Choreographies for Reactive Programming

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Abstract

Modular programming is a cornerstone in software development, as it allows to build complex systems from the assembly of simpler components, and support reusability and substitution principles. In a distributed setting, component assembly is supported by communication that is often required to follow a prescribed protocol of interaction. In this paper, we present a language for the modular development of distributed systems, where the assembly of components is supported by a choreography that specifies the communication protocol. Our language allows to separate component behaviour, given in terms of reactive data ports, and choreographies, specified as first class entities. This allows us to consider reusability and substitution principles for both components and choreographies. We show how our model can be compiled into a more operational perspective in a provably-correct way, and we present a typing discipline that addresses communication safety and progress of systems, where a notion of substitutability naturally arises.

1 Introduction

In Component-Based Software Engineering (CBSE), software is built by composing loosely-coupled components. The hallmark of CBSE is reusability: the same component can be taken “off the shelf” and reused in many different systems, as long as it is used accordingly to its interface [17].

Recently, CBSE is experiencing a renaissance. One reason is that it adapts well to the complexity of modern computing paradigms, like cloud computing, where building software whose components can be deployed on separate computers is an advantage. The extreme of this method is the emerging development paradigm of microservices, where all components are autonomous and reusable services (the microservices) that communicate through message passing [12]. Another reason is that programming techniques such as reactive programming, where computation is performed in response to newly available data, are becoming mainstream and make easier the development of responsive components (e.g., as in services or graphical user interfaces).

In settings where components exchange messages, e.g., microservices, communications are expected to follow some predefined protocols. Protocols are typically expressed in terms of some choreography, an “Alice and Bob” description that prescribes which communications should take place among participants, and in which order. Choreography specifications can be found in the Web Services Choreography Description Language by the W3C [26] and in the Business Process Modelling Notation by the Object Management Group [6]. Message Sequence Charts can also be seen as early choreography models [15].

To implement its role in a protocol, a component must implement a certain sequence of I/O actions. A direct way of achieving this is to use a language that natively supports sequencing I/O, like a workflow language (e.g., the Business Process Execution Language [27]) or languages with actor- or process calculus-like constructs (e.g., Erlang [3] or Jolie [20]). Then, we can check that the sequence of I/O actions for each protocol used by a program follows the correct order [14].

Unfortunately, this way of proceeding hinders reusability, in that a component can then be used only in environments that accept exactly the sequence of I/O performed by it. This makes the whole method depend on how future protocols are designed. For example, assume that we design a protocol where a component receives a number and then must output its square root exactly once. What if, tomorrow, we need to use this component in an context that requires computing a square root twice?

Reactive programming addresses this kind of problems by defining behaviour in response to external stimulus. For example, we can design a component that outputs the square root of a received number whenever requested. Thus reusability is better. However, here we lose the clear connection to the notion of protocol, since reactive components can be “too wild”. What if the designer actually cares about the fact that the
component for computing the square root is invoked exactly once or twice (maybe for resource reasons)? En-
forcing this kind of constraints usually requires obscure bookkeeping or side-effects, making programming
error-prone and verification challenging.

In this paper, we attempt at having the best of both worlds. We propose a new language model, called
Governed Components (GC), where reactive programming is married to choreographic specifications of com-
munication protocols. We believe that our results represent a first fundamental step towards merging the
flexibility of reactive programming with the necessity of generating provably-correct I/O behaviour in com-
municating systems.

In GC, the computation performed by components is defined in the reactive style, using binders that
dynamically produce results as soon as they get the input data that they need. The key novelty is then in
how components can be composed: a composition of components is always associated to a protocol,
given as a choreography, that governs the flow of communications among the components. This means that,
among all the possible reactions supported by the composed components, only those that are allowed by the
protocol are actually executed. The composition of some components is itself a component which can be
used in further compositions. We study the applicability of GC by formally defining a compiler from GC to
a model of concurrent processes with standard I/O primitives. The compiler translates the protocols used in
compositions to a distributed process implementation, illustrating how GC can be used in practice. We prove
that the compiler preserves the intended semantics of components, through an operational correspondence
result.

Thanks to the marriage of reactive programming and protocol specifications, GC supports a new in-
teresting substitution principle that is not supported by previous models based on processes (like [14]): a
component may be used in compositions under different protocols, as long as the reactions supported by the
component are enough to implement its part in the protocols. This principle improves reusability in different
directions. One example is abstraction from message ordering: if a component needs two values to perform a
computation, it can be used with any protocol that provides them without caring about the order in which the
protocol will make them arrive. Another example is abstraction from the number of reactions: if a component
can perform a computation in reaction to some data inputs, then it can be used with different protocols that
require such computation different numbers of times (e.g., zero, exactly two, or an unbounded number of
times). We first present our model and informally illustrate the semantics with a series of examples. Then,
we define a typing discipline that is sound with respect to the substitution principle. In other words, typ-
ing guarantees that each component provides at least enough reactive behaviour as needed by the protocol
that it participates in, which we use to prove that well-typed component systems enjoy progress (never get
stuck). From our operational correspondence result, it follows that also concurrent processes compiled from
well-typed GC programs never get stuck. We end our development by presenting a preliminary formal in-
vestigation of a sound subtyping relation for our typing, which captures part of the sound substitutions in our
model.

2 Language Preview

We informally introduce our language by revisiting the Buyer-Seller-Shipper example (BSS) [13, 14]. This
example consists of a Buyer sending a purchase request for some item to a Seller. Seller reacts by sending
back the price of the item. Based on the received price, Buyer either accepts or rejects the offer. In the
first case, both Seller and a third-party delivery service Shipper are notified by Buyer which will end the
transaction by sending its credit card details to Seller and its delivery address to Shipper. If Buyer rejects the
offer, the protocol ends.

Choreographically, the behaviour of the BSS protocol can be written as follows:

\[ G_{BSS} = \begin{array}{c}
Buyer \xrightarrow{\text{prod}} \text{Seller}; \\
\text{Seller} \xrightarrow{\text{price}} \text{Buyer}; \\
\text{Buyer} \xrightarrow{\text{decision}} \text{Shipper, Seller, Buyer}(\text{Buyer} \xrightarrow{\text{cc}} \text{Seller}, \text{Buyer} \xrightarrow{\text{dst}} \text{Shipper, end})
\end{array} \]

The protocol above describes the expected interactions between roles Buyer, Seller and Shipper. For example,
Buyer \xrightarrow{\text{prod}} Seller says that Buyer must send a message labeled as \text{prod} to Seller. In the last line, Buyer
can take the decision whether to accept or not the purchase. Here, the protocol branches to two different
subprotocols: it either proceeds with the payment or terminates.

If we were to implement a system ruled by the protocol above, we may use off-the-shelf modules im-
plementing the various roles, provided that they comply with the BSS protocol. For example, Buyer could be
implemented by the following component \( G_{\text{Buyer}} \), where the Buyer role annotation is a mere graphical
friendly annotation since our components are anonymous for the purpose of reuse:
The one above is an informal but intuitive graphic representation of the formal syntax which will be introduced in the next section. The component has an interface, denoted by \([x \rightarrow y_1, y_2, y_3, y_4]\), specifying that it can always receive values on the input port \(x\) and may output values on output ports \(y_1, y_2, y_3,\) and \(y_4\). Local binders (dashed lines) define how such values are provided. For example, the local binder \(y_4 = \text{"Varapodio, Italy"}\) says that output variable \(y_4\) is constantly able to output the value (address) "Varapodio, Italy" and \(y_2 = \text{if (x < 50)} \text{inl else inr}\) is able to output a choice decision based on the value received on input variable \(x\), where \text{inl} and \text{inr} indicate a left or a right choice. In the case of \(y_2\), the component is able to output a decision for each value received on \(x\).

Similarly, we could implement Seller and Shipper with the components \(C_{\text{Seller}}\) and \(C_{\text{Shipper}}\):

![Diagram of Seller and Shipper components](image)

Seller is a component that can always input on the three ports \(x'_1, x'_2,\) and \(x'_3\) and, for every message received on \(x'_1\) it can output on \(y'\) the value \(\text{price}(x'_1)\), where \(\text{price}\) is a local function. Shipper, instead, only specifies the input receptiveness on \(x'_1\) and \(x'_2\).

The three components seen above are called base components. Using the BSS protocol, we can assemble them together, obtaining the following composite component:

![Diagram of composite component](image)

The composite component above has three main ingredients: the protocol \(G_{\text{BSS}}\) that governs the internal communications, the subcomponents \(C_{\text{Buyer}}, C_{\text{Seller}},\) and \(C_{\text{Shipper}}\) that implement the roles in the protocol, and connection binders (full lines). The latter link outputs ports of a component to input ports of other components. For example, the binder \(x \xleftarrow{\text{price}} \text{Seller}\) connects Seller’s output port \(y'\) to Buyer’s input port \(x\); here is how we ensure that the price given by Seller reaches Buyer, while decoupling the choreography specification from the actual ports used in the implementation.

Now, suppose that we wish to replace the base component implementing Seller with a composite component that contains a Sales department and a Bank:

![Diagram of composite component with Sales and Bank](image)

The composite component above differs from the composite component previously seen. First, it has a non-empty interface identical to that of \(C_{\text{Seller}}\). Second, it has a special role \(\text{Sales}\) that, apart from interacting in the internal choreography, also deals with messages originating/directed from/to the external interface. This is done through forwardsers (dotted lines) that link the interface of Sales with the external interface, yielding encapsulation. For example, one of Sales’s input ports is linked to the interface variable \(x'_1\) meaning that any external request for a product is immediately forwarded. Similarly, any output on Sales’s top output port is forwarded to the output port \(y'\). We remark that Sales specifies an input port that is actually used in two local binders, one directed to the output port \(y'\) while the other is directed to message \(\text{val}\). The other role Bank is implemented by a component \(C_{\text{Bank}}\) which we leave unspecified. The component is governed by the protocol \(G_{\text{Shop}}\), defined as:

\[
\text{Sales} \xrightarrow{\text{buy}} \text{Bank}(\text{Sales} \xrightarrow{\text{val}} \text{Bank}; \text{Sales} \xrightarrow{\text{ccnum}} \text{Bank}, \text{end})
\]
3 A Language for Modular Choreographies

We now move to the formal presentation of the syntax and semantics of Governed Components (GC). The syntax of terms is displayed in Fig. 1. Programs in GC are components, denoted $C$. Components communicate over the network by using ports, ranged over by $x, y, u, z, w$. A component is either a base component or a composite component. In both base and composite components, the definition of the component consists of two parts: an interface $[\tilde{x} \, \tilde{y}][L]$, which defines a series of input ports $\tilde{x}$—used for receiving values from other components—and a series of output ports $\tilde{y}$—used for sending values to other components; and an implementation (in curly brackets, $\{\cdots\}$), which determines how ports are going to be used and how internal computation is performed.

