Lightweight session types in Scala

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Imperial College London

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Session types in Scala: why...

$$S_h = \mu_X.\Big(!\texttt{Greet}(\mathsf{String}).\big(?\texttt{Hello}(\mathsf{String}).X \;\&\; ?\texttt{Bye}(\mathsf{String}).\textbf{end}\big) \oplus !\texttt{Quit}.\textbf{end}\Big)$$

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"Session Scala" (pseudo-code)

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Session types in Scala: why... and what we achieve

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    }
  } else {
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  }
}
```

Scala + `lchannels`

```
def hello(c: Out[Start]): Unit = {
  if (Random.nextBoolean()) {
    val c2 = c !! Greet("Alice")_

    c2 ? {
      case m @ Hello(name) => hello(m.cont)
      case Bye(name)       => ()
    }
  } else {
    c ! Quit()
  }
}
```

Scala

- **Object-oriented** and **functional**
- Immutable `val`s vs. mutable `var`s
- **Case classes** for OO pattern matching

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```
sealed abstract class Term(val descr: String)
case class Var(name: String)             extends Term("Variable")
case class Lam(arg: String, body: Term)  extends Term("Lambda")
case class App(f: Term, v: Term)         extends Term("Application")
```

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- Immutable `val`s vs. mutable `var`s
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```

```scala
def term2string(term: Term): String = {
  term.descr + ": " + {
    term match {
      case Var(n)    => n
      case Lam(x, b) => f"${x} . ${term2string(b)}"
      case App(f, v) => f"(${term2string(f)}) (${term2string(v)})"
    }
  }
}
```

Promises and futures

From the **standard library**:
concurrent programming via **promises** and **futures**

Promises and futures

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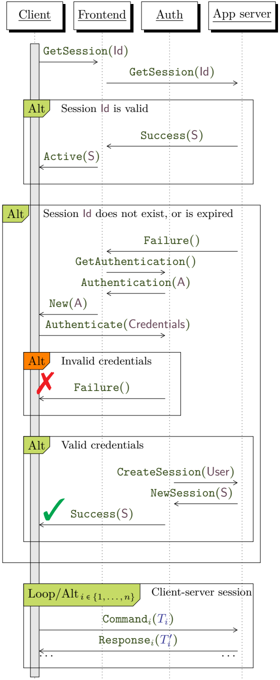
concurrent programming via **promises** and **futures**

```scala
import scala.concurrent.{Promise, Future, Await}

val p = Promise[Int]
val f = p.future // Type: Future[Int]

// In one thread...
p success 42

// ...and in another thread...
val v = Await.result(f, timeout) // Will be Success(42)
```

Case study: app server with frontend

(R. Kuhn, “Project Gålbma: Actors vs Types”, slide 42)



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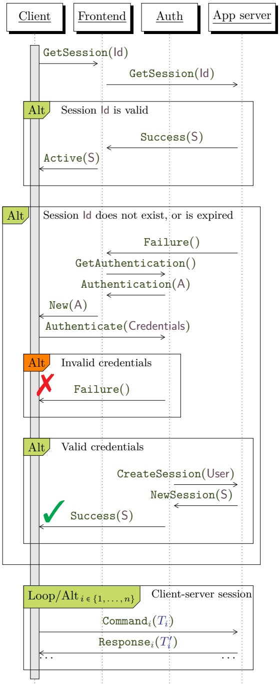
Actors interact via **untyped** mailboxes.
What about **protocols** with **sequencing** and **choices**?



Client | Frontend | Auth | App server

`GetSession`(Id)

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Alt — Session Id is valid

`Success`(S)

`Active`(S)

Alt — Session Id does not exist, or is expired

`Failure`()

`GetAuthentication`()

`Authentication`(A)

`New`(A)

`Authenticate`(Credentials)

Alt — Invalid credentials

✗ `Failure`()

Alt — Valid credentials

`CreateSession`(User)

`NewSession`(S)

✓ `Success`(S)

