafeRun()

}
```

IO execution is sequential

```
def deleteAllUserOrders(userId: UserId): IO[Unit] =
  for {
    user <- getUser(userId)
    // User("1234", "Rob", List("1111", "5555"))
    _    <- deleteOrder(user.orderIds(0)) // 1111
    _    <- deleteOrder(user.orderIds(1)) // 5555
  } yield ()

object Main extends App {

  deleteAllUserOrders(UserId("1234")).unsafeRun()

}
```

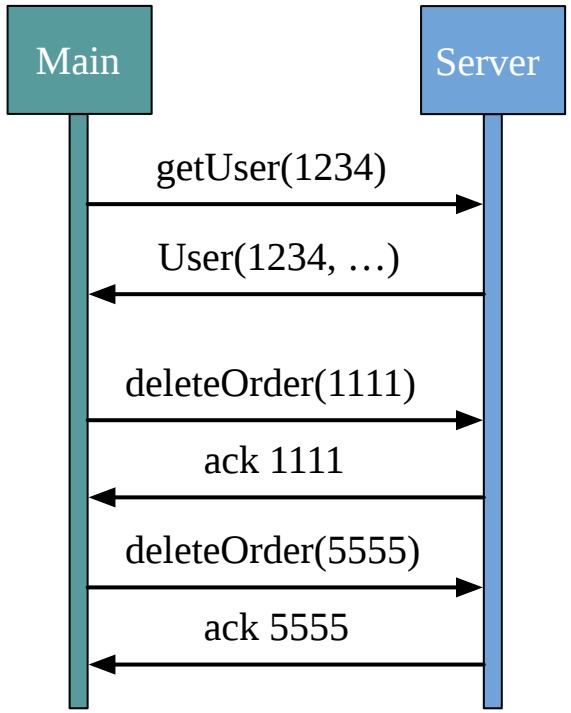


How can we evaluate IO concurrently?

Which IO can be evaluated concurrently?

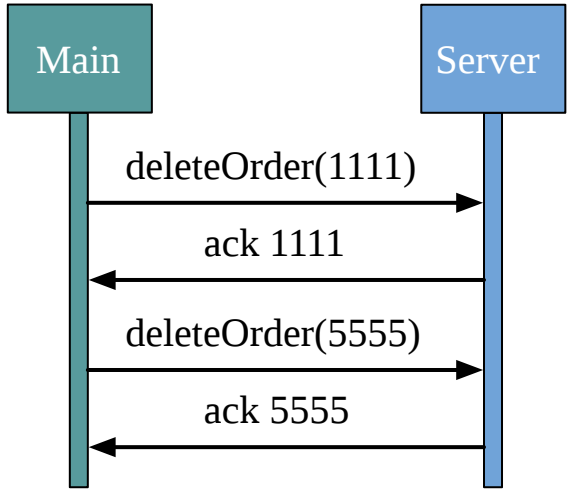
For comprehension cannot be done concurrently

```scala
def deleteAllUserOrders(userId: UserId): IO[Unit] =
  for {
    user <- getUser(userId)
    // User("1234", "Rob", List("1111", "5555"))
    _    <- deleteOrder(user.orderIds(0)) // 1111
    _    <- deleteOrder(user.orderIds(1)) // 5555
  } yield ()
```



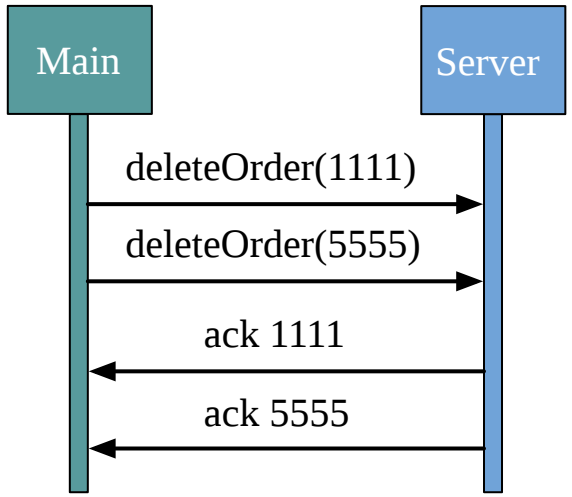
For comprehension cannot be done concurrently

```scala
def delete2Orders(orderId1: OrderId, orderId2: OrderId): IO[Unit] =
  for {
    ackOrder1 <- deleteOrder(orderId1)
    ackOrder2 <- deleteOrder(orderId2)
  } yield ()
```



Concurrent execution

```
def parExec(io1: IO[Unit], io2: IO[Unit]): IO[Unit] = ???

def delete2Orders(orderId1: OrderId, orderId2: OrderId): IO[Unit] =
  parExec(deleteOrder(orderId1), deleteOrder(orderId2))
```

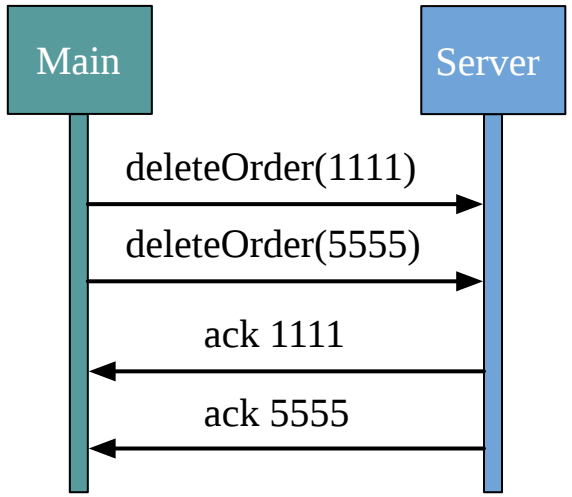


parExec is loosely defined

