A Linear Decomposition of Multiparty Sessions for Safe Distributed Programming

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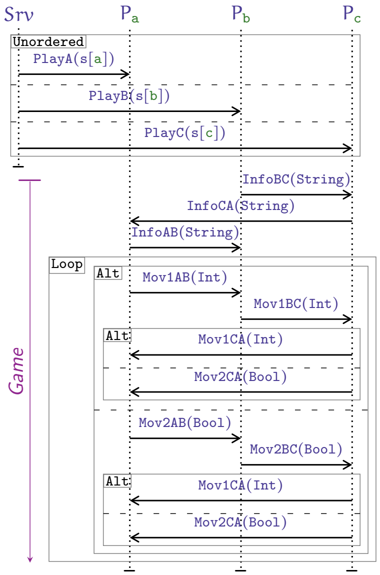
Open Problems in Concurrency Theory — Vien, 27 June 2017

Supported by the UK EPSRC grant EP/K034413/1, *From Data Types to Session Types: A Basis for Concurrency and Distribution* (ABCD)

A Motivating Example: Peer-to-Peer Game



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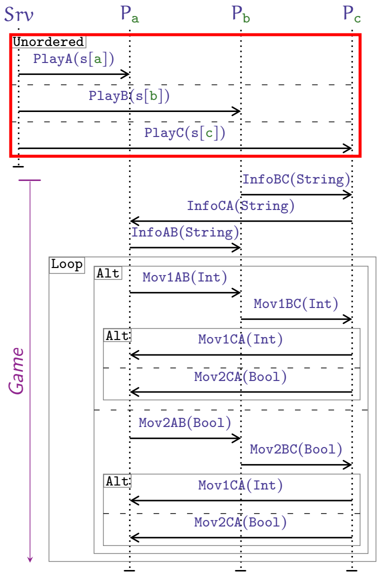

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The server $\mathcal{S}rv$ sends some networking data to the clients, so they **"know each other"**

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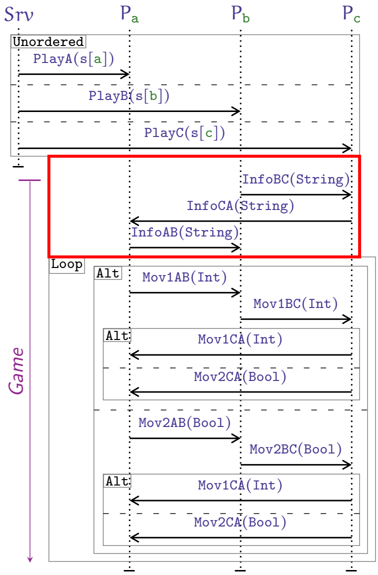

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The clients can now interact directly in a **multiparty session**: they first exchange some information...

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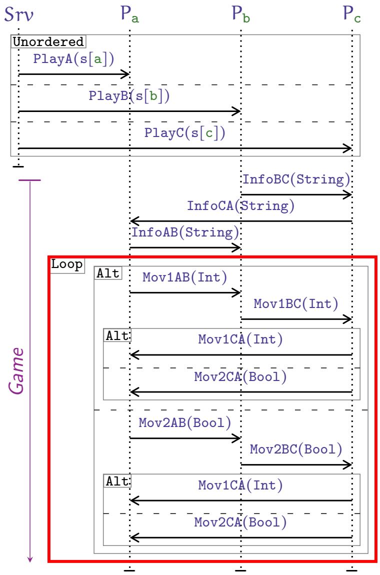

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. . . and then begin the main *Game* loop

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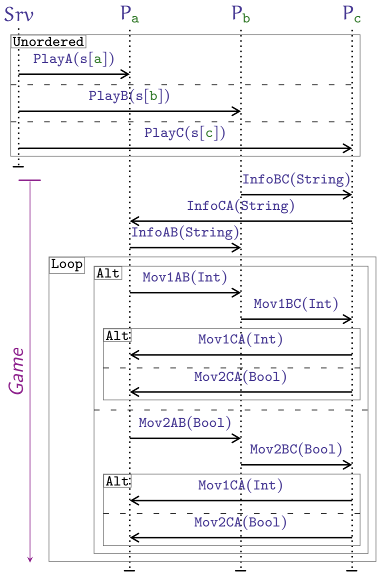