Loop/Alt$_{i \in \{1,\dots,n\}}$ — Client-server session

`Command`$_i(T_i)$

`Response`$_i(T'_i)$

… …

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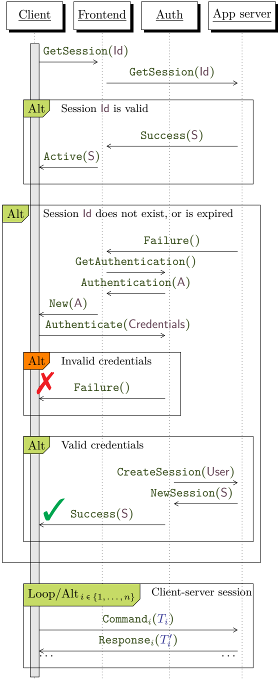

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Failure()
GetAuthentication()
Authentication(A)
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Alt Invalid credentials
✗ Failure()

Alt Valid credentials
CreateSession(User)
NewSession(S)
✓ Success(S)

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… …

akka **Actors** interact via **untyped** mailboxes.
What about **protocols** with **sequencing** and **choices**?

Akka Typed proposes typed references `ActorRef[A]`

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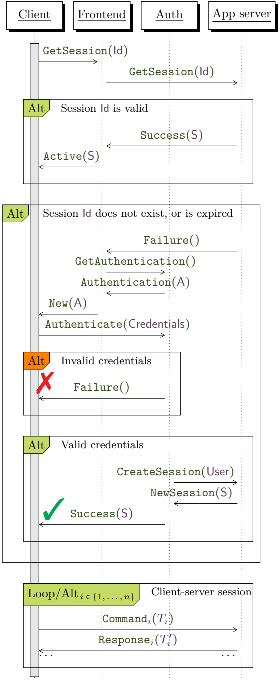

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What about **protocols** with **sequencing** and **choices**?

Akka Typed proposes typed references `ActorRef[A]` and **Continuation-Passing Style protocols**

```scala
case class GetSession(id: Int,
                      replyTo: ActorRef[GetSessionResult])

sealed abstract class GetSessionResult
case class Active(service: ActorRef[Command])
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case class Authenticate(username: String, password: String,
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// ... case classes for the client-server session loop ...
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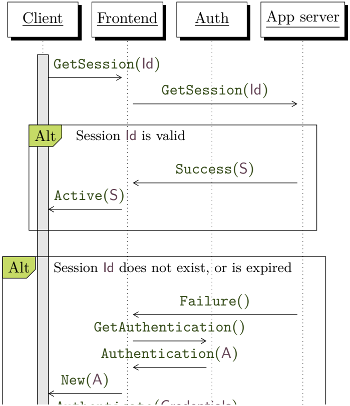

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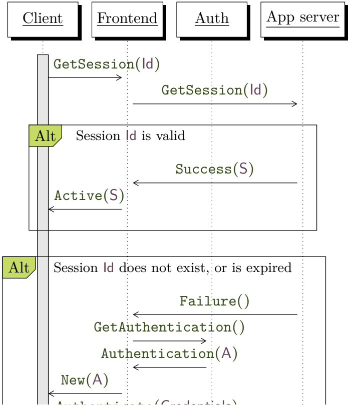

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// ... case classes for authentication, etc ...
```

To get a continuation, **spawn a new actor** (pseudo-code follows)

```scala
def client(frontend: ActorRef[GetSession]) = {
  val cont = spawn[GetSessionResult] {
    case New(a)    => doAuthentication(a)
    case Active(s) => doSessionLoop(s)
  }
  frontend ! GetSession(42, cont)
}
```

CPS protocols vs. session types

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CPS protocols are **Scala types** providing **structured interaction** in Akka

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CPS protocols are **Scala types** providing **structured interaction** in Akka

But they are also:

- **low-level**, cumbersome to write (and read)
- not related with any **high-level protocol formalism**
- ambiguous about **linearity of (typed) actor references**

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Idea: if you squint a bit, CPS protocols remind the **encoding of session types into linear and variant types for standard π-calculus**
— i.e., *represent sessions in a language without session primitives*
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We develop this idea to obtain **lightweight session types in Scala**

Session vs. linear types (in pseudo-Scala)

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```

“Linear Scala”

```
def lHello(c: LinOutChannel[?]): Unit = {
  if (...) {
    val (c2in, c2out) = createLinChannels[?]()
    c.send( Greet("Alice", c2out) )
    c2in.receive match {
      case Hello(name, c3out) => lHello(c3out)
      case Bye(name)          => ()
    }
  } else {
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```

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Goals:

- define and implement linear in/out channels
- instantiate the "?" type parameter
- automate channel endpoint creation

`lchannels`: **interface**