```
def parExec(io1: IO[Unit], io2: IO[Unit]): IO[Unit] =
  io1

def parExec(io1: IO[Unit], io2: IO[Unit]): IO[Unit] =
  io2

def parExec(io1: IO[Unit], io2: IO[Unit]): IO[Unit] =
  for {
    _ <- io1
    _ <- io2
  } yield ()

def parExec(io1: IO[Unit], io2: IO[Unit]): IO[Unit] =
  IO.succeed(())
```

Concurrent execution

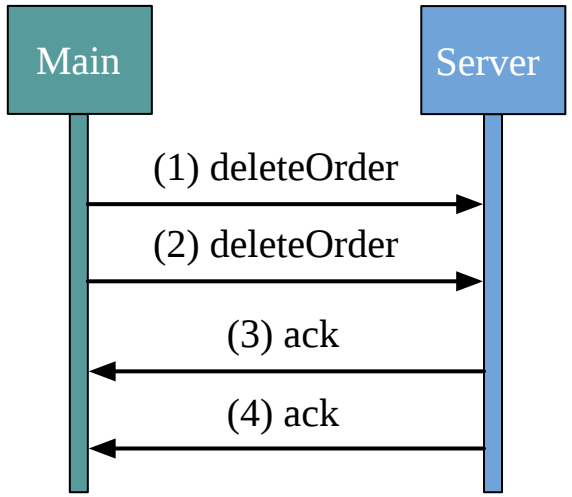
```
def parMap2[A, B, C](fa: IO[A], fb: IO[B])(f: (A, B) => C): IO[C] = ???

def delete2Orders(orderId1: OrderId, orderId2: OrderId): IO[Unit] =
  parMap2(
    deleteOrder(orderId1),
    deleteOrder(orderId2)
  )((_,_) => ())
```



How is it done with Future?

Future

```scala
import scala.concurrent.{ExecutionContext, Future}

def deleteOrder(orderId: OrderId)
  (implicit ec: ExecutionContext): Future[Unit] =
  Future { ??? }

def delete2Orders(
  orderId1: OrderId,
  orderId2: OrderId
)(implicit ec: ExecutionContext): Future[Unit] = {

  val delete1: Future[Unit] = deleteOrder(orderId1) // (1) side effect
  val delete2: Future[Unit] = deleteOrder(orderId2) // (2) side effect

  for {
    _ /* (3) */ <- delete1
    _ /* (4) */ <- delete2
  } yield ()
}
```



Execution Context

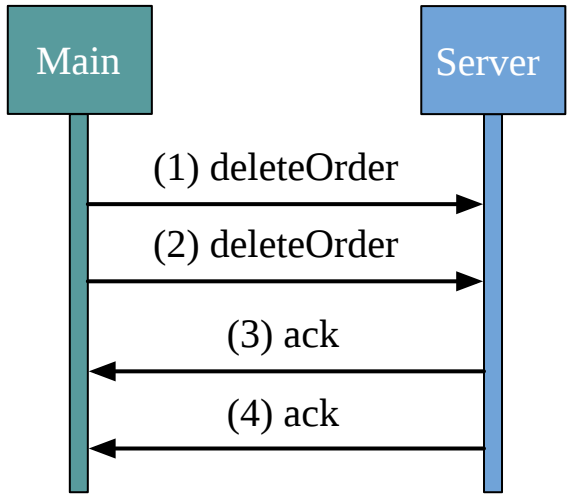
```scala
import scala.concurrent.{ExecutionContext, Future}

def deleteOrder(orderId: OrderId)(ec: ExecutionContext): Future[Unit] =
  Future { ??? }(ec)

def delete2Orders(
  orderId1: OrderId,
  orderId2: OrderId
)(ec: ExecutionContext): Future[Unit] = {

  val delete1 = deleteOrder(orderId1)(ec) // (1) side effect
  val delete2 = deleteOrder(orderId2)(ec) // (2) side effect

  delete1.flatMap(_ =>       // (3)
    delete2.map(_ => ())(ec) // (4)
  )(ec)
}
```



Execution Context

```
import java.util.concurrent.Executors
import scala.concurrent.ExecutionContext

val factory = threadFactory("test")
val pool = Executors.newFixedThreadPool(2, factory)
val ec = ExecutionContext.fromExecutorService(pool)