A base component term $[\tilde{x} \, \tilde{y}][L]$ denotes a component with interface $[\tilde{x} \, \tilde{y}]$ and an implementation that consists solely of some local binders $L$. A local binder $y = f(\tilde{x})$ is a reactive construct, in the sense that it performs a computation in response to incoming messages on the ports $\tilde{x}$. Intuitively, whenever all of its parameters can be instantiated by receiving values on its input ports $\tilde{x}$, the value computed by function $f$ will be sent through the output port $y$. We abstract from how functions are defined, and assume that they can be computed when supplied with the required parameters ($\tilde{x}$).

A composite component term $[\tilde{x} \, \tilde{y}][G; R; D; \tau[F]]$ denotes a component obtained by composing other components. We explain each subterm separately. The protocol $G$ prescribes how the internal components are going to interact. A protocol is a global description of communications among roles, ranged over by $p, q, r$. In a communication term $p \xrightarrow{\ell} \tilde{q}; G$, role $p$ communicates some value to the roles $\tilde{q}$ (we assume $\tilde{q}$ to be nonempty) and then proceeds as protocol $G$. In term $p \xrightarrow{\ell} \tilde{q}(G_1, G_2)$, role $p$ communicates to roles $\tilde{q}$ its choice of proceeding either according to protocol $G_1$ or $G_2$. All communications are labelled with a label $\ell$, which uniquely identifies the communication step in the protocol. Terms $\mu X.G$ and $X$ are for, respectively, defining recursion variables and their invocation. Term $\text{end}$ is the terminated protocol.

Given a protocol $G$, we need to define the implementation for each role in the protocol. This is done in the subterm $R$. Specifically, $p = C$ assigns the component $C$ as the implementation for role $p$. Once both protocol and implementation of each role are given, we define how each communication in the protocol is going to be realised by the implementing components. This is covered by the connection binders $D$. A connection binder $p.x \xleftarrow{\ell} q.y$ connects the input port $x$ of (the component implementing) role $p$ with the output port $y$ of (the component implementing) role $q$. The label $\ell$ in the connection binder declares which communication in the protocol of the composite component will be realised by the message exchange enacted by the binder. This will be key to defining the dynamics of composite components. The intuition is that when the protocol of a composite component prescribes a communication with label $\ell$, the composite component will enact the communication according to the specification of the connection binder with the same label: by taking a message available from the output port of the role on the right to the input port of the role on the left of the binder.

\begin{itemize}
  \item Components $C ::= [\tilde{x} \, \tilde{y}][L]$ base
  \item Local binders $L ::= y = f(\tilde{x})$ composite
  \item Protocols $G ::= p \xrightarrow{\ell} \tilde{q}; G$ communication
  \item Connection binders $D ::= p.x \xrightarrow{\ell} q.y$ implementation
  \item Forwards $F ::= z \leftrightarrow w$
\end{itemize}

Figure 1: Governed Components, Syntax
The last subterm—\(r \cdot F\)—instead, serves the purpose of defining externally-observable behaviour. Namely, it allows the internal component \(r\) to interact with the external context of the composite component through the ports of the latter. This is obtained by defining appropriate forwarders \(F\), of the form \(z \leftarrow w\). The syntax can be used to specify two kinds of forwarders that can either forward inputs or outputs, depending on the port names of the composite component. An input forwarder binds an input port of the internal component \(r\), say \(x\), to an external input port of the composite component, say \(x'\), written \(x \leftarrow x'\). This means that all incoming messages at \(x'\) from the outer context of the composite component will be made available to the sub-component implementing role \(r\) at its input port \(x\). Dually, an output forwarder binds an output port, say \(y\), of the internal component to an output port of the composite component, say \(y'\), written \(y' \leftarrow y\). This makes all output messages from the sub-component sent through \(y\) available to the outer context of the composite component through \(y'\). Notice that the flow of messages in a forwarder is always from right to left (\(\leftarrow\)). In the remainder, we abstract from ordering in \(L, R, D\), and \(F\) (implicit exchange).

### 3.1 Semantics

We give an operational semantics for GC in terms of a labelled transition system (LTS). We write \(C \xrightarrow{\lambda} C'\) when there is a transition from \(C\) to \(C'\) with label \(\lambda\). Labels can denote: (i) the output of a value \(v\) through a port \(y\), written \(y \downarrow v\); (ii) the input of a value \(v\) through a port \(x\), written \(x ?? v\); and (iii) an internal move, written \(!\). The syntax of labels is thus: \(\lambda ::= y \downarrow v | x ?? v | !\). We present the rules that define \(\rightarrow\) in two parts, respectively for base and composite components.

#### 3.1.1 Base components.

The rules defining the semantics of base components are displayed in Fig. 2. Rule OutBase states that if the local binders \(L\) in a base component can produce a value \(v\) for one of the output ports of the components \(\tilde{y}\), then the component performs the corresponding output. Rule InpBase is similar, but models inputs instead.

The other rules, whose names start with \(L\), define the semantics of local binders, which are used by base components to perform computation. The key idea is that a local binder \(y = f(\tilde{x})\) can generate an output value for \(y\) when a value for each \(x\) in \(\tilde{x}\) has been received, as required by \(f\). Since we may need to receive on more than one input port before we can compute \(f\), we augment the syntax of local binders to runtime queues of value stores: \(L ::= y = f(\tilde{x}) (\tilde{\sigma} \mid L, L)\). A store \(\tilde{\sigma}\) is a partial mapping from ports to values, which we use to store incoming messages until we have enough values to compute \(f\). In the remainder, we use \(y = f(\tilde{x})\) in programs as a shortcut for \(y = f(\tilde{x}) (\cdot\), where \(\cdot\) is the empty sequence. We write \(f(\tilde{v}) \downarrow v\) for "computing \(f\) by instantiating its parameters with the values \(\tilde{v}\) yields the value \(v\)"; abstracting from the concrete definition of function evaluation (\(\cdot\)).

Rule LConst is the rule for binders that require no inputs (the function has no parameters), and thus can always output the value computed by the related function. Rule LOut is the output rule for local binders with
functions that require parameters (we assume $\bar{x}$ nonempty in this rule, to distinguish from rule LConst). It states that if all parameters ($\bar{x}$) of the function $f$ in the binder are instantiated by the first store available in the queue, then we can output the value computed by the function.

Rules LInpNew and LInpUpd receive a value for an input port used by a local binder. Rule LInpNew is used for creating a new store (all current stores already have a value for the port on which we receive). Note that $\sigma$ may be empty, so this could be the first store that we are creating in the queue of the binder. Specifically, we write $\{x \mapsto v\}$ for the store with a single mapping, from $x$ to $v$. Rule LInpUpd deals with receiving a value in a store that already exists. We check that all stores before the one that we are going to update already have a value for the port $x$ that we are receiving from $(x \in \{x \mapsto v\})$, and that the store $\sigma$ that we are updating ($\{x \mapsto v\}$) does not have a value for $x$ yet ($x \not\in \text{dom}(\sigma)$)—this gives us the first store in the queue without a value for $x$. Rule LInpDis discards inputs on ports that are not needed by a local binder.

Rule LOutLift lifts outputs to groups of binders (if a binder can output a value, so can the group of binders). Rule LInpList states that whenever we can receive a value for an input port, all binders are allowed to react to it.

**Example 3.1.** Let us consider the base component $C_{\text{Seller}}$ from page 3. Clearly, by applying rules LInpNew and LInpBase, a new message is added to the queue of $x'_1$. Then, we can use rules LOut and OutBase to output on $y'$.

### 3.1.2 Composite Components.

We now move to the semantics of composite components. The rules are displayed in Fig. 3.

The key rules are OutChor and InpChor, which allow internal components (those inside of the composite) to interact. Rule OutChor allows an internal component to send a message to another internal component. In the first premise, we require that the sender component can output some value, $v$, over some port, $u$ ($C \xrightarrow{u,v} C'$). In the second premise, we check that port $u$ at the role of the sender component ($p$) is connected (through a connection binder) to a port of some other (role of $a$) component ($\tilde{D} = q,z \xleftarrow{\ell} p,u,\tilde{D}'$). In the third premise, we check that the protocol of the composite allows for the message to be sent. This is formalised by the protocol transition $G \xrightarrow{p(v)} G'$, which reads “the protocol prescribes a message send from role $p$ for interaction $\ell$ carrying value $v$”. We give the formal rules for protocol transitions below. Rule InpChor is similar to rule OutChor, but models inputs instead of outputs. The premises are equivalent, only now they require labels for input actions instead of output actions, and the receiving component must be assigned to the receiver role of the connection binder instead of the sender role.

Rule Internal is standard and allows for internal actions in sub-components. Rules OutComp and InpComp capture externally-observable behaviour. OutComp allows the internal component that can interact with the environment (that with the role declared in the last subterm, $r$ in the rule) to fire an external output on one of the ports of the composite. The renaming specified by the forwarder in $\tilde{F}$ is applied to convert the port name of the internal component to one of the output ports in the interface.
of the composite, since the environment expects outputs from the composite on one of such ports. Similarly, \text{InpComp} applies the same reasoning to externally-observable inputs.