Implementing this specification is **challenging**:

- **structured protocol**
  - **choices**
  - inter-role **message dependencies**
  - **recursion**
- **non-fixed communication topology**
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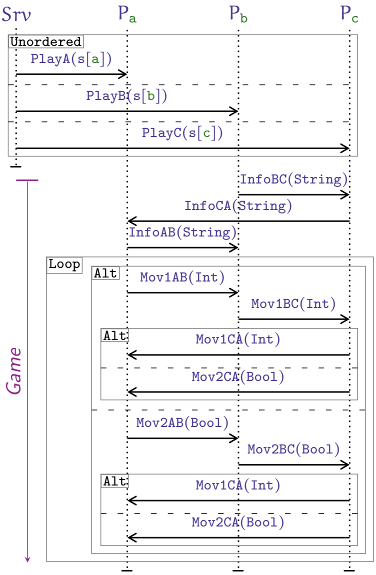

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Can we provide a **formally grounded** way to address these challenges?

Our Contribution

We leverage the **multiparty session types (MPST) theory** to turn **multiparty protocol specifications** into **Scala APIs**

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1. we **encode** the **full MPST calculus** into **linear π-calculus**
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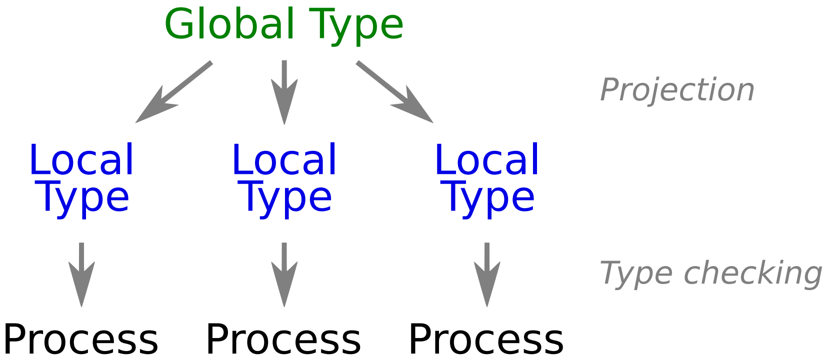
With this approach, the resulting Scala APIs:

- are **formally grounded** (exploit formal correctness properties)
- are **type-safe** (many protocol errors detected **at compile time**)
- are **choreographic** (no centralised orchestration middleware)
- **reuse existing libraries** for type-safe binary channels
- support **distributed multiparty session delegation** (first time!)

MPST Theory: Overview



(Honda *et al.*, POPL'08/JACM'16; Bettini *et al.*, CONCUR'08; Coppo *et al.*, MSCS'16)

MPST Theory: Protocols as Types

The **global type** G is the **game protocol** with **3 players** a, b, c:

$$G = b \to c{:}\mathtt{InfoBC}(\mathtt{String})\,.\,c \to a{:}\mathtt{InfoCA}(\mathtt{String})\,.\,a \to b{:}\mathtt{InfoAB}(\mathtt{String})\,.$$

$$\mu t.a \to b{:}\left\{ \begin{array}{l} \mathtt{Mov1AB}(\mathtt{Int}).b \to c{:}\mathtt{Mov1BC}(\mathtt{Int}).c \to a{:}\left\{ \begin{array}{l} \mathtt{Mov1CA}(\mathtt{Int}).t\,, \\ \mathtt{Mov2CA}(\mathtt{Bool}).t \end{array} \right\}, \\ \mathtt{Mov2AB}(\mathtt{Bool}).b \to c{:}\mathtt{Mov2BC}(\mathtt{Bool}).c \to a{:}\left\{ \begin{array}{l} \mathtt{Mov1CA}(\mathtt{Int}).t\,, \\ \mathtt{Mov2CA}(\mathtt{Bool}).t \end{array} \right\} \end{array} \right\}$$

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The **projection** $G \upharpoonright b$ yields the **(local) session type** describing how a **communication channel** should be used to play as b:

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This **client-server session type** allows **delegation** for player b (*"send or receive a channel over a channel"*):

$$\mathtt{srv}?\mathtt{PlayB}(T_{\mathsf{b}}).\mathbf{end}$$

MPST Theory: Delegation

```
val msg = sb[srv].receive()
val y = msg.payload

y[c].send(InfoBC("..."))
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loop(y)

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A process for player b, in **pseudo-Scala**

Note the **multiparty session delegation**

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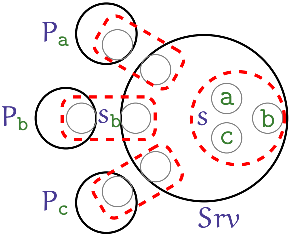

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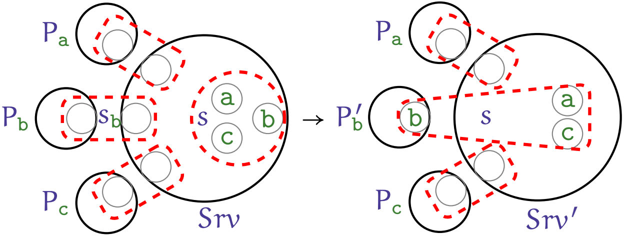

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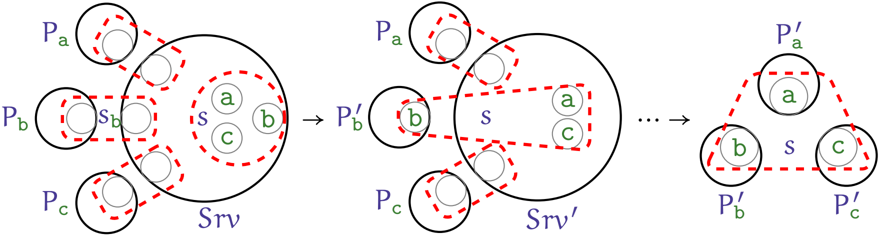

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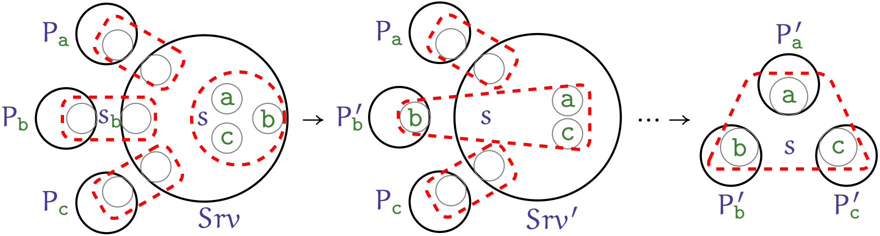

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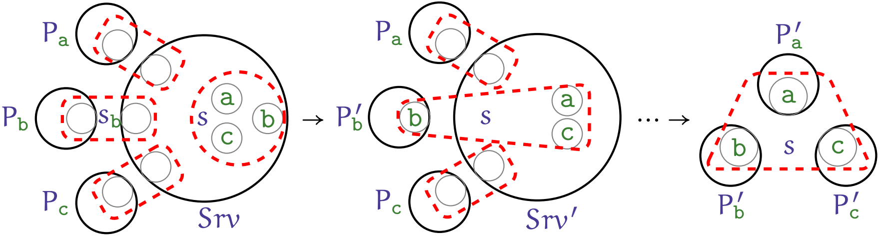
It can also check if a **set of processes** follows a **global type** G, **without deadlocks**



From MPST Theory to Practice: Challenges

MPST offer **useful modelling and verification** features. **But:**

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- the **theory is rich** and sometimes **intricate**
- calculus/types are **far from "mainstream" programming**

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2. figure out **how to implement multiparty delegation**
3. provide **types and APIs in a "mainstream" prog. lang.**

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2. figure out **how to implement multiparty delegation**
    - unsupported in existing works (Hu & Yoshida, FASE'16/FASE'17)
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A New Approach to "Practical" Multiparty Sessions

Binary Sessions

Encoding

Linear π-Calculus

Specs

Scala Types + `lchannels`

ECOOP 2016

ECOOP · Artifact · AEC · Evaluated
Consistent · Complete · Well Documented · Easy to Reuse

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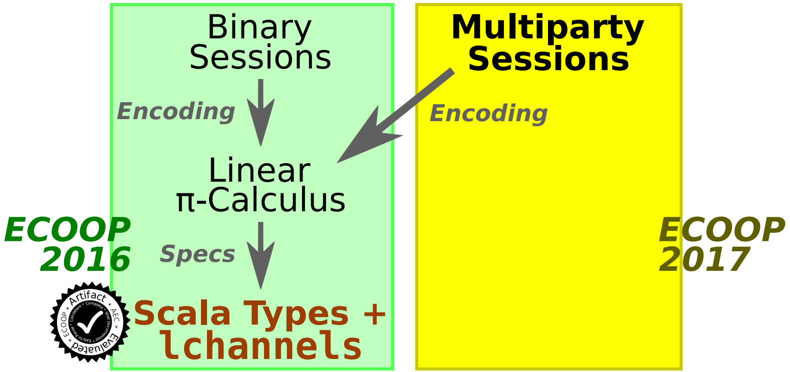

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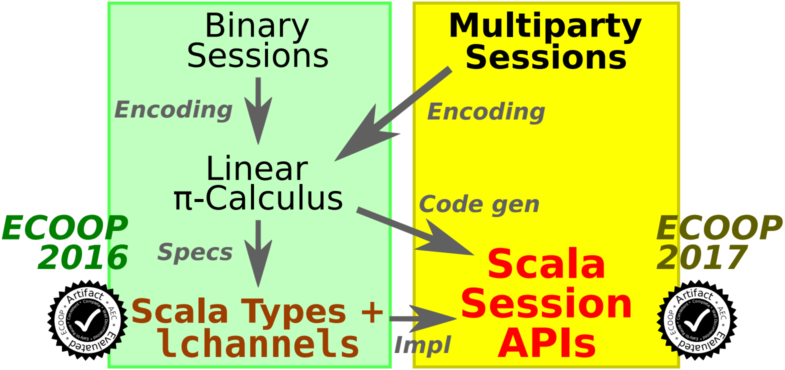
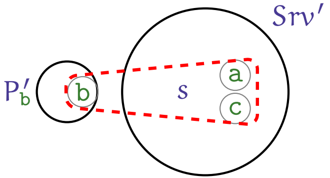