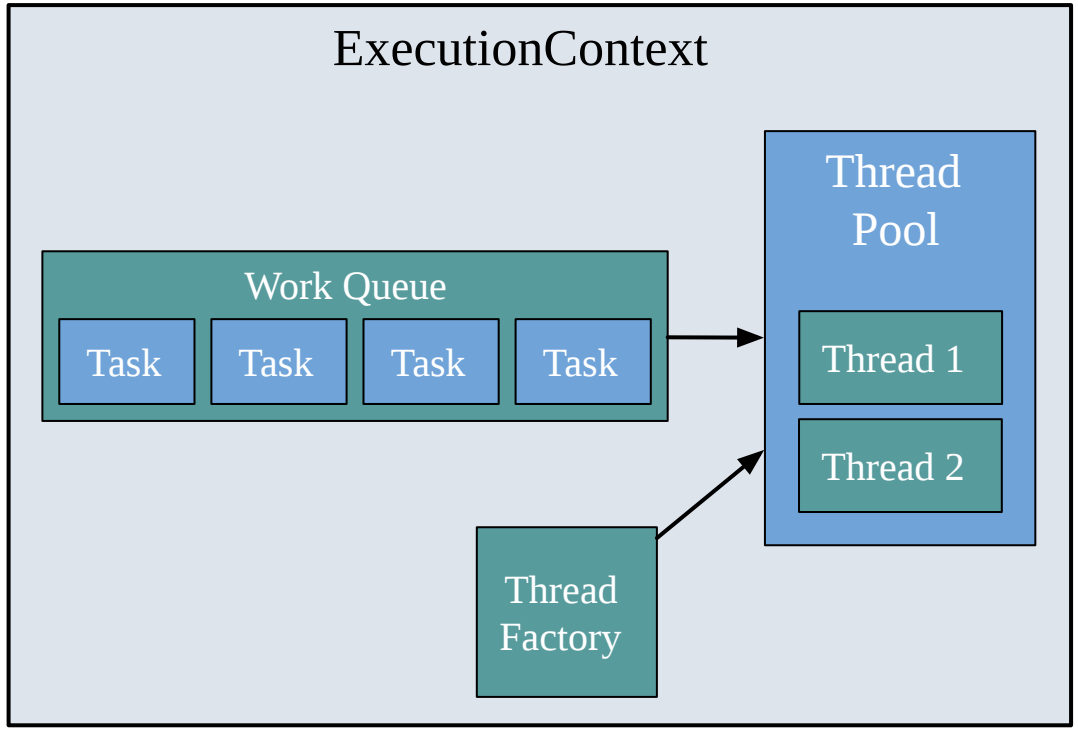
var x: Int = 0

val inc: Runnable = new Runnable {
  def run(): Unit = x += 1
}
```

```
scala> x
res3: Int = 0

scala> (1 to 10).foreach(_ => ec.execute(inc))

scala> x
res5: Int = 10
```

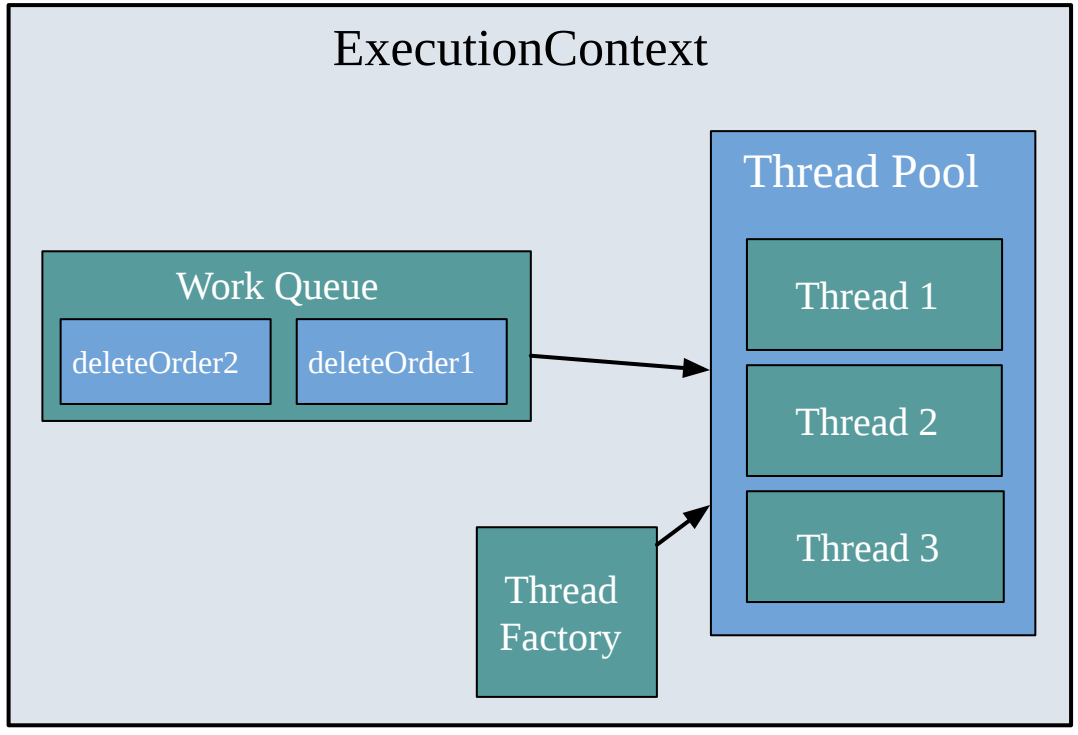


Execution Context

```
def delete2Orders(
  orderId1: OrderId,
  orderId2: OrderId
)(ec: ExecutionContext): Future[Unit] = {

  val delete1 = deleteOrder(orderId1)(ec) // (1)
  val delete2 = deleteOrder(orderId2)(ec) // (2)

  delete1.flatMap(_ =>       // (3)
    delete2.map(_ => ())(ec) // (4)
  )(ec)
}
```

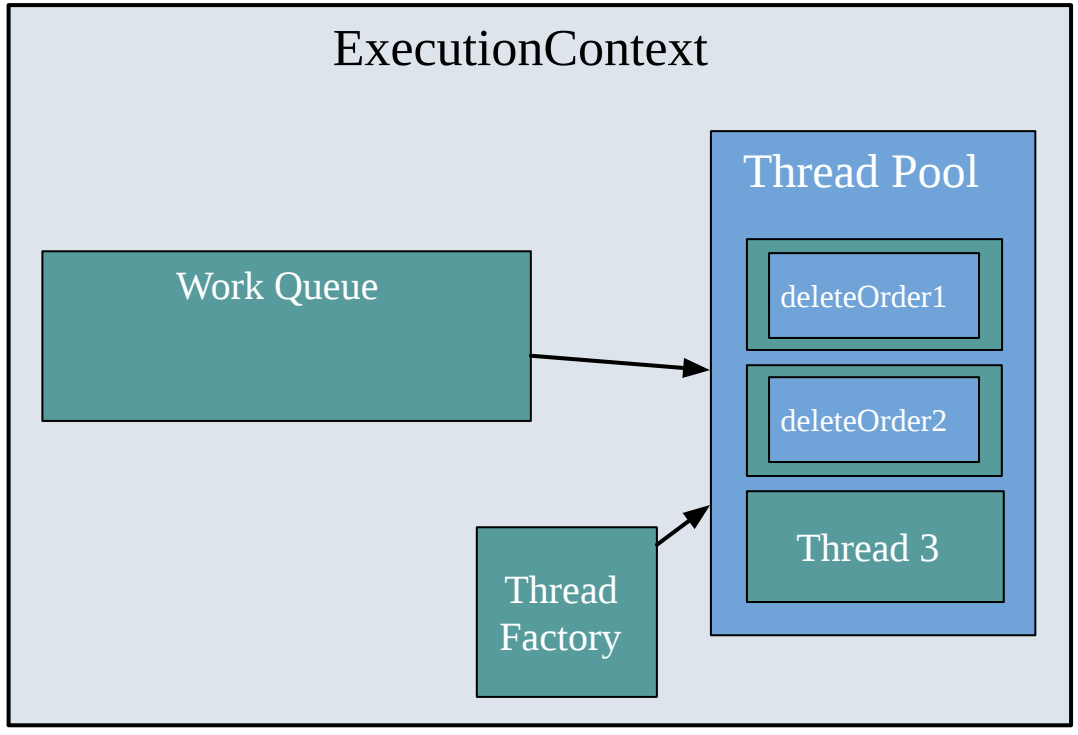


Execution Context