Our semantics abstracts from the concrete rules that are used to derive protocol transitions—we need protocol transitions in rules \text{OutChor} and \text{InpChor}. We only need that such transitions have labels that are either of the form $pl(\ell(v))$ (read “role $p$ sends value $v$ on interaction $\ell$”) or of the form $p?l(\ell(v))$ (read “role $p$ receives value $v$ on interaction $\ell$”). We use $\alpha$ to range over these labels in the remainder. However, if we want to reason about the behaviour and meta-theoretical properties of components (as we are going to do in the remainder), we need to fix a semantics for protocols. We adopt an unsurprising one, by adapting the asynchronous semantics of choreographies from \cite{8,12,10} to our setting. This method requires augmenting the syntax of protocols with runtime terms (i.e., they are not intended to be used by programmers using our model, only by our semantics) to store intermediate communication states, as follows:

$$G ::= \ldots | \ell.v \to q; G | \ell.v \to \bar{q}(G_1, G_2)$$

The terms above denote intermediate states where a message has been sent by the sender but still not received by the receiver (the first term is for a value communication, the second for a choice). Given the augmented syntax for protocols, their semantics is given by the rules displayed in Fig. 4.

Rule \text{GSVal} models outputs: an interaction labelled $\ell$ from a role $p$ to many roles $q$ can transition with label $pl(\ell(v))$ to the runtime term $\ell.v \to \bar{q}$. The runtime term registers that, on communication $\ell$, there is now an in-transit value $v$ that still has to be received by the roles $q$. Rule \text{GSChoice} is similar, but for choices. In particular, we require the transmitted value to be one of the two constants $\inl$ and $\inr$, since this value should inform the receivers of which continuation branch has been chosen by the sender ($G_1$ or $G_2$, respectively).

Rule \text{GRVal} models input: if there is an in-transit message, this can be consumed by one of the intended receivers. Similarly for choices, in rule \text{GRChoice}. When there remains only one intended receiver, the protocol proceeds with the intended continuation, as specified by rules \text{GRVal2} and \text{GRChoice2}. Observe that, for choices, the value is used to determine which branch should be used to continue ($\inl$ goes left, $\inr$ goes right). Rule \text{GRec} captures recursion in the standard way.

The rules prefixed with \text{GConc} model concurrent and asynchronous execution of protocols, recalling full $\beta$-reduction in $\lambda$-calculus. In these rules, we use the function role to extract the subject of a label. Formally: $\text{role}(pl(\ell(v))) = \text{role}(p?l(\ell(v))) = p$. Then, the \text{GConc} rules cover all possible cases where the continuation of a protocol can execute an action that does not involve a role in the prefix of the protocol. Whenever this is the case, the continuation is allowed to make the transition without affecting the prefix. Intuitively, consider that...
two interactions that involve separate roles are non-interfering.

**Example 3.2.** Let us consider the BSS protocol implementation previously described in pag. 3. Since $C_{Buyer} \xrightarrow{y_1} \text{"The Winds of Winter"} C'_{Buyer}$ (for some $C'_{Buyer}$) and $G \xrightarrow{prod, \text{"The Winds of Winter"}} G'$, we have that the whole component can reduce by rule OutChor because of the connection binder $\xrightarrow{prod} \text{Seller}.x' \xleftarrow{Buyer.y_1}$. The new protocol $G'$ is obtained by replacing $G$’s first interaction with $\xrightarrow{prod, \text{"The Winds of Winter"}} \text{Seller}$.

For the purpose of the following sections and in order to simplify presentation we only consider well-formed components where certain simple structural constraints are valid, namely: (1) output ports and input ports are disjoint sets; (2) a port can only be defined (lhs) once in local binders; (3) composite components specify choreographies where sender is never included in receivers; (4) forwarders given in composite components are defined for distinct port identifiers; (5) composite components specify connection binders where receiver ports are used at most once and sender ports are always used together with the same message label.

### 3.2 Examples

We now describe a series of examples that inform on the semantics of our model.

**Example A.** Let us consider a protocol where a role $p$ communicates a decision to another role $q$ which then replies with different messages according to such decision:

$$G = p \xrightarrow{l_1 \rightarrow} q (q \xrightarrow{l_2 \rightarrow} p, q \xrightarrow{l_3 \rightarrow} p)$$

We then consider the following component (dummy, for the sake of illustration):

Notice that the internal decision ($l_1$) actually originates from the external interface (port $x$). In this case, we can see how the inner protocol $G$ refines the internal behaviour, since an output will be observable from only one of the external ports $y_1$ and $y_2$, given the decision on $x$ and the fact that either message $l_2$ or $l_3$ is passed. This pattern is not possible to capture using a base component.

**Example B.** We now briefly change the protocol from the previous example, where $p$, based on the decision communicated to $q$, sends different messages to $q$:

$$G = p \xrightarrow{l_1 \rightarrow} q (q \xrightarrow{l_2 \rightarrow} p, p \xrightarrow{l_3 \rightarrow} p)$$

We may design a component where $p$ sends constants to $q$ which are forwarded to $y_1$, $y_2$, and $y_3$:

Note that, depending on value emitted on $y_1$, there may be a value available to be sent on $y_2$ or $y_3$, exclusively, similarly to Example A. The difference is that here the decision is internal to the component and exposed via $y_1$.

**Example C.** Let us consider the two protocols $G_0 = p \xrightarrow{l_1 \rightarrow} q; q \xrightarrow{l_2 \rightarrow} p$ and $G_1 = \mu X.p \xrightarrow{l_1 \rightarrow} q; q \xrightarrow{l_2 \rightarrow} p; X$. Roles $p$ and $q$ send a message to each other. In $G_1$ the behaviour is repeated continuously, while in $G_0$ it happens only once. And let us consider the component:

If the component is governed by $G_0$, then we have a “one shot” component (one $x$ received, one $y$ emitted).
However, if we use $G_1$, the component becomes “reactive”, i.e., every time a value is received on $x$, a value on $y$ is emitted. So the component governed by $G_1$ is as reactive as a base component, while the “one shot” usage is not representable via a base component.

**Example D.** Let us consider the following component together with the protocols from example C:

In this example, we can see that the internal protocol does not interfere with external reactive behaviour (no data passes from the outside to the inner protocol). In such case reactions to the external environment (for each $x$ received a $y$ may be emitted) are completely independent from the internal communications (possibly several if the component is governed by $G_1$).

**Example E.** In the protocol $G = p \xrightarrow{l_1} q; \mu X.q \xrightarrow{l_2} p; X$, $p$ sends an initial message to $q$ who will then repeatedly send a message to $q$. If used to govern the component:

we have the effect that receiving one $x$ kickstarts the internal interaction and then an unbounded number of $y$’s can be emitted.

**Example F.** We now consider a protocol that specifies a choice similar to the one given in Example A, but wrapped in a recursion so the protocol is repeating (in both branches):

$$G = \mu X.p \xrightarrow{l_1} q \mid (q \xrightarrow{l_2} p; X, q \xrightarrow{l_3} p; X)$$

We then consider that the protocol governs the following component:

In this case, for each decision received on $x$ either there is no (external) output or a value is available to be sent on $y$.

### 4 Target Process Model

In this section, we present an operational realisation of the GC model, by showing how specifications can be compiled down to a more foundational process model. The crucial point is to show that the centralised control provided by protocols in GC can be realised in a distributed manner. We consider a language that includes communication primitives that are faithful with respect to the original communication model, leaving out specialised constructs to represent the structure of components. Our choice of target model allows us, on the one hand, to tighten the gap towards a concrete implementation, and, on the other hand, to show an operational correspondence between source specifications and respective compilations.

We adopt a variant of the π-calculus [23] where communication is mediated by both queues and forwarders, and (disciplined) non-determinism is supported via a specialised branching primitive. The syntax of processes ($P, Q, \ldots$) is given in Fig. 5, where we (re)use port identifiers and recursion variables. In addition, we consider variables, ranged over by $a, b, c, \ldots$, and objects ($o$) to represent both variables and values.

The static fragment of the language is standard π-calculus. The inactive process is represented by 0, the parallel composition $P \mid Q$ specifies that processes $P$ and $Q$ are simultaneously active, restriction ($\nu z$)$P$ scopes port $z$ to process $P$, and recursion is captured by the combination of the $\mu X.P$ and $X$ constructs.
the behaviours that \( P \) (delimited) set of local binders exhibits the same behaviours as the local binders. Rule \( \text{PRes} \) where \( \lambda \) [behaviour of local binders in different ways falls outside the purpose of this paper. We represent by purpose of representing queues, since, on the one hand, they have a straightforward operational interpretation mediated by message queues, hence output and input (and branching) primitives synchronise with queues and (inversely).

Communication primitives are specified using three language constructs: (1) The output \( z!(o).P \) represents a process ready to send object \( o \) (either a value or a variable that will be instantiated) on (port) \( z \), after which activating the continuation process \( P \); (2) The input \( z?(a).P \) captures a process ready to receive on \( z \) after which activating the continuation process \( P \), replacing the variable \( a \) by the received value; (3) The branching \( z\&(P, Q) \) represents a process that receives a selection value on \( z \) and activates either \( P \) or \( Q \), depending if the received value is \( \text{inl} \) or \( \text{inr} \), respectively. The input \( z!(a).P \) binds free occurrences of variable \( a \) in \( P \). \( (vz)P \) binds occurrences of port \( z \) in \( P \) and \( \mu X.P \) binds occurrences of variable \( X \) in \( P \). We use the usual abbreviation \( (vz)P \).

The main difference with respect to the (synchronous) \( \pi \)-calculus is that in our model communication is mediated by message queues, hence output and input (and branching) primitives synchronise with queues and not directly between them, similarly to the multiparty session calculus [14]. We reuse local binders for the purpose of representing queues, since, on the one hand, they have a straightforward operational interpretation and, on the other hand, it allows us to compile GC base components in a direct way. We find capturing the behaviour of local binders in different ways falls outside the purpose of this paper. We represent by \( [L] \) a (delimited) set of local binders \( L \). We also consider the constructs \( (z \ll w)P \) and \( (z \gg w)P \) that forward the behaviours that \( P \) exhibits on \( w \) as behaviours that \( (z \ll w)P \) and \( (z \gg w)P \) exhibit on \( z \), and exhibit the same behaviours for other subjects. The difference is that \( (z \ll w)P \) forwards exclusively outputs, while \( (z \gg w)P \) forwards solely inputs.