1. **encode** the **full** multiparty session calculus into **linear π-calculus**
   - π-calculus only has **binary channels**, and **no session primitives**
2. use the encoding to **guide multiparty session API generation**
   - "inherit" **correctness**, reuse **code**, better **APIs**, **delegation** for free!

A Linear Decomposition of Multiparty Sessions



$s[b] : T_b = c!\mathtt{InfoBC}(\mathtt{String}).a?\mathtt{InfoAB}(\mathtt{String})\ldots.$

We **decompose** s **into binary linear channels**, and **encode** P'_{b} and Srv' so that they use the decomposed channels **"correctly"**:

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- **channel usage ordering** must be preserved

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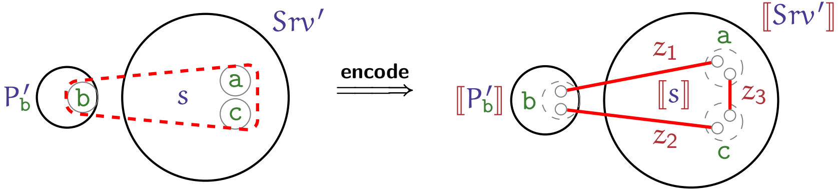

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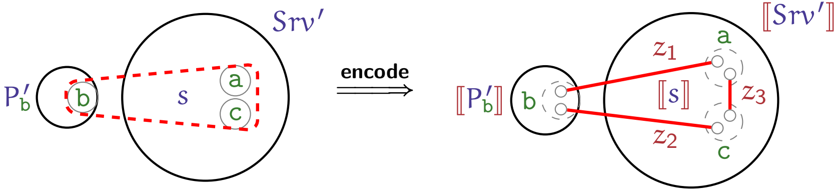

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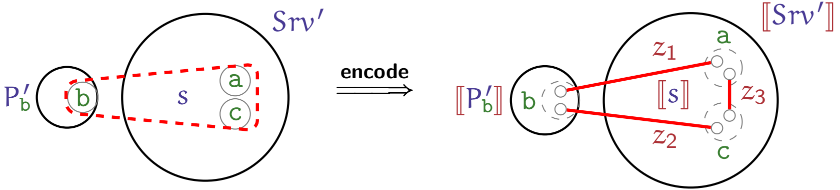

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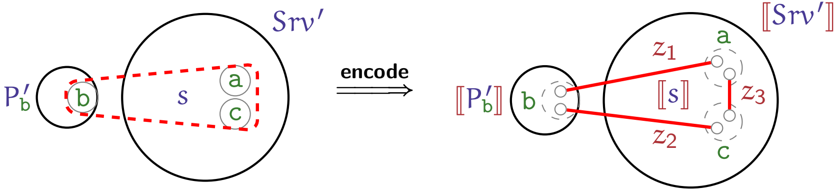

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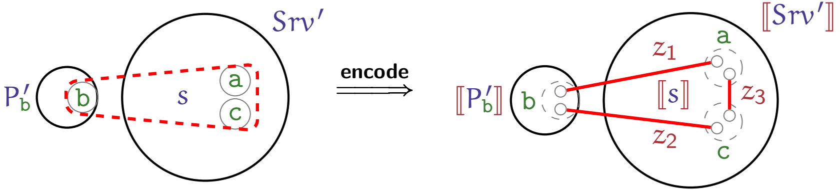

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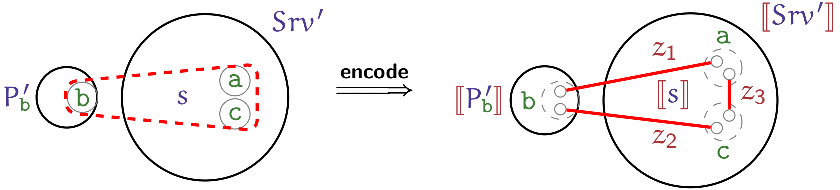

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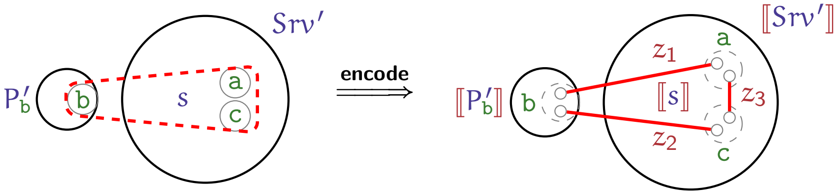
- **channel usage ordering** must be preserved

A Linear Decomposition of Multiparty Sessions



$s[\mathtt{b}] : \mathsf{T}_{\mathtt{b}} = \mathtt{c}!\mathtt{InfoBC}(\mathtt{String}).\mathtt{a}?\mathtt{InfoAB}(\mathtt{String})\ldots.$

encode $\Longrightarrow$

$$z_1 \;:\; [\![\, \mathsf{T}_{\mathtt{b}} \upharpoonright \mathtt{a} \,]\!] = \mathbf{In}\langle \mathtt{InfoAB\_}(\mathtt{String},\ \mathbf{In}\langle \ldots \rangle) \rangle$$

$$z_2 \;:\; [\![\, \mathsf{T}_{\mathtt{b}} \upharpoonright \mathtt{c} \,]\!] = \mathbf{Out}\langle \mathtt{InfoBC\_}(\mathtt{String},\ \mathbf{In}\langle \ldots \rangle) \rangle$$

$$[\![s[\mathtt{b}]]\!] = \begin{bmatrix} \mathtt{a}: z_1\,, \\ \mathtt{c}: z_2 \end{bmatrix} : \begin{bmatrix} \mathtt{a}: [\![\mathsf{T}_{\mathtt{b}} \upharpoonright \mathtt{a}]\!]\,, \\ \mathtt{c}: [\![\mathsf{T}_{\mathtt{b}} \upharpoonright \mathtt{c}]\!] \end{bmatrix}$$