```
def delete2Orders(
  orderId1: OrderId,
  orderId2: OrderId
)(ec: ExecutionContext): Future[Unit] = {

  val delete1 = deleteOrder(orderId1)(ec) // (1)
  val delete2 = deleteOrder(orderId2)(ec) // (2)

  delete1.flatMap(_ =>       // (3)
    delete2.map(_ => ())(ec) // (4)
  )(ec)
}
```

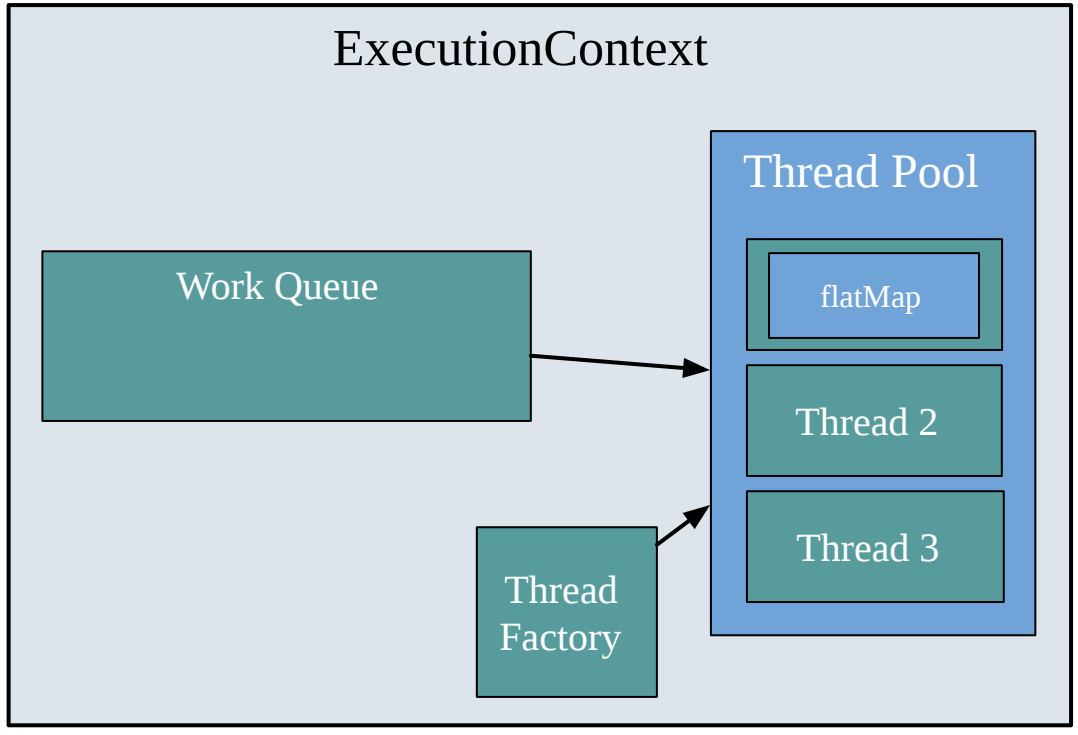


Execution Context

```
def delete2Orders(
  orderId1: OrderId,
  orderId2: OrderId
)(ec: ExecutionContext): Future[Unit] = {

  val delete1 = deleteOrder(orderId1)(ec) // (1)
  val delete2 = deleteOrder(orderId2)(ec) // (2)

  delete1.flatMap(_ =>       // (3)
    delete2.map(_ => ())(ec) // (4)
  )(ec)
}
```

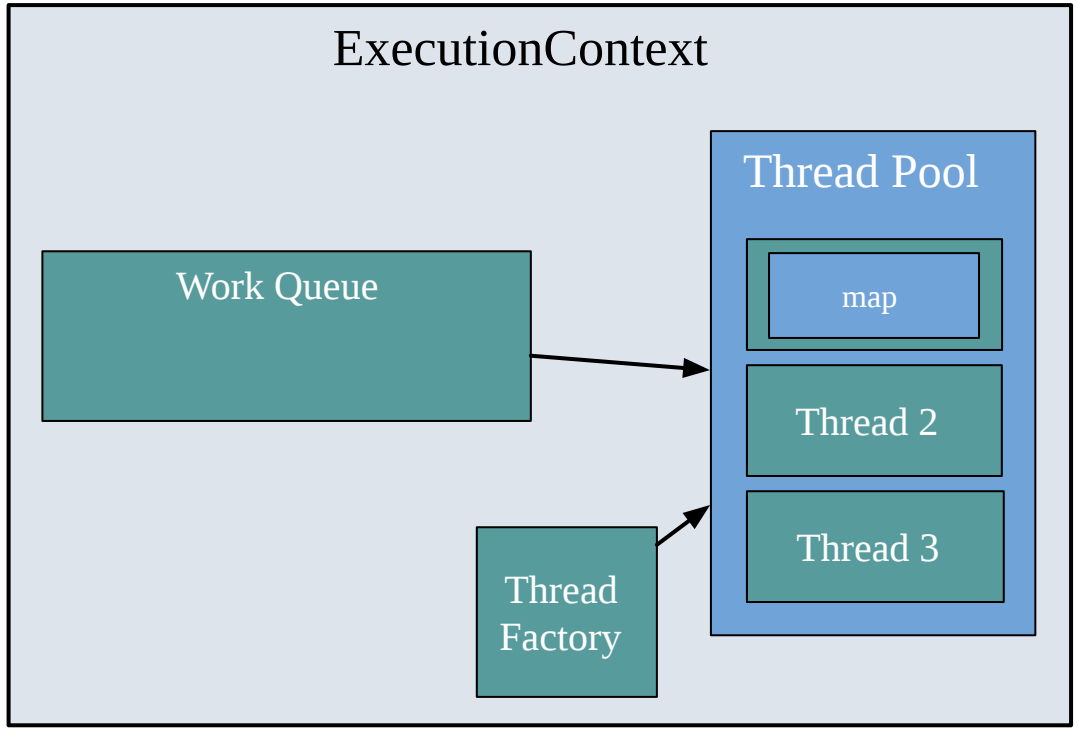


Execution Context