The semantics of the language is given by a labeled transition system defined by the rules shown in Fig. 6 and the ones for local binders shown in Fig. 5 hence excluding rules OutBase and InpBase which refer to base components. By \( P \xrightarrow{\lambda} Q \) we denote that process \( P \) evolves to process \( Q \) exhibiting label \( \lambda \). The set of labels, ranged over by (overloaded) \( \lambda \), extends the set of labels of GC semantics by considering \( \overline{\lambda} \) transitions, where \( \lambda \neq \tau \), hence \( \lambda ::= y?v | x?v | \tau | y?\overline{v} | x?\overline{v} \). This allows us to distinguish actions originating from communication primitives (\( \overline{\lambda} \)) and queues (\( \lambda \)), so as to ensure primitives synchronise only with queues (and inversely).

We briefly comment on the rules shown in Fig. 6 where we use \( \lambda_z \) to identify a transition that specifies port \( z \), be it an input, an output or the respective \( \lambda \) variants. Rule \( \text{PAct} \) specifies that a delimited set of local binders exhibits the same behaviours as the local binders. Rule \( \text{PRes} \) says \( (vz)P \) exhibits transitions of \( P \) that specify subject \( w \) different from the restricted \( z \) (notice only values can be communicated). Rule \( \text{PPar} \)
\[
\begin{align*}
[p \xrightarrow{\ell} q; G]_{r,D,\gamma} & \triangleq z?((a).u!(a)).[G]_{p,D,\gamma} \\
(D = q.w \xrightarrow{\ell} p.z, D' \land \gamma(p,z) = z' \land \gamma(p,\ell) = u) \\
[p \xrightarrow{\ell} q, q; G]_{q,D,\gamma} & \triangleq u?(a).w!(a).[G]_{q,D,\gamma} \\
(D = q.w \xrightarrow{\ell} p.z, D' \land \gamma(q,w) = w' \land \gamma(q,\ell) = u) \\
[p \xrightarrow{\ell} q; G]_{r,D,\gamma} & \triangleq [G]_{r,D,\gamma} \\
([ \ell \xrightarrow{\epsilon} q; G]_{r,D,\gamma} & \triangleq u?(a).w!(a).[G]_{q,D,\gamma} \\
(D = q.w \xrightarrow{\ell} p.z, D' \land \gamma(q,w) = w' \land \gamma(q,\ell) = u) \\
[p \xrightarrow{\ell} q; (G_1, G_2)]_{q,D,\gamma} & \triangleq \gamma & \land w!(\text{inl}).[G_1]_{q,D,\gamma}, w!(\text{inr}).[G_2]_{q,D,\gamma} \\
(D = q.w \xrightarrow{\ell} p.z, D' \land \gamma(q,w) = w' \land \gamma(q,\ell) = u) \\
[p \xrightarrow{\ell} q; (G_1, G_2)]_{q,D,\gamma} & \triangleq [G_1]_{r,D,\gamma}, [G_2]_{r,D,\gamma} \\
([ \ell \xrightarrow{\epsilon} q; (G_1, G_2)]_{q,D,\gamma} & \triangleq u?(\text{inl}).[G_1]_{q,D,\gamma}, w!(\text{inr}).[G_2]_{q,D,\gamma} \\
(D = q.w \xrightarrow{\ell} p.z, D' \land \gamma(q,w) = w' \land \gamma(q,\ell) = u) \\
[p \xrightarrow{\ell} q; (G_1, G_2)]_{r,D,\gamma} & \triangleq [G_1]_{r,D,\gamma} \\
([ \ell \xrightarrow{\epsilon} q; (G_1, G_2)]_{r,D,\gamma} & \triangleq [G_2]_{r,D,\gamma} \\
([ \mu x.G]_{r,D,\gamma} & \triangleq \mu x.[G]_{r,D,\gamma} \\
([ \mu x.G]_{r,D,\gamma} & \triangleq 0 \\
([ \text{end}])_{r,D,\gamma} & \triangleq 0
\end{align*}
\]

Figure 7: Choreography Encoding.

specifies the parallel composition exhibits transitions of one of the subprocesses. Rule \textsc{PCom} captures the synchronisation between two processes, yielding a \(\tau\) move of the parallel composition, where one of the labels originates from a communication primitive \(\lambda\) and the other from a queue \(\lambda\). We omit the symmetric versions of rules \textsc{PCom} and \textsc{PPar}. Rule \textsc{PRec} says the recursive processes exhibits the transitions of its unfolding.

The rules that start with PFwd capture the behaviour of the forwarders. Rules \textsc{PFwd1} and \textsc{PFwd2} say that the forwarder constructs exhibit the same transitions as the scoped process as long as the port given in the transition is different from the ones involved in the forwarding. Rules \textsc{PFwdInp} and \textsc{PFwdInp2} capture input forwarding, while \textsc{PFwdOut} and \textsc{PFwdOut2} capture output forwarding, where the transition on the (external) port \(z\) is derived from a transition on the (internal) port \(w\). We distinguish the cases of \(\lambda\) (\textsc{PFwdInp} and \textsc{PFwdOut}) and \(\overline{\lambda}\) (\textsc{PFwdInp2} and \textsc{PFwdOut2}) to avoid introducing dedicated notation. Rule \textsc{POut} describes the behaviour of the output construct that exhibits the corresponding output transition \(\overline{\gamma}(\overline{w})\), identifying that the transition originates in a communication primitive. Rule \textsc{Plnp} shows the symmetric case. Rules \textsc{PChoL} and \textsc{PChoR} capture the behaviour of the branching construct, which is ready to receive on \(z\) a selection value, either \text{inl} or \text{inr}, evolving to \(P\) or to \(Q\), respectively.

Having presented the target language, we may now turn to the encoding of GC, starting by the encoding of choreographies which are central in the operational model. We denote by \([G]_{r,D,\gamma}\) the encoding of choreography \(G\) for role \(r\) considering connection binders \(D\) and mapping \(\gamma\). The connection binders provide the association between message labels and communication ports. \(\gamma\) is an injective mapping from role port pairs \((r,z)\) and role label pairs \((r,\ell)\) into ports used in the target model, so as to omit role identifiers and map message labels, while ensuring a unique relation.

In the GC model components evolve via actions prescribed by the choreography. This is captured in the encoding via interaction between the choreography encoding and the component encoding, presented afterwards. Also, as usual, the encoding of choreographies is carried out for each participant, so choreographic monitoring is actually carried out in a distributed way. We therefore specify interaction points between the distributed monitors so as to ensure they evolve in a coordinated way. Following these principles we may now comment on the definition of choreography encoding, defined inductively in the structure of choreographies, for a given role, as shown in Fig. 7.

The first case considers a communication projected for the sender role, encoded as an input on \(z'\) followed
by an output on \( u \) that forwards the received value, and continuation defined as the respective projection of the continuations of each \( G \). We use the connection of component and choreography encoding realised through local binders semantics. Given connection binders \( D \) and mapping \( \gamma \) we use \( \text{queues}(D, \gamma) \) to denote the set of local binders (queues) defined as: \( \text{queues}(q, w \leftarrow p, z, D', \gamma) \triangleq (\gamma(q, \ell) = \text{id}(\gamma(p, \ell)), \text{queues}(D', \gamma)). \)

Hence, there is a local binder for each connection binder, defined using the identity function \( (\text{id}) \) for the purpose of value forwarding. Each local binder inputs messages originating from the sender monitor, using the port given by \( \gamma(p, \ell) \), and outputs messages towards the receiver monitor, using the port \( \gamma(q, \ell) \). Since choreographies themselves may carry (in transit) values, we introduce an operation that places the values in the respective queues, denoted by \( \text{fill}(G, L, \gamma) \) for a given choreography \( G \), local binders \( L \) and mapping \( \gamma \) (defined in expected lines, see Appendix A). We remark that such operation targets only choreography encoding directly considers the relevant branch since the value is registered in the choreography.

We now present the encoding of components which is shown in Fig. 8. In order to match GC component behaviour and ensure a modular specification, the encoding yields processes that have as set of free ports (\( f_p \)) only identifiers in the interface \( \bar{x}, \bar{y} \) and can only exhibit inputs on \( \bar{x} \) ports and exhibit outputs on \( \bar{y} \) ports. The former is ensured by a (total) renaming given by a mapping \( \gamma \) combined with the appropriate name restrictions, while the latter is enforced via the forwarding constructs. So, firstly, the encoding of a base component \( \{ \bar{x} \bar{y}, L \} \) considers \( \gamma \) using a (dummy) role \( r \) to replace all identifiers given in the source GC specification, and specifies a name (list) restriction for all ports yielded by the mapping (the distinguished set \( \bar{z} \)). The original local binders are also renamed using the mapping (denoted \( \gamma(r, L) \)). Secondly, the encoding specifies input forwarders for \( \bar{x} \) and output forwarders for \( \bar{y} \) targeting their mappings.