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Encoding of Typed Processes

Our **process encoding**:

- is **"low-level"**, close to an **imperative prog. lang.**
- uses **binary** channels **once** with **continuation-passing style**
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$$z_c.\textbf{send}\big(\mathtt{InfoBC}(\text{"..."}\,,\, z'_I)\big);$$
$$\textbf{let } [\![s[b]]\!] = [a : z_a\,,\; c : z'_O] \textbf{ in } [\![P']\!]$$

Moreover, our encoding is **choreographic**: $[\![P \mid Q]\!] = [\![P]\!] \mid [\![Q]\!]$

- unlike previous works (Caires & Pérez, FORTE'16; Carbone *et al.*, CONCUR'16)

Formal Correctness Properties

Encoding is type-preserving. $\Gamma \vdash P$ implies $[\![\Gamma]\!] \vdash_{\pi} [\![P]\!]$.

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Operational correspondence. (Gorla, Inf. & Comput., 2010)

If $\varnothing \vdash P$, then:

1. **(Completeness)** $P \to^* P'$ implies $\exists \widetilde{x}, P''$ such that $[\![P]\!] \to^* (\nu\widetilde{x})P''$ and $P'' = [\![P']\!]$;
2. **(Soundness)** $[\![P]\!] \to^* P_*$ implies $\exists \widetilde{x}, P'', P'$ such that $P_* \to^* (\nu\widetilde{x})P''$ and $P \to^* P'$ and $[\![P']\!] \xrightarrow{\textbf{with}}{}^* P''$.

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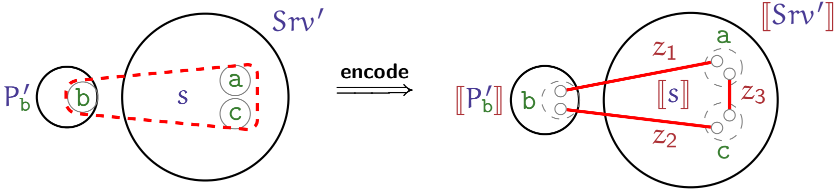
Our linear decomposition is precise!
$[\![\Gamma]\!]$ is defined *if and only if* Γ is well-formed (*"consistent"*).

- $\Longleftarrow$: we support the full MPST theory
- $\Longrightarrow$: we uncover a deep connection between MPST and π-calculus

Multiparty Channels, in Scala



$s[b]$: $T_b = c!\mathtt{InfoBC}(\mathtt{String}).a?\mathtt{InfoAB}(\mathtt{String})\ldots$

encode $\Longrightarrow$ $[\![s[b]]\!]$: $[\![T_b]\!] = \left[\begin{array}{l} a : \mathbf{In}\langle \mathtt{InfoAB\_}(\mathtt{String}, \mathbf{In}\langle \ldots\rangle)\rangle, \\ c : \mathbf{Out}\langle \mathtt{InfoBC\_}(\mathtt{String}, \mathbf{In}\langle \ldots\rangle)\rangle \end{array}\right]$

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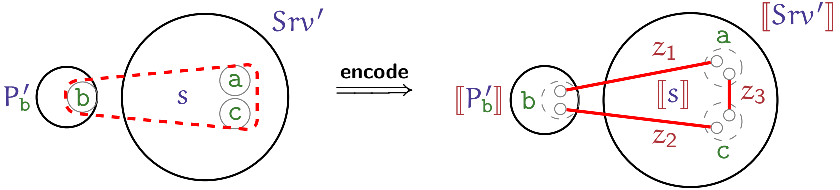

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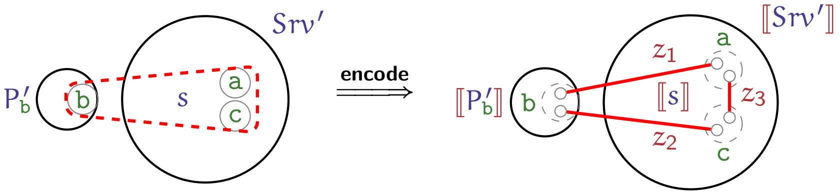
A **multiparty channel** typed by $[\![T_{\mathtt{b}}]\!]$ is a **Scala object** of type:

```
case class Tb( a:              , c:                 )
```

Multiparty Channels, in Scala



$$s[b] \;:\; T_b = \mathtt{c!InfoBC(String).a?InfoAB(String)....}$$

$$\xrightarrow{\textbf{encode}} \quad [\![s[b]]\!] \;:\; [\![T_b]\!] = \left[\begin{array}{l} \mathtt{a}:\mathbf{In}\langle \mathtt{InfoAB\_(String,}\ \mathbf{In}\langle\ldots\rangle)\rangle\,, \\ \mathtt{c}:\mathbf{Out}\langle \mathtt{InfoBC\_(String,}\ \mathbf{In}\langle\ldots\rangle)\rangle \end{array}\right]$$

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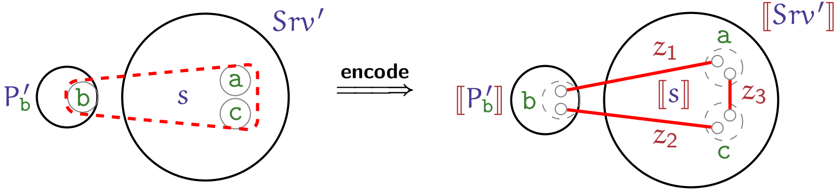

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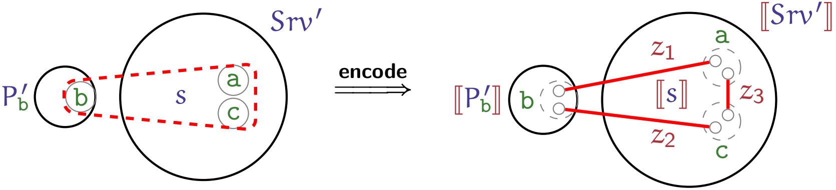
A **multiparty channel** typed by $[\![T_b]\!]$ is a **Scala object** of type:

```
case class Tb( a: In[InfoAB], c: Out[InfoBC] )

case class InfoAB( p: String, cont:In[...] )
case class InfoBC( p: String, cont:In[...] )
```

Multiparty Channels, in Scala



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case class InfoBC( p: String, cont:In[...] )
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`In[·]`/`Out[·]` are provided by `lchannels` (Scalas & Yoshida, ECOOP'16)

Tuples of channels (like s_b) can be **delegated (remotely) for free!**

Multiparty Channel Endpoints, in Scala (cont'd)

To **guide channel usage order** and **avoid deadlocks**, we **enrich channel tuples** with **typed send/receive methods**

Their implementation **is based on our process encoding**

$$T_b \quad = \quad c!\texttt{InfoBC}(\texttt{String}) \,.\, a?\texttt{InfoAB}(\texttt{String}) \,.\, \ldots$$

```
case class T_b(a: In[InfoAB], c: Out[InfoBC])
```

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```
case class Tb( a: In[InfoAB], c: Out[InfoBC] )
{
    def send(v: String) = {      // v: payload of InfoBC msg
        val c′ = c !! InfoBC(v)_ // send v, return continuation
        T′b(a, c′)               // return "continuation object"
    }
}
```

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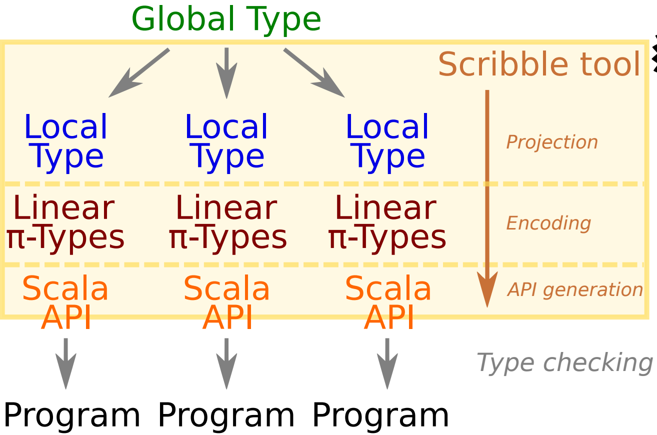
The resulting API includes **dynamic linearity checks**, and is:

- **fully type safe** (no type casts)
- **complete** (full MPSTs, incl. type projection/merge and delegation)
- **simple** (most functionality comes from `lchannels`)
- **mechanical** (so we can generate it **automatically!**)

Artifact: Scala API Generation in Scribble

We extended the **Scribble protocol verification tool** to **autogenerate Scala APIs**, following our formal encoding



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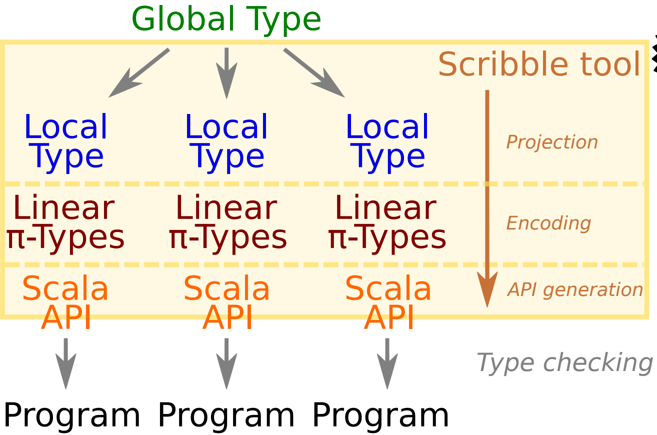

Tutorial and examples: peer-to-peer game, HTTP server. . .

Artifact: Scala API Generation Usage

A **working implementation** of a client playing the game as b, based on our Scribble-generated APIs

```
def client(c: MPPlayB) = { // "c" is the channel to the game server
  val g = c.receive().p // Receive multiparty game channel

  val i = g.send(InfoBC("...")).receive() // Send info to C, recv from A
  loop(i.cont) // Game loop
}

def loop(g: MPMov1ABOrMov2AB): Unit = {
  g.receive() match {                  // Check A's move
    case Mov1AB(p, cont) => {
      val g2 = cont.send(Mov1BC(p)) // cont only allows to send Mov1BC
      loop(g2)                      // Keep playing
    }
    case Mov2AB(p, cont) => {
      val g2 = cont.send(Mov2BC(p)) // cont only allows to send Mov2BC
      loop(g2)                      // Keep playing
} } }
```

Artifact: Scala API Generation Usage

A **working implementation** of a client playing the game as b, based on our Scribble-generated APIs with **static protocol checks**

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def loop(g: MPMov1ABOrMov2AB): Unit = {
  g.receive() match {                  // Check A's move
    case Mov1AB(p, cont) => {
      val g2 = cont.send(Mov2BC(true)) ✗ // cont                    1BC
      loop(g2)                         // Keep pl
    }
    case Mov2AB(p, cont) => {
      val g2 = cont.send(Mov2BC(p)) // cont only allows to send Mov2BC
      loop(g2)                      // Keep playing
} } }
```

Type mismatch
found: Mov2BC
required: Mov1BC

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    }
  ✗
} }
```

Match may not be exhaustive

It would fail on the input: `Mov2AB(_,_)`

Conclusions

We presented the **first choreographic encoding** of the **"full" MPST calculus** into **linear π-calculus**

- key: **type-preserving decomposition into linear π-types**
- important achievement since *Session Types Revisited*

  (Dardha, Giachino, Sangiorgi. PPDP'12)

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Our encoding gives the **formal basis** for a **complete implementation of multiparty sessions**, in Scala + `lchannels`

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Future work:

- adapt to **other languages and binary session implementations**
  - Haskell, OCaml, Rust, ... (might not support distribution)
- **reuse and compare theoretical results and tools**
  - e.g., **deadlock freedom** (with **interleaved sessions**)
    - MPSTs (Bettini, Coppo *et al.*, CONCUR'08 ...)
    - π-calculus, with TyPiCal tool (Kobayashi *et al.*, CONCUR'06 ...)

Thank you!

Try Scribble and `lchannels`!

http://scribble.org

http://alcestes.github.io/lchannels

ECOOP 2016

ECOOP 2017