```
def delete2Orders(
  orderId1: OrderId,
  orderId2: OrderId
)(ec: ExecutionContext): Future[Unit] = {

  val delete1 = deleteOrder(orderId1)(ec) // (1)
  val delete2 = deleteOrder(orderId2)(ec) // (2)

  delete1.flatMap(_ =>       // (3)
    delete2.map(_ => ())(ec) // (4)
  )(ec)
}
```



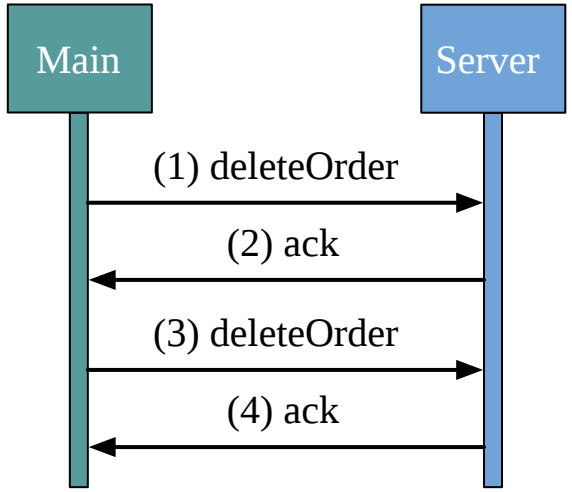
Future is not referentially transparent

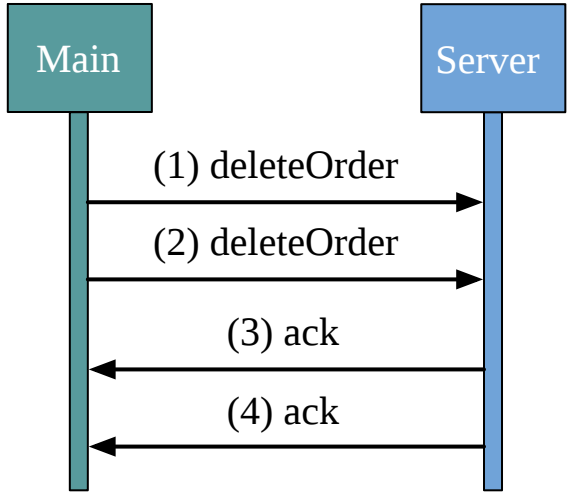
```
def deleteOrdersConcurrent(orderId1: OrderId,orderId2: OrderId)
  (implicit ec: ExecutionContext): Future[Unit] = {

  val delete1 = deleteOrder(orderId1) // (1)
  val delete2 = deleteOrder(orderId2) // (2)

  for {
    _ /* (3) */ <- delete1
    _ /* (4) */ <- delete2
  } yield ()
}
```

```
def deleteOrdersSequential(orderId1: OrderId,orderId2: OrderId)
  (implicit ec: ExecutionContext): Future[Unit] =
  for {
    _ /* (2) */ <- deleteOrder(orderId1) // (1)
    _ /* (4) */ <- deleteOrder(orderId2) // (3)
  } yield ()
```





How can we adapt Future behaviour to pure IO?

Concurrent IO

```
trait IO[+A] {
  def start(ec: ExecutionContext): ???
}
```

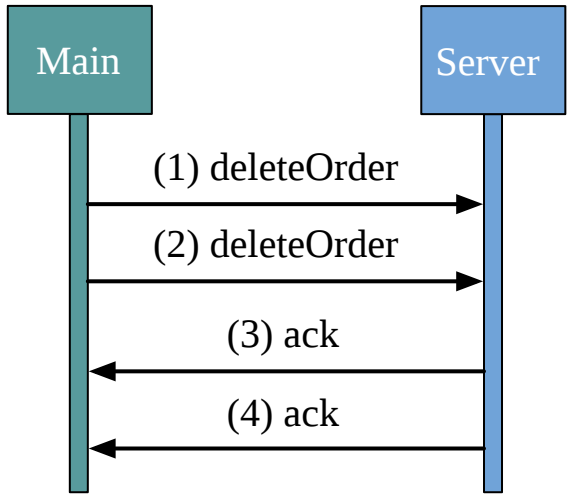
Concurrent IO

```
trait IO[+A] {
  def start(ec: ExecutionContext): IO[IO[A]]
}
```

Concurrent IO: parMap2