```scala
abstract class In[+A] {
  def future: Future[A]






}

abstract class Out[-A] {
  def promise[B <: A]: Promise[B] // Impl. must be constant



}
```

Based on standard `Promise`s/`Future`s

- reuse **runtime linearity checks** and **error handling**

Note **input/output co/contra-variance**

`lchannels`: interface

```
abstract class In[+A] {
  def future: Future[A]
  def receive(implicit d: Duration): A = {
    Await.result[A](future, d)
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  def send(msg: A): Unit    = promise.success(msg)


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  def ?[B](f: A => B)(implicit d: Duration): B = {
    f(receive)
  }
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  def send(msg: A): Unit     = promise.success(msg)
  def !(msg: A)                         = send(msg)
  def create[B](): (In[B], Out[B])
}
```

Based on standard `Promise`s/`Future`s

- reuse **runtime linearity checks** and **error handling**

Note **input/output co/contra-variance**

`lchannels`: non-distributed implementation

```
class LocalIn[+A](val future: Future[A]) extends In[A]

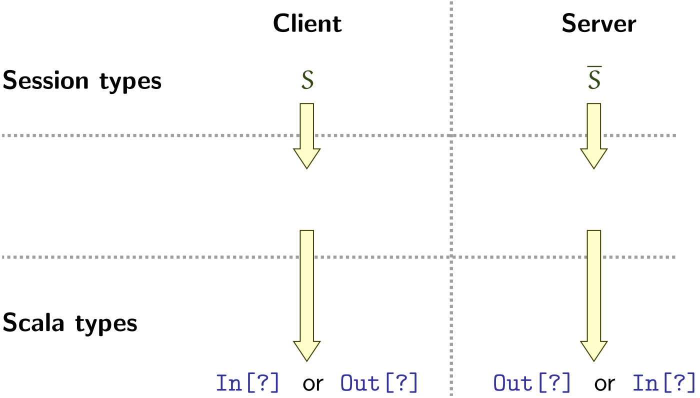
class LocalOut[-A](p: Promise[A]) extends Out[A] {
  override def promise[B <: A] = {
    p.asInstanceOf[Promise[B]] // Type-safe cast
  }
  override def create[B]() = LocalChannel.factory[B]()
}

object LocalChannel {
  def factory[A](): (LocalIn[A], LocalOut[A]) = {
    val promise = Promise[A]()
    val future = promise.future
    (new LocalIn[A](future), new LocalOut[A](promise))
  }
}
```

Just a **thin abstraction layer on top of a** `Promise`/`Future` **pair**

Session programming = In[·] / Out[·] + CPS protocols

How do we **instantiate the** In[·] / Out[·] **type parameters**?



Client

Server

Session types

S

$\overline{S}$

Scala types

`In[?]` or `Out[?]`

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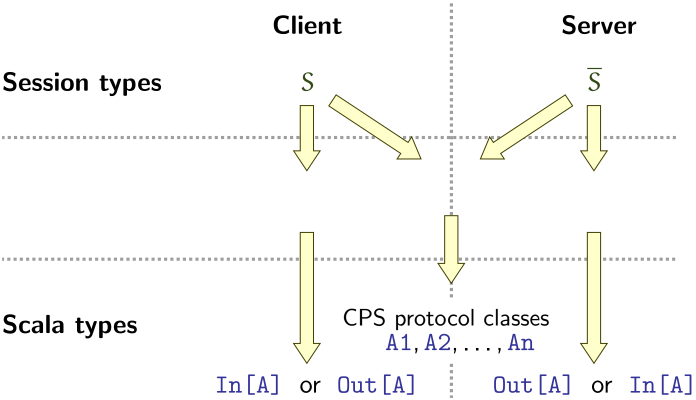

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Scala types

CPS protocol classes
`A1`, `A2`, . . . , `An`

`In[A]` or `Out[A]`

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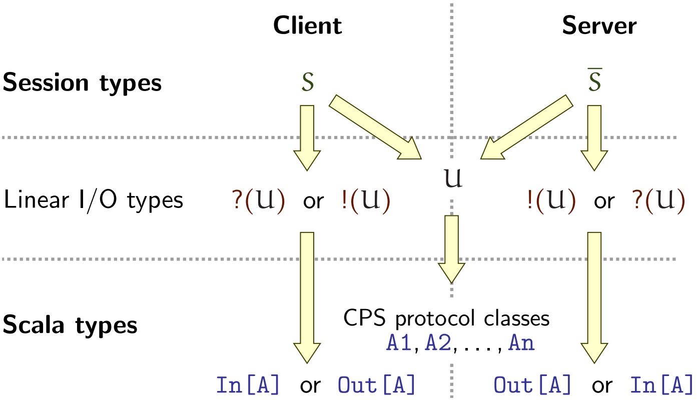

Client | **Server**

Session types S $\overline{S}$

Linear I/O types $?(U)$ or $!(U)$ U $!(U)$ or $?(U)$

Scala types

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`A1`, `A2`, . . . , `An`

`In[A]` or `Out[A]` | `Out[A]` or `In[A]`

Programming with `lchannels` (I)

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  if (Random.nextBoolean()) {
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Automating channel endpoint creation

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Let us **add the `!!` method** to `Out[·]`:

```
abstract class Out[-A] {
  ...
  def !![B](h: Out[B] => A): In[B] = {
    val (cin, cout) = this.create[A]()
    this ! h(cout)
    cin
  }
  def !![B](h: In[A] => B): Out[B] = {
    val (cin, cout) = this.create[A]()
    this ! h(cin)
    cout
  }
}
```

Programming with `lchannels` (II)

$$S_h = \mu_X.\Big(\texttt{!Greet}(\mathsf{String}).\big(\texttt{?Hello}(\mathsf{String}).X \;\&\; \texttt{?Bye}(\mathsf{String}).\textbf{end}\big) \oplus \texttt{!Quit}.\textbf{end}\Big)$$

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“Session Scala” (pseudo-code)

```
def hello(c: S_h): Unit = {
  if (...) {
    c ! Greet("Alice")

    c ? {
      case Hello(name) => hello(c)
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    }
  } else {
    c ! Quit()
  }
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sealed abstract class Start
case class Greet(p: String)(val cont: Out[Greeting]) extends Start
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```

Scala + `lchannels`

```
def hello(c: Out[Start]): Unit = {
  if (Random.nextBoolean()) {
    val c2 = c !! Greet("Alice")_

    c2 ? {
      case m @ Hello(name) => hello(m.cont)
      case Bye(name)       => ()
    }
  } else {
    c ! Quit()
  }
}
```

Run-time and compile-time checks

Well-typed output / int. choice	**Compile-time**
Exhaustive input / ext. choice	**Compile-time**

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Double use of linear input endp.	**Run-time (allowed, constant)**
"Forgotten" output	**Run-time (timeout on input side)**
"Forgotten" input	**Unchecked**