The encoding of the composite component follows the same principles, specifying a complete identifier replacement and restricting all ports not part of the interface. Also forwards are specified, following precisely the forwards given in the GC specification, up to the respective mapping. The elements of the component are then encoded as the parallel composition of the monitor queues with the encodings of role
Proposition 4.2 (Encoding Completeness) \( \tau \) represent zero or more by the source component and also that the encoding does not diverge. of) a configuration reachable by the component. We thus have that behaviours of the encoding are matched precisely by their encodings, and that component evolutions are matched by two actions of their transitions.

\[ [\tilde{x}] \tilde{y} \{L\} \equiv (\nu \tilde{z}) \\
(x_1 \triangleright \gamma(x_1)) \ldots (x_k \triangleright \gamma(x_k)) \\
(y_1 \triangleleft \gamma(y_1)) \ldots (y_n \triangleleft \gamma(y_n)) \\
[\gamma(r, L)] \\
(\tilde{x} = x_1, \ldots, x_k \land \tilde{y} = y_1, \ldots, y_n \land \tilde{z} \cap (\tilde{x}, \tilde{y}) = \emptyset \\
\land \tilde{z} = ca(\gamma) \land dom(\gamma) = r \times (fp(L) \cup \tilde{x} \cup \tilde{y}) \\
] [\tilde{x}] \tilde{y} \{G; R; D; r[F]\} \equiv (\nu \tilde{z}) \\
(x_1 \triangleright \gamma(r, w_1)) \ldots (x_k \triangleright \gamma(r, w_k)) \\
(y_1 \triangleleft \gamma(r, z_1)) \ldots (y_n \triangleleft \gamma(r, z_n)) \\
[[R_1] \mid [G;p;\gamma], \ldots \mid [G;p;\gamma], \ldots \mid [\text{fill}(G,(\text{queues}(D, \gamma)), \gamma))] \\
(x_1, \ldots, x_k \subseteq \tilde{x} \land y_1, \ldots, y_n \subseteq \tilde{y} \land \tilde{z} \cap (\tilde{x}, \tilde{y}) = \emptyset \\
\land F = w_1 \leftarrow x_1, \ldots, w_k \leftarrow x_k, y_1 \leftarrow z_1, \ldots, y_n \leftarrow z_n \\
\land \tilde{z} = ca(\gamma) \land dom(\gamma) = (\text{rplp}(D) \cup r \times \bar{w} \cup r \times \bar{z}) \\
\land p_1, \ldots, p_j = \text{roles}(G) \\
] [r=C] \gamma \equiv (\nu \tilde{x}, \tilde{y}) \\
(\gamma(r, x_1) \triangleright x_1) \ldots (\gamma(r, x_k) \triangleright x_k) \\
(\gamma(r, y_1) \triangleleft y_1) \ldots (\gamma(r, y_n) \triangleleft y_n) \\
[C] \\
(C = [\tilde{x}] \tilde{y} \{\ldots\} \land \tilde{x} = x_1, \ldots, x_k \land \tilde{y} = y_1, \ldots, y_n) \\
[R_1, R_2] \gamma \equiv [R_1] \gamma \mid [R_2] \gamma \\
Figure 8: Component Encoding.

assignments and the choreography. The monitor queues are specified by the queues\(_{(\ldots)}\), considering the original connection binders and the mapping, up to the placement of in transit values given by fill\(_{(\ldots)}\). The encoding of the choreography is carried out for all roles specified in the choreography, considering the original connection binders and the mapping. The encodings of role assignments consider the respective mapping, where the ports used in the mapping in the context of the composite component are forwarded to the ports specified in the interface of the (sub)component. The conditions specified for the encoding ensure that the renaming is total, that the yielded processes operate on a distinguished set of ports, and only the ports in the interface are free ports of the process. We use rplp\((D)\) to denote the set of role ports and role labels used in \(D\).

We may now present our results that show there is a precise operational correspondence between GC specifications and their encodings, starting by ensuring each (internal) evolution in the source specification is matched by precisely two (internal) evolutions in the target model. For the purpose of our results we use a standard notion of structural congruence (denoted \(\equiv\)), extended with forwarder swapping (provided the names involved in the forwarder are distinct).

Proposition 4.1 (Encoding Soundness). If \( C \xrightarrow{\tau} C' \) then \( [C] \xrightarrow{\tau} P \xrightarrow{\tau} \equiv [C'] \).

Proof. By induction on the derivation of \( C \xrightarrow{\tau} C' \). 

Proposition 4.2 (Encoding Completeness). If \( [C] \xrightarrow{\tau} P \) then there is \( C' \) such that \( C \xrightarrow{\tau} C' \) and \( P \xrightarrow{\tau} \equiv \equiv [C'] \).

Proof. By induction on the derivation of \( [C] \xrightarrow{\tau} P \).

Proposition 4.2 says that any configuration reachable by the encoding may always evolve to (the encoding of) a configuration reachable by the component. We thus have that behaviours of the encoding are matched by the source component and also that the encoding does not diverge.

The operational results attest the correctness of our encoding, ensuring that component and encoding behaviour match. However correctness of component themselves is not addressed, so for instance if the
component has some undesired behaviour, also will the encoding. In order to single out components that enjoy desired properties we introduce a typing discipline, described next, which results can be carried down to the compilation thanks to the operational correspondence.

5 Types for Components

In this section we present our type system that addresses communication safety and progress, and also a preliminary investigation on the notion of substitutability supported by our model. We start by mentioning some notions auxiliary to the typing. First of all we introduce the type language that captures component behaviour, equipped with an operational semantics for the purpose of showing the correspondence with GC version of local binders, equipped with an operational semantics, used to check the conformance of a base component w.r.t. a local type.

The syntax of local types, given in Fig. 9, builds on communication actions carried out on ports. We assume a set of base types, ranged over by $B$ (e.g., $T_{\text{Inp}}$). Output type $z!B.T$ describes a component that sends a value of type $B$ on port $z$ and that afterwards follows specification $T$; likewise for the symmetric input type $z?B.T$. Choice type $z \oplus (T_1, T_2)$ describes a component that sends a selection value, either $\text{inl}$ or $\text{inr}$, on port $z$ and that afterwards follows specification $T_1$ or $T_2$, respectively. The symmetric branch type $z \& (T_1, T_2)$ describes a component that receives a selection value, either $\text{inl}$ or $\text{inr}$, on port $z$ and that afterwards follows specification $T_1$ or $T_2$ respectively. The type of the communicated values in the case of choice and branch types is implicit, but since it will be useful later on, we introduce $\text{Cho}$ as the type for $\text{inl}$ and $\text{inr}$. Local types include standard recursion constructs and termination that is specified by $\text{end}$. By convention we identify alpha-equivalent recursive types.

The labelled transition system given in Fig. 10 defines the semantics of local types, intuitively explained above. Since we are interested in showing the correspondence of local types and component behaviour, the set of labels considered is the same considered for GC (except for $\tau$). Rule $\text{TOut}$ says an output type exhibits an output on the respective port of any value of the respective type, after which activating continuation $T$; likewise for $\text{TInp}$. Rules for choice and branch types specify the continuation to be activated according to the sent/received value. The rule for recursion is standard.

In GC the interaction in a composite component is controlled by a protocol, hence inner components must support the behaviour expected by the protocol for the corresponding role. We thus require an operation that projects the expected behaviour (i.e., local type) of a component given the protocol and the respective role. Also, the operation requires the relations between the protocol message labels and their respective communication ports together with the types of the communicated values. We denote by $G \downarrow_{p,D,\Delta}$ the projection of protocol $G$ for role $p$ considering connection binders $D$ and mapping $\Delta$. Connection binders provide the association between message labels and communication ports (like in the encoding), while $\Delta$ maps message labels to the (base) types of the communicated values, allowing to ensure that both sender and receivers agree on the type of the value. We remark that projection is a partial function since some conditions

```
T ::= z!B.T (output) | z?B.T (input) |
z \oplus (T_1, T_2) (choice) | z \& (T_1, T_2) (branch) |
\mu X.T (recursion) | X (variable) |
\text{end} (termination)
```

Figure 9: Local Types

```
v : B \rightarrow y!B.T \rightarrow y!_{y'} T \rightarrow TOut
vx : B \rightarrow z?B.T \rightarrow z?_{z'} T \rightarrow TInp
\mu X.T \rightarrow T_{\{X/\mu X.\tau\}} \rightarrow T' \rightarrow TRec
\mu X.T \rightarrow T_{\{X/\lambda X.\tau\}} \rightarrow T' \rightarrow TRec
y \oplus (T_1, T_2) \rightarrow y!_{\text{inl}} T_1 \rightarrow TChoL
y \oplus (T_1, T_2) \rightarrow y!_{\text{inr}} T_2 \rightarrow TChoR
x \& (T_1, T_2) \rightarrow x?_{\text{inl}} T_1 \rightarrow TChoL
x \& (T_1, T_2) \rightarrow x?_{\text{inr}} T_2 \rightarrow TChoR
```

Figure 10: Local Type Semantics
are necessary for the projection to exist.

We briefly present the projection operation, defined inductively on the structure of the protocol as shown in Fig. 11. Protocol \( p \xrightarrow{\ell} \bar{q}; G \) specifies that \( p \) sends message \( \ell \) to \( \bar{q} \), so the projection for the emitter role \( p \) is an output type \( z!B \cdot (\ldots) \), considering a respective connection binder \( q.w \xleftarrow{\ell} q.z \) to identify (output) port \( z \), and mapping \( \Delta \) to identify the type \( (B) \) of the value. The continuation of the output type is the projection of the continuation \( G \). The projection for any of the receiver roles follows similar lines, differing in the resulting (input) type and the (input) port considered in the connection binders. The projection for a role \( r \), different from \( p \) and \( \bar{q} \), considers directly the projection of the continuation since \( r \) is not involved in the message exchange.

The projection of protocol \( \xrightarrow{\ell} \bar{q}; G \), where value \( v \) is in transit, has two cases: for any of the roles waiting to receive the message, which follows similar lines to the input but where the mapping \( \Delta \) is not used since (the type of) the value is known; for any other role, which is defined as the projection of the continuation \( G \). In the latter case, notice that any other role may refer for instance to the emitting role, who has already sent the message. The respective type at this stage does not specify the output since the protocol no longer expects the output from the respective component (the value is already in transit), and analogously for roles that have already received the message.

The projection of protocol \( \xrightarrow{\ell} \bar{q}(G_1, G_2) \) also considers the respective connection binders to identify the ports used by the emitter and by the receivers, yielding choice or branch types respectively. In both cases the continuations are given by the projections of the respective continuations of the protocol \( G_1 \) and \( G_2 \). For a role \( r \) not involved in the selection, the projection is defined only if the projection of the continuations \( G_1 \) and \( G_2 \) for role \( r \) is the same. When the selection value is in transit in protocol \( \xrightarrow{\ell} \bar{q}(G_1, G_2) \), the projection for roles waiting to receive the selection follows the same lines as before, where we check that the value in transit is of the appropriate type (ChoT). For other roles, since the selection is known, the projection considers the implied continuation, which is crucial for the sake of typing preservation given that, for instance, the sender has already committed on the selected branch. The remaining cases for the projection are direct, where we ensure (like in the encoding) that the projection for the recursive protocol is meaningful.