```
trait IO[+A] {
  def start(ec: ExecutionContext): IO[IO[A]]
}
```

```
def parMap2[A, B, C](
  fa: IO[A],
  fb: IO[B]
)(f: (A, B) => C)(ec: ExecutionContext): IO[C] =
  for {
    waitForA <- fa.start(ec) // (1)
    waitForB <- fb.start(ec) // (2)
    a        <- waitForA     // (3)
    b        <- waitForB     // (4)
  } yield f(a, b)
```

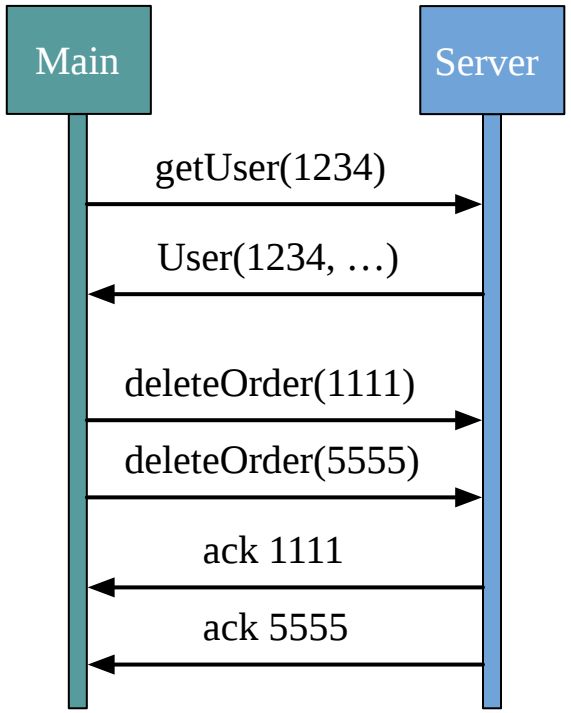


Concurrent IO: parTraverse

```
def parTraverse[A, B](xs: List[A])(f: A => IO[B])
                     (ec: ExecutionContext): IO[List[B]] =
  traverse(xs)(f(_).start(ec)).flatMap(sequence)

def deleteAllUserOrders(userId: UserId)(ec: ExecutionContext): IO[Unit] =
  for {
    user <- getUser(userId)
    _    <- parTraverse(user.orderIds)(deleteOrder)(ec)
  } yield ()

def deleteAllUserOrdersSequential(userId: UserId): IO[Unit] =
  for {
    user <- getUser(userId)
    _    <- traverse(user.orderIds)(deleteOrder)
  } yield ()
```



Concurrent IO with Async

```
type Callback[-A] = Either[Throwable, A] => Unit

sealed trait IO[+A]

object IO {
  case class Thunk[+A](f: () => A) extends IO[A]

  case class Async[+A](f: Callback[A] => Unit, ec: ExecutionContext) extends IO[A]
}
```

Concurrent IO with Async

```
type Callback[-A] = Either[Throwable, A] => Unit

sealed trait IO[+A]

object IO {
  case class Thunk[+A](f: () => A) extends IO[A]

  case class Async[+A](f: Callback[A] => Unit, ec: ExecutionContext) extends IO[A]
}
```