`lchannels` for distributed interaction

We have seen a **local** implementation of `lchannels`, allowing **thread interaction**

```
val (cin, cout) = LocalChannel.factory[Start]()
// cin, cout  have type  LocalIn[Start], LocalOut[Start]

spawnThread( server(cin) )
spawnThread( client(cout) )
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However, `LocalIn`/`LocalOut` instances **cannot be serialised**, and thus **cannot be sent/received** over a network

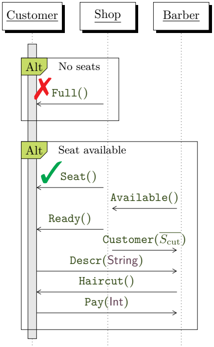
Still, `In`/`Out` can **abstract a distributed communication medium**

- we implemented interaction via **Akka actors** and **TCP/IP sockets**

Examples and case studies

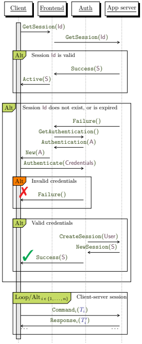
We used session types, CPS protocols and `lchannels` to implement several examples and case studies, including e.g.:

Sleeping barber



(types: ~20 LOC)

Chat server with frontend



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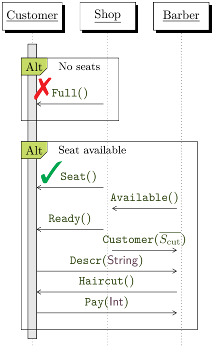

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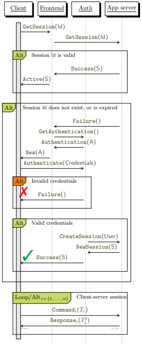
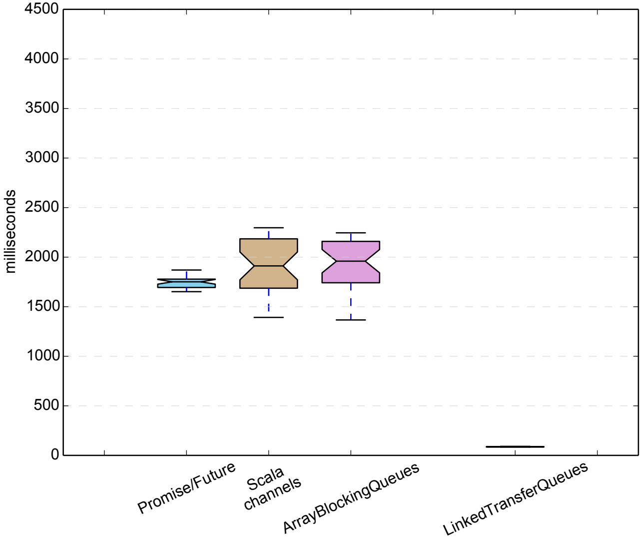


(types: ~100 LOC)

- Most typical protocol errors are **statically ruled out**
- **Timeouts** and **linearity exceptions** take care of the rest
- **Session delegation** is supported — even encouraged!

Benchmark: ping-pong (448,000 message transmissions, 30 runs)



Intel Core i7-4790 (4 cores, 3.6 GHz), 16 GB of RAM, Ubuntu 14.04, Oracle JDK 8u72, Scala 2.11.8, Akka 2.4.2

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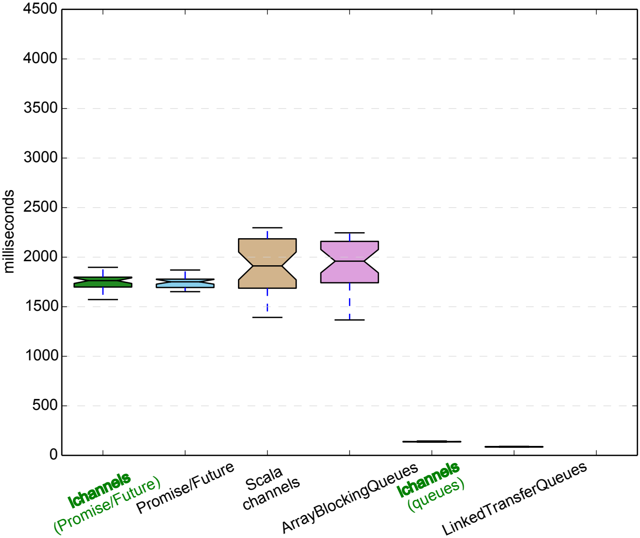

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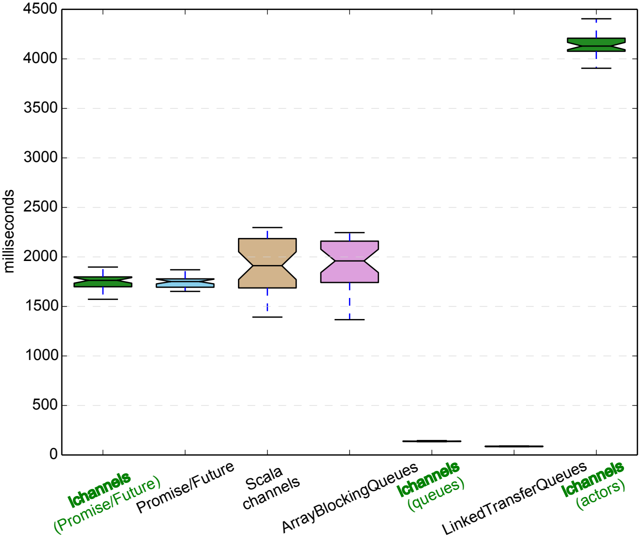

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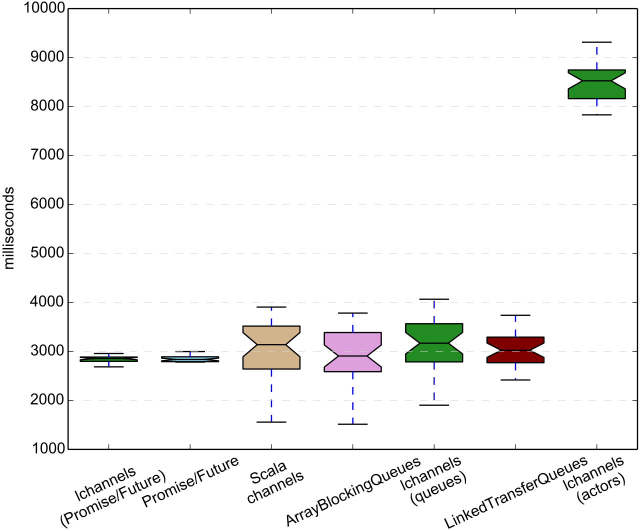
Benchmark: ring (448,000 message transmissions, 30 runs)



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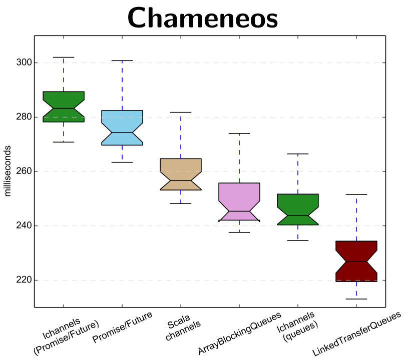
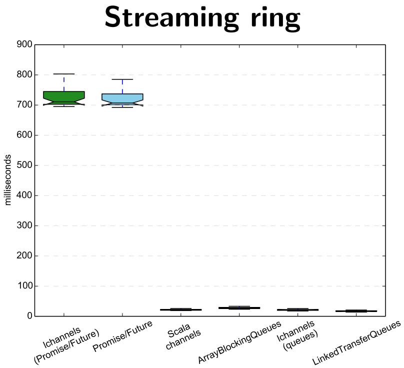
More benchmarks (448,000 message transmissions, 30 runs)



Chameneos



Streaming ring

Intel Core i7-4790 (4 cores, 3.6 GHz), 16 GB of RAM, Ubuntu 14.04, Oracle JDK 8u72, Scala 2.11.8, Akka 2.4.2

Formal properties

Theorem *(Preservation of duality).*

$\langle\!\langle \overline{S} \rangle\!\rangle_{\mathcal{N}} = \overline{\langle\!\langle S \rangle\!\rangle_{\mathcal{N}}}$ (where $\overline{\texttt{In[A]}} = \texttt{Out[A]}$ and $\overline{\texttt{Out[A]}} = \texttt{In[A]}$).

