ICE 2024 Pre-Proceedings

Clément Aubert Cinzia Di Giusto Simon Fowler Violet Ka I Pun

19th June 2024

This document contains the *informal* pre-proceedings of the 19th Interaction and Concurrency Experience (ICE 2024). The post-proceedings will be published on EPTCS.

Some of the slides can be found on the workshop's website.

Contents

Safe Composition of Systems of Communicating Finite State Machines

Franco Barbanera
Dipartimento di Matematica e Informatica
University of Catania
franco.barbanera@unict.it

Rolf Hennicker
Institute for Informatics
LMU Munich
hennicke@pst.ifi.lmu.de

The *Participants-as-Interfaces* (PaI) approach to system composition suggests that participants of a system may be viewed as interfaces. Given a set of systems, one participant per system is chosen to play the role of an interface. When systems are composed, the interface participants are replaced by *gateways* which communicate to each other by forwarding messages. The PaI-approach for systems of asynchronous communicating finite state machines (CFSMs) has been exploited in the literature for binary composition only, with a (necessarily) unique forwarding policy. In this paper we consider the case of multiple system composition when forwarding gateways are not uniquely determined and their interactions depend on specific *connection policies* complying with a *connection model*. We represent connection policies as CFSM systems and prove that a bunch of relevant communication properties (deadlock-freeness, reception-error-freeness, etc.) are preserved by *PaI multicomposition*, with the proviso that also the used connection policy does enjoy the communication property taken into account.

1 Introduction

Concurrent/Distributed systems are hardly – especially nowadays – stand-alone entities. They are part of "jigsaws" never completely finished. Either in their design phase or after their deployment, they should be considered as *open* and ready for interaction with their environment, and hence with other systems. The possibility of extending and improving their functional and communication capabilities by composing them with other systems is also a crucial means against their obsolescence. Compositional mechanisms and techniques are consequently an important subject for investigation. As mentioned in [3], system composition investigations should focus on three relevant features of these mechanisms/techniques:

- *Conservativity:* They should alter as little as possible the single systems we compose.
- *Flexibility:* They should not be embedded into the systems we compose, i.e. they should be "system independent". In particular, they should allow to consider **any** system as potentially **open**.
- *Safety:* Relevant properties of the single systems should not be "broken" by composition.

A fairly general and abstract approach to binary composition of systems was proposed in [1] and dubbed afterwards *Participants-as-Interfaces* (PaI). Roughly, the composition is achieved by transforming two selected participants – one per system, say h and k, – into coupled forwarders (gateways), provided the participants exhibit "compatible" behaviours. The graphics in Fig. 1 illustrates the PaI idea for the binary case. If interface participant h of the first system S_1 can receive a message a from some participant of S_1 and interface participant k of the second system S_2 can send a to some participant of S_2, then the gateway replacing the first interface (also called h) will forward the received message to the gateway for k. How PaI works for multicomposition of systems will be illustrated in Section 2. It is

To appear in EPTCS.

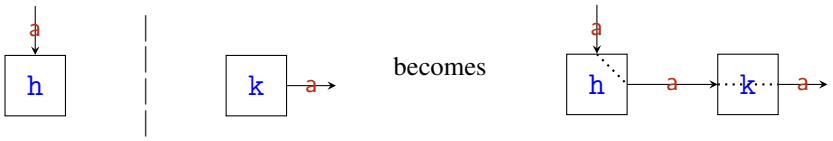


Figure 1: The PaI idea for binary composition

worth remarking that the PaI approach to system composition does not expect any particular condition to be satisfied by a single participant in order to be used as an interface.

Conservativity as well as *flexibility* are definitely features of the PaI composition idea. Conservativity holds since all participants not acting as interfaces remain untouched and flexibility holds since, in principle, any participant can play the role of an interface. This fact is independent of the concrete formalism used for protocol descriptions and system designs/implementations. *Safety*, instead, can be checked only once we take into account a specific formalism. Such checks were carried out in a number of papers where two relevant formalisms for the description and verification of concurrent communicating systems were considered: MultiParty Session Types (MPST) [21, 22] and Communicating Finite State Machines (CFSM) [12]. Safety of the binary PaI approach was investigated for MPST in [4], where a synchronous communication model was considered. The PaI approach to multicomposition for MPST has been exploited in [3, 2], again for synchronous communications. In particular, in [2], a restricted notion of multiple connections in a client-server setting has been considered. For the synchronous MPST formalism used in those papers, PaI proved to be safe. The binary PaI approach for safety in systems of (standard) asynchronous CFSMs was taken into account in [1], whereas safety of PaI for a synchronous version of the CFSM formalism was investigated in [6, 7, 8], again for binary composition.

Contributions. In the present paper we investigate safety of PaI multicomposition for the asynchronous formalism of CFSMs. For this purpose we reuse the PaI multicomposition idea of [3] but realise it – instead of the synchronous MPST framework – in the asynchronous CFSM setting which needs completely different design and proof techniques. At the same time we go beyond the binary composition of asynchronous CFSMs of [1] and study multicomposition of CFSM systems. Clearly this goes also beyond the aforementioned papers [6, 7, 8] dealing with binary composition of synchronous CFSMs. In particular, in the asynchronous case different communication properties, like freeness of unspecified receptions, are relevant.

A crucial role in our approach to multicomposition is played by *connection policies* which can be individually chosen by the system designer on the basis of a given concrete *connection model*. A connection model describes architectural aspects of compositions. It specifies which forwarding links between interface roles of different systems are meaningful from a static perspective. The concrete behavioural instantiation of such links, in terms of which message of an interface role, say h, is forwarded in which state of h to which interface role of another system, is determined by a connection policy which therefore also determines the construction of gateway CFSMs. The *multicomposition* of n systems of CFSMs is then simply defined by taking all CFSMs of the single systems but replacing each CFSM of an interface participant by its gateway CFSM. The use of connection models is methodologically important since it is more likely that a connection policy complying with a connection model will satisfy desired communication properties. Otherwise connection models are not relevant to our proofs.

In other words, we assume the existence of some connection model with which the connection policy used for the multicomposition is compliant. However, the specifics of the connection model are irrelevant for the safety results.

We show that a number of relevant communication properties (deadlock-freeness, orphan-message

freeness, unspecified-reception freeness, and progress) are preserved by PaI multicomposition of CFSM systems whenever the particular property is satisfied also by the connection policy used, which is formalised as a CFSM system itself. Apart from orphan-message-freeness preservation we need, however, an additional assumption which requires that interface participants do not have a state with at least one outgoing output action and one outgoing input action, a condition referred to in the literature as *no-mixed-state* [15]. We shall provide counterexamples illustrating the role played by the no-mixed-state condition in guaranteeing safety of composition. In contrast with deadlock-freeness, the stronger property of lock-freeness will be shown (by means of a counterexample) not to be preserved in general, even in absence of of mixed-states.

Outline. The main ideas underlying PaI multicomposition are intuitively described in Section 2. In Section 3 we recall the definitions of communicating finite state machine, communicating system and their related notions. There we also provide the definitions of a number of relevant communication properties. In Section 4, PaI multicomposition is formally defined on the basis of the definitions of connection policy and gateway. Our main results are presented in Section 5 including counterexamples spotting the role of the no-mixed-state condition and a counterexample for lock-freeness preservation. Section 6 concludes with a brief summary, by pointing out a few more approaches to system composition, and with hints for future work.

2 The PaI Approach to Multicomposition

In order to illustrate the idea underlying *PaI multicomposition*[1], we consider an example of [3] with four systems S_1, S_2, S_3 and S_4. As shown in Fig. 2, we have selected for each system one participant as an interface, named h, k, v and w. As in Fig. 1, we consider here only static aspects abstracting from dynamic issues, like the logical order of the exchanged messages, whose representation depends on the chosen formalism.

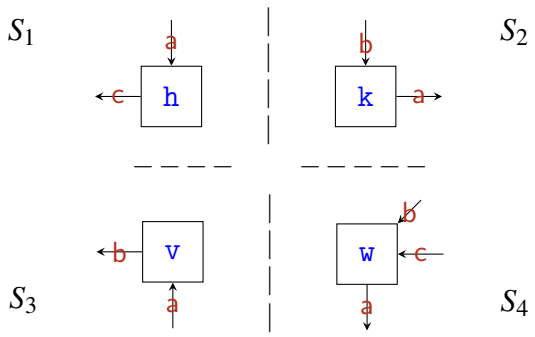


Figure 2: Four interface participants

Following the PaI approach, the composition of the four systems above consists in replacing the participants h, k, v and w, chosen as interfaces, by gateways. Note that a message, like a in S_1 sent to h, could be forwarded (unlike the binary case) to different other gateways. This means that a *connection policy* has to be set up in order to appropriately define the gateways. Such a policy primarily depends on which partner is chosen for the current message to be exchanged.

For what concerns the present example, one could decide that message a received by h has to be forwarded to w; the a received by v to k; the b received by k and w to v; the c received by w to h. Another possible choice could be similar to the previous one but for the forwarding of the messages a: the one received by h could be forwarded now to k whereas the one received by v could be forwarded to w. Such different "choices of partners", that we formalise by introducing the notion of *connection model*, can be graphically represented, respectively, by Choice A and Choice B in Fig. 3.

[1] It is of course possible to compose, two by two, several systems using binary composition, but in that way – by looking at systems as vertices and gateway connections as undirected edges – we can get only tree-like structures of systems.

Figure 3: Two possible choices of partners.

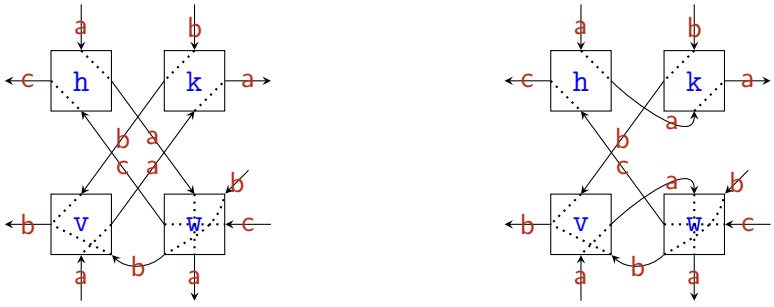


Figure 4: Two possible PaI multicompositions via gateways

The architecture of the resulting composed systems, according to the particular choices of partners (i.e. connection models), are represented by the diagrams in Fig. 4.

In both drawings of Fig. 4, the names h, k, etc. do now represent gateways. It is important to see that even if the original CFSMs for the participants in the single systems, like the CFSM for v in S_3, are given, the connection models and the drawings in Fig. 4 do not always provide what a gateway CFSM, modelling the dynamic forwarding strategy, should look like. This can be illustrated by looking at message b and participant v. No matter whether we consider Choice A or Choice B it is not determined when the gateway for v will accept b from k and when from w. For instance, a message b from w could be accepted by v only after two b's are received from k. Therefore, a given choice of partners needs, in general, to be "refined" – according to the formalism taken into account – into a specific *connection policy* taking care of the dynamic choice of partners.

This PaI approach to multicomposition has been exploited in [3] for a MPST formalism with synchronous communications. We are now going to realise PaI multicomposition in the context of CFSM systems with asynchronous communications.

3 Systems of Communicating Finite State Machines

Communicating Finite State Machines (CFSMs) is a widely investigated formalism for the description and analysis of distributed systems, originally proposed in [12]. CFSMs are a variant of finite state I/O-automata that represent processes which communicate by asynchronous exchanges of messages via FIFO channels. We now recall (partly following [15, 17, 24, 1]) the definitions of CFSM and system of

CFSMs.

We assume given a countably infinite set $\mathbf{P}_{\mathfrak{U}}$ of participant names (ranged over by $\mathtt{p},\mathtt{q},\mathtt{r},\mathtt{h},\mathtt{k},\ldots$) and a countably infinite alphabet $\mathbb{A}_{\mathfrak{U}}$ of messages (ranged over by a, b, c, l,$\mathsf{m},\ldots$).

Definition 3.1 (CFSM)**.** *Let* $\mathbf{P}$ *and* $\mathbb{A}$ *be finite subsets of* $\mathbf{P}_{\mathfrak{U}}$ *and* $\mathbb{A}_{\mathfrak{U}}$ *respectively.*

i) The set $C_{\mathbf{P}}$ *of* channels *over* $\mathbf{P}$ *is defined by* $C_{\mathbf{P}} = \{\mathtt{pq} \mid \mathtt{p},\mathtt{q} \in \mathbf{P}, \mathtt{p} \neq \mathtt{q}\}$

ii) The set $Act_{\mathbf{P},\mathbb{A}}$ *of* actions *over* $\mathbf{P}$ *and* $\mathbb{A}$ *is defined by* $Act_{\mathbf{P},\mathbb{A}} = C_{\mathbf{P}} \times \{!,?\} \times \mathbb{A}$
The subject *of an output action* $\mathtt{pq}!\mathsf{m}$ *and of an input action* $\mathtt{qp}?\mathsf{m}$ *is* $\mathtt{p}$.

iii) A communicating finite-state machine over $\mathbf{P}$ and $\mathbb{A}$ *is a finite transition system given by a tuple*
$$M = (Q, q_0, \mathbb{A}, \delta)$$
where Q *is a finite set of states,* $q_0 \in Q$ *is the initial state, and* $\delta \subseteq Q \times Act_{\mathbf{P},\mathbb{A}} \times Q$ *is a set of transitions such that all the actions have the same subject, to which we refer as the* name *of* M.

We shall write $M_{\mathtt{p}}$ to denote a CFSM with name $\mathtt{p}$. Where no ambiguity arises we shall refer to a CFSM by its name.

Notice that the above definition of CFSM is generic with respect to the underlying sets $\mathbf{P}$ and $\mathbb{A}$. This is necessary, since we shall not deal with a single system of CFSMs but with an arbitrary number of systems of CFSMs that can be *composed*. We shall write C and Act instead of $C_{\mathbf{P}}$ and $Act_{\mathbf{P},\mathbb{A}}$ when no ambiguity can arise. We assume $l, l', \ldots$ to range over Act; $\varphi, \varphi', \ldots$ to range over Act^* (the set of finite words over Act), and $w, w', \ldots$ to range over $\mathbb{A}^*$ (the set of finite words over $\mathbb{A}$). The symbol ε ($\varepsilon \notin \mathbb{A} \cup Act$) denotes the empty word and $\mid v \mid$ the lenght of a word $v \in Act^* \cup \mathbb{A}^*$.

The transitions of a CFSM are labelled by actions; a label $\mathtt{sr}!\mathsf{a}$ represents the asynchronous sending of message a from machine $\mathtt{s}$ to $\mathtt{r}$ through channel $\mathtt{sr}$ and, dually, $\mathtt{sr}?\mathsf{a}$ represents the reception (consumption) of a by $\mathtt{r}$ from channel $\mathtt{sr}$.

Given a CFSM $M = (Q, q_0, \mathbb{A}, \delta)$, we also define
$$\mathsf{in}(M) = \{\mathsf{a} \mid (\_, \_?\mathsf{a}, \_) \in \delta\} \quad \text{and} \quad \mathsf{out}(M) = \{\mathsf{a} \mid (\_, \_!\mathsf{a}, \_) \in \delta\}.$$
If M is a CFSM with name $\mathtt{p}$, we also write $\mathsf{in}(\mathtt{p})$ for $\mathsf{in}(M)$ and $\mathsf{out}(\mathtt{p})$ for $\mathsf{out}(M)$. Note that, in concrete examples, the name of a CFSM together with its input and output messages can be graphically depicted as in Fig. 2.

A state $q \in Q$ with no outgoing transition is *final*; q is a *sending* (resp. *receiving*) state if it is not final and all outgoing transitions are labelled with sending (resp. receiving) actions; q is a *mixed* state if there are at least two outgoing transitions such that one is labelled with a sending action and the other one is labelled with a receiving action.

A *communicating system*, called "protocol" in [12], is a finite set of CFSMs. In [15, 17, 24] the names of the CFSMs in a system are called *roles*. In the present paper we call them *participants*.

The dynamics of a system is formalised as a transition relation on configurations, where a configuration is a pair of tuples: a tuple of states of the machines in the system and a tuple of buffers representing the content of the channels.

Definition 3.2 (Communicating system and configuration)**.** *Let* $\mathbf{P}$ *and* $\mathbb{A}$ *be as in Def. 3.1.*

i) A communicating system (CS) over $\mathbf{P}$ and $\mathbb{A}$ *is a set* $S = (M_{\mathtt{p}})_{\mathtt{p} \in \mathbf{P}}$ *where for each* $\mathtt{p} \in \mathbf{P}$, $M_{\mathtt{p}} = (Q_{\mathtt{p}}, q_{0\mathtt{p}}, \mathbb{A}, \delta_{\mathtt{p}})$ *is a CFSM over* $\mathbf{P}$ *and* $\mathbb{A}$.

ii) A configuration *of a system* S *is a pair* $s = (\vec{q}, \vec{w})$ *where*
$$\vec{q} = (q_{\mathtt{p}})_{\mathtt{p} \in \mathbf{P}} \text{ with } q_{\mathtt{p}} \in Q_{\mathtt{p}}, \qquad \text{and} \qquad \vec{w} = (w_{\mathtt{pq}})_{\mathtt{pq} \in C} \text{ with } w_{\mathtt{pq}} \in \mathbb{A}^*.$$

The component $\vec{q}$ is the control state *of the system and $q_{\mathtt{p}} \in Q_{\mathtt{p}}$ is the* local state *of machine $M_{\mathtt{p}}$. The component $\vec{w}$ represents the state of the channels of the system and $w_{\mathtt{pq}} \in \mathbb{A}^*$ is the state of the channel $\mathtt{pq}$, i.e. the messages sent from $\mathtt{p}$ to $\mathtt{q}$. The initial configuration of S is $s_0 = (\vec{q}_0, \vec{\varepsilon})$ with $\vec{q}_0 = (q_{0_{\mathtt{p}}})_{\mathtt{p} \in \mathbf{P}}$.*

In the following we shall often denote a communicating system $(M_{\mathtt{p}})_{\mathtt{p} \in \{\mathtt{r}_i\}_{i \in I}}$ by $(M_{\mathtt{r}_i})_{i \in I}$.

Definition 3.3 (Reachable configuration)**.** *Let S be a communicating system over $\mathbf{P}$ and $\mathbb{A}$, and let $s = (\vec{q}, \vec{w})$ and $s' = (\vec{q'}, \vec{w'})$ be two configurations of S. Configuration s'* is reachable from *s by firing a transition with action l, written $s \xrightarrow{l} s'$, if there is $\mathtt{a} \in \mathbb{A}$ such that one of the following conditions holds:*

1. *$l = \mathtt{sr}!\mathtt{a}$ and $(q_{\mathtt{s}}, l, q'_{\mathtt{s}}) \in \delta_{\mathtt{s}}$ and*
   a) *for all $\mathtt{p} \neq \mathtt{s}$: $q'_{\mathtt{p}} = q_{\mathtt{p}}$ and*
   b) *$w'_{\mathtt{sr}} = w_{\mathtt{sr}} \cdot \mathtt{a}$ and for all $\mathtt{pq} \neq \mathtt{sr}$: $w'_{\mathtt{pq}} = w_{\mathtt{pq}}$;*
2. *$l = \mathtt{sr}?\mathtt{a}$ and $(q_{\mathtt{r}}, l, q'_{\mathtt{r}}) \in \delta_{\mathtt{r}}$ and*
   a) *for all $\mathtt{p} \neq \mathtt{r}$: $q'_{\mathtt{p}} = q_{\mathtt{p}}$ and*
   b) *$w_{\mathtt{sr}} = \mathtt{a} \cdot w'_{\mathtt{sr}}$ and for all $\mathtt{pq} \neq \mathtt{sr}$: $w'_{\mathtt{pq}} = w_{\mathtt{pq}}$.*

We write $s \to s'$ if there exists l such that $s \xrightarrow{l} s'$ and we write $s \not\to$ if no s' and no l exist with $s \xrightarrow{l} s'$. As usual, we denote the reflexive and transitive closure of $\to$ by $\to^*$. The set of reachable configurations *of S is $\mathsf{RC}(S) = \{s \mid s_0 \to^* s\}$.*

According to the above definition, communication happens via buffered channels following the FIFO principle.

The overall behaviour of a system can be described (at least) by the traces of configurations that are reachable from a distinguished initial one. Configurations may exhibit some pathological properties, like various forms of *deadlock* or *progress violation*, channels containing messages that will never be consumed (*orphan messages*) or just sent to a participant who is expecting another message to come (*unspecified receptions*). The goal of the analysis of communicating systems is to check whether such kinds of configurations are reachable or not. Although the desirable system properties are undecidable in general [12], sufficient conditions are known that are effectively checkable relying, for instance, on half-duplex communication [15], on the form of network topologies [16], or on synchronous compatibility checking [19].

We formalise now a number of relevant communication properties for systems of CFSMs that we shall deal with in the present paper.

Definition 3.4 (Communication properties)**.** *Let S be a communicating system, and let $s = (\vec{q}, \vec{w})$ be a configuration of S.*

i) s is a deadlock configuration *of S if $\vec{w} = \vec{\varepsilon}$ and $\forall \mathtt{p} \in \mathbf{P}$. $q_{\mathtt{p}}$ is a receiving state.*
I.e. all buffers are empty, but all machines are waiting for a message.
We say that S is deadlock-free *whenever, for any $s \in \mathsf{RC}(S)$, s is not a deadlock configuration.*

ii) s is an orphan-message configuration *of S if $\forall \mathtt{p} \in \mathbf{P}$. $q_{\mathtt{p}}$ is final and $\vec{w} \neq \vec{\varepsilon}$.*
I.e. each machine is in a final state, but there is still at least one non-empty buffer. We say that S is orphan-message free *whenever, for any $s \in \mathsf{RC}(S)$, s is not an orphan-message configuration.*

iii) s is an unspecified reception configuration *of S if $\exists \mathtt{r} \in \mathbf{P}$ such that*
   a) *$q_{\mathtt{r}}$ is a receiving state; and*

b) $\forall \mathtt{s} \in \mathbf{P}.[\ (q_{\mathtt{r}}, \mathtt{sr}?\mathtt{a}, q'_{\mathtt{r}}) \in \delta_{\mathtt{r}} \implies (|w_{\mathtt{sr}}| > 0 \ \wedge \ w_{\mathtt{sr}} \notin \mathtt{a} \cdot \mathbb{A}^*)\ ]$.

I.e. there is a receiving state $q_{\mathtt{r}}$ which is prevented from receiving any message from any of its buffers. (In other words, in each channel $\mathtt{sr}$ from which role $\mathtt{r}$ could consume there is a message which cannot be received by $\mathtt{r}$ in state $q_{\mathtt{r}}$.) We say that S is reception-error free *whenever, for any $s \in \mathsf{RC}(S)$, s is not an unspecified reception configuration.*

iv) *S satisfies the* progress property *if for all $s = (\vec{q}, \vec{w}) \in \mathsf{RC}(S)$, either there exists s' such that $s \to s'$ or $(\forall \mathtt{p} \in \mathbf{P}.\ q_{\mathtt{p}}$ is final$)$.*

v) *s is a* $\mathtt{p}$-lock configuration *of S if $\mathtt{p} \in \mathbf{P}$, $q_{\mathtt{p}}$ is a receiving state and*

$\mathtt{p}$ *does not appear as subject in any label of any transition sequence from s*

i.e. $\mathtt{p}$ remains stuck in all possible transition sequences from s. We say that S is lock-free *whenever, for each $\mathtt{p} \in \mathbf{P}$ and each $s \in \mathsf{RC}(S)$, s is not a $\mathtt{p}$-lock configuration.*

Note that progress property (iv) implies deadlock-freeness. Moreover, an unspecified reception configuration is trivially a $\mathtt{p}$-lock for some $\mathtt{p}$. This immediately implies that lock-freeness implies reception-error-freeness. It is also straightforward to check that lock-freeness does imply both deadlock-freeness and progress. The other properties are mutually independent.

The above definitions of communication properties (i)–(iv) are the same as the properties considered in [17], though the above formulation of progress is slightly simpler but equivalent to the one in [17]. The notions of orphan message and unspecified reception are also the same as in [24]. The same notions of deadlock and unspecified reception are given in [15] and inspired by [12]. The deadlock notions in [12] and [24] coincide with [15] and [17] if the local CFSMs have no final states. Otherwise deadlock in [24] is weaker than deadlock above. A still weaker notion of deadlock configuration, and hence a stronger notion of deadlock-freeness, has been suggested in [28]. This deadlock notion has been formally related to the above communication properties in [1].

4 PaI Multicomposition of Communicating Systems

As described in Section 2, the PaI approach to multicomposition of systems consists in replacing, in each to-be-composed system, one participant identified as an interface by a forwarder (that we dub "gateway"). Any participant in a system, say $\mathtt{h}$, can be considered as an interface. This means that we can look at the CFSM $\mathtt{h}$ as an abstract description of what the system expects from a number of "outer" systems (the environment) through their respective interfaces. Hence, any message received by $\mathtt{h}$ from another participant $\mathtt{p}$ of the system (to which $\mathtt{h}$ belongs) is interpreted as a message to be forwarded to some other interface $\mathtt{h}'$ among the available ones. Conversely, any message sent from $\mathtt{h}$ to another participant $\mathtt{p}$ of the system (to which $\mathtt{h}$ belongs) is interpreted as a message to be received from some other interface $\mathtt{h}'$ and to be forwarded to $\mathtt{p}$.

In order to clarify the notions introduced in this section, we present below an example from [3], "implemented" here in the CFSM formalism.

Example 4.1 (Working example)**.** Let us consider the following four systems[2]:

System-1 with participants $\mathtt{h}_1$ and $\mathtt{p}$.

Participant $\mathtt{h}_1$ controls the entrance of customers in a mall (via some sensor). As soon as a customer enters, $\mathtt{h}_1$ sends a message start to the participant $\mathtt{p}$ which controls a display for advertisements.

[2]For the sake of simplicity, the example considers only systems with two or three participants. Our definitions and results are of course independent of the number of participants in the single systems.

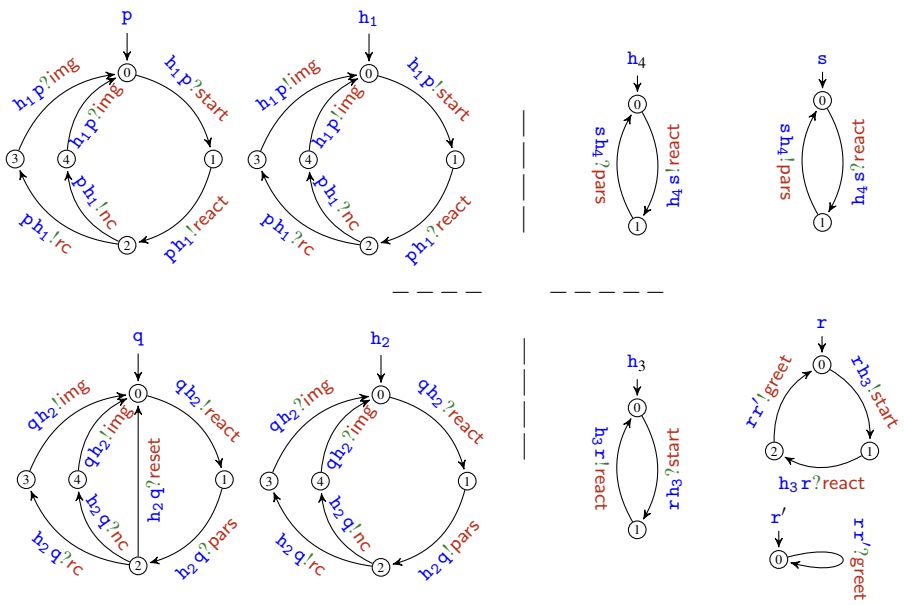


Figure 5: The four communicating systems formalising the systems of Example 4.1

On receiving the start message, p displays a general advertising image. Participant p does also control a sensor detecting emotional reactions as well as a card reader distinguishing regular from new customers. Such information, through the messages react, rc and nc is sent to h_1. Using that information h_1 sends to p a customised image, depending on the kind of the customer, through message img.

System-2 with participants h_2 and q.

Participant h_2 controls an image display. Images are provided by participant q according to some parameters sent by h_2 itself and depending on the reaction acquired by a sensor driven by q. Images are chosen also in terms of the kind of customers, on the basis of their cards. Participant q is able to receive a reset message too, even if h_2 cannot ever send it.

System-3 with participants h_3, r and r'.

Participant r controls a sensor detecting the entrance of people from a door. Once someone enters, a message start is sent by r to participant h_3 which turns on a light. The reaction of who enters, detected by a sensor driven by h_3, is sent back to r which, according to the reaction, communicates to r' the greeting to be broadcasted from the loudspeakers.

System-4 with participants h_4 and s.

Some sensors driven by Participant h_4 acquire the first reactions of people getting into a hall adorned by several Christmas lights. Such reactions, sent to participant s through a message react, enable s to send to h_4 a set of parameters (pars) allowing the latter to adjust the lights of the hall.

The behaviours of the participants of the above systems – assuming an asynchronous model of communication – can be formalised as CFSMs. So the systems above can be formalised as the following communicating systems

$$S_1 = (M_x)_{x\in\{h_1,p\}} \quad S_2 = (M_x)_{x\in\{h_2,q\}} \quad S_3 = (M_x)_{x\in\{h_3,r,r'\}} \quad S_4 = (M_x)_{x\in\{h_4,s\}}$$

as described, anticlockwise, in Figure 5. ◇

Notation: We use the following notation to denote the above set of communicating systems: $\{S_i\}_{i\in\{1,2,3,4\}}$ where $S_i = (M_{\mathtt{x}})_{\mathtt{x}\in\mathbf{P}_i}$ with $\mathbf{P}_1 = \{\mathtt{h}_1, \mathtt{p}\}$, $\mathbf{P}_2 = \{\mathtt{h}_2, \mathtt{q}\}$, $\mathbf{P}_3 = \{\mathtt{h}_3, \mathtt{r}, \mathtt{r}'\}$ and $\mathbf{P}_4 = \{\mathtt{h}_4, \mathtt{s}\}$.

The composition of a set of systems relies on a selection of participants, one for each system, considered as interfaces.

Definition 4.2 (Interfaces)**.** *Let $\{S_i\}_{i\in I}$ be a set of communicating systems such that, for each $i \in I$, $S_i = (M_{\mathtt{x}})_{\mathtt{x}\in\mathbf{P}_i}$, where the $\mathbf{P}_i$'s are pairwise disjoint. A set of participants $H = \{\mathtt{h}_i\}_{i\in I} \subseteq \bigcup_{i\in I}\mathbf{P}_i$ is a* set of interfaces *for $\{S_i\}_{i\in I}$ whenever, for each $i \in I$, $\mathtt{h}_i \in \mathbf{P}_i$. An interface $\mathtt{h}_i$ has* no mixed states *if the CFSM $M_{\mathtt{h}_i}$ in S_i has no mixed states.*

Example 4.3. We choose $\{\mathtt{h}_i\}_{i\in\{1,2,3,4\}}$ as set of interfaces for the communicating systems of Figure 5. ◇

We introduce now the notion of *connection model*[3], formalising what we have informally called "choice of partners" in Section 2. A connection model is intended to specify the structural (architectural) aspects of possible "reasonable" connections between interfaces of systems. Connection models should be provided before systems are composed since they help the system designer to avoid blatantly unreasonable compositions. Formally, a connection model is a set of *connections*, where a connection is a triple $(\mathtt{h},\mathtt{a},\mathtt{h}')$ in which $\mathtt{h}$ and $\mathtt{h}'$ are, respectively, interfaces of two systems, say S and S', and $\mathtt{a}$ is an input message for $\mathtt{h}$ and an output message for $\mathtt{h}'$. Being $\mathtt{a}$ an input for $\mathtt{h}$, this participant is supposed to receive $\mathtt{a}$ from the "inside" of S, i.e. from another participant of S. As previously mentioned, PaI multicomposition relies on the idea that $\mathtt{a}$ can be forwarded to the interface of some other system. The connection $(\mathtt{h},\mathtt{a},\mathtt{h}')$ hence specifies that $\mathtt{h}'$ is one of the possible interfaces $\mathtt{a}$ can be forwarded to. This is sound since $\mathtt{a}$ is an output of $\mathtt{h}'$, i.e. it is sent by $\mathtt{h}'$ to some participant of S'. The actual composition will then rely on gateways (forwarders) which comply with the connection model taken into account.

Definition 4.4 (Connection model)**.** *Let $\{S_i\}_{i\in I}$ be a set of communicating systems and let H be a set of interfaces for it.*

i) A connection model for H *is a ternary relation* $\mathrm{CM} \subseteq H \times \mathbb{A}_{\text{!?}} \times H$ *such that, for each $\mathtt{h} \in H$ and $\mathtt{a} \in \mathbb{A}_{\text{!?}}$,*

- $\mathtt{a} \in \mathsf{in}(\mathtt{h})$ *implies* $\exists\, \mathtt{h}' \in H$ *s.t.* $\mathtt{a} \in \mathsf{out}(\mathtt{h}')$ *and* $(\mathtt{h},\mathtt{a},\mathtt{h}') \in \mathrm{CM}$
- $\mathtt{a} \in \mathsf{out}(\mathtt{h})$ *implies* $\exists\, \mathtt{h}' \in H$ *s.t.* $\mathtt{a} \in \mathsf{in}(\mathtt{h}')$ *and* $(\mathtt{h}',\mathtt{a},\mathtt{h}) \in \mathrm{CM}$

where $\mathtt{h} \neq \mathtt{h}'$.
Elements of CM *are called* connections*. In particular, $(\mathtt{h},\mathtt{a},\mathtt{h}') \in \mathrm{CM}$ is called* connection for $\mathtt{a}$ (from $\mathtt{h}$ to $\mathtt{h}'$)*. We also define* $\mathsf{Msg}(\mathrm{CM}) = \{\mathtt{a} \mid (\_,\mathtt{a},\_) \in \mathrm{CM}\}$ *and assume that any message $\mathtt{a} \in \mathsf{Msg}(\mathrm{CM})$ occurs in one of the interfaces in H either as an input or as an output.*

ii) A connection model CM *for H is* strong *if, for each $\mathtt{h} \in H$ and $\mathtt{a} \in \mathbb{A}_{\text{!?}}$,*

- $\mathtt{a} \in \mathsf{in}(\mathtt{h})$ *implies* $\exists!\, \mathtt{h}' \in H$ *s.t.* $(\mathtt{h},\mathtt{a},\mathtt{h}') \in \mathrm{CM}$
- $\mathtt{a} \in \mathsf{out}(\mathtt{h})$ *implies* $\exists!\, \mathtt{h}' \in H$ *s.t.* $(\mathtt{h}',\mathtt{a},\mathtt{h}) \in \mathrm{CM}$.

where $\mathtt{h} \neq \mathtt{h}'$ and the unique existential quantifier '$\exists!$' stands for "there exists exactly one".

Connection models can be graphically represented by diagrams, like those used in Fig. 3.

[3] Such a notion was informally introduced in [3] in the setting of MultiParty Session Types.

Example 4.5 (Some connection models)**.** Let $H = \{\mathtt{h},\mathtt{k},\mathtt{v},\mathtt{w}\}$ be the set of interfaces for the systems $\{S_i\}_{i\in\{1,2,3,4\}}$ in Section 2. Fig. 3 represents the following connection models for H:

$$\begin{array}{rcl} \text{CM}_\text{A} & = & \{(\mathtt{h},\mathtt{a},\mathtt{w}),(\mathtt{v},\mathtt{a},\mathtt{k}),(\mathtt{w},\mathtt{c},\mathtt{h}),(\mathtt{k},\mathtt{b},\mathtt{v}),(\mathtt{w},\mathtt{b},\mathtt{v})\} \\ \text{CM}_\text{B} & = & \{(\mathtt{h},\mathtt{a},\mathtt{k}),(\mathtt{v},\mathtt{a},\mathtt{w}),(\mathtt{w},\mathtt{c},\mathtt{h}),(\mathtt{k},\mathtt{b},\mathtt{v}),(\mathtt{w},\mathtt{b},\mathtt{v})\} \end{array}$$

Obviously, both connection models are not strong, because of the presence of the connections $(\mathtt{k},\mathtt{b},\mathtt{v})$ and $(\mathtt{w},\mathtt{b},\mathtt{v})$.

Let us now provide a connection model for the systems in Fig. 5 with set of interfaces $H = \{\mathtt{h}_i\}_{i\in\{1,2,3,4\}}$. First we determine $\mathsf{in}(\mathtt{h}_1) = \{\mathtt{react},\mathtt{nc},\mathtt{rc}\}$, $\mathsf{out}(\mathtt{h}_1) = \{\mathtt{img},\mathtt{start}\}$, $\mathsf{in}(\mathtt{h}_2) = \{\mathtt{react},\mathtt{img}\}$, $\mathsf{out}(\mathtt{h}_2) = \{\mathtt{nc},\mathtt{rc},\mathtt{pars}\}$, $\mathsf{in}(\mathtt{h}_3) = \{\mathtt{start}\}$, $\mathsf{out}(\mathtt{h}_3) = \{\mathtt{react}\}$, and $\mathsf{in}(\mathtt{h}_4) = \{\mathtt{pars}\}$, $\mathsf{out}(\mathtt{h}_4) = \{\mathtt{react}\}$. A connection model for H is

$$\begin{array}{rcl} \text{CM} & = & \{(\mathtt{h}_1,\mathtt{react},\mathtt{h}_4),(\mathtt{h}_3,\mathtt{start},\mathtt{h}_1),(\mathtt{h}_2,\mathtt{img},\mathtt{h}_1),(\mathtt{h}_1,\mathtt{nc},\mathtt{h}_2), \\ & & (\mathtt{h}_1,\mathtt{rc},\mathtt{h}_2),(\mathtt{h}_4,\mathtt{pars},\mathtt{h}_2),(\mathtt{h}_2,\mathtt{react},\mathtt{h}_3)\} \end{array}$$

The representation of CM is as in Fig. 6. Obviously, this connection model is strong. ◇

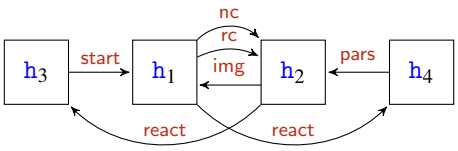


Figure 6: A connection model for the interfaces of Fig. 5.

When we have more than two systems to compose, the gateways are, in general, not uniquely determined. In order to produce gateways out of interfaces we need to decide which connection model we wish to take into account and how the interfaces do actually interact "complying" with the connection model. Once a connection model is selected, the forwarding strategy of the gateway is still not uniquely determined if the connection model is not strong. The reason is that in the case of at least two connectors with the same source or the same target, like $(\mathtt{k},\mathtt{b},\mathtt{v})$ and $(\mathtt{w},\mathtt{b},\mathtt{v})$ in Example 4.5, the gateway for $\mathtt{v}$ has a dynamic choice when to accept message $\mathtt{b}$ from $\mathtt{k}$ and when from $\mathtt{w}$. Therefore we need further (dynamic) information which will be provided by *connection policies*. A connection policy is itself a communicating system which describes the dynamic choice of partners among the possible gateways by respecting the constraints of (that is, complying with) the connection model. Technically, we first associate a set of CFSMs (the "local connection policy set") to each interface. Any element of this set specifies which communications to the "outside" are allowed in which state. Technically these communications are dual to the communications of its corresponding interface.

Definition 4.6 (Local Connection Policy Set)**.** *Let* CM *be a connection model for a set of interfaces H and let $\mathtt{h} \in H$ with CFSM $M_\mathtt{h} = (Q, q_0, \mathbb{A}, \delta)$.*
The local connection policy set *of $M_\mathtt{h}$ w.r.t.* CM *is the set of CFSMs $\mathsf{LCPS}(M_\mathtt{h}, \text{CM})$ defined as follows:*

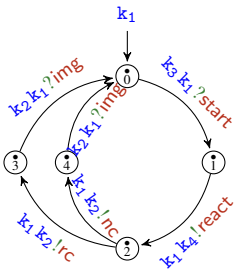
$$\mathsf{LCPS}(M_\mathtt{h}, \text{CM}) = \{(\dot{Q}, \dot{q}_0, \mathbb{A}, \dot{\delta}) \mid \quad \dot{\delta} \textit{ is a minimal relation s.t. } (*) \textit{ and } (**)\}$$

where $\dot{Q} = \{\dot{q} \mid q \in Q\}$ and
$(*) = q \xrightarrow{\mathtt{rh?a}} q' \in \delta$ *implies* $\exists \mathtt{p} \in H \setminus \{\mathtt{h}\}$ *s.t.* $\dot{q} \xrightarrow{\dot{\mathtt{h}}\dot{\mathtt{p}}\mathtt{!a}} \dot{q}' \in \dot{\delta}$ *and* $(\mathtt{h},\mathtt{a},\mathtt{p}) \in$ CM,
$(**) = q \xrightarrow{\mathtt{hr!a}} q' \in \delta$ *implies* $\exists \mathtt{p} \in H \setminus \{\mathtt{h}\}$ *s.t.* $\dot{q} \xrightarrow{\dot{\mathtt{p}}\dot{\mathtt{h}}\mathtt{?a}} \dot{q}' \in \dot{\delta}$ *and* $(\mathtt{p},\mathtt{a},\mathtt{h}) \in$ CM.

Notice that, in the above definition, each CFSM in $\mathsf{LCPS}(M_{\mathtt{h}}, \mathrm{CM})$ has name $\dot{\mathtt{h}}$. Moreover, $\dot{q}$ (resp. $\dot{\mathtt{h}}$) is to be looked at as a "decoration" of the state q (resp. the name $\mathtt{h}$). This will enable us to immediately retrieve q (resp. $\mathtt{h}$) out of $\dot{q}$ (resp. $\dot{\mathtt{h}}$).

Notation: In the following, for the sake of readability, we shall write $\mathtt{k}$ (resp. $\mathtt{k}_i$) for $\dot{\mathtt{h}}$ (resp. $\dot{\mathtt{h}}_i$).

Local connection policy sets are finite, since they contain machines which only differ in the names of participants and these names belong to a finite set. Any element $(\dot{Q}, \dot{q}_0, \mathbb{A}, \dot{\delta})$ of $\mathsf{LCPS}(M_{\mathtt{h}}, \mathrm{CM})$ does comply with the connection model CM, since it can only have transitions $\dot{q} \xrightarrow{\dot{\mathtt{h}}\mathtt{p}!\mathtt{a}} \dot{q}' \in \dot{\delta}$ with $(\mathtt{h}, \mathtt{a}, \mathtt{p}) \in \mathrm{CM}$ and transitions $\dot{q} \xrightarrow{\dot{\mathtt{p}}\mathtt{h}?\mathtt{a}} \dot{q}' \in \dot{\delta}$ with $(\mathtt{p}, \mathtt{a}, \mathtt{h}) \in \mathrm{CM}$, Moreover, $\mathsf{LCPS}(M_{\mathtt{h}}, \mathrm{CM})$ is a singleton if the connection model CM is strong.



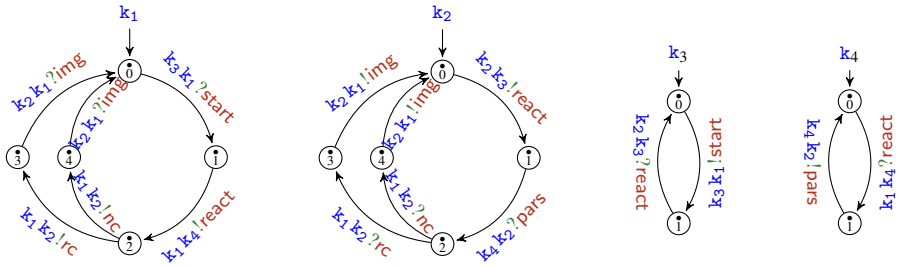
Example 4.7 (An element of a local connection policy set)**.** Let $M_{\mathtt{h}_1}$ be the CFSM for the participant $\mathtt{h}_1$ of Example 4.1 and let CM be the strong connection model for $H = \{\mathtt{h}_i\}_{i\in\{1,2,3,4\}}$ of Example 4.5. The CFSM on the right is the unique element of $\mathsf{LCPS}(M_{\mathtt{h}_1}, \mathrm{CM})$. ◇

Given a connection model, a connection policy is obtained by choosing, for each interface, an element of its local connection policy set.

Definition 4.8 (Connection policy)**.** *Let $\{S_i\}_{i\in I}$ be a set of communicating systems such that, for each $i \in I$, $S_i = (M_{\mathtt{x}})_{\mathtt{x}\in\mathbf{P}_i}$, and let* CM *be a connection model for a set of interfaces $H = \{\mathtt{h}_i\}_{i\in I}$. A* connection policy (for H) complying with CM *is a communicating system $\mathbb{K} = (M_{\mathtt{k}_i})_{i\in I}$ such that, for each $i \in I$, $M_{\mathtt{k}_i} \in \mathsf{LCPS}(M_{\mathtt{h}_i}, \mathrm{CM})$.*

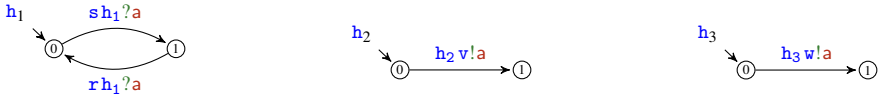
Connection policies are made of local connection policies which, due to the conditions $(*)$ and $(**)$ in Definition 4.6, are compliant with the given communication model CM. Consequently, in the above definition, the connection policy is said to be compliant with CM. If we dropped the two requirements $(*)$ and $(**)$ in Definition 4.6 we would get non-compliant connection policies.

Example 4.9 (A connection policy)**.** The following four CFSMs constitute a connection policy for $H = \{\mathtt{h}_i\}_{i\in I}$ complying with CM, where the $M_{\mathtt{h}_i}$'s are as in Figure 5 and CM is the connection model of Example 4.5.

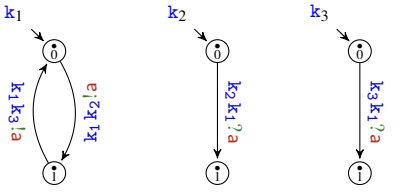


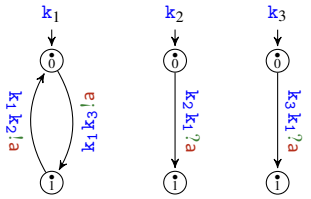
◇

Remark 4.10. A connection model can be looked at as a static and abstract description of connection policies. In particular a connection model abstracts from the order of exchanged messages. As already pointed out above there may be several connection policies complying with a given connection model CM if CM is not strong. As an example assume given three systems with the following interfaces:



We can now consider the following (non-strong) connection model: $\text{CM} = \{(\mathtt{h}_1, \mathtt{a}, \mathtt{h}_2), (\mathtt{h}_1, \mathtt{a}, \mathtt{h}_3)\}$.
It is easy to check that the connection policies $\mathbb{K}_1$ and $\mathbb{K}_2$ below do both comply with CM.

$\mathbb{K}_1 =$ 

$\mathbb{K}_2 =$ 

◇

By now we have almost all the necessary notions to formally define the PaI multicomposition of systems of communicating systems. The only missing piece is that of building the gateways using a connection policy.

We get a gateway essentially by transforming an interface $M_\mathtt{h}$ by inserting a fresh state in between any transition. Any input transition $q \xrightarrow{\mathtt{sh?a}} q'$ (resp. output transition $q \xrightarrow{\mathtt{hs!a}} q'$) of $M_\mathtt{h}$ is then transformed into two consecutive transitions

$$q \xrightarrow{\mathtt{sh?a}} \hat{q} \xrightarrow{\mathtt{hh'!a}} q' \qquad (\text{resp. } q \xrightarrow{\mathtt{h'h?a}} \hat{q} \xrightarrow{\mathtt{hs!a}} q')$$

where $\hat{q}$ is a fresh state and $\dot{q} \xrightarrow{\mathtt{kk'!a}} \dot{q}'$ (resp. $q \xrightarrow{\mathtt{k'k?a}} \dot{q}'$) belonging to the connection policy taken into account. In the formal definition below we distinguish the fresh states by superscripting them by the transition they are "inserted in between".

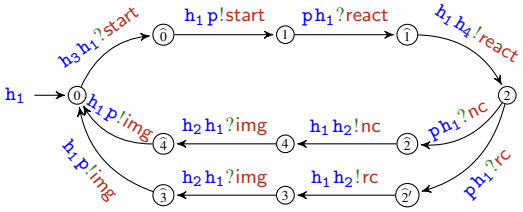
Definition 4.11 (Gateway)**.**
Assume given a connection model CM *and two CFSMs* $M_\mathtt{h}$ *and* $M_\mathtt{k}$ *such that* $M_\mathtt{h} = (Q, q_0, \mathbb{A}, \delta)$ *and* $M_\mathtt{k} = (\dot{Q}, \dot{q}_0, \mathbb{A}, \dot{\delta}) \in \mathsf{LCPS}(M_\mathtt{h}, \text{CM})$. *The* gateway $M_\mathtt{h} \leftarrow\!\!\!\rho M_\mathtt{k}$ *obtained out of* $M_\mathtt{h}$ *and* $M_\mathtt{k}$ *is defined by*

$$M_\mathtt{h} \leftarrow\!\!\!\rho M_\mathtt{k} = (Q \cup \widehat{Q}, q_0, \mathbb{A}, \hat{\delta})$$

where
– $\widehat{Q} = \bigcup_{q \in Q} \{q^{(q,l,q')} \mid (q, l, q') \in \delta\}$,
– $\widehat{\delta} = \{(q, \mathtt{rh?a}, \widehat{q}), (\widehat{q}, \mathtt{hs!a}, q') \mid (q, \mathtt{hs!a}, q') \in \delta, (\dot{q}, \dot{\mathtt{r}}\mathtt{k?a}, \dot{q}') \in \dot{\delta},\ \widehat{q} = q^{(q,\mathtt{hs!a},q')}\}$
$\quad \cup \{(q, \mathtt{sh?a}, \widehat{q}), (\widehat{q}, \mathtt{hr!a}, q') \mid (q, \mathtt{sh?a}, q') \in \delta,\ (\dot{q}, \mathtt{k}\dot{\mathtt{r}}\mathtt{!a}, \dot{q}') \in \dot{\delta},\ \widehat{q} = q^{(q,\mathtt{sh?a},q')}\}$.

We refer to $\widehat{\delta}$ *as* $\widehat{\delta}_\mathtt{h}$ *whenever* h *is not clear from the context; similarly for* $\widehat{Q}$.

Example 4.12 (A gateway)**.** Let $M_{\mathtt{h}_1}$ be as in Example 4.1, and let $M_{\mathtt{k}_1}$ be as in the connection policy of Example 4.9. The gateway $M_{\mathtt{h}_1} \leftarrow\!\!\!\rho M_{\mathtt{k}_1}$ is as follows.



◇

Definition 4.13 (Composability)**.** *Let* $\{S_i\}_{i \in I}$ *be a set of communicating systems such that, for each* $i \in I$, $S_i = (M_\mathtt{x})_{\mathtt{x} \in \mathbf{P}_i}$. *Moreover, let* $H = \{\mathtt{h}_i\}_{i \in I}$ *be a set of interfaces for it. We say that* $\{S_i\}_{i \in I}$ *is* composable with respect to H *whenever the sets* $\mathbf{P}_i$*'s are pairwise disjoint.*

Let us now describe how systems are composed on the basis of a given connection policy.

Definition 4.14 (Multicomposition of communicating systems)**.** *Let $\{S_i\}_{i\in I}$ be a set of communicating systems composable with respect to $H = \{\mathtt{h}_i\}_{i\in I}$ and let $\mathbb{K} = (M_{\mathtt{k}_i})_{i\in I}$ be a connection policy complying with a connection model* CM *for H. The* multicomposition of $\{S_i\}_{i\in I}$ with respect to $\mathbb{K}$ *is the communicating system*

$$\mathscr{MC}(\{S_i\}_{i\in I}, \mathbb{K}) = (M'_{\mathtt{p}})_{\mathtt{p}\in\bigcup_{i\in I}\mathbf{P}_i}$$

where

$$M'_{\mathtt{p}} = \begin{cases} M_{\mathtt{p}} & \text{if } \mathtt{p} \notin \{\mathtt{h}_i\}_{i\in I} \\ M_{\mathtt{h}_i} \leftarrowtriangle M_{\mathtt{k}_i} & \text{if } \mathtt{p} = \mathtt{h}_i \text{ with } i \in I \end{cases}$$

Note that the CFSMs of a composition are CFSMs over $\mathbf{P} = \bigcup_{i\in I}\mathbf{P}_i$ and $\mathbb{A} = \bigcup_{i\in I}\mathbb{A}_i$. Graphically, the architectural structure of a multicomposition via gateways can be shown as in Fig. 4.

5 On the Preservation of Communication Properties

The main result of the present paper is the safety of PaI multicomposition of CFSM systems for all communication properties of Definition 3.4 but lock-freeness. Apart from orphan-message-freeness we need the no-mixed-state assumption for interfaces to obtain the preservation results.

Theorem 5.1 (Safety of PaI multicomposition of CFSM systems)**.** *Let $\{S_i\}_{i\in I}$ be a set of communicating systems composable with respect to a set $H = \{\mathtt{h}_i\}_{i\in I}$ of interfaces with no mixed states (cf. Definition 4.2) and let $\mathbb{K}$ be a connection policy for H. Let $\mathscr{P}$ be either the property of* deadlock-freeness *or* reception-error-freeness *or* progress*. If $\mathscr{P}$ holds for each S_i with $i \in I$ and for $\mathbb{K}$, then $\mathscr{P}$ holds for $S = \mathscr{MC}(\{S_i\}_{i\in I}, \mathbb{K})$. Moreover, the above holds also if the no-mixed-state condition is removed and $\mathscr{P}$ is* orphan-message-freeness*.*

Remark 5.2. The above result about safety of multicomposition is actually independent of a concrete connection model. Considering connection policies which comply with a connection model is, however, helpful at the design stage of the multicomposition and enhances the possibility of getting connection policies which satisfy communication properties and hence support the preservation of communication properties of the composed systems. ◇

Theorem 5.1 can be proved for each property $\mathscr{P}$ separately by contradiction. In particular by showing that if $\mathscr{P}$ does not hold for S then it does not hold either for one of the S_i's or for $\mathbb{K}$.

A key notion for the proofs is that of *projection* of a reachable configuration of the composed system to configurations of each of the single systems S_i and also of the connection policy $\mathbb{K}$. On this basis, the most important tool to get contradictions is the subsequent Proposition 5.4 which essentially shows that projections of reachable configurations involving no intermediate gateway states are reachable configurations again. The complete proofs of property preservations are provided in [5]. They are independent of the communication model $\mathbb{K}$ complies with.

Definition 5.3 (Configuration projections)**.** *Let $S = \mathscr{MC}(\{S_i\}_{i\in I}, \mathbb{K})$ be as in Theorem 5.1 (but without no-mixed-state assumption). Let $s = (\vec{q}, \vec{w}) \in \mathsf{RC}(S)$ where $\vec{q} = (q_{\mathtt{p}})_{\mathtt{p}\in\mathbf{P}}$ and $\vec{w} = (w_{\mathtt{pq}})_{\mathtt{pq}\in C_{\mathbf{P}}}$. For each $i \in I$, the projection $s_{|_{\mathbf{i}}}$ of s to S_i is defined by*

$$s_{|_{\mathbf{i}}} = (\vec{q}_{|_{\mathbf{i}}}, \vec{w}_{|_{\mathbf{i}}})$$

where $\vec{q}_{|_{\mathbf{i}}} = (q_{\mathtt{p}})_{\mathtt{p}\in\mathbf{P}_i}$ and $\vec{w}_{|_{\mathbf{i}}} = (w_{\mathtt{pq}})_{\mathtt{pq}\in C_{\mathbf{P}_i}}$.
The projection $s_{|_{\mathbb{K}}}$ of $s = (\vec{q}, \vec{w})$ to $\mathbb{K}$ is defined if $q_{\mathtt{h}_i} \notin \widehat{Q}_{\mathtt{h}_i}$ for each $i \in I$ and then

$$s_{|_{\mathbb{K}}} = (\vec{q}_{|_{\mathbb{K}}}, \vec{w}_{|_{\mathbb{K}}})$$

where $\vec{q}_{|\mathbb{K}} = (p_{\mathtt{k}_i})_{i\in I}$ *is such that, for each* $i \in I$, $p_{\mathtt{k}_i} = \dot{q}_{\mathtt{h}_i}$ *(with* $\dot{q}_{\mathtt{h}_i}$ *being the "dotted decoration" of the local state* $q_{\mathtt{h}_i}$*) and where* $\vec{w}_{|\mathbb{K}} = (w'_{\mathtt{pq}})_{\mathtt{p},\mathtt{q}\in\{\mathtt{k}_i\}_{i\in I},\mathtt{p}\neq\mathtt{q}}$ *is such that, for each pair* $i, j \in I$ *with* $i \neq j$, $w'_{\mathtt{k}_i\mathtt{k}_j} = w_{\mathtt{h}_i\mathtt{h}_j}$.

Proposition 5.4 (On reachability of projections)**.** *Let* $s = (\vec{q}, \vec{w}) \in \mathsf{RC}(S)$.

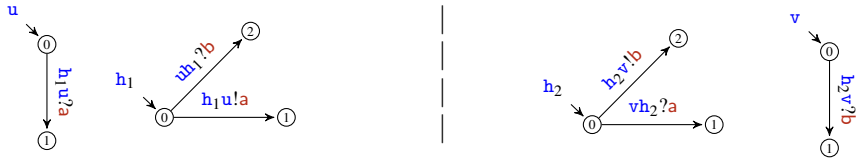
i) For each $i \in I$, $(q_{\mathtt{h}_i} \notin \widehat{Q_{\mathtt{h}_i}} \implies s_{|\mathtt{i}} \in \mathsf{RC}(S_i))$;

ii) $(q_{\mathtt{h}_i} \notin \widehat{Q_{\mathtt{h}_i}}$ *for each* $i \in I) \implies s_{|\mathbb{K}} \in \mathsf{RC}(\mathbb{K})$.

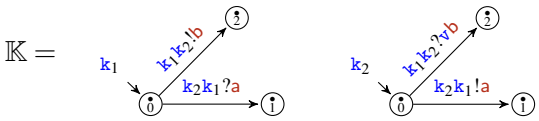
The connection policy of Example 4.9 does enjoy all the properties of Definition 3.4. Moreover, the interfaces of the four systems of Example 4.1 are all with no mixed state. Hence Theorem 5.1 guarantees that any property (among those of Definition 3.4, but lock-freedom) enjoyed by the systems is also enjoyed by their PaI multicomposition.

Now we provide some examples for cases in which communication properties are not preserved. First we show that all the three properties for which we have assumed the no-mixed-state condition in Theorem 5.1 would, in general, not be preserved by composition if the condition is dropped. In the counterexamples, the receiving states introduced by the gateway construction cause the breaking of the property taken into account.

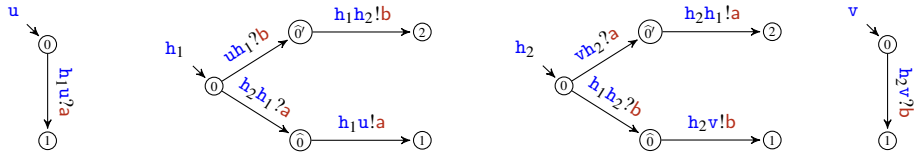
Example 5.5 (No-mixed-state counterexample for deadlock-freeness and progress preservation)**.** Let us consider the two following systems S_1 and S_2 with interfaces, respectively, $\mathtt{h}_1$ and $\mathtt{h}_2$ containing mixed states.



S_1 and S_2 are both deadlock free and both enjoy the progress property. There is a unique communication model for their composition: $\text{CM} = \{(\mathtt{h}_2, \mathtt{a}, \mathtt{h}_1), (\mathtt{h}_1, \mathtt{b}, \mathtt{h}_2)\}$ The unique communication policy complying with CM is the following one.

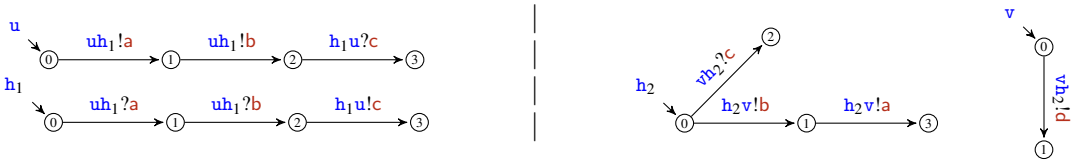


Also $\mathbb{K}$ is deadlock free and enjoys the progress property. The system $\mathscr{MC}(\{S_1, S_2\}, \mathbb{K})$ is the following one.



The initial configuration is actually a deadlock, and hence the system does also not enjoy progress. ◇

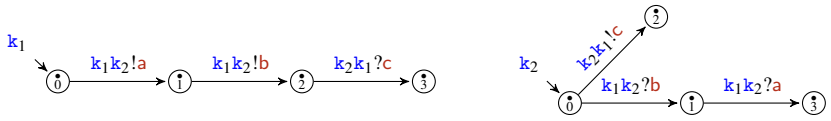
Example 5.6 (No mixed-state counterexample for reception-error-freeness preservation)**.** Let us consider the two following systems S_1 and S_2 with interfaces, respectively, $\mathtt{h}_1$ and $\mathtt{h}_2$ containing mixed states.



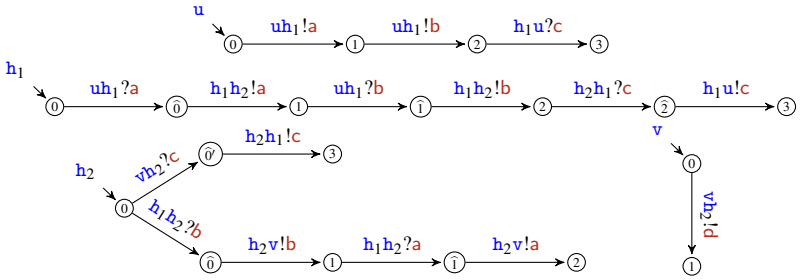
S_1 and S_2 are both reception-error free. The unique communication model for their composition is

$$\text{CM} = \{(\mathtt{h}_1, \mathtt{a}, \mathtt{h}_2), (\mathtt{h}_1, \mathtt{b}, \mathtt{h}_2), (\mathtt{h}_2, \mathtt{c}, \mathtt{h}_1)\}$$

The unique communication policy complying with CM is

$\mathbb{K} =$ 

Also $\mathbb{K}$ is reception-error free. The system $\mathscr{MC}(\{S_1, S_2\}, \mathbb{K})$ is the following one.



This communication system, however, is not reception-error free, since it is possible to reach the configuration $s = (\vec{q}, \vec{w})$ where

$$\vec{q} = (2_{\mathtt{u}}, 2_{\mathtt{h}_1}, 0_{\mathtt{h}_2}, 1_{\mathtt{v}}), \qquad w_{\mathtt{h}_1\mathtt{h}_2} = \langle \mathtt{a} \cdot \mathtt{b} \rangle, \qquad w_{\mathtt{vh}_2} = \langle \mathtt{d} \rangle, \qquad w_c = \varepsilon \ \ (\forall c \notin \{\mathtt{h}_1\mathtt{h}_2, \mathtt{vh}_2\})$$

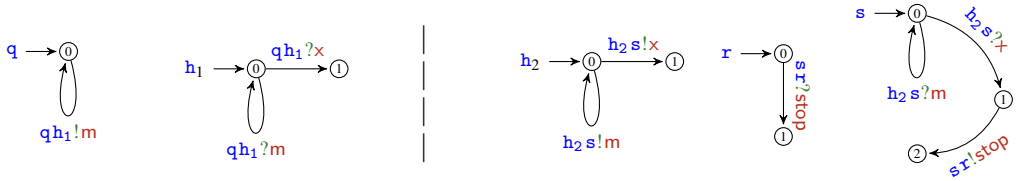
In the configuration s, the CFSM $\mathtt{h}_2$ is in a receiving state, namely 0, from which there are two transitions, namely $(0, \mathtt{vh}_2?\mathtt{c}, \hat{0}')$ and $(0, \mathtt{h}_1\mathtt{h}_2?\mathtt{b}, \hat{0})$. Moreover, the channels $\mathtt{vh}_2$ and $\mathtt{h}_1\mathtt{h}_2$ are both not empty and their first element is different from both b and c. The above configuration is hence an unspecified reception configuration. ◇

Notice that in case we dropped the requirement that $\mathbb{K}$ has to comply with a communication model, the interfaces $\mathtt{h}_1$ and $\mathtt{h}_2$ of Example 5.6 could be simplified to get the counterexample. In particular, they could have just, respectively, two and three states. The use of communication models hence limits the possibility of getting systems whose properties are not preserved by composition. This is an indication that connection models increase the possibility of getting safe compositions.

Let us now turn to the last communication property stated in Definition 3.4 which is lock-freeness. This property is also meaningful in the context of synchronous communication.

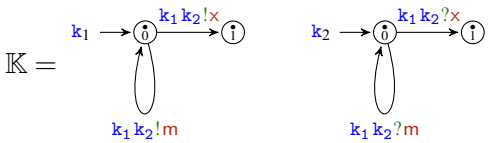
In [8, Example 6.7] a counterexample is provided, showing that in the formalism of *synchronous* CFSMs the properties of (synchronous) lock-freeness and deadlock-freeness are, in general, not preserved. As a matter of fact, lock-freeness is problematic also for the case of asynchronous communications and no mixed states, as shown in the following example, adapted from [8].

Example 5.7 (Lock-freeness is not preserved by composition)**.** Let us consider the following communicating systems S_1 and S_2.

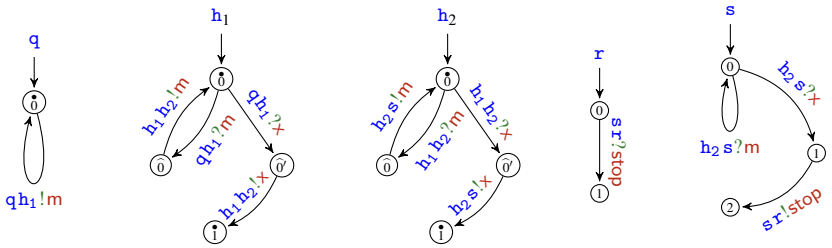


Note that both S_1 and S_2 are lock-free and their respective interfaces $\mathtt{h}_1$ and $\mathtt{h}_2$ have no mixed states.

Let us now consider the (unique) connection policy $\mathbb{K} = (M_{k_i})_{i\in\{1,2\}}$ where $M_{k_1} \in \mathsf{LCPS}(M_{h_1}, \mathrm{CM})$ and $M_{k_2} \in \mathsf{LCPS}(M_{h_2}, \mathrm{CM})$ with connection model $\mathrm{CM} = \{(h_1, x, h_2), (h_1, m, h_2)\}$.



It is easy to see that $\mathbb{K}$ is lock-free. The multicomposition $\mathscr{MC}(\{S_i\}_{i\in\{1,2\}}, \mathbb{K})$ is the following communicating system:



The initial configuration s_0 of $\mathscr{MC}(\{S_i\}_{i\in\{1,2\}}, \mathbb{K})$ is an $\mathtt{r}$-lock, since the transition $\mathtt{q}\,\mathtt{h}_1\,?\mathsf{x}$ of $\mathtt{h}_1$ can never be fired, so implying, in turn, that also $\mathtt{h}_1\,\mathtt{h}_2\,!\mathsf{x}$ of $\mathtt{h}_1$, $\mathtt{h}_1\,\mathtt{h}_2\,?\mathsf{x}$ of $\mathtt{h}_2$, $\mathtt{h}_2\,\mathtt{s}\,!\mathsf{x}$ of $\mathtt{h}_2$, $\mathtt{h}_2\,\mathtt{s}\,?\mathsf{x}$ of $\mathtt{s}$ and $\mathtt{s}\,\mathtt{r}\,!\mathsf{stop}$ of $\mathtt{s}$ can never be fired. Hence, no transition sequence out of s_0 will ever involve the participant $\mathtt{r}$. Thus $\mathscr{MC}(\{S_i\}_{i\in\{1,2\}}, \mathbb{K})$ is not lock-free. ◇

6 Conclusions

The necessity of supporting the modular development of concurrent/distributed systems, as well as the need to extend/modify/adapt/upgrade them, urged the investigation of composition methods. Focusing on such investigations in the setting of abstract formalisms for the description and verification of systems enables to get general and formal guarantees of relevant features of the composition methods.

An investigation of composition in a formalism for choreographic programming was carried out in [25]. In [23] a modular technique was developed for the verification of aspect-oriented programs expressed as state machines. Team Automata is another formalism in which compositionality issues have been addressed [10, 9], as well as in assembly theories considered in [20]. Composition for protocols described via a process algebra has been investigated in [11]. In [14, 26] a technique for modular design in the setting of reactive programming is proposed. A possible approach to composition for a MultiParty Session Type (MPST) formalism is developed in [27]. The mentioned papers provide just a glimpse of the variety of approaches to system composition in the literature.

Papers dealing with the (binary) composition of systems on the basis of the *participants-as-interfaces* (PaI) approach have been pointed out already in Section 1 and the idea of PaI for multicomposition of systems has been explained in Section 2. In the present paper we study the PaI approach to multicomposition for systems of asynchronously communicating finite state machines (CFSMs). We show that (under mild assumptions) important communication properties relevant in the context of asynchronous communication, like freeness of orphan messages and unspecified receptions, are preserved by composition (a feature dubbed *safety* in [3]). For this we assume that for each single system one participant is chosen as an interface. A key role in our work, inspired by [3], is played by *connection policies*, which

are CFSM systems which determine the ways how interfaces can interact when they are replaced by gateways (forwarders) in system compositions.

For an "unstructured" formalism like CFSM, the natural generalisation from multicomposition with single interfaces to multicomposition with multiple interfaces (per system) is not trouble-free, as discussed in [1, Sect.6] for binary composition. This is mainly due to the possible indirect interactions which could occur among the interfaces inside the single systems. In more structured formalisms, however, such possible interactions can be controlled. This is the case, for instance, in MPST formalisms. In fact, in [18] the authors devise a direct composition mechanism without using gateways for MPST systems. Such a mechanism allows for the presence of multiple interfaces thanks to an hybridisation with local and external information of the standard notion of global type. A combination of global and local constructs in order to get flexible specifications (uniformly describing both the internal and the interface behavior of systems) is also present in [13].

There are several directions to be pursued in future work starting from our results. On the first place, we want to generalise the notion of connection policy such that PaI multicomposition could actually be obtained by replacing interfaces by gateways which, instead of interacting directly with each other, can interact through an "interfacing infrastructure" represented via a system of CFSMs. Such a generalisation would be equivalent to multicomposition where exactly one system is enabled to have multiple interfaces. Let us consider a possible application of the above idea. In Example 4.1, in the resulting composed system, both participants `p` and `q` do emit a react message. It would be more natural to have only one of them produce such a message, e.g., to have `p` be the sole sensor registering reactions which then passes that information to both `r` and `s`. This would not be possible by our composition mechanisms and we cannot but make the best of the fact that we are dealing with two sensors. One could think, instead, about using an "interfacing infrastructure" containing some further participant enabling to ignore the messages from one sensor and properly duplicating the messages from the other.

It is worth noticing how, in Examples 5.5, 5.6 and 5.7, the interfaces of the systems we compose do have unreachable states. It is hence natural to wonder whether it is the presence of unreachable states in interfaces that entails the possibility of getting counterexamples for the properties taken into account.

We are also planning to consider further communication properties, like strong lock-freeness (any participant can eventually progress in any continuation of any reachable configuration), as well as to investigate conditions to get lock-freeness preservation, not guaranteed yet.

Unlike the present paper, in [1] safeness is ensured for the binary case by assuming compatibility of interfaces and an extra condition (called ?!-determinism) on them. We are currently considering a generalisation of the binary compatibility relation. Such generalisation should imply relevant communication properties for the communication policy it depends on.

We are planning also to identify some conditions ensuring Theorem 5.1 to hold for any communication property $\mathscr{P}$ satisfying them.

Finally, we could consider "partial" gateways, where only some communications of an interface are interpreted as communications with the environment. Such an idea was actually implemented in [2] in a MPTS setting for a restricted client-multiserver composition with synchronous communications.

Acknowledgements We warmly thank the ICE'24 reviewers for their careful reading, their thoughtful comments/suggestions and the helpful discussion on the forum. We also thank Emilio Tuosto for his nice tikz style for automata.

References

[1] Franco Barbanera, Ugo de'Liguoro & Rolf Hennicker (2019): *Connecting open systems of communicating finite state machines*. *J. Log. Algebraic Methods Program.* 109, article 100476, doi:10.1016/J.JLAMP.2019.07.004.

[2] Franco Barbanera, Mariangiola Dezani-Ciancaglini & Ugo de'Liguoro (2022): *Open compliance in multiparty sessions*. In S. Lizeth Tapia Tarifa & José Proença, editors: *Proc. FACS 2022*, *LNCS* 13712, Springer, pp. 222–243, doi:10.1007/978-3-031-20872-0_13. Extended version at `http://www.di.unito.it/~dezani/papers/bd23b.pdf`.

[3] Franco Barbanera, Mariangiola Dezani-Ciancaglini, Lorenzo Gheri & Nobuko Yoshida (2023): *Multicompatibility for Multiparty-Session Composition*. In Santiago Escobar & Vasco T. Vasconcelos, editors: *Proc. PPDP 2023*, ACM, pp. 2:1–2:15, doi:10.1145/3610612.3610614.

[4] Franco Barbanera, Mariangiola Dezani-Ciancaglini, Ivan Lanese & Emilio Tuosto (2021): *Composition and decomposition of multiparty sessions*. *J. Log. Algebraic Methods Program.* 119, article 100620, doi:10.1016/j.jlamp.2020.100620.

[5] Franco Barbanera & Rolf Hennicker: *Safe Composition of Systems of Communicating Finite State Machines (Full Version)*. Available at `https://github.com/francobarbanera/asychCFSM-multicomposition/blob/20392804aab754b05735a19547c1ee7524149a6a/CFSM-multicomposition-Full.pdf`.

[6] Franco Barbanera, Ivan Lanese & Emilio Tuosto (2020): *Composing communicating systems, synchronously*. In Tiziana Margaria & Bernhard Steffen, editors: *Proc. ISoLA 2020*, *LNCS* 12476, Springer, pp. 39–59, doi:10.1007/978-3-030-61362-4_3.

[7] Franco Barbanera, Ivan Lanese & Emilio Tuosto (2022): *On composing communicating systems*. In Clément Aubert, Cinzia Di Giusto, Larisa Safina & Alceste Scalas, editors: *Proc. ICE 2022*, *EPTCS* 365, Open Publishing Association, pp. 53–68, doi:10.4204/EPTCS.365.4.

[8] Franco Barbanera, Ivan Lanese & Emilio Tuosto (2023): *Composition of synchronous communicating systems*. *J. Log. Algebraic Methods Program.* 135, article 100890, doi:10.1016/J.JLAMP.2023.100890.

[9] Maurice H. ter Beek, Rolf Hennicker & Jetty Kleijn (2020): *Compositionality of Safe Communication in Systems of Team Automata*. In Violet Ka I Pun, Volker Stolz & Adenilso Simão, editors: *Proc. ICTAC 2020*, *LNCS* 12545, Springer, pp. 200–220, doi:10.1007/978-3-030-64276-1_11.

[10] Maurice H. ter Beek & Jetty Kleijn (2003): *Team Automata Satisfying Compositionality*. In Keijiro Araki, Stefania Gnesi & Dino Mandrioli, editors: *Proc. FME 2003*, *LNCS* 2805, Springer, pp. 381–400, doi:10.1007/978-3-540-45236-2_22.

[11] Laura Bocchi, Dominic Orchard & A. Laura Voinea (2023): *A Theory of Composing Protocols*. *Art Sci. Eng. Program.* 7(2), doi:10.22152/PROGRAMMING-JOURNAL.ORG/2023/7/6. Article 6.

[12] Daniel Brand & Pitro Zafiropulo (1983): *On Communicating Finite-State Machines*. *J. ACM* 30(2), pp. 323–342, doi:10.1145/322374.322380.

[13] Luís Caires & Hugo Torres Vieira (2010): *Conversation types*. *Theor. Comput. Sci.* 411(51-52), pp. 4399–4440, doi:10.1016/J.TCS.2010.09.010.

[14] Marco Carbone, Fabrizio Montesi & Hugo Torres Vieira (2018): *Choreographies for Reactive Programming*. *CoRR* abs/1801.08107. Available at `http://arxiv.org/abs/1801.08107`.

[15] Gérard Cécé & Alain Finkel (2005): *Verification of programs with half-duplex communication*. *Inf. Comput.* 202(2), pp. 166–190, doi:10.1016/j.ic.2005.05.006.

[16] Lorenzo Clemente, Frédéric Herbreteau & Grégoire Sutre (2014): *Decidable Topologies for Communicating Automata with FIFO and Bag Channels*. In Paolo Baldan & Daniele Gorla, editors: *Proc. CONCUR 2014*, *LNCS* 8704, Springer, pp. 281–296, doi:10.1007/978-3-662-44584-6_20.

[17] Pierre-Malo Deniélou & Nobuko Yoshida (2012): *Multiparty Session Types Meet Communicating Automata*. In Helmut Seidl, editor: *Proc. ESOP 2012*, pp. 194–213, doi:10.1007/978-3-642-28869-2_10.

[18] Lorenzo Gheri & Nobuko Yoshida (2023): *Hybrid Multiparty Session Types: Compositionality for Protocol Specification through Endpoint Projection*. Proc. ACM Program. Lang. 7(OOPSLA1), pp. 112–142, doi:10.1145/3586031.

[19] Rolf Hennicker & Michel Bidoit (2018): *Compatibility Properties of Synchronously and Asynchronously Communicating Components*. Log. Meth. in Comp. Sci. 14(1), pp. 1–31, doi:10.23638/LMCS-14(1:1)2018.

[20] Rolf Hennicker & Alexander Knapp (2015): *Moving from interface theories to assembly theories*. Acta Informatica 52(2-3), pp. 235–268, doi:10.1007/S00236-015-0220-7.

[21] Kohei Honda, Nobuko Yoshida & Marco Carbone (2008): *Multiparty asynchronous session types*. In George C. Necula & Philip Wadler, editors: Proc. POPL 2008, ACM, pp. 273–284, doi:10.1145/1328438.1328472.

[22] Kohei Honda, Nobuko Yoshida & Marco Carbone (2016): *Multiparty asynchronous session types*. J. ACM 63(1), pp. 9:1–9:67, doi:10.1145/2827695.

[23] Shriram Krishnamurthi, Kathi Fisler & Michael Greenberg (2004): *Verifying aspect advice modularly*. In Richard N. Taylor & Matthew B. Dwyer, editors: Proc. SIGSOFT 2004, ACM, pp. 137–146, doi:10.1145/1029894.1029916.

[24] Julien Lange, Emilio Tuosto & Nobuko Yoshida (2015): *From Communicating Machines to Graphical Choreographies*. In Sriram K. Rajamani & David Walker, editors: Proc. POPL 2015, ACM, pp. 221–232, doi:10.1145/2676726.2676964.

[25] Fabrizio Montesi & Nobuko Yoshida (2013): *Compositional Choreographies*. In Pedro R. D'Argenio & Hernán C. Melgratti, editors: Proc. CONCUR 2013, LNCS 8052, Springer, pp. 425–439, doi:10.1007/978-3-642-40184-8_30.

[26] Zorica Savanovic, Letterio Galletta & Hugo Torres Vieira (2020): *A type language for message passing component-based systems*. In Julien Lange, Anastasia Mavridou, Larisa Safina & Alceste Scalas, editors: Proc. ICE 2020, EPTCS 324, pp. 3–24, doi:10.4204/EPTCS.324.3.

[27] Claude Stolze, Marino Miculan & Pietro Di Gianantonio (2023): *Composable partial multiparty session types for open systems*. Softw. Syst. Model. 22(2), pp. 473–494, doi:10.1007/S10270-022-01040-X.

[28] Emilio Tuosto & Roberto Guanciale (2018): *Semantics of global view of choreographies*. J. Log. Algebr. Meth. Program. 95, pp. 17–40, doi:10.1016/j.jlamp.2017.11.002.

The B2Scala Tool: integrating Bach in Scala with Security in Mind

Doha Ouardi
Nadi Research Institute
Faculty of Computer Science
University of Namur
Namur, Belgium
doha.ouardi@unamur.be

Manel Barkallah
Nadi Research Institute
Faculty of Computer Science
University of Namur
Namur, Belgium
manel.barkallah@unamur.be

Jean-Marie Jacquet
Nadi Research Institute
Faculty of Computer Science
University of Namur
Namur, Belgium
jean-marie.jacquet@unamur.be

Process algebras have been widely used to verify security protocols in a formal manner. However they mostly focus on synchronous communication based on the exchange of messages. We present an alternative approach relying on asynchronous communication obtained through information available on a shared space. More precisely this paper first proposes an embedding in Scala of a Linda-like language, called Bach. It consists of a Domain Specific Language, internal to Scala, that allows us to experiment programs developed in Bach while benefiting from the Scala eco-system, in particular from its type system as well as program fragments developed in Scala. Moreover, we introduce a logic that allows to restrict the executions of programs to those meeting logic formulae. Our work is illustrated on the Needham-Schroeder security protocol, for which we manage to automatically rediscover the man-in-the-middle attack first put in evidence by G. Lowe.

1 Introduction

Besides the use of theorem provers, process algebras have been widely used to verify security protocols in a formal manner. A seminal effort in this direction is reported in [19]. There the author illustrates how modeling in CSP [12] and utilizing the FDR tool [10] can be used to produce an attack on the Needham-Schroeder protocol. As another example, the article [2] demonstrates how state reduction techniques can be applied to analyze a model of the Bilateral Key Exchange protocol written in mCRL [6]. In these two cases the models rely on synchronous communication obtained by the exchange of messages. Although this type of communication has been fundamental in the theory of concurrency and has consequently benefited from extensive research support, it is not necessarily intuitive for analyzing security protocols. Indeed, the idea of exchanging messages in a synchronous manner between partners rests on the assumption that the communication takes place instantaneously on agreed actions and thus does not naturally leave room for an intruder to intercept messages. As an evidence at the programming level, in the above two pieces of work, this has lead the authors to duplicate the exchange of messages in their model.

Another path of research has been initiated by Gelernter and Carriero, who advocated in [9] that a clear separation between the interactional and the computational aspects of software components has to take place in order to build interactive distributed systems. Their claim has been supported by the design of a model, Linda [3], originally presented as a set of inter-agent communication primitives which may be added to almost any programming language. Besides process creation, this set includes primitives for adding, deleting, and testing the presence/absence of data in a shared dataspace. In doing so they proposed a new form of synchronization of processes, occurring asynchronously, through the availability or absence of pieces of information on a shared space. A number of other models, now referred to as

Preliminary Report. Final version to appear in:
ICE 2024

coordination models, have been proposed afterwards. These models seem highly attractive to us because, in practice, message exchanges do not occur atomically through the synchronous communication of actors. Instead, they must happen through a medium – such as a network – which can be easily modeled as a shared space.

The aim of this paper is to explore how coordination models can be used to analyze security protocols. More concretely, we will focus on a specific coordination model, named Bach, will derive a tool, named B2Scala, and will employ it to produce the attack on the Needham-Schroeder protocol [20] first put in evidence by G. Lowe (see [19]).

Implementing coordination models can be done in three different ways. First, as illustrated by Tucson [7], one may provide an implementation as a stand alone language. This has the advantage of offering support for a complete algebra-like incarnation of Linda but at the expense of having to re-implement classical programming constructs that are proposed in conventional languages (like variables, loops, lists, ...). The second approach, illustrated by pSpaces [18] is to provide a set of APIs in a conventional language in order to access the shared space through dedicated functions or methods. This approach benefits from the converse characteristics of the first one: it is easy to access classical programming constructs but the abstract control flow that is offered at a process algebraic level, like non-deterministic choice and parallel composition, is to be coded in an ad hoc manner. Finally, a third approach consists in using a domain specific language embedded inside an existing language. We will turn to this approach since, in principle, it enjoys the benefits of the first two approaches. More specifically, this paper proposes to embody the Bach coordination language inside Scala. In doing so we will profit from the Scala ecosystem while benefiting from all the abstractions offered by the Bach coordination language. A key feature is that we will interpret control flow structures, which we put in good use to restrict computations to those verifying logic formulae. As an interesting consequence, we shall be able to produce the man-in-the-middle attack of the Needham-Schroeder security protocol first put in evidence by G. Lowe.

The rest of the paper is structured as follows. Section 2 presents the Needham-Schroeder use-case as well as the Bach and Scala languages. Section 3 describes the B2Scala tool, both from the point of view of its usage by programmers and from the implementation point of view. A logic is proposed in Section 4 together with its effect on reducing executions. Section 5 illustrates how B2Scala coupled to constraint executions can be used to analyze the Needham-Schroeder protocol. Finally Section 6 draws our conclusions and compares our work with related work.

2 Background

2.1 Use-case: the Needham-Schroeder Protocol

The Needham-Schroeder protocol, developed by Roger Needham and Michael Schroeder in 1978 [20], is a pioneering cryptographic solution aimed at ensuring secure authentication and key distribution within network environments. Its primary objective is to establish a shared session key between two parties, typically referred to as the principal entities, facilitating encrypted communication to safeguard data confidentiality and integrity. The protocol unfolds in a series of steps: initialization, where a client (A) requests access to another client (B) from a trusted server (S), followed by the server's response, which involves authentication, session key generation, and ticket encryption. Subsequently, communication with party B ensues, facilitated by the transmission of the encrypted ticket, along with nonces to ensure freshness. Parties exchange messages encrypted with the session key and incorporate nonces to prevent replay attacks. Mutual authentication is achieved through encrypted messages exchanged between A and B, leveraging the established session key and nonces. Despite its early contributions, the original protocol

exhibited vulnerabilities, notably the reflection attack. In response, refined versions have emerged, such as the Needham-Schroeder-Lowe [19] and Otway-Rees protocols [17].

The description of the Needham-Schroeder public key protocol is often slimmed down to the three following actions:

$$\begin{array}{lcl} Alice \longrightarrow Bob & : & message(na : a)_{pkb} \\ Bob \longrightarrow Alice & : & message(na : nb)_{pka} \\ Alice \longrightarrow Bob & : & message(nb)_{pkb} \end{array}$$

where each transition of the form $X \to Y : m$ represents message m being sent from X to Y. Moreover, the notation m_k represents message m being encrypted with the public key k.

This version assumes that the public keys of Alice and Bob (resp. *pka* and *pkb*) are already known to each other. The full version also involves communication between the parties and a trusted server to obtain the public keys.

In this model, Alice initiates the protocol by sending to Bob her nonce *na* together with her identity *a*, the whole message being encrypted with Bob's public key *pkb*. Bob responds by sending to Alice her nonce *na* together with his nonce *nb*, the whole message being encrypted this time with Alice's public key *pka*. Finally Alice sends to Bob his nonce *nb*, as a proof that a session has been safely made between them. The message is this time encrypted with Bob's public key.

It is worth stressing that, although public keys are known publicly (as the noun suggests), it is only the owners of the corresponding private keys that can decrypt encrypted messages. For instance, the first message sent to Bob can only be decrypted by him.

It is also worth noting that, although sending messages appears as an atomic action in the above description, this is in fact not the case. Messages are transmitted through some medium, say the network, and thus are subject to be read or picked up by opponents. This will be illustrated in Section 5 where a more detailed model will be examined.

2.2 The Bach Coordination Language

Bach [8, 15] is a Linda dialect developped at the University of Namur by the authors. It borrows from Linda the idea of a shared space and reformulates data and the primitives according to the constraint logic programming setting [24]. The following presentation is based on the one of article [1].

2.2.1 Definition of data

According to the logic programming setting, we assume a non-empty set of function names, each one associated with an arity, which indicates the number of arguments the function takes. We assume a non-empty subset of function names associated with an arity 0, namely taking no argument. Such function names are subsequently referred to as *tokens*. Based on their existence, so-called structured pieces of information are introduced inductively as expressions of the form $f(a_1, \cdots, a_n)$ where f is a function name associated with arity n and where arguments $a_1, \ldots, a_n$ are structured pieces of information, understood either as tokens or in the structured form under description. Note that, as the special case where $n = 0$, tokens are considered as being structures information terms. The set of structured pieces of information is subsequently denoted by $\mathscr{I}$. For short, *si-term* is used later to denote a structured piece of information.

Example 1 *The nounces used by Alice and Bob in the Needham-Schroeder protocol are coded by the tokens* `na` *and* `nb`*, respectively. Similarly, their public keys are coded by the tokens* `pka` *and* `pkb`*. A*

$$(\mathbf{T}) \quad \langle\, tell(t) \mid \sigma \,\rangle \longrightarrow \langle\, E \mid \sigma \cup \{t\} \,\rangle \qquad (\mathbf{G}) \quad \langle\, get(t) \mid \sigma \cup \{t\} \,\rangle \longrightarrow \langle\, E \mid \sigma \,\rangle$$

$$(\mathbf{A}) \quad \langle\, ask(t) \mid \sigma \cup \{t\} \,\rangle \longrightarrow \langle\, E \mid \sigma \cup \{t\} \,\rangle \qquad (\mathbf{N}) \quad \frac{t \notin \sigma}{\langle\, nask(t) \mid \sigma \,\rangle \longrightarrow \langle\, E \mid \sigma \,\rangle}$$

Figure 1: Transition rules for the primitives (taken from [1])

$$(\mathbf{S}) \quad \frac{\langle A \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}{\langle A \,;\, B \mid \sigma \rangle \longrightarrow \langle A' \,;\, B \mid \sigma' \rangle} \qquad (\mathbf{C}) \quad \frac{\langle A \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}{\begin{array}{c}\langle A \,+\, B \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle \\ \langle B \,+\, A \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle\end{array}}$$

$$(\mathbf{P}) \quad \frac{\langle A \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}{\begin{array}{c}\langle A \,||\, B \mid \sigma \rangle \longrightarrow \langle A' \,||\, B \mid \sigma' \rangle \\ \langle B \,||\, A \mid \sigma \rangle \longrightarrow \langle B \,||\, A' \mid \sigma' \rangle\end{array}} \qquad (\mathbf{Pc}) \quad \frac{P(\overline{x}) = A, \langle A[\overline{x}/\overline{u} \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}{\langle P(\overline{u}) \mid \sigma \rangle \longrightarrow \langle A' \mid \sigma' \rangle}$$

Figure 2: Transition rules for the operators (taken from [1])

message encrypted by Alice with Bob's public key and providing Alice's nounce with her identity 'a' is encoded as the following structured piece of information `encrypt(na, a, pkb)`.

2.2.2 Agents

Following the concurrent constraint setting, Linda primitives `out`, `rd` and `in` respectively used to output a tuple, check its presence and consume one occurrence are reformulated as `tell`, `ask`, `get`, acting on si-terms. We add to them a negative counterpart, `nask` checking the absence of a si-term. The execution of these primitives is described by the transition relation defined in Figure 1. The configurations to be considered are pairs of instructions, for the moment reduced to simple primitives, coupled to the contents of the shared space. Following the concurrent constraint setting, the shared space is referred to as the *store*. It is taken as a multiset of si-terms. Moreover, the E symbol is used to denote a terminated computation. Consequently, rule (T) expresses that the execution of the $tell(t)$ primitive always succeeds and add an occurrence of t to the store. Rule (A) requires $ask(t)$ to succeed that t is present on the store. As this primitive just makes a test, the contents of the store is unchanged. According to rule (G), the $get(t)$ primitive acts similarly but remove one occurrence of t. Finally, as specified by rule (N), the primitive $nask(t)$ succeeds in case t is absent from the store.

Primitives are combined to form more complex agents by means of traditional operators from concurrency theory: sequential composition, denoted by the ; symbol, parallel composition, denoted by the || symbol, and non-deterministic choice, denoted by the + symbol.

Procedures are defined by associating an agent with a procedure name possibly coupled to parameters. As usual, we shall assume that the associated agents are guarded, in the sense that the execution of a primitive preceeds any call or can be rewritten in such a form. Procedures are subsequently declared after the `proc` keyword.

The execution of complex agents is defined by the transition rules of Figure 2. Sequential, parallel and choice composition operators are given the convention semantics in rules (S), (P) and (C), respec-

tively. Rule (Pc) dictates that the procedure call $P(\overline{u})$ operates as the agent A that defines P with the formal arguments $\overline{x}$ replaced by the actual ones $\overline{u}$. It is important to note that, in these rules, agents of the form $(E;A)$, $(E \,||\, A)$ and $(A \,||\, E)$ are rewritten as A.

Example 2 *As an example, the behavior of Alice and Bob can be coded as follows:*

```
proc Alice = tell(encrypt(na,a,pkb)); get(encrypt(na,nb,pka));
             tell(encrypt(nb,pkb)).

     Bob = get(encrypt(na,a,pkb)); tell(encrypt(na,nb,pka));
           get(encrypt(nb,pkb)).
```

Note that Alice and Bob only tell messages encrypted with the public key of the other and only get messages encrypted with their public key, which simulates their sole use of their private key.

It is also worth stressing that we will present a model of the Needham-Schroeder protocol and not a concrete implementation. Hence the above tokens (na, nb, ...) are to be understood as globally defined and not as a form of local variables.

2.3 The Scala Programming Language

Scala is a statically typed language known for its concise syntax and seamless fusion of object-oriented and functional programming. Variables can be declared as immutable or mutable, as illustrated by the following code snippet.

```
val immutableVariable: Int = 42
var mutableVariable: String = "Hello, Scala!"
```

Methods are introduced with the *def* keyword, can be generic (with type parameters specified in square brackets), can be written in curried form (with multiple parameter lists) and have a return type which is specified at the end of the signature. Here is a simple example for adding two integers.

```
def add(x: Int, y: Int): Int = x + y
```

Methods are typically included in the definition of objects, classes and traits, which act as interfaces in Java. Of particular interest for the implementation of B2Scala is the definition of *case classes* which are classes that automatically define setter, getter, hash and equal methods.

Two main additional features of Scala are worth stressing.

2.3.1 Functions and objects

Functions may be coded by defining objects with an apply function. For instance, if we define

```
object tell {
    def apply(siterm: SI_Term) = TellAgent(siterm)
}

object Agent {
        def apply(agent: BSC_Agent) = CalledAgent(agent)
}
```

then the evaluation of

```
val P = Agent { tell(f(1,2)) }
```

consists first in evaluating *tell* on the si-term $f(1,2)$, which results in the structure $TellAgent(f(1,2))$, and then in evaluating the function *Agent* on this value, which results in the structure $CalledAgent(TellAgent(f(1,2)))$. It is that result which is assigned to *P*.

2.3.2 Strictness and lazyness

Scala is a strict language that eagerly evaluates expressions. However there are cases in which it is desirable to postpone the evaluation of expressions, for instance to handle recursive definitions of agents. To that end, Scala proposes two basic mechanisms: call-by-name of arguments of functions and so-called thunks. To understand these two concepts, let us modify the `add` function so that it returns the double of its first argument, regardless of the value of the second one:

```
def doubleAdd(x: Int, y: => Int) = x + x
```

The first argument is passed using the call-by-value strategy. It is evaluated whenever the function is called. In contrast, the second argument is passed using the call-by-name strategy. Accordingly, it is evaluated when needed and thus in our example not evaluated at all. However one step further needs to be made to handle recursive expressions that we want to evaluate step by step. In that case, so-called thunks are used. They amount to consider functions requiring no arguments, as in the following definition

```
def myIf[A](cond: Boolean, onTrue: () => A,
                           onFalse: () => A): A = {
    if (cond) onTrue() else onFalse()
}
```

Note that the arguments *onTrue* and *onFalse* are functions taking no arguments and leading to expressions rather than simply expressions.

To conclude this point, it is possible to delay the evaluation of val-declared expression by using the *lazy* keyword, such as in

```
lazy val recursiveExpression = (1+recursiveExpression)*2
```

3 The B2Scala Tool

3.1 Programming interface

To embed Bach in Scala, two main issues must be tackled: on the one hand, how is data declared, and, on the other hand, how are agents declared.

3.1.1 Data

As regards data, the trait *SI_Term* is defined to capture si-terms. Concrete si-terms are then defined as case classes of this trait. For instance in order to manipulate $f(1,2)$ in one of the primitives (tell, ask, ...) the following declaration has to be made:

```
case class f(x:Int, y: Int) extends SI_Term
```

Similarly, tokens can be declared as in

```
case class a() extends SI_Term
```

However that leads to duplicate parentheses everywhere as in $tell(a())$. To avoid that a *Token* class has been defined as a case class of *SI_Term*. It takes as argument a string so that token *a* can be declared as

```
val a = Token(``a'')
```

Accordingly, *a* may now be used without parentheses, as in $tell(a)$.

Example 3 *As examples, the public keys and nonces used in the Needham-Schroeder protocol are declared as the following tokens:*

```
val pka = Token(``pka'')
val pkb = Token(``pkb'')
val na = Token(``na'')
val nb = Token(``nb'')
```

Encrypted messages are coded by the following si-terms:

```
case class encrypt2(n: SI_Term,k: SI_Term) extends SI_Term
case class encrypt3(n: SI_Term,x: SI_Term,k: SI_Term) extends SI_Term
```

Note that Scala does not allow the same name to be used for different case classes. We have thus renamed them according to the number of arguments.

3.1.2 Agents

The main idea for programming agents is to employ constructs of the form

```
val P = Agent { (tell(f(1,2))+tell(g(3))) || (tell(a)+tell(b)) }
```

which encapsulate a Bach agent inside Scala definitions. The *Agent* object is the main ingredient to do so. It is defined as an object with an apply method as follows

```
object Agent {
   def apply(agent: BSC_Agent) = CalledAgent(() => agent)
}
```

It thus consists of a function mapping a *BSC_Agent* into the Scala structure *CalledAgent* taking a thunk, which consists of a function taking no argument and returning an agent. As we saw above, this is needed to treat in a lazy way recursively defined agent.

The *BSC_Agent* type is in fact a trait equipped with the methods needed to parse Bach composed agents. Technically it is defined as follows:

```
trait BSC_Agent { this: BSC_Agent =>
  def *(other: => BSC_Agent) =
          ConcatenationAgent( () => this, other _)
  def ||(other: => BSC_Agent) =
          ParallelAgent( () => this, other _)
  def +(other: => BSC_Agent) =
          ChoiceAgent( () => this, other _)
}
```

As ; is a reserved symbol in Scala, sequential composition is rewritten with the $*$ symbol.

The definition of the composition symbol $*$, $||$ and $+$ employs Scala facility to postfix operations. Using the above definitions, a construct of the form $tell(t)+tell(u)$ is interpreted as the call of method $+$ to $tell(t)$ with argument $tell(u)$.

It is worth observing that the composition operators take agent arguments with call-by-name and deliver structures using thunks, namely functions without arguments to agents.

It will be useful later to generalize choices such that they offer more than two alternatives according to an index ranging over a set, such as in $\sum_{x \in L} ag(x)$ where $ag(x)$ is an agent parameterized by x. This is obtained in B2Scala by the following construct

```
GSum(L, x => ag(x))
```

where `L` is a list.

3.2 Implementation of the Domain Specific Language

The implementation of the domain specific language is based on the same ingredients as those employed in the Scan and Anemone workbenches [13, 14]. They address two main concerns: how is the store implemented and how are agents interpreted.

3.2.1 The store

The store is implemented as a mutable map in Scala. Initially empty, it is enriched for each told structured piece of information by an association of it to a number representing the number of its occurrences on the store. The implementation of the primitives follows directly from this intuition. For instance, the execution of a tell primitive, say `tell(t)`, consists in checking whether `t` is already in the map. If it is then the number of occurrences associated with it is simply incremented by one. Otherwise a new association `(t,1)` is added to the map. Dually, the execution of `get(t)` consists in checking whether `t` is in the map and, in this case, in decrementing by one the number of occurrences. In case one of these two conditions is not met then the get primitive cannot be executed.

3.2.2 Interpretation of agents

Agents are interpreted by repeatedly executing transition steps. This boils down to the definition of function `run_one`, which assumes given an agent in an internal form, namely as a subtype of *BSC_Agent*, and which returns a pair composed of a boolean and an agent in internal form. The boolean aims at specifying whether a transition step has taken place. In this case, the associated agent consists of the agent obtained by the transition step. Otherwise, failure is reported with the given agent as associated agent.

The function is defined inductively on the structure of its argument, say `ag`. If `ag` is a primitive, then the `run_one` function simply consists in executing the primitive on the store. If `ag` is a sequentially composed agent ag_i ; ag_{ii}, then the transition step proceeds by trying to execute the first subagent ag_i. Assume this succeeds and delivers ag' as resulting agent. Then the agent returned is ag' ; ag_{ii} in case ag' is not empty or more simply ag_{ii} in case ag' is empty. Of course, the whole computation fails in case ag_i cannot perform a transition step, namely in case `run_one` applied to ag_i fails.

The case of an agent composed by a parallel or choice operator is more subtle. Indeed for both cases one should not always favor the first or second subagent. To avoid that behavior, we use a boolean variable, randomly assigned to 0 or 1, and depending upon this value we start by evaluating the first or second subagent. In case of failure, we then evaluate the other one and if both fails we report a failure. In case of success for the parallel composition we determine the resulting agent in a similar way to what we did for the sequentially composed agent. For a composition by the choice operator the tried alternative is simply selected.

The computation of a procedure call is performed by computing the defining agent.

4 Constrained executions

The fact that Bach agents are interpreted in the B2Scala tool opens the door to select computations of interest. This is obtained by stating logic formulae to be met.

Two main approaches have been used in concurrency theory to describe properties by means of logic formulae. One approach, exemplified by Linear Temporal Logic (LTL) [22], is based on Kripke structures. In two words, LTL extends classical propositional logic by introducing temporal operators that allow to describe how properties evolve over time. For instance, $X\,\Phi$ means that Φ holds in the next state while $\Phi U \Psi$ specifies that Φ holds until Ψ holds. Central to this approach are, on the one hand, a transition relation between states, indicating which states can be reached from which states, and, on the other hand, a labelling function that assigns to each state a set of atomic propositions that are true in that state.

The other approach is based on labelled transition systems. It is exemplified by the Hennessy-Milner logic (HML) [11]. This logic provides a way to specify properties in terms of actions and capabilities. The two following modalities are the key concepts of HML:

- $<a>\Psi$ means that, by following the labelled transition system, it is possible to make a transition by a such that the resulting process satisfies Ψ
- $[a]\Psi$ means that, whenever a is performed the resulting process satisfies Ψ.

However, since they are finite HML formulae can only describe properties with a finite depth of reasoning. A way to circumvent this problem is to use a generalisation called the μ-calculus [16]. It extends HML with fixed-point operators, such as in $\mu X.(\Phi \vee <a>X)$ which states that there is a path where Φ holds directly or after having repeatedly taken a-transitions.

The logic we use is inspired by these three logics. It is subsequently presented in two steps by describing so-called basic formulae and the bsL-calculus. The effect on computations is then specified. This yields so-called constrainted computations.

4.1 Basic formulae

Similarly to LTL logic, we first specify formulae that are true on states. Obviously, a key concept in our coordination setting is whether a si-term is present on the store under consideration. This is specified by a construct of the form $bf(t)$ which requires that the si-term t is present on the current store. The formal definition is as follows.

Definition 1 *For any si-term t, the formula $bf(t)$ holds on store σ iff $t \in \sigma$. This is subsequently denoted as $\sigma \models bf(t)$. Such formulae are subsequently called bf-formulae.*

As expected, bf-formulae can be combined with the classical logic operators. Formulae built in this way are called *basic formulae*. The formal definition is as follows.

Definition 2 *Basic formulae are the formulae meeting the following grammar:*

$$b ::= bf(t) \mid !b \mid b_1 \vee b_2 \mid b_1 \wedge b_2$$

where $bf(t)$ denotes a bf-formula, b, b_1, b_2 denote basic formulae and the symbols $!$, $\vee$, $\wedge$ respectively express the negation, the disjunction and the conjuction of basic formulae.

The fact that a basic formula f holds on the store σ is defined from the relation $\models$ on bf-formulae according to the traditional truth tables of propositional logic. By extension, this will be subsequently denoted by $\sigma \models f$.

Example 4 *As an example, $bf(i\_running(Alice,Bob))$ is a bf-formula that states that the si-term $i\_running(Alice,Bob)$ is on the store, which can be used to specify that Alice and Bob have initiated a session.*

4.2 The bsL calculus

Similarly to Hennessy-Milner logic and the mu-calculus, we now turn to specify sequences of properties that have to hold on the sequences of stores produced by computations. Obviously, as we want to restrict computations, we have to discard the $[\ldots]$ modality. However we can use the $<\ldots>$ modality in the following manner. Remember that in HML the formula $<a><b>F$ expresses that it is possible to do an a step followed by a b step and reach a process in which F holds. In a similar way, we will express by $bf(a);bf(b)$ the property that it is possible to do a step which leads to $bf(a)$ being true followed by a step after which $bf(b)$ is true. This is for instance performed by the Bach agent $tell(a);tell(b)$. Note that as a reminder of the sequential composition of agents in Bach, we have used the ";" to compose sequentially bf-formulae. As noticed in the above mu-calculus formula, besides sequential composition, we shall also use disjunction to allow the choice between several paths. This leads us to the following grammar where, by analogy to Bach operators, the "+" symbol is used to indicate disjunction.

Definition 3 *BsL-formulae are the formula defined by the following grammar:*

$$f \quad ::= \quad b \mid P \mid f_1 \; + \; f_2 \mid f_1 \; ; \; f_2$$

where b denotes a basic formula, f_1 and f_2 are bsL-formulae and P a variable to be defined by an equation of the form $P = f'$ with f' being a bsL-formula. As usual in concurrency theory, we assume that f' is guarded in the sense that a bf-formula is requested before variable P is called recursively.

Example 5 *As an example, the attack on the Needham-Schroeder protocol may be discovered by finding a computation that obeys the bsL-formula X defined by*

$$X \quad = \quad (\,not(i\_running(Alice,Bob))\;;\;X\,) + r\_commit(Alice,Bob)$$

that is by a computation that does not produce the si-term $i\_running(Alice,Bob)$ and that ends when $r\_commit(Alice,Bob)$ appears on the store. Restated in other terms such a computation never includes the start of a session between Alice and Bob but terminates with Alice and Bob ending the session by committing together.

4.3 Constrained computations

We are now in a position to detail how computations may be constrained by bsL-formulae. Intuitively, if f is a bsL-formula composed of a sequence of basic formulae, a computation c is considered to be constrained by f if the sequence of stores involved in c successively obeys the successive basic formulae in f. This is defined by means of the auxiliary $\vdash$ relation, itself defined by the rules of Figure 3. Intuitively, the notation $\sigma \vdash f\ [f']$ states that a first basic formula of f is satisfied on the store σ and that the remaining formulae of f' need to be satisfied. Accordingly rule (BF) asserts that if the basic formula b

$$(\mathbf{BF}) \quad \frac{\sigma \models b}{\sigma \vdash b\,[\varepsilon]} \qquad (\mathbf{PF}) \quad \frac{P = f, \quad \sigma \vdash f\,[f']}{\sigma \vdash P\,[f']}$$

$$(\mathbf{CF}) \quad \frac{\sigma \vdash f_1\,[f_3]}{\begin{array}{c}\sigma \vdash (f_1 + f_2)\,[f_3] \\ \sigma \vdash (f_2 + f_1)\,[f_3]\end{array}} \qquad (\mathbf{SF}) \quad \frac{\sigma \vdash f_1\,[f_3]}{\sigma \vdash (f_1\ ;\ f_2)\,[(f_3\ ;\ f_2)]}$$

Figure 3: Transition rules for the $\vdash$ relation

$$(\mathbf{ET}) \quad \frac{\langle A \mid \sigma\rangle \longrightarrow \langle A' \mid \sigma'\rangle, \quad \sigma' \vdash f\,[f']}{\langle A@f \mid \sigma\rangle \hookrightarrow \langle A'@f' \mid \sigma'\rangle}$$

Figure 4: Extended transition rule

is satisfied by the store σ then it is also the first formula to be satisfied and nothing remains to be established. The symbol ε is used there to denote an empty sequence of basic formulae. Rule (PF) states that if formula P is defined as f and if a first bf-formula of f is satisfied by σ yielding f' to be satisfied next then so does P with f' to be satisfied next. Finally rules (CF) and (SF) specify the choice and sequential composition of bsL-formulae as one may expect.

Given the $\vdash$ relation, we can define constrained computations by extending the $\rightarrow$ transition relation as the $\hookrightarrow$ relation specified by rule (ET) of Figure 4. Informally this rule states that if, on the one hand, agent A can do a transition from the store σ yielding a new agent A' and a new store σ' and if, on the other hand, a first formula of f is met by σ' yielding f' as a remaining bsL-formula to be established, then agent A can make a constrained transition from store σ and bHM-formula f to agent A' to be computed on store σ' and with respect to bHM-formula f'.

It is worth noting that the encoding in B2Scala is quite easy. On the one hand, bf-formulae are defined similarly to Bach primitives through the `bf` function and are combined as primitives are. On the other hand, bsL formulae are defined by the `bsL` function and recursive definitions are handled in the same way as recursive agents.

The interpretation of agents is then made with respect to a bsL-formula. Basically, a step is allowed by the `run_one` function if one step can be made according to the bsL-formula, as specified by the $\hookrightarrow$ transition relation. This results in a new agent to be solved together with the continuation of the bsL-formula to be satisfied.

5 The Needham-Schroeder protocol in B2Scala

As an application of the B2Scala tool, let us now code the Needham-Schroeder protocol and exhibit a computation that reflects G. Lowe's attack. The interested reader will find the code, the tool and a video of its usage under the web pages of the authors at the addresses mentioned in [21].

Allowing for an attack requires us to introduce an intruder. It is subsequently named Mallory. This being said, the first point to address is to declare nonces and public keys for all the participants of the

protocol, namely Alice, Bob and Mallory. This is achieved by the following token declarations:

```
val na = Token("Alice_nonce")
val nb = Token("Bob_nonce")
val nm = Token("Mallory_nonce")

val pka = Token("Alice_public_key")
val pkb = Token("Bob_public_key")
val pkm = Token("Mallory_public_key")
```

It will also be useful later to refer to the three participants, which can be achieved by means of the following token declarations:

```
val alice   = Token("Alice_as_agent")
val bob     = Token("Bob_as_agent")
val mallory = Token("Mallory_as_intruder")
```

To better view who takes which message produced by whom, encrypted messages introduced in Section 3, are slightly extended as si-terms of the form *message*(*Sender*,*Receiver*,*Encryted_Message*). Moreover, to highlight which message is used in the protocol, we shall subsequently rename encrypted messages as *encrypt_n*, with *n* the number in the sequence of messages. This has the additional advantage of avoiding to overload case classes, which is forbidden in Scala. The following declarations follow.

```
case class encrypt_i(vNonce: SI_Term, vAg: SI_Term,
                     vKey: SI_Term) extends SI_Term
case class encrypt_ii(vNonce: SI_Term, wNonce: SI_Term,
                     vKey: SI_Term) extends SI_Term
case class encrypt_iii(vNonce: SI_Term,
                     vKey: SI_Term) extends SI_Term
case class message(agS: SI_Term, agR: SI_Term,
                     encM: SI_Term) extends SI_Term
```

Finally, si-terms are introduced to indicate with whom Alice and Bob start and close their sessions. They are declared as follows:

```
case class a_running(vAg: SI_Term) extends SI_Term
case class b_running(vAg: SI_Term) extends SI_Term
case class a_commit(vAg: SI_Term) extends SI_Term
case class b_commit(vAg: SI_Term) extends SI_Term
```

We are now in a position to code the behavior of Alice, Bob and Mallory. Coding Alice's behavior follows the description we gave in Example 2 in Section 2. The code is provided in Figure 5. Although Alice wants to send a first encrypted message to Bob, she can just put her message on the network, hoping that it will reach Bob. The network is simulated here by the store, which leaves room to Mallory to intercept it. As a result, the first action is for Alice to start of a session. Hopefully it is with Bob but, to test for a possible attack, we have to take into account the fact that Mallory can take Bob's place. This is coded by offering a choice between Bob and Mallory by the `GSum([bob,mallory], ...)` construct. Calling this actor *Y*, Alice's first action is to tell the initialization of the session with *Y*, thanks to the `a_running(Y)` si-term being told and then to tell the first encrypted message with her nonce, her identity and the public key of Y. The sender and receiver of this message are respectively *Alice* and *Y*. Then Alice waits for a second encrypted message with her nonce and what she hopes to be Bob's nonce, this message being encrypted by her public key. As the second nonce is unknown a new choice is offered with the *WNonce* si-term. Finally, Alice sends the third encrypted message with this nonce, encoded with

```
val Alice = Agent {
  GSum( List(bob,mallory), Y => {
      tell(a_running(Y)) *
      tell( message(alice, Y, encrypt_i(na, alice, public_key(Y))) ) *
      GSum( List(na,nb,nm), WNonce => {
          get( message(Y, alice, encrypt_ii(na,WNonce,pka)) ) *
          tell( message(alice,Y,encrypt_iii(WNonce,public_key(Y))) ) *
          tell( a_commit(Y) )
      })
  })
}
```

Figure 5: Coding of Alice in B2Scala

```
val Bob = Agent {
   GSum( List(alice,mallory), Y => {
       tell(b_running(Y)) *
       GSum( List(alice,mallory), VAg => {
           get( message(Y,bob,encrypt_i(na,VAg,pkb)) ) *
           tell( message(bob,Y,encrypt_ii(na,nb,public_key(VAg))) ) *
           get( message(Y,bob,encrypt_iii(nb,pkb)) ) *
           tell( b_commit(VAg) )
       })
   })
}
```

Figure 6: Coding of Bob in B2Scala

the public key of Y and terminates the session by telling the `a_commit(Y)` si-term. It is worth noting that `public_key(Y)` consists of a call to a Scala function that returns the public key corresponding to the Y argument.

Coding Bob's behavior proceeds in a dual manner. This time the coding has to take into account that Mallory can have taken Alice's place. Hence the first choice `GSum([alice,mallory], ...)` with Y denoting the sender of the message. Moreover, the identity of the agent in the first message being got can be different from Y. A second choice `GSum([alice,mallory], ...)` results from that. The whole agent is given in Figure 6.

As an intruder, Mallory gets and tells messages from Alice and Bob, possibly modifying some parts in case the messages are encrypted with his public key. This applies for the three kinds of message sent/received by Alice and Bob. Figure 7 provides the code for the first message. It presents three `GSum` choices resulting from the three unknown arguments `VNonce`, `VAg`, `VPK` of the message. In all the cases, Bob's attitude is to get the message and to resend it, by modifying the public key if he can decrypt the message, namely if `VPK` is his public key.

To conclude the encoding of the protocol in B2Scala, a bsL-formula F is specified, on the one hand, by excluding a session starting between Bob and Alice and, on the other hand, by requiring the end of the session by Bob with Alice. These two requirements are obtained through the basic formulae `inproper_init` and `end_session`, as specified below:

```
val inproper_init = not( bf(a_running(bob)) or bf(b_running(alice)) )
```

```
lazy val Mallory:BSC_Agent = Agent {

  ( GSum( List(na,nb,nm), VNonce => {
     GSum( List(alice,bob), VAg => {
      GSum( List(pka,pkb,pkm), VPK => {
        get( message(alice,mallory,encrypt_i(VNonce,VAg,VPK)) ) *
        ( if ( VPK == pkm) {
            tell( message(mallory,bob,encrypt_i(VNonce,VAg,pkb)) )
          } else {
            tell( message(mallory,bob,encrypt_i(VNonce,VAg,VPK)) )
          } ) * Mallory
       })
      })
     }) )      + ...
```

Figure 7: Coding of Mallory in B2Scala

```
val end_session = bf(b_commit(alice))
```

Formula F is then coded recursively by requiring F after a step meeting `inproper_init` and by stopping the computation once a step is done that makes `end_session` holds. This is specified as follows.

```
val F = bsL { (inproper_init * F) + end_session }
```

Computations are started by invoking the following Scala instructions

```
val Protocol = Agent { Alice || Bob || Mallory }

val bsc_executor = new BSC_Runner
bsc_executor.execute(Protocol,F)
```

The result is given in Figure 8 in a verbose form in which all the primitives are displayed as Scala objects. As we shall see in a few lines, it produces G. Lowe's attack. To view that, let us reformulate the Scala objects *TellAgent*, *GetAgent* and *BSC_Token* in their corresponding Bach counterparts. The listing of Figure 8 then becomes as follows, where numbers are introduce to facilitate the explanation:

```
(1)  tell(a_running(mallory))
(2)  tell(b_running(mallory))
(3)  tell(message(alice,mallory,encrypt_i(na,alice,pkm)))
(4)  get(message(alice,mallory,encrypt_i(na,alice,pkm)))
(5)  tell(message(mallory,bob,encrypt_i(na,alice,pkb)))
(6)  get(message(mallory,bob,encrypt_i(na,alice,pkb)))
(7)  tell(message(bob,mallory,encrypt_ii(na,nb,pka)))
(8)  get(message(bob,mallory,encrypt_ii(na,nb,pka)))
(9)  tell(message(mallory,alice,encrypt_ii(na,nb,pka)))
(10) get(message(mallory,alice,encrypt_ii(na,nb,pka)))
(11) tell(message(alice,mallory,encrypt_iii(nb,pkm)))
(12) get(message(alice,mallory,encrypt_iii(nb,pkm)))
(13) tell(a_commit(mallory))
(14) tell(message(mallory,bob,encrypt_iii(nb,pkb)))
(15) get(message(mallory,bob,encrypt_iii(nb,pkb)))
(16) tell(b_commit(alice))
```

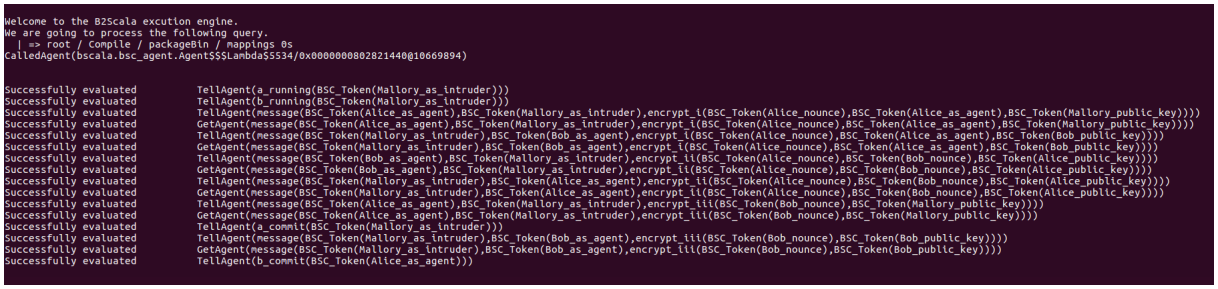


Figure 8: Screenshot of the computation

Lines (1), (2), (13) and (16) evidence that Alice and Bob have actually exchanged messages with Mallory whereas they thought they would speak to each other. In fact Mallory manages to make himself appear as Bob to Alice and as Alice to Bob. Let us abstract from these lines. It is then worth observing that the above listing makes appear tell and get in pairs employing the same message. This corresponds to one actor sending the message to another actor, which is translated in our framework as the first actor telling the message and the second one getting it. By reusing the description of Section 2.1, the listing can then be summed up as follows:

$$
\begin{array}{rcll}
Alice \longrightarrow Mallory & : & message(na : alice)_{pkm} & \text{(lines 3 and 4)} \\
Mallory \longrightarrow Bob & : & message(na : alice)_{pkm} & \text{(lines 5 and 6)} \\
Bob \longrightarrow Mallory & : & message(na : nb)_{pka} & \text{(lines 7 and 8)} \\
Mallory \longrightarrow Alice & : & message(na : nb)_{pka} & \text{(lines 9 and 10)} \\
Alice \longrightarrow Mallory & : & message(nb)_{pkm} & \text{(lines 11 and 12)} \\
Mallory \longrightarrow Bob & : & message(nb)_{pkb} & \text{(lines 14 and 15)}
\end{array}
$$

This is in fact the attack identified by G. Lowe in [19]. It consists essentially in placing Mallory in between Alice and Bob, in having him forward Alice's first message, by changing the public key encrypting the message, in getting Bob's reply and transfer it as such, and finally in forwarding Alice's reply to Bob, again by changing the public key encrypting the message.

Note that a key ingredient for producing the above computation is that imposing `inproper_init` to hold forces the first choice in Alice's code and Bob's code to be made such that Y takes Mallory as value.

6 Conclusion

In the aim of formally verifying security protocols, this paper has proposed an embedding of the coordination language Bach in Scala, in the form of an internal Domain Specific Language, named B2Scala. It has also proposed a logic that allows for constraining executions. The Needham-Schroeder protocol has been modeled with our proposal to illustrate its interest in practice.

The choice for an internal Domain Specific Language has been motivated by the possibility of taking profit from the Scala eco-system, notably its type system, while benefiting from all the abstractions offered by the Bach coordination language. We hope to have convinced the reader of these two features through the coding of the Needham-Schroeder protocol. Indeed, on the one hand, the *BSC_Agents* coding Alice, Bob and Mallory mimick the procedures that would have been written directly in Bach. Moreover the sequential composition operator, the parallel composition operator and the non-deterministic choice

operator have been used as one would have used them in Bach. This feature allows to embed the Bach control flow operators in B2Scala. It is here also worth observing that a similar description could have been written in a pure process algebra setting like the one used in the workbenches Scan and Anemone. However type checking is not supported by these workbenches but is given for free in B2Scala. Moreover, auxiliary concepts like *public_key*(Y) would have been rewritten as mapping functions, with care for completeness of the code left to the programmer while it is provided for free in B2Scala (through completeness verification done by Scala for the match operation).

On the other hand, the code to be written is a real Scala code. Examples of that are the definitions of tokens or si-terms, which are Scala case classes. In that respect, it is worth stressing that arguments of si-terms need to be declared with a type, which is verified at compilation time. Moreover, they can be obtained as the result of a Scala function, as exemplified by the use of *public_key*(Y) in the coding of Alice and Bob (see Figures 5 and 6). It is also to be noted that the *GSum* construct offers a form of local variable, binding the Scala and Bach worlds. Take for instance the first GSum of Figure 5 :

```
GSum( List(bob,mallory), Y => {
      tell(a_running(Y)) * ...
```

There Y plays the role of a local variable which has to be bound to *bob* or *mallory*. Once the value has been decided (by the `run_one` function through the alternative selected for the choice, see Section 3.2.2), it can be used later in the code. Similarly, the second *GSum* construct allows to bind *WNonce* to the value selected by the *get* primitive:

```
GSum( List(na,nb,nm), WNonce => {
      get( message(Y, alice, encrypt_ii(na,WNonce,pka)) ) * ...
```

This being said, our main goal in this paper is to offer a modelling language to describe and reason on systems, such as the Needham-Schroeder protocol, rather than a programming language to code the implementation of the protocol. In these lines, it is worth observing that a direct modelling for analysis purposes would not have been possible in (pure) Scala since we would lack the abstraction offered by process algebras like Bach.

As reported in [5], many coordination languages have been implemented, in some cases as stand alone languages, like Tucson [7], but mostly as API's of conventional languages, accessing tuple spaces through dedicated functions or methods, as in pSpaces [18]. To the best or our knowledge, B2Scala is the first implementation of a coordination language as a Domain Specific Language. We are also not aware of an implementation done in Scala. However, our work is linked to the work on Caos [23], which provides, by using Scala, a generic tool to implement structured operational semantics and to generate intuitive and interactive websites. In practice, one has however to define the semantics of the language under consideration by using Scala. In contrast, we take an opposite approach which already offers an implementation of the Bach constructs and in which programmers need to code Bach-like programs in a Scala manner. Moreover we propose a logic to constraint executions, which is not proposed in [23].

Scafi [4] is another research effort to integrate a coordination language in Scala. It targets a different line of research in the coordination community by being focussed on aggregate computing. Moreover, to the best of our knowledge, no support for constrained executions is proposed.

This work is a continuation of previous work on the Scan and Anemone workbenches [13, 14]. It differs by the fact that both Scan and Anemone interpret directly Bach programs. Moreover the PLTL logic they use is different from the logic proposed in this paper.

As regards the Needham-Schroeder protocol, to our best knowledge, it has been never been modeled in a coordination language, most probably because the Coordination community and the one on security are quite different. Nevertheless it has been modeled in more classical process algebras. In [19] the

author uses CSP and its associated FDR tool to produce an attack on the protocol. This analysis has been complemented in [2] by using the mCRL process algebra and its associated model checker. Our work differs by using a process algebra of a different nature. Indeed the Bach coordination language rests on asynchronous communication which happens by information being available or not on a shared space. This allows to naturally model messages being put on the network as si-terms told on the store. Similarly the action of an intruder is very intuitively modeled by getting si-terms. In contrast, [2] and [19] use synchronous communication which does not naturally introduce the network as a communication medium and which technically forces them to model the intruder by duplicating Alice and Bob's send and receive actions by intercept and fake messages.

Our work open several paths for future research. First the synergy with Scala given by B2Scala offers a natural way of making interfaces much more user friendly than the one of Figure 8. Second we have only investigated the use of B2Scala to analyze the Needham-Schroeder protocol. Our current research aims at exploring the security of other protocols, such as the Quic protocol. Finally, our logic is used to restrict computations at run-time without lookahead strategies, which could lead to select computations that fail later to meet the remaining logic formulae. As a solution to that problem, we are investigating how statistical model checking can be married with B2Scala.

7 Acknowledgment

The authors warmly thank the anonymous reviewers for their insightful comments, which greatly contributed to the improvement of this article. They also thank the University of Namur for its support as well as the Walloon Region for partial support through the Ariac project (convention 210235) and the CyberExcellence project (convention 2110186).

References

[1] M. Barkallah & J.-M. Jacquet (2023): *On the Introduction of Guarded Lists in Bach: Expressiveness, Correctness, and Efficiency Issues*. In C. Aubert, C. Di Giusto, S. Fowler & L. Safina, editors: *Proceedings 16th Interaction and Concurrency Experience (ICE) 2023*, *EPTCS* 383, pp. 55–72.

[2] S. Blom, J.F. Groote, S. Mauw & A. Serebrenik (2004): *Analysing the BKE-security Protocol with μCRL*. In I. Ulidowski, editor: *Proceedings of the 6th AMAST Workshop on Real-Time Systems*, *Electronic Notes in Theoretical Computer Science* 139, Elsevier, pp. 49–90.

[3] N. Carriero & D. Gelernter (1989): *Linda in Context*. *Communications of the ACM* 32(4), pp. 444–458.

[4] R. Casadei, M. Viroli, G. Aguzzi & D. Pianini (2022): *ScaFi: A Scala DSL and Toolkit for Aggregate Programming*. *SoftwareX* 20, p. 101248.

[5] G. Ciatto, S. Mariani, G. Di Marzo Serugendo, M. Louvel, A. Omicini & F. Zambonelli (2020): *Twenty Years of Coordination Technologies: COORDINATION Contribution to the State of Art*. *Journal of Logical and Algebraic Methods in Programming* 113, p. 100531.

[6] S. Cranen, J.F. Groote, J.J.A. Keiren, F.P.M. Stappers, E.P. de Vink, W. Wesselink & T.A.C. Willemse (2013): *An Overview of the mCRL2 Toolset and Its Recent Advances*. In N. Piterman & S.A. Smolka, editors: *Proceedings of the 19th International Conference on Tools and Algorithms for the Construction and Analysis of Systems*, *Lecture Notes in Computer Science* 7795, Springer, pp. 199–213.

[7] M. Cremonini, A. Omicini & F. Zambonelli (2000): *Coordination and Access Control in Open Distributed Agent Systems: The TuCSoN Approach*. In A. Porto & G.-C. Roman, editors: *Proceedings of 4th International Conference on Coordination Languages and Models*, *Lecture Notes in Computer Science* 1906, Springer, pp. 99–114.

[8] D. Darquennes, J.-M. Jacquet & I. Linden (2018): *On Multiplicities in Tuple-Based Coordination Languages: The Bach Family of Languages and Its Expressiveness Study*. In G. Di Marzo Serugendo & M. Loreti, editors: *Proceedings of the 20th International Conference on Coordination Models and Languages*, *Lecture Notes in Computer Science* 10852, Springer, pp. 81–109.

[9] D. Gelernter & N. Carriero (1992): *Coordination Languages and Their Significance*. *Communications of the ACM* 35(2), pp. 97–107.

[10] T. Gibson-Robinson, P. Armstrong, A. Boulgakov & A.W. Roscoe (2014): *FDR3 — A Modern Refinement Checker for CSP*. In E. Abraham & K. Havelund, editors: *Tools and Algorithms for the Construction and Analysis of Systems*, *Lecture Notes in Computer Science* 8413, pp. 187–201.

[11] M. Hennessy & R. Milner (1980): *On Observing Nondeterminism and Concurrency*. In J.W. de Bakker & J. van Leeuwen, editors: *Proceedings of the International Conference on Automata, Languages and Programming*, *Lecture Notes in Computer Science* 85, Springer, pp. 299–309.

[12] C.A.R. Hoare (1985): *Communicating Sequential Processes*. Prentice-Hall International Series in Computer Science, Prentice Hall.

[13] J.-M. Jacquet & M. Barkallah (2019): *Scan: A Simple Coordination Workbench*. In H. Riis Nielson & E. Tuosto, editors: *Proceedings of the 21st International Conference on Coordination Models and Languages*, *Lecture Notes in Computer Science* 11533, Springer, pp. 75–91.

[14] J.-M. Jacquet & M. Barkallah (2021): *Anemone: A workbench for the Multi-Bach Coordination Language*. *Science of Computer Programming* 202, p. 102579.

[15] J.-M. Jacquet & I. Linden (2007): *Coordinating Context-aware Applications in Mobile Ad-hoc Networks*. In T. Braun, D. Konstantas, S. Mascolo & M. Wulff, editors: *Proceedings of the first ERCIM workshop on eMobility*, The University of Bern, pp. 107–118.

[16] D. Kozen (1983): *Results on the Propositional mu-Calculus*. *Theoretical Computer Science* 27, pp. 333–354.

[17] Kening Liu, Junyao Ye & Yinglian Wang (2012): *The Security Analysis on Otway-Rees Protocol Based on BAN Logic*. In: *Proceedings of the Fourth International Conference on Computational and Information Sciences*, pp. 341–344.

[18] M. Loreti & A. Lluch Lafuente (2024): *Programming with Spaces*. Available at `https://github.com/pSpaces/Programming-with-Spaces/blob/master/README.md`.

[19] G. Lowe (1996): *Breaking and Fixing the Needham-Schroeder Public-Key Protocol using FDR*. In T. Margaria & B. Steffen, editors: *Proceedings of the International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS)*, *Lecture Notes in Computer Science* 1055, Springer, pp. 147–166.

[20] R.M. Needham & M.D. Schroeder (1978): *Using Encryption for Authentication in Large Networks of Computers*. *Communication of the ACM* 21, pp. 993–999.

[21] D. Ouardi, M. Barkallah & J.-M. Jacquet (2024): *Coding and Breaking the Needham-Schroeder Protocol using B2Scala*. Available at `https://github.com/UNamurCSFaculty/B2Scala`. Created on February 26th, 2024.

[22] A. Pnueli (1977): *The Temporal Logic of Programs*. In: *Proceedings of the 18th Annual Symposium on Foundations of Computer Science*, IEEE Computer Society, pp. 46–57.

[23] J. Proença & L. Edixhoven (2023): *Caos: A Reusable Scala Web Animator of Operational Semantics*. In S.-S. Jongmans & A.Lopes, editors: *Proceedings of the 25th International Conference on Coordination Models and Languages*, *Lecture Notes in Computer Science* 13908, Springer, pp. 163–171.

[24] V. Saraswat (1993): *Concurrent Constraint Programming*. ACM Doctoral dissertation awards, MIT Press.

An Overview of the Decentralized Reconfiguration Language Concerto-D through its Maude Formalization

Farid Arfi, Hélène Coullon, Frédéric Loulergue, Jolan Philippe, Simon Robillard

We propose an overview of the decentralized reconfiguration language CONCERTO-D through its Maude formalization. CONCERTO-D extends the already published CONCERTO language. CONCERTO-D improves on two different parameters compared with related work: the decentralized coordination of numerous local reconfiguration plans which avoid a single point of failure when considering unstable networks such as edge computing, or cyber-physical systems (CPS) for instance; and a mechanized formal semantics of the language with Maude which offers guarantees on the executability of the semantics. Throughout the paper, the CONCERTO-D language and its semantics are exemplified with a reconfiguration extracted from a real case study on a CPS. We rely on the Maude formal specification language, which is based on rewriting logic, and consequently perfectly suited for describing a concurrent model.

1 Introduction

Running and maintaining large-scale distributed software is now a commonplace activity, but managing the inherent complexity of this task requires dedicated tools, models, and languages. The complexity is particularly apparent when distributed software needs to be reconfigured during execution, either to satisfy changing requirements or to carry out maintenance operations.

The DevOps community (and associated tools) as well as component-base software engineering (CBSE) are the main domains focussing on the deployment and reconfiguration of distributed software systems. A reconfiguration consists of a set of tasks to execute on the different pieces of software, distributed across the network, to lead the system in the new desired configuration (i.e., state). In these domains, tasks are almost always orchestrated by a central coordinator [24, 9], i.e., an entity that keeps track of the tasks to apply and their dependencies, as well as the global state of the distributed system.

However, a centralized model is necessarily limited in terms of resilience, as it creates a single point of failure. For instance, in the context of constrained (e.g., energy, communications) cyber-physical systems [20, 21], or edge computing where network disconnections are commonplace, as well as in the context of large-scale projects where cross-DevOps teams [15, 22, 24, 25] have to collaborate, decentralized reconfiguration models are preferred.

With this work, we extend the semantics of the reconfiguration language CONCERTO [6] and turn it into a decentralized model called CONCERTO-D, by extending the semantics to describe the specifics of communication and synchronization between components. In CONCERTO-D multiple coordinators collaborate to achieve their respective local reconfigurations (one for each node). Both CONCERTO [4, 5] and CONCERTO-D [22, 20, 21] have been the subject of experimental studies to validate the approach and compare it to related work [10, 24]. In particular, and while this is not the main subject of this paper, CONCERTO and CONCERTO-D allow better parallel execution of reconfiguration tasks compared to the related work, thus leading to faster reconfigurations.

To support the development of this decentralized semantics, it appeared necessary to go beyond a pen-and-paper approach and to provide a mechanized formalization of the semantics. To this end, we

Submitted to:
ICE 2024

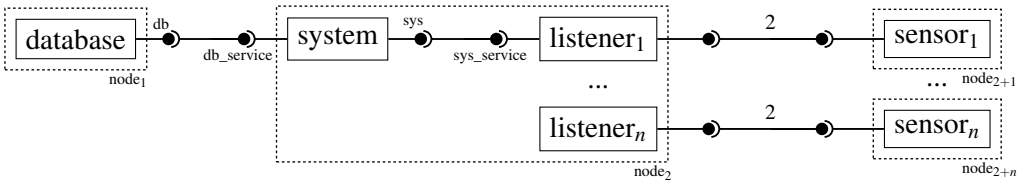


Figure 1: Full overview of the CPS use case with $2+n$ nodes hosting *database*, *system*, *n listeners*, and *n sensors*.

used Maude [8, 19], a language based on rewriting logic, and consequently perfectly suited to describing a concurrent model. Developing and formalizing the semantics of CONCERTO-D in Maude helped us manage the complexity of the model, and clarify it where needed, but it also allowed us to generate tools such as an interpreter and a model-checker for these semantics. A Maude program describes a logical theory, while a Maude computation consists of logical deductions using the axioms specified in the theory.

Throughout the paper, we will use an example taken from a real case study from the literature: a wildlife monitoring system that utilizes sensors to capture animal sounds [18] illustrated in Figure 1. These sensors are linked to a gateway and calibrated to specific sound frequencies. Reconfiguration is regularly required in this system to adjust the listening frequency of each sensor. However, during the reconfiguration process, the sensor must temporarily cease listening. Similarly, if the gateway fails to receive data from a sensor, the sensor is required to halt its observation activities. The collected data is stored in a remote database. In such a use case, disconnections are common between listeners and sensors. A central coordination of the reconfiguration program is typically a single point of failure, which makes the system fully inactive during unavailability. Furthermore, when facing disconnections, it is more difficult to maintain the global state of the system, which slows down the process: synchronization with the central entity is required even for purely local actions. A decentralized language such as CONCERTO-D is preferable in such a context.

In this paper, we give an overview of the semantics of CONCERTO-D through its Maude formalization. The complete Maude specification with all the rules is available at `https://github.com/Concerto-D/concertod-maude/tree/ice24-conference`. First, Section 2 presents how the life cycles of components, and the creation and modification of a components assembly are formalized in CONCERTO-D. Second, Section 3 gives an overview of the main semantics rules of CONCERTO-D and how are formalized communications in CONCERTO-D. Finally, Section 4 and Section 5 respectively give the related work and a conclusion on this contribution.

2 Control components and reconfiguration language

This section presents the structural concepts of CONCERTO-D as well as its reconfiguration language. Some elements of the formalization in Maude are included, as well as examples based on our case study.

2.1 Control components

In CONCERTO-D, a distributed software system is modeled as an assembly of control component instances, linked together via *ports* (i.e., interfaces), to represent dependencies in their life cycles (e.g., data exchanges, or other interactions between components). There are two types of ports in such con-

nections: *provide* ports and *use* ports. A provide port represents information or a resource offered by a component when the port is active. Conversely, a use port indicates that a component requires some information or resources to perform.

Each piece of software (i.e., component, service), identified by a unique identifier, is an instance of a control component type, that models a component's life cycle as a set of *places* and *transitions*. Each port is bound to a subset of the life cycle (i.e., places and transitions) that is called a group. Places represent milestones of the life cycle. A specific initial place serves as the starting point for the component's life cycle. Transitions represent concrete actions to perform between places (e.g., admin commands).

The dynamic nature of components is captured by their *behaviors*. A behavior is a subset of the component's transitions. At any given point, a control component instance executes one behavior, i.e., only the transitions in this behavior can be fired. Requests to change the active behavior for a component (see reconfiguration instructions in Section 2.2) are queued and executed in the order in which they are received: a behavior remains active until no more transitions in it can be fired, at which point the behavior is changed to the next requested behavior, if any. This mechanism makes up the behavioral interface of components.

Informal example. Figure 1 depicts an assembly modeling our use case, where distributed sensors interact with a system through listeners. Physically, the components are distributed on several nodes. The first node serves as a host for the *database* component responsible for storing recorded data obtained from sensors. The second node comprises the components `system` and `listener`. The *system* component establishes a connection with the database through a *use* port (represented using the UML notation), enabling the usage of the database's service. Furthermore, the *system* is interconnected with *n listeners*, each corresponding to a program responsible for monitoring and reconfiguring remote sensors. These listeners are connected to `system` via their use port. Finally, each $\texttt{sensor}_i$ is hosted on a node and is connected to its associated $\texttt{listener}_i$.

Figure 2 shows the internals of some components of this assembly, omitting others (i.e., *database*, *system*) for clarity. Each listener has four places: `off`, `paused`, `configured`, and `running`; and three behaviors `deploy`, `update`, and `destroy`. The sensors have five places: `off`, `provisioned`, `installed`, `configured`, and `running`; and also three behaviors: `start`, `pause`, `stop`. Each listener has two connections with its respective sensor. Through the first connection, the listener exposes the configuration to apply on the sensor (e.g., frequency of listening). Through the second connection, the listener offers a service to which data can be sent by the sensor when observing.

Maude specification. Let us present the definitions of sorts, subsorts, and operators used to encode the above syntactic aspects of the CONCERTO-D model, starting from elementary concepts to the construction of a net of CONCERTO-D components. In Maude, a type hierarchy can be defined using the keywords `sort` and `subsort`. An operator definition starts with the keyword `op` followed by the operator name and type signature; several operators with the same signature can be defined using `ops`.

A component type is defined by a set of places, an initial place, and a set of transitions. The definition also includes the behaviors (sets of transitions) of the component type, and its use and provide ports, each bound to a group of places. In the definition below, some details are omitted for simplicity.

We use predefined data structures and the module system of Maude to import the parameterized module `SET{Place}` and define the sort `Places` to be a supersort of `SET{Place}`. Generally, given a sort `T`, we let `Ts` stand for `SET{T}` and `QT` stand for `LIST{T}`.

```
1 sorts Place InitialPlace Transition Behavior UsePort ProvidePort GroupUse GroupProvide
2       ComponentType .
```

```
sorts Places Transitions Behaviors GroupUses GroupProvides .
subsort InitialPlace < Place .

--- [...]
op b(_) : Transitions -> Behavior .
op (_!_) : UsePort Places -> GroupUse .
op (_?_) : ProvidePort Places -> GroupProvide .

op { places: _,
     initial: _,
     --- [...]
     transitions: _,
     behaviors: _,
     groupUses: _,
     groupProvides: _
   } :
     Places InitialPlace
     --- [...]
     Transitions Behaviors GroupUses GroupProvides -> ComponentType .
```

Example in Maude. We can now describe the component type `sensor` (an instance of which is displayed on the right of Figure 2). We first define a few constants corresponding to the element of the component type, then the type itself:

```
ops Running Configured Installed Provisioned Off : -> Place .
op Off : -> InitPlace .
--- [...]
ops RcvService ConfigService : -> UsePort .
ops Deploy11 Deploy12 Deploy13 Deploy2 Deploy3 Deploy4 Pause1 Stop1 : -> Transition .
ops Deploy Pause Stop : -> Behavior .

eq Deploy = b(Deploy11,Deploy12,Deploy13,Deploy2,Deploy3,Deploy4) .
eq Pause = b(Pause1) .
eq Stop = b(Stop1) .

op sensor : -> ComponentType .
eq sensor =
  { places: Running, Configured, Installed, Provisioned, Off,
    initial: Off,
    --- [...]
    transitions: (Deploy11,Deploy12,Deploy13,Deploy2,Deploy3,Deploy4,Pause1, Stop1),
    behaviors: (Deploy, Pause, Stop),
    groupUses: RcvService ! (Running, Configured),
               ConfigService ! (Configured, Running, Installed),
    groupProvides: empty } .
```

2.2 Reconfiguration language and assembly of components

To allow the modification of assemblies, CONCERTO-D proposes a simple imperative language for writing reconfiguration programs, that offers four commonly used topological instructions to create or modify the existing assemblies: $add(id_c, c)$, $del(id_c)$ (creation and deletion of control component instances),

Listing 1: Listeners reconfiguration on $node_2$

```
for i in range(nb_listener):
  pushB(listener_i, update, 2+i*2)
  pushB(listener_i, deploy, 3+i*2)
```

Listing 2: One sensor reconfiguration on $node_{2+i}$

```
pushB(sensor_i, pause, 0)
wait(listener_i, 2+i*2)
pushB(sensor_i, start,1)
```

$con(id_{c1},u,id_{c2},p)$, $dcon(id_{c1},u,id_{c2},p)$ (connection and disconnection between two control component instances), where id_c is an instance identifier, c a component type, u a use port, p a provide port. Besides these instructions, two additional instructions manage the execution of behaviors: $pushB(id_c,b,id_b)$ to request the execution of a behavior b on the component instance id_c; and $wait(id_c,id_b)$ to synchronize onto the end of a given behavior. id_c is a component instance identifier, and id_b the identifier of a given *pushB*.

As a decentralized coordination model, CONCERTO-D considers a network of n nodes, and a partition of component instances over these nodes. Each node operates its own local CONCERTO-D controller and runs its own reconfiguration program. Concrete communications allow the synchronization of actions between paired components. This is an evolution of previous work on the CONCERTO model [6], in which a single central entity executed the reconfiguration and synchronization of components, and communications were implicit. Two examples of CONCERTO-D reconfiguration programs in our case study are given in Listings 1 and 2.

In CONCERTO-D reconfiguration, programs apply changes to the current assembly of components, i.e., component instances and their connection, and to the queue of requested behaviors for each component instance. A specific instance of a component (and its state at any given point of the execution) is specified by its component type, a queue of identified behaviors to be executed by the instance, and a marking that indicates the places reached and transitions fired.

```
sorts IdInstance Instance IdBehavior BehaviorWithId TransitionEnding
     Marking .
sorts TransitionEndings .
sort QBehaviorWithId .

--- [...]
op (_;_) : IdBehavior Behavior -> BehaviorWithId .
op m(_,_,_) : Places Transitions TransitionEndings -> Marking .

op < type: _,
     queueBehavior: _,
     marking: _
   > :
   ComponentType QBehavoirWithId Marking -> Instance .
```

To illustrate this, the definition below describes an instance `sensor1` of type `sensor`, in a state where only the place `running` is marked, and a single behavior `pause` is pending in the queue of behaviors. This corresponds to the state (0) in Figure 2.

```
eq instanceS1 = < type: sensor,
                  queueBehavior: (0 ; Pause),
                  marking: m(Running, empty, empty) > .
```

In order to describe an assembly, it is also necessary to specify the connections between the ports of its component instances, through their identifiers.

```
sort Connection .
sorts Connections .
op (_,_,_,_) : IdInstance UsePort IdInstance ProvidePort -> Connection .
```

Here is an example of such connections between node2 and node3:

```
eq connectionSL1 = (sensor1, RcvService, listener1, Rcv) .
eq connectionSL2 = (sensor1, ConfigService, listener1, Config) .
```

We now define instructions that can be executed to perform a reconfiguration on a CONCERTO-D assembly.

```
sorts Instruction Program .
subsort List{Instruction} < Program .

op add(_,_) : IdInstance ComponentType -> Instruction .
op del(_) : IdInstance -> Instruction .
op pushB(_,_,_) : IdInstance Behavior IdBehavior -> Instruction .
op con(_) : Connection -> Instruction .
op dcon(_) : Connection -> Instruction .
op wait(_,_) : IdInstance IdBehavior -> Instruction .
```

The reconfiguration program given in Listing 2 (as instantiated specifically for node3) can thus be specified in Maude as follows:

```
eq programNode3 =
pushB(sensor1,start,1) wait(listener1, 2) pushB(sensor1, start, 1) .
```

3 Elements of operational semantics

CONCERTO-D is equipped with a small-step semantics. We first illustrate the execution of a reconfiguration on our use case to give an intuition of this semantics.

We consider deployed and running components, i.e., the places running are marked in all listener and sensor components. From there, we aim to trigger an update of each sensor's listening frequency. Hence, each listener has to pause to change its configuration, forcing the sensors to pause as well.

Listings 1 and 2 give the reconfiguration programs respectively for all listeners (all hosted on the same node $node_2$) and one sensor i (corresponding to the update of the frequency of each sensor). These programs are executed concurrently on each node. The execution of these scripts is illustrated in Figure 2 to give the reader an intuition of the semantics of CONCERTO-D. Some possible steps of the execution are represented by a number representing the current configuration of the system (i.e., a snapshot). Using these numbers, three pieces of information are given: (i) the marking, represented by the red dots on marked places and transitions; (ii) the status of the behavior queue, and (iii) the coordination information required between nodes introduced by decentralized execution of CONCERTO-D. In the following, we describe the state of each configuration according to its number. We decompose each state, and we highlight communication steps using the notation Δ.

0. Both $listener_i$ and $sensor_i$ services are running. Thus, the running places are marked. The behaviors to trigger the update are pushed in the queue, i.e., update and deploy for $listener_i$, and pause

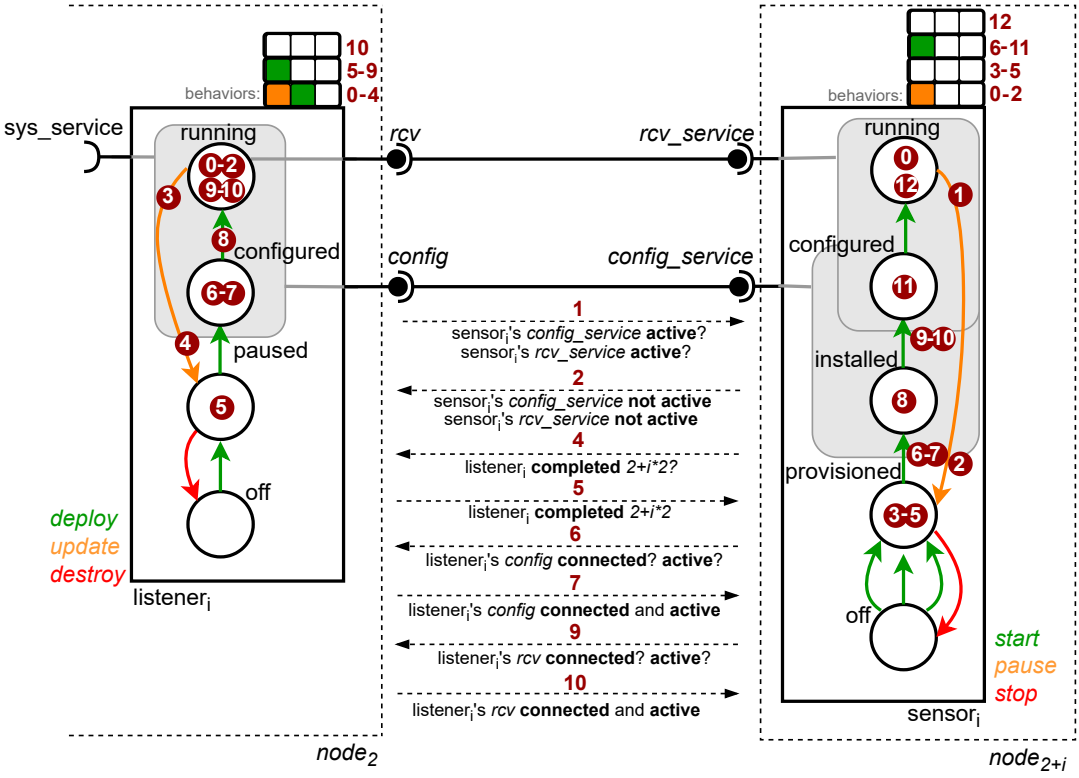


Figure 2: Control components of `listener`$_i$ on *node*$_2$ and `sensor`$_i$ from *node*$_{2+i}$. State example when applying the reconfiguration plans of Listings 1 and 2.

for *sensor*$_i$. The behavior `start` for *sensor*$_i$ is not pushed due to wait instruction of a behavior of *listener*$_i$.

1. By triggering `pause`, *sensor*$_i$ leaves the place `running`.

Δ *listener*$_i$ needs to know if any component is using its ports before executing `update`. Then, *listener*$_i$ requests information on *sensor*$_i$'s use ports *rcv_service* and *config_service*, to know if they are active or not.

2. *sensor*$_i$ ends its previously fired transition.

Δ *sensor*$_i$ answers *listener*$_i$ about its use ports *rcv_service* and *config_service*, indicating that both are inactive. To maintain the consistency of the communicated information between nodes, information previously received from *listener*$_i$ is disregarded, i.e., the connection and activity status of *listener*$_i$ ports are marked `unknown` since this information is subject to change as a result of this communication (as shown in 3).

3. *listener*$_i$ can begin the `update` behavior, therefore deactivating its provide ports. *sensor*$_i$ removes the `pause` behavior from its queue, as no more transitions in this behavior can be fired.

Δ The information sent in 2 is received by *listener*$_i$, allowing it to start its `update`.

4. *listener*$_i$ finishes its transition related to its `update` behavior.

Δ *sensor*$_i$ is now waiting the behavior identified by 2+i*2, and runs on *listener*$_i$, to be ended. Then it sends a request to *listener*$_i$ to know if the behavior 2+i*2 (`update`) is completed.

5. The behavior `update` of $listener_i$ is retrieved from its queue.

Δ $sensor_i$ is informed that this behavior is completed, which allows it to continue its execution, i.e., to push and execute the transitions of the `start` behavior.

6. After pushing the behavior `start` and completing its first transition.

Δ $sensor_i$ sends a request to determine whether the port *config* of $listener_i$ is connected and active, before entering in *config_service* group.

7. Δ $sensor_i$ receives information on $listener_i$'s port *config*. It is now active and connected.
8. $sensor_i$ enters the place `installed`. $listener_i$ begins the activation of its service.
9. $listener_i$ activates its service and provides the port *rcv*.

Δ $sensor_i$ sends a request asking whether the port *rcv* is active and connected before entering the place `configured`.

10. $listener_i$ removes the `deploy` behavior from its queue.

Δ $sensor_i$ get the information that $listener_i$ provides the port *rcv*.

11. $sensor_i$ enters the place `configured`.
12. $sensor_i$ reactivates its service and removes the `start` behavior from its queue.

The rest of this section gives some formal elements of the small-step semantics of CONCERTO-D. Because of space reasons, we cannot fully detail all rules of the semantics. Instead, the section first illustrates one execution rule at a component level and then details communications: the main formalization challenge in a decentralized model as CONCERTO-D.

3.1 Execution and synchronization of reconfiguration actions

As described in Section 2, the life cycles of components are modeled by places (milestones in the reconfiguration) and transitions between places (reconfiguration actions). A marking on places and transitions indicates the current state of the reconfiguration. When a place is marked, its outgoing transitions can be fired. The place is then unmarked, and the fired transitions are marked. Conversely, when all the incoming transitions toward a place are finished, those transitions are unmarked and the place is entered. This model is well suited to represent concurrent execution, in particular, multiple transitions can be marked simultaneously, corresponding to parallel execution of reconfiguration tasks.

The program execution is possible thanks to six semantics rules, one for each instruction (i.e., adding, deleting a component instance, connecting, disconnecting component instances, pushing a behavior to a component instance, and waiting for a given behavior identifier of a given component instance). When executing behaviors, the execution and synchronization of control components are guaranteed by four rules: *FiringTransitions*, *EndingTransition*, *EnteringPlace*, and *FinishingBehavior*.

For space reasons, we only detail one of these rules: *Firing Transitions* given in Listing 3. It modifies the marking in one component on one node, namely unmarking a place `P` and marking the outgoing transitions of `Ts` (only those transitions that belong to the active behavior of the component). Note that this is a conditional rule, as indicated by the keyword `crl` and the boolean conditions after the rule. The first condition merely ensures that there are transitions to fire. The second condition relies on the predicate `safeToFire` to check dependencies towards other components, modeled by ports, are not violated by the firing of the transitions. In particular, this predicate is true only if the firing of the transitions does not lead to deactivating a provide port that is being used, i.e., connected to an active use port. The rule to end a transition (not given) is somewhat similar but instead requires that use ports

attached to the reached place are connected to an active provide port. Thus, ports impose inter-component synchronization conditions on the execution.

Listing 3: The rule to fire a transition. The rule applies to a node (as defined in Section 3.2) but rewrites a single component instance in that node.

```
crl [FiringTransitions] :
    < nodeInventory: Ids,
      instances: (Id1 | -> { type: Ct,
                             queueBehavior: (IdBeh ; b(TsBeh)) Qb,
                             marking: m((P, Ps), Ts, Tes)
                           }), I,
      connections: C,
      --- [...]
      receivedAnswers: Rcv,
      --- [...]
    >
     =>
    < nodeInventory: Ids,
      instances: (Id1 | -> { type: Ct,
                             queueBehavior: (IdBeh ; b(TsBeh)) Qb,
                             marking: m(Ps, union(Ts,
                                                  restrictTransitionsToPlace(TsBeh,P)),
                                        Tes)
                           }), I,
      connections: C,
      --- [...]
      receivedAnswers: Rcv,
      --- [...]
    >
    if (restrictTransitionsToPlace(TsBeh,P) =/= empty and
        safeToFire(Ids,
                   m(Ps, union(Ts, restrictTransitionsToPlace(TsBeh,P) ),Tes),
                   (Id1 | -> { type: Ct,
                               queueBehavior: (IdBeh ; b(TsBeh)) Qb,
                               marking: m(P, Ps,Ts,Tes) }, I),
                   Rcv,
                   connectionProIdent(Id1, C))
        ) .
```

3.2 Communications

Firing or ending a transition on one component may require checking the activity status of a port on another component. In previous work [6], the coordination was assumed to be carried out by a central entity that kept track of the status of every port. Instead, CONCERTO-D is meant to represent a decentralized process, it is therefore necessary to explicitly model communications between the nodes that host components. Thus, when evaluating the status of a port (such as above, in the predicate `safeToFire`), we distinguish the case where the port belongs to a component located on the same node, from the case where messages must be exchanged between nodes:

```
eq evaluation(Req, Ids, RcvA, I, L, P) = if isProcessedLocallyEvaluation(Req, Ids))
    then localEvaluation(Req, I, L, P) else externEvaluation(Req, RcvA) fi .
```

More generally, the following information may be needed for synchronization, and can be requested by components on remote nodes: (1) the completion of a *dcon* action; (2) the completion of an anticipated behavior (i.e., *wait* instruction); (3) the activity of a use or provide port.

Essentially, each CONCERTO-D node maintains a localized perspective of its components and communicates with neighboring nodes (i.e., other CONCERTO-D controllers hosting connected control components). In CONCERTO-D, an asynchronous message-based communication model, increasingly favored in distributed systems, manages the communication [20]. Asynchronous communication is modeled via a buffer: each node is equipped with a queue of messages, and messages must transit through this queue before being effectively received (this assumes that the order of messages is preserved). Thus a message exchange involves two steps, one for sending the message and one for receiving it.

A message can either be a `Request` or an `Answer`. The former is aimed at a specified component instance and contains one of several possible queries

```
sorts Query Request.
op isActive(_) : Port -> Query [ctor] .
op isRefusing(_) : Port -> Query [ctor] .
op isConnected(_) : Connection -> Query [ctor] .
op isDisconnect(_) : Connection -> Query [ctor] .
op isCompleted(_) : IdBehavior