Protocol projection is a crucial operation when typing the composite component, allowing to specify the behaviour of all inner components. However, in the case of the distinguished component that interacts also
with the external context, the expected behaviour is given by a combination of both the protocol projection for the respective role and the (external) behaviour of the composite component itself. We introduce an auxiliary notion that allows us to build such combination of two local types, a ternary relation which we refer to as the respective role and the (external) behaviour of the composite component itself. We introduce an auxiliary MChoiceL type. We notice that, in rules and right source types respectively, where the yielded continuation is obtained by merging the continuation actions of the two source types so as to yield the combined one.

We briefly comment on the rules of Fig. [12]. Protocol projection and merge are used in the typing of composite components, identifying the expected behaviour for each subcomponent, while accounting for the external interface. For base components instead we model the return type of the function, leaving the handling of constants open to runtime functions.

### Protocol Projection

- **Protocol Projection**
  - **MOutL**: \( T_1 \times T_2 = T_3 \) if \( z!B.T_1 \times T_2 = z!B.T_3 \)
  - **MOutR**: \( T_1 \times T_2 = T_3 \) if \( z?B.T_1 \times T_2 = z?B.T_3 \)
  - **MVar**: \( X \times X = X \)

### Type Merge

- **Type Merge**
  - **MChoiceL**: \( T_1 \times T_2 = T_3 \) if \( MChoiceL \)
  - **MChoiceR**: \( T_1 \times T_2 = T_3 \) if \( MChoiceR \)
  - **MBranchL**: \( T_1 \times T_3 = T_4 \) if \( MBranchL \)
  - **MBranchR**: \( T_1 \times T_3 = T_4 \) if \( MBranchR \)
  - **MRec**: \( \mu X.T_1 \times \mu X.T_2 = \mu X.T_3 \) if \( MRec \)
  - **MEndL**: \( T_1 \times T_2 = T_3 \) if \( MEndL \)
  - **MEndR**: \( T \times end = T \) if \( MEndR \)

Figure 12: Type Merge
\[
\begin{align*}
L & \xrightarrow{y:B} \Gamma \vdash L \equiv T & \text{ClnP} \\
L & \xrightarrow{x:T,B:T} \Gamma \vdash L \equiv x?B.T & \text{COut} \\
L & \xrightarrow{x:y:B} \Gamma \vdash L \equiv Y^{\inl} & \text{CBra} \\
L & \xrightarrow{y:y:B,T} \Gamma \vdash L \equiv y?B,T & \text{CCho} \\
L & \xrightarrow{y:y:B,T} \Gamma \vdash L \equiv y?B,T & \text{CChoL} \\
L & \xrightarrow{x:y:B,T} \Gamma \vdash L \equiv x\oplus (T_1,T_2) & \text{CChoR} \\
\Gamma, X : \mathcal{L} \vdash L \equiv T & \text{CRec} \\
\Gamma, \mathcal{X} : \mathcal{L} \vdash \mathcal{L} \equiv \mathcal{X} & \text{CVar} \\
\Gamma, \mathcal{L} \vdash \mathcal{L} \equiv \mathcal{X} & \text{CEnd}
\end{align*}
\]

Figure 13: Abstract Local Binder Semantics.

Figure 14: Conformance.

The rules shown in Fig. 14 describe next. Essentially conformance simulates the (abstract) behaviour of the local binders so as to assert its compatibility to the behaviour prescribed by the local type. Rule \text{CInp} says that \( L \) is compatible with the input, if \( L \) exhibits the (abstract) input, leading to a configuration that is conformant with the continuation of the input. Rule \text{COut} follows similar lines. Rule \text{CBra} considers the two possible continuations, taking into account the actual value that corresponds to each branch (\inl or \inr). In such a way we may (statically) inform on the selection value of choices that depend on the branching. This notion is captured in rules \text{CChoL} and \text{CChoR} where the selection value is available, hence the conformance may focus on the relevant branch. However, it is not always possible to statically determine the selection value, hence the binders exhibit an output of \text{ChoT} type, for which rule \text{CCho} ensures that both branches are conformant with the type.

Rules \text{CRec} and \text{CVar} ensure that the recursion body leaves the state unaltered, using a dedicated environment \( \Gamma \) (an association between recursion variables and abstract local binders). Intuitively, this means that local binder queues are of the same size at the start of each iteration of the recursion, hence that inputs are matched by respective outputs and vice-versa. Rule \text{CEnd} says that local binders are always conformant with inaction \text{end}, which reveals our interpretation for conformance: binders can actually have more behaviour than the one prescribed by the local type, hence the focus is on ensuring local binders can carry out the specified behaviour. We remark that the simulation carried out for abstract local binders strictly follows the type structure.

Having presented the main principles of our type system, we now introduce auxiliary syntactic notions

17
used in the typing rules. Namely, we require an operation that given local binders \( L \) yields the abstract counterpart, denoted \( \text{abs}(L) \). The operation replaces all values different from \( \text{inl} \) and \( \text{inr} \) by their respective values in the queues, leaving \( \text{inl} \) and \( \text{inr} \) untouched. In order to realize the forwarder specification, we introduce an operation that renames a given type \( T \) considering forwarders \( F \), up to the sets of input and output ports, denoted \( F_{x,y}(T) \), defined in expected lines (see Appendix A). We consider the set of ports so as to check that inputs (and branches) specified in the type use input ports and that outputs (and choices) use output ports. This operation thus ensures composite components respect the specified interfaces (otherwise it is undefined), while the same principle is ensured for base components using a dedicated predicate, denoted \( \text{inl} \) and \( \text{inr} \), defined in non-surprising lines.

We may now present our typing rules, shown in Fig. 15. Rule \( \text{TBaseC} \) addresses the base component, asserting it is well-typed provided the abstract version of the local binders is conformant with the type of the component (considering an empty recursion environment). We also check that inputs (and branches) are specified in the type considering input ports and symmetrically for output ports \( (x; y \vdash T) \). Rule \( \text{TCompC} \) shows the typing for the composite component. To type the subcomponent that interacts both with other subcomponents and with the external environment we consider a type merge: on the one hand the component participates in the protocol so the the projection of the protocol for the respective role is considered as part of the behaviour of the component. On the other hand the behaviour expected externally, up to a forwarder renaming \( (F_{x,y}(T)) \), is also carried out by the component. So the type merge combines the two separate behaviours and yields the type expected for the component. For the remaining components we consider directly the projection of the protocol in the respective roles, where the association between message labels and base types \( \Delta \) is the same so as to ensure communication safety. The set of roles considered is the set of roles assigned in \( R \) (noted \( \text{roles}(R) \)) so as to ensure all components are typed, potentially w.r.t. an end projection since the set of roles used in the protocol may be smaller. This is the case for roles/components that have finished their contribution in the protocol, relevant for typing preservation. Rules \( \text{TRole} \) and \( \text{TRoleL} \) distribute the typing assignments to the respective role assignments.

Although an actual implementation of the type-checking procedure is out of the scope of this paper, we nevertheless remark that type-checking is decidable given all the required derivations (namely merge and conformance) are strictly bound by the structure of types. Our type system ensure systems enjoy communication safety and progress and informs on reuse and substitution principles.

We now present our main results and briefly discuss the proof structure. We first capture soundness, by showing typing is preserved under system evolution.

**Theorem 5.1** (Typing Preservation). Let \( C : T \) and \( C \xrightarrow{\lambda} C' \). Then:

- If \( \lambda = \tau \) then \( C' : T \).
- If \( \lambda \neq \tau \) and \( T\xrightarrow{\lambda} T' \) then \( C' : T' \).

**Proof.** By induction on the derivation of \( C \xrightarrow{\lambda} C' \), building on auxiliary results. \( \square \)

Theorem 5.1 identifies two separate cases: if the component performs an internal action, then the interface is untouched; if the components exhibits an input or output and the local type matches the communication action, then typing is preserved by the continuations. Since GC semantics considers interaction is controlled by protocols, only behaviours prescribed by the protocol can actually occur. We may then focus on actions available in the type as the protocol projections capture the behaviour realisable by the respective component. However, when typing the component that interfaces with external and internal contexts we must lift this notion up to type merge. Intuitively the component may exhibit actions that have been shuffled in the type structure (not immediately observable in the type), in which case we show that such actions can be shuffled
out or swapped and preserve typing. We remark that this property does not entail that any action can be shuffled out (otherwise merge would not be meaningful), as the proof regards actions that the component immediately exhibits (see Appendix C).

Theorem 5.2 states our progress property, attesting well-typed components can, after a number of internal steps, carry out the actions prescribed by the types.

**Theorem 5.2** (Progress). If \( C : T \text{ and } T \xrightarrow{\lambda} T' \) then \( C \xrightarrow{\lambda} C' \).

**Proof.** By induction on the derivation of \( C : T \) and on the derivation of the merge in the composite case, building on auxiliary results.

The proof of Theorem 5.2 crucially relies on an underlying progress principle for interaction controlled by protocols in the composite case. Actions expected by the external interface can only be ensured if all actions specified for the interfacing component can be carried out, namely actions which depend on the protocol which in turn depend on other components. Corollary 5.3 captures protocol progress.

**Corollary 5.3** (Protocol Progress). If \([\tilde{x}] \tilde{y} \{ G; R; D; r[F] \} : \text{end} \) and there is \( G' \) such that \( G \xrightarrow{\sigma} G' \) then \([\tilde{x}] \tilde{y} \{ G; R; D; r[F] \} \xrightarrow{\tau} [\tilde{x}] \tilde{y} \{ G'; R'; D; r[F] \} \).