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Theorem *(Scala subtyping implies session subtyping).*
For all $S, \mathcal{N}$:

- if $\langle\!\langle S \rangle\!\rangle_{\mathcal{N}} = \texttt{In[A]}$ and $\texttt{B} <: \texttt{In[A]}$,
  then $\exists S', \mathcal{N}'$ such that $\texttt{B} = \langle\!\langle S' \rangle\!\rangle_{\mathcal{N}'}$ and $S' \leqslant S$;
- if $\langle\!\langle S \rangle\!\rangle_{\mathcal{N}} = \texttt{Out[A]}$ and $\texttt{Out[A]} <: \texttt{B}$,
  then $\exists S', \mathcal{N}'$ such that $\texttt{B} = \langle\!\langle S' \rangle\!\rangle_{\mathcal{N}'}$ and $S \leqslant S'$.

Conclusions

We presented a **lightweight integration of session types in Scala**

We leveraged **standard Scala features** (from its type system and library) with a **very thin abstraction layer** (`lchannels`)

- lower **cognitive overhead**, **integration** and **maintenance** costs
- naturally supported by **modern IDEs** (e.g. **Eclipse**)

We found a **formal connection** between **CPS protocols** and session types, based on their **encoding into linear/variant types** for standard π-calculus

We validated our session-types-based programming approach with **case studies** (from literature and industry) and **benchmarks**

Future work

Lightweight integration of **multiparty session types**, using **Scribble** to generate (more complicated) CPS protocol classes

Generalise the approach to other frameworks beyond `lchannels`, and study its properties.
Natural candidate: **Akka Typed**

Investigate other programming languages. Possible candidate: **C#** (declaration-site variance and FP features)

Thanks!

(questions?)

Session types = $\texttt{In}[\cdot]/\texttt{Out}[\cdot]$ + CPS protocols (cont'd)

$$S_{\mathsf{h}} = \mu_X.\Big(!\texttt{Greet}(\mathsf{String}).\big(?\texttt{Hello}(\mathsf{String}).X \;\&\; ?\texttt{Bye}(\mathsf{String}).\mathbf{end}\big) \oplus !\texttt{Quit}.\mathbf{end}\Big)$$

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Let us **give a name to each non-singleton int/ext choice**:

$$\mathcal{N}\left(\begin{array}{l} !\mathtt{Greet}(\mathsf{String}).\left(\begin{array}{l} ?\mathtt{Hello}(\mathsf{String}).X \\ \&\; ?\mathtt{Bye}(\mathsf{String}).\mathbf{end} \end{array}\right) \\ \oplus\; !\mathtt{Quit}(\mathsf{Unit}) \end{array}\right) = \mathtt{Start} \qquad \mathcal{N}\left(\begin{array}{l} ?\mathtt{Hello}(\mathsf{String}).X \\ \&\; ?\mathtt{Bye}(\mathsf{String}).\mathbf{end} \end{array}\right) = \mathtt{Greeting}$$

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Intermediate encoding into **linear types with variants and records**:

$$[\![S_h]\!] = !\left(\mu_X.\left[\begin{array}{l} \texttt{Greet}\_\left\{\mathrm{p} : \mathrm{String}, \mathrm{c} : !\left(\left[\begin{array}{l} \texttt{Hello}\_\{\mathrm{p} : \mathrm{String}, \mathrm{c} : !(X)\}, \\ \texttt{GoodNight}\_\{\mathrm{p} : \mathrm{String}, \mathrm{c} : \bullet\} \end{array}\right]\right)\right\}, \\ \texttt{Quit}\_\{\mathrm{p} : \mathrm{Unit}, \mathrm{c} : \bullet\} \end{array}\right]\right)$$

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$$\langle\!\langle S_h \rangle\!\rangle_{\mathcal{N}} = \texttt{Out}[\texttt{Start}]$$

Actor-based channels

`ActorIn` and `ActorOut` extend `In`/`Out`, and send/receive messages by **automatically spawning Akka Typed actors**

- they are **both serialisable** (unlike `LocalIn`/`LocalOut`)
- **distributed interaction for free!** (on top of Akka Remoting)

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For example, on one JVM:

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On **another** JVM, we can **proxy** `out` **through its Actor Path**:

```
val c = ActorOut[Start]("akka.tcp://sys@host.com/user/start")
// c  has type  ActorOut[Start]
client(c)
```

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Message	Text format
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`Quit`()	`QUIT`

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We define a `StreamManager` to read/write it (on the right)

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class HelloStreamManager(in: InputStream, out: OutputStream)
      extends StreamManager(in, out) {
  private val outb = new BufferedWriter(new OutputStreamWriter(out))

  override def streamer(x: scala.util.Try[Any]) = x match {
    case Failure(e) => close() // StreamManager.close() closes in & out
    case Success(v) => v match {
      case Greet(name) => outb.write(f"GREET ${n}\n"); outb.flush()
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  private val inb = new BufferedReader(new InputStreamReader(in))
  private val helloR = """HELLO (.+)""".r // Matches Hello(name)
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  override def destreamer() = inb.readLine() match {
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```
val conn = new Socket("host.com", 1337) // Hostname and port of greeting server
val strm = new HelloStreamManager(conn.getInputStream, conn.getOutputStream)
val c = StreamOut[Start](strm) // Output channel endpoint, to host.com:1337
client(c)
```