```
def unsafeRunAsync[A](fa: IO[A])(cb: Callback[A]): Unit =
  fa match {
    case Thunk(f) =>
      val res: Either[Throwable, A] = Try(f()).toEither
      cb(res)
    case Async(f, ec) =>
      ec.execute(new Runnable {
         def run(): Unit = f(cb)
      })
  }
```

IO Async Exercises

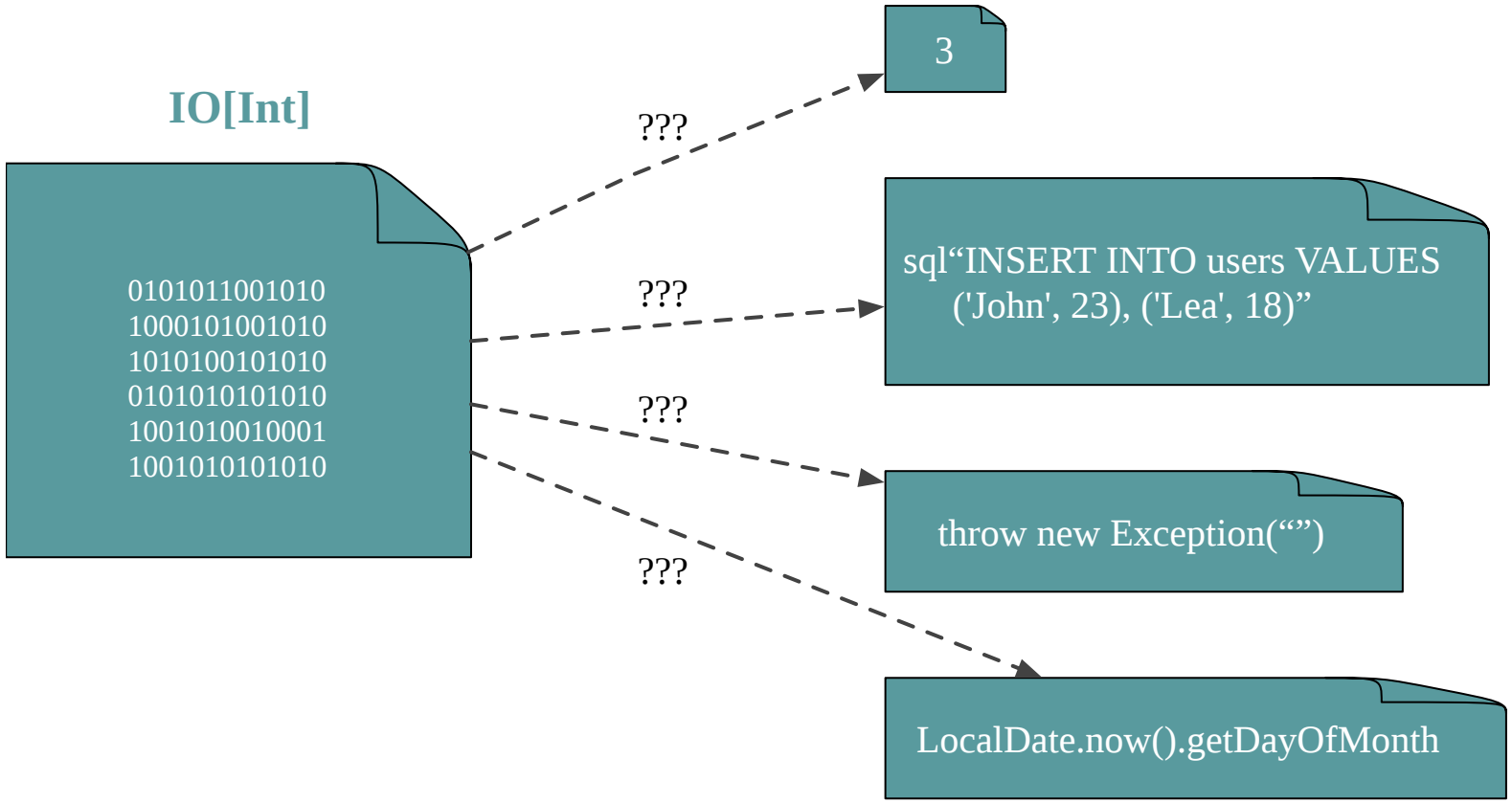
`exercises.sideeffect.IOAsyncExercises.scala`

Library IO implementations do much more

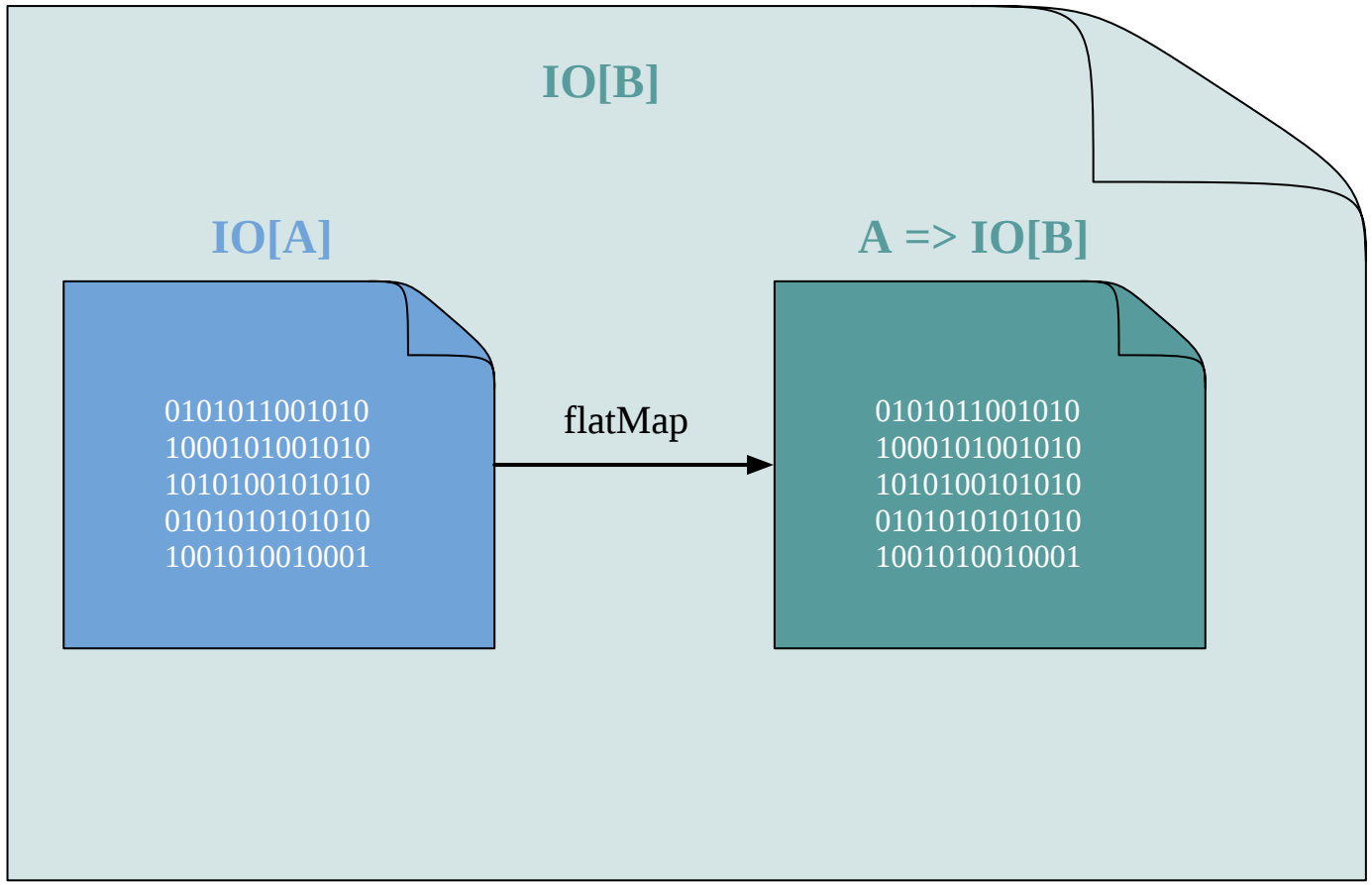
- Stack safety and JVM optimisation
- Cancellation, e.g. race two IO and cancel the loser
- Safe resource shutdown, e.g. close file, shutdown server
- Help to chose right thread pool for different type of work: blocking, compute, dispatcher

What are the limitations of IO?

IO cannot be introspected



IO cannot be introspected



How can we encode side effects more precisely?

Warning: this is an advanced technique

Effect Algebra

```
sealed trait Description[A]

object Description {
  case object Today                       extends Description[LocalDate]
  case class  FetchString(url: String)    extends Description[String]
  case class  WriteLine(message: String) extends Description[Unit]
}
```

Effect Algebra

```
sealed trait Description[A]

object Description {
  case object Today                      extends Description[LocalDate]
  case class  FetchString(url: String)   extends Description[String]
  case class  WriteLine(message: String) extends Description[Unit]
}
```

```
import Description._

def unsafeRun[A](fa: Description[A]): A =
  fa match {
    case Today            => LocalDate.now()
    case FetchString(url) => Source.fromURL(url).mkString("")
    case WriteLine(msg)   => println(msg)
  }
```

Effect Algebra

```
object Main extends App {

  val description: Description[Unit] = WriteLine("Hello World")

  unsafeRun(description)

}
```

```
scala> Main.main(Array.empty)
Hello World
```

Interpret algebra in different ways

```
def testInterpreter[A](fa: Description[A]): A =
  fa match {
    case Today           => LocalDate.of(2019, 8, 17)
    case FetchString(url) => "Hello World"
    case WriteLine(msg)   => ()
  }
```

```
def loggerInterpreter[A](fa: Description[A]): String =
  fa match {
    case Today           =>  "call Today"
    case FetchString(url) => s"call FetchString for $url"
    case WriteLine(msg)   => s"call WriteLine with $msg"
  }
```

How to add new descriptions?

How to combine description together?

How to add new descriptions?

```
sealed trait Description[A]
object Description {
  case object Today                      extends Description[LocalDate]
  case class  FetchString(url: String)   extends Description[String]
  case class  WriteLine(message: String) extends Description[Unit]
}
```

How to add new descriptions?

```
sealed trait Description[A]
object Description {
  case object Today                      extends Description[LocalDate]
  case class  FetchString(url: String)   extends Description[String]
  case class  WriteLine(message: String) extends Description[Unit]
}
```

1. Add primitive (□ not really scalable)

```
case object FetchJson extends Description[Json]
```

How to add new descriptions?

```
sealed trait Description[A]
object Description {
  case object Today                      extends Description[LocalDate]
  case class  FetchString(url: String)   extends Description[String]
  case class  WriteLine(message: String) extends Description[Unit]
}
```

1. Add primitive (□ not really scalable)

```
case object FetchJson extends Description[Json]
```

2. Transform existing actions (□ composable)

```
FetchString.map(parseJson)
```

Problem

```
sealed trait Description[A]

object Description {
  case object Today                      extends Description[LocalDate]
  case class  FetchString(url: String)   extends Description[String]
  case class  WriteLine(message: String) extends Description[Unit]
}
```

```
import Description._

def map[A, B](fa: Description[A])(f: A => B): Description[B] =
  fa match {
    case Today            => ???
    case FetchString(url) => ???
    case WriteLine(msg)   => ???
  }
```

Free structures (brief introduction)

```
sealed trait FreeMap[A]

object FreeMap {
  case class Map[X, A](description: Description[X], update: X => A) extends FreeMap[A]
}
```

Free structures (brief introduction)

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}
```

```
import io.circe.Json

def parseJson(x: String): Json =
  io.circe.parser.parse(x).getOrElse(Json.obj())

def fetchJson(url: String): FreeMap[Json] =
  Map(FetchString(url), parseJson)
```

Free structures

```
sealed trait FreeMap[A] {
  def map[C](f: A => C): FreeMap[C]
}

object FreeMap {
  def lift[A](description: Description[A]): FreeMap[A] =
    Map(description, identity[A])

  case class Map[X, A](description: Description[X], update: X => A) extends FreeMap[A] {
    def map[C](f: A => C): FreeMap[C] = Map(description, update andThen f)
  }
}
```

```
def fetchString(url: String): FreeMap[String] = FreeMap.lift(FetchString(url))

def fetchJson(url: String)   : FreeMap[Json]  = fetchString(url).map(parseJson)
```

Free structures

1. Primitives

```
val today                    : FreeMap[LocalDate] = FreeMap.lift(Today)
def fetchString(url: String): FreeMap[String]    = FreeMap.lift(FetchString(url))
def writeLine(msg: String)  : FreeMap[Unit]      = FreeMap.lift(WriteLine(msg))
```

2. Derived description

```
def fetchJson(url: String): FreeMap[Json] = fetchString(url).map(parseJson)
```

Free structures

3. Interpreters

```
def unsafeRun[A](fa: Description[A]): A =
  fa match {
    case Today            => LocalDate.now()
    case FetchString(url) => Source.fromURL(url).mkString("")
    case WriteLine(msg)   => println(msg)
  }

def unsafeRunFree[A](fa: FreeMap[A]): A =
  fa match {
    case Map(fa, f) => f(unsafeRun(fa))
  }
```

Tadam!

```scala
object Main extends App {

  val description = fetchJson("https://api.github.com/users/julien-truffaut/orgs").map(println)

  unsafeRunFree(description)

}
```

```
scala> Main.main(Array.empty)
[
  {
    "login" : "http4s",
    "id" : 1527492,
    "node_id" : "MDEyOk9yZ2FuaXphdGlvbjE1Mjc0OTI=",
    "url" : "https://api.github.com/orgs/http4s",
    "repos_url" : "https://api.github.com/orgs/http4s/repos",
    "events_url" : "https://api.github.com/orgs/http4s/events",
    "hooks_url" : "https://api.github.com/orgs/http4s/hooks",
    "issues_url" : "https://api.github.com/orgs/http4s/issues",
    "members_url" : "https://api.github.com/orgs/http4s/members{/member}",
    "public_members_url" : "https://api.github.com/orgs/http4s/public_members{/member}",
    "avatar_url" : "https://avatars3.githubusercontent.com/u/1527492?v=4",
    "description" : ""
  },
  {
    "login" : "typelevel",
    "id" : 3731824,
```

Free translates functions to data structures (GADT)

```
def         readLine :                   String
case object ReadLine extends Description[String]

def         writeLine(message: String) :                   Unit
case object WriteLine(message: String) extends Description[Unit]

def        map[X, A](action: Description[X], update: X => A) :       Description[A]
case class Map[X, A](action: Description[X], update: X => A) extends     FreeMap[A]
```

Algebra Exercises

`exercises.sideeffect.AlgebraExercises.scala`

Free Summary

- Free translates code into data
- Easy to interpret an algebra in many ways (log, test, real, metrics)
- Complex (GADT, natural transformation, Coproduct, ...)
- Can miss some features from target effect like parallel execution, resource handling

All problems in computer science can be solved by another level of indirection

David Wheeler

Free is several order of magnitude more complex than IO

Resources and further study

- Seven Sketches in Compositionality: An Invitation to Applied Category Theory
- Constraints Liberate, Liberties Constrain