Corollary 5.3 thus attests that actions prescribed by the protocol are carried out in well-typed components, focusing on components with a closed interface (end). We thus have that protocols not only control interaction among (sub)components but also provide a specification that is guaranteed to be carried out. Thanks to the operational correspondence result we may also ensure that well-typed components are compiled to systems that enjoy communication safety and progress.

### 5.1 Examples

We return to the examples shown in Section 3.2 now considering a typing perspective. Regarding Example A consider type \( y_1 \oplus (x_2 ? B. \text{end}, x_3 ? B. \text{end}) \) is obtained by projecting the protocol in role \( p \), where we use the message labels as subscripts of port identifiers so as to yield the respective association and assuming some base type \( B \). Now consider the type prescribed by the external environment is \( x &\{ (y_2 ! B. \text{end}, y_1 ! B. \text{end}) \) (notice the association of \( y_1 \) and \( y_2 \) with the decision is “inverted” in the illustration given previously). A possible merge is:

\[
x &\{ (y_1 \oplus (x_2 ? B. y_2 ! B. \text{end}, x_3 ? B. y_3 ! B. \text{end}), y_1 \oplus (x_4 ? B. y_4 ! B. \text{end}, x_5 ? B. y_5 ! B. \text{end}))
\]

which the component implementing role \( p \) conforms to, thanks to the fact that the abstract local binder semantics is able to capture the association between the branching on \( x \) and the selection on \( y_1 \), after which the dependencies between \( x_1 \) and \( y_2 \) and between \( x_3 \) and \( y_4 \) are met (notice this is so only in the relevant branches). We remark that if such external branching on \( x \) is not present then the example would be untypable, since the component must somehow inform on the alternative behaviours to the outer context. Such reasoning is also present in Example B given type \( y_1 \oplus (y_2 ! B. \text{end}, y_1 ! B. \text{end}) \) where the outer context is informed of the alternative behaviours via the selection on \( y_1 \).

Regarding Example C we remark that the choice of protocol (either \( G_0 \) or \( G_1 \)) is constrained by the type expected externally. If the external type is \( \mu X. x ? B. y ! B. X \) then necessarily (recursive) protocol \( G_1 \) must be used as otherwise the infinite behaviour expected externally will not be realisable by the component. If the external type is \( x ? B. y ! B. \text{end} \) then necessarily protocol \( G_0 \) must be used since the internal infinite dependencies are not met. The use of protocol \( G_1 \) in such circumstances would be safe in a behavioural perspective but our current development does not capture this. Instead in Example D the use of both protocols \((G_0 \text{ and } G_1)\) can be typed as there are no dependencies from external behaviour and internal communications.

In Example E the component is typable when considering the type prescribed by the environment is \( x ! B. x k \{ X \}, y ! B. X \), given the “one shot” dependency between receiving on \( x \) and the internal communication \( l_1 \) is met, after which the (infinite) dependencies between the internal communication \( l_2 \) and the output on \( y \) are also met. Example F is typable considering external type \( \mu X. x &\{ (X, y ! B. X) \}, \) but is untypable if we consider that the component is governed by protocol \( \mu X. p \xrightarrow{l_1} q \ (q \xrightarrow{l_2} p; \text{end}, \ q \xrightarrow{l_3} p; X) \), a challenging pattern given the mixture of infinite and finite dependencies together with the choice propagation between external and internal communications.

Lastly we return to the example given in the language preview so as to illustrate further the notion of possible (type safe) substitutions of the protocols specified in components. Namely, consider \( G_{\text{Shop}} \) defined as \( \text{Sales} \xrightarrow{\text{buy}} \text{Bank} ; \text{Sales} \xrightarrow{\text{val}} \text{Bank} ; \text{Sales} \xrightarrow{\text{cum}} \text{Bank} ; \text{end} \). In the context of the composite component implementing the Seller we may replace \( G_{\text{Shop}} \) with \( G'_{\text{Shop}} \) defined as \( \text{Sales} \xrightarrow{\text{val}} \text{Bank} ; \text{Sales} \xrightarrow{\text{buy}} \).
Bank(Sales $\xrightarrow{\text{conum}}$ Bank, end) or $G_{\text{Shop}}'$ defined as Sales $\xrightarrow{\text{buy}}$ Bank(Sales $\xrightarrow{\text{conum}}$ Bank; Sales $\xrightarrow{\text{val}}$ Bank, end), where the val message is swapped around, since the value of the product is determined (in $C_{\text{Sales}}$) as soon as the product name is available (originating from Buyer, corresponding to the first message of the external protocol $G_{\text{BSS}}$).

Also, considering the first composite component that uses $G_{\text{BSS}}$ and base components to implement the three roles, we may consider a recursive version of $G_{\text{Shop}}$ since the base components are able to continuously react. However, such recursive $G_{\text{BSS}}$ cannot be used when considering the Seller role is implemented by the composite component, since its internal protocol $G_{\text{Shop}}$ does not specify a recursion, and hence the type merge is undefined (but a recursive version of $G_{\text{Shop}}$ would work).

### 5.2 On Substitutability

We now present preliminary results and some insights regarding the substitution principle supported by our typed model. In particular we show a notion of subtyping that naturally arises in our setting which, combined with the standard subsumption rule, technically realises the usual substitution principle (cf. [16]): a component may be safely used in a context where one of the outputs provided by the component is actually able to interact, regardless of being mentioned or not initially in the type, and base components to implement the underlying semantics.

Subtyping is given by the rules in Fig. [16] including type language closure, transitivity, and reflexivity and four other rules described next under the light of the substitution principle. Rules SIShuffle and SOSHuffle say that two inputs and two outputs can be safely shuffled between them, and rule SODiscard says a component may be safely used in a context where one of the outputs provided by the component is not expected. Notice the queues in local binders can store (unused) data, and receive two inputs or exhibit two outputs in any order. Instead, rule SIBefore addresses shuffling of one output and one input: when the component is able to first output and then input then it is safe to use it in a context that prescribes that the input happens first. We remark that the symmetric does not hold, in particular when the output depends on the input. We may show type safety considering the extension with the subsumption rule for components in Fig. [16] (TSubsC) and the presented subtyping relation, and we can already identify extensions to the subtyping relation.

As hinted above, the shuffling of outputs and inputs does not hold in general, in particular when the component actually requires a received value in order to be able to exhibit some output. So considering the rule symmetric to SIBefore (dubbed SOBefore) is unsound in our setting, however an extension of our typing system so as capture input/output value dependencies would allow the precise application of SOBefore. The extension would collect direct dependencies in local binders of base components and inductively extend them by adding the dependencies introduced by protocols in composite components. Such information would also support a rule for discarding inputs (analogous to SODiscard) when no (relevant) outputs depend on the (discarded) input. Also, extending the typing information so as to include information on the ports in which the component is actually able to interact, regardless of being mentioned or not initially in the type, would allow to reason on subtyping principles such as $T <: x?B.T$ and $T <: y!B.T$ which are sound up to such “unused” capabilities of the component (and when the dependencies are met in the case of the output). Resorting to the used/unused information on ports and the mentioned dependencies we may also reason on principles such as $\mu X.T$ is a subtype of $T$ and $T$ is a subtype of end, which are not sound in our current setting since the underlying dependencies may be impossible to satisfy.

Finally, we remark that we may synthesise components that may be used in a context when a given type...
is expected, for any given type. In particular given type $T$ we may devise a base component that defines input ports for all inputs and branches specified in $T$ (not used in internal local binders), and output ports for all outputs and choices (defined with functions of the appropriate type and without parameters). We expect to find such components at the bottom of the hierarchy when considering a semantic notion for substitutability, going up to components of closed interfaces at the top for which adaptation to surrounding contexts is limited.

6 Concluding Remarks

The protocol language used in this article sits in between the two related approaches of Multiparty Session Types (MPST) \cite{MPST} and Choreographic Programming \cite{Choreographic}. MPST are types for specifying distributed protocols that can be used for checking whether a given distributed implementation respects the given protocol. The methodology approach for MPST is different from ours: protocols are also given as choreographies, but they are only used statically. In our setting, choreographies are used at runtime for governing the way components, our data handlers, communicate with each other. MPST have also been used as monitors during runtime execution of concurrent programs \cite{Monitoring, Monitoring2}. However, rather than monitoring reactive components like in our work, they monitor $\pi$-calculus-like processes, hindering modularity.

Choreographic Programming \cite{Choreographic} allows to program distributed systems directly as choreographies which define both the communications among components and the data that they carry. Then, the choreography is used to synthesise a correct process implementation. Differently, our language decouples the component behaviour where choreographies are used to synthesise correct-by-construction process implementations. Similarly, the I/O actions performed by components in this work are synthesised from the choreographies that they participate in. Also in this case, the absence of decoupling component interaction from component behaviour limits modularity.

Reo \cite{Reo} is a coordination language which separates protocols and implementation of components. However, their model for implementing processes still requires to provide sequences of communication actions, making reusability (hence modularity) harder. Instead, in our language, thanks to the usage of reactive programming, we can be more flexible with the type of components that can be used. MECo \cite{MECo} is a calculus where components interact through their input and output ports, similar to our interfaces. MECo supports notions of passivation and component mobility, which could be an interesting future extensions for our language.

Orc \cite{Orc} is an orchestration language that uses connectives between components similar to our binders. However, the language has no choreographic coordination on the message flow. Similarly, BIP \cite{BIP} is a coordination language for modularly assembling components. Also in BIP, there is no usage of choreographic specification for governing the interaction between components.

We are yet to fully explore the relation with existing literature addressing reactive programming and related models (e.g., \cite{GC,GC1,GC2,GC3}), which we believe may be used so as to enrich our setting. We have already identified some connection points, in particular at the level of the subtyping notion \cite{GCsub}. It would also be interesting to enrich our setting by exploring the relation between linear logic and session types \cite{Linear} and also integrating with dependent types so as to, for instance, capture choice propagation in a more refined way (cf. \cite{Dependent}).

We have presented GC, a language designed for the modular development of distributed systems, where reactive components are assembled in a choreographic governed way. We show a provably-correct operational interpretation of our model, which shows a distributed implementation of the governing carried out by protocols, and a type discipline that ensures communication safety and progress, already supporting a notion of substitutability. Future directions for this work include an actual implementation to serve as an experimental proof of concept. Also, at the level of typing, it would be interesting to consider an interpretation of component types that capture their behaviour in the most general way. In particular this is crucial to obtain a more precise notion of substituting so as to provide further support for reuse and substitution, thus a fundamental research direction for this work.
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\[ \text{fill}(p \xrightarrow{\ell} q; G, L, \gamma) \triangleq \text{fill}(G, L, \gamma) \]
\[ \text{fill}(\ell, v \xrightarrow{\ell, v} q; G, L, u_1 = \text{id}(u') \langle \bar{s}_1, \ldots, u_k = \text{id}(u') \langle \bar{s}_k, \gamma \rangle) \]
\[ \triangleq \text{fill}(G, L, u_1 = \text{id}(u') \langle \bar{s}_1, \{u' \mapsto v\}, \ldots, u_k = \text{id}(u') \langle \bar{s}_k, \{u' \mapsto v\}, \gamma \rangle) \]
\[ (u_i = \gamma(q_i, \ell) \wedge \bar{q} = q_1, \ldots, q_k) \]
\[ \text{fill}(\ell, v \xrightarrow{\ell, v} q; G_1, G_2), L, \gamma) \triangleq \text{fill}(G_1, L, \gamma) \]
\[ \text{fill}(\ell, v \xrightarrow{\ell, v} q; G_1, G_2), L, u_1 = \text{id}(u') \langle \bar{s}_1, \ldots, u_k = \text{id}(u') \langle \bar{s}_k, \gamma \rangle) \]
\[ \triangleq \text{fill}(G_1, L, u_1 = \text{id}(u') \langle \bar{s}_1, \{u' \mapsto \text{in1}\}, \ldots, u_k = \text{id}(u') \langle \bar{s}_k, \{u' \mapsto \text{in1}\}, \gamma \rangle) \]
\[ (u_i = \gamma(q_i, \ell) \wedge \bar{q} = q_1, \ldots, q_k) \]
\[ \text{fill}(\mu X G, L, \gamma) \triangleq \text{fill}(G, L, \gamma) \quad \text{fill}(L, L, \gamma) \triangleq L \]

Figure 17: Fill Operation.

\[ F_{\bar{x}, \bar{y}}(T) = T' \quad x_i \in \bar{x} \quad F = z \leftarrow x_i, F' \]
\[ \text{Flnp} \quad \frac{F_{\bar{x}, \bar{y}}(x_i : B . T) = z ? B . T'}{F_{\bar{x}, \bar{y}}(y_1 : B . T) = z ! B . T'} \]
\[ F_{\bar{x}, \bar{y}}(T_1) = T_1' \quad F_{\bar{x}, \bar{y}}(T_2) = T_2' \quad x_i \in \bar{x} \quad F = z \leftarrow x_i, F' \]
\[ \frac{F_{\bar{x}, \bar{y}}(x_i \& (T_1, T_2)) = z \& (T_1', T_2')}{F_{\bar{x}, \bar{y}}(y_1 \oplus (T_1, T_2)) = z \oplus (T_1', T_2')} \]
\[ F_{\bar{x}, \bar{y}}(T) = T' \quad \frac{F_{\bar{x}, \bar{y}}(\mu X T) = \mu X T'}{F_{\bar{x}, \bar{y}}(X) = X} \quad \frac{F_{\bar{x}, \bar{y}}(\text{end}) = \text{end}}{F_{\bar{x}, \bar{y}}(T)} \]

Figure 18: Forwarder Renaming

A Auxiliary Definitions

Given choreography \( G \), local binders \( L \) and mapping \( \gamma \) we define \( \text{fill}(G, L, \gamma) \) for a given by induction on the structure of the choreography, as shown in Fig. 17. For the case of (in transit) communication, the queues for receivers waiting to receive the message, identified via the mapping \( \gamma(q_i, \ell) \), are augmented considering the value registered in the choreography and the input port \( u' \). The operation is defined only for local binders defined by \( \text{queues}(\ell) \), hence by construction the port \( u' \) is the same (originally given by \( \gamma(p, \ell) \) for sender role \( p \)). The operation proceeds to the continuation considering the augmented queues, thus ensuring message order is preserved. The difference in the cases for (in transit) choice is that the the focus is on the branch implied by the registered value.

Given type \( T \) and ports \( \bar{x} \) and \( \bar{y} \), forwarder renaming \( F_{\bar{x}, \bar{y}}(T) \) is given by the rules shown in Fig. 18 and interface check \( \bar{x}; \bar{y} \vdash T \) is defined by the rules shown in Fig. 19.

\[ \frac{\bar{x}; \bar{y} \vdash T}{\bar{x}; \bar{y} \vdash z \in \bar{x}} \quad \text{Inlp} \]
\[ \frac{\bar{x}; \bar{y} \vdash T_1 \quad \bar{x}; \bar{y} \vdash T_2 \quad z \in \bar{x}}{\bar{x}; \bar{y} \vdash z \& (T_1, T_2)} \quad \text{Ibra} \]
\[ \frac{\bar{x}; \bar{y} \vdash T_1 \quad \bar{x}; \bar{y} \vdash T_2 \quad z \in \bar{y}}{\bar{x}; \bar{y} \vdash z \oplus (T_1, T_2)} \quad \text{Icho} \]
\[ \frac{\bar{x}; \bar{y} \vdash T}{\bar{x}; \bar{y} \vdash \mu X T} \quad \text{Rec} \quad \frac{\bar{x}; \bar{y} \vdash X}{\bar{x}; \bar{y} \vdash \text{end}} \quad \text{IEnd} \]

Figure 19: Interface
B Auxiliary Results for Encoding

Lemma B.1. We have that:

- If \( C \xrightarrow{y^\ell} C' \) then \( \llbracket C \rrbracket \xrightarrow{y^\ell} \llbracket C' \rrbracket \).
- If \( C \xrightarrow{x^\ell} C' \) then \( \llbracket C \rrbracket \xrightarrow{x^\ell} \llbracket C' \rrbracket \).

Proof. By induction on the derivation of \( C \xrightarrow{y^\ell} C' \) and of \( C \xrightarrow{x^\ell} C' \).

Lemma B.2. We have that:

- If \( G \xrightarrow{pl^{(v)}} G' \) then \( \llbracket G \rrbracket_{p,D,\gamma} \xrightarrow{x^\ell} P \xrightarrow{w^\ell} \llbracket G' \rrbracket_{p,D,\gamma} \) given \( D = q.w \leftarrow p.z, D' \) and \( \gamma(p,z) = z' \) and \( \gamma(p,\ell) = u \).
- If \( G \xrightarrow{q^{\ell}(v)} G' \) then \( \llbracket G \rrbracket_{q,D,\gamma} \xrightarrow{w^\ell} P \xrightarrow{w'^\ell} \llbracket G' \rrbracket_{q,D,\gamma} \) given \( D = q.w \leftarrow p.z, D' \) and \( \gamma(q,w) = w' \) and \( \gamma(q,\ell) = u \).

Proof. By induction on the derivation of \( G \xrightarrow{pl^{(v)}} G' \) and of \( G \xrightarrow{q^{\ell}(v)} G' \).

C Auxiliary Results for Typing

Lemma C.1 (Swap Composite). If \( C : T \) and \( T = T_1 \times T_2 \) and \( C \xrightarrow{\lambda} C' \) and \( T_1 \xrightarrow{\lambda} T_1' \) then there is \( T' \) such that \( T' = T_1' \times T_2 \) and \( C' : T' \).

Proof. By induction on the derivation of \( T = T_1 \times T_2 \), using Lemmas C.2 and C.5.

Lemma C.2 (Swap Base). If \( \emptyset \vdash \text{abs}(L) \vdash T \) and \( L \xrightarrow{\lambda} L' \) and \( T = T_1 \times T_2 \) and \( T_1 \xrightarrow{\lambda} T_1' \) then there is \( T' \) such that \( T' = T_1' \times T_2 \) and \( \emptyset \vdash \text{abs}(L') \vdash T' \).

Proof. By induction on the derivation of \( T = T_1 \times T_2 \), using Lemmas C.3 and C.5.

Lemma C.3 (Swap Abstract). If \( \mathcal{L} \xrightarrow{\lambda_1} \mathcal{L}_1 \) and \( \mathcal{L} \xrightarrow{\lambda_2} \mathcal{L}_2 \) then there is \( \mathcal{L}_3 \) such that \( \mathcal{L}_1 \xrightarrow{\lambda_3} \mathcal{L}_3 \) and \( \mathcal{L}_2 \xrightarrow{\lambda_3} \mathcal{L}_3 \).

Proof. The proof follows directly from the semantics of abstract local binders.

Lemma C.4 (Harmony of the Abstract Semantics). If \( y^{\text{linc}} \neq \lambda \neq y^{\text{linc}} \).

- \( L \xrightarrow{\lambda} L' \text{ iff } \text{abs}(L) \xrightarrow{\text{abs}(\lambda)} \text{abs}(L') \) when \( y^{\text{linc}} \neq \lambda \neq y^{\text{linc}} \).

- \( L \xrightarrow{y^{\text{linc}}} L' \text{ iff } \text{abs}(L) \xrightarrow{y^{\text{linc}}} \text{abs}(L') \) or \( \text{abs}(L) \xrightarrow{y^{\text{ChoT}}} \text{abs}(L') \).

Proof. The proof follows directly by the definition of \( \text{abs}(\cdot) \).

Lemma C.5 (Merge is Associative and Commutative). If \( T = T_1 \times T_2 \):

- and \( T_2 = T'_2 \times T'''_2 \) then there is \( T_3 \) such that \( T_3 = T'_1 \times T'_2 \) and \( T = T_3 \times T'''_2 \).

- then \( T = T_2 \times T_1 \).

Proof. By induction on the derivation of \( T = T_1 \times T_2 \) and \( T_2 = T'_2 \times T'''_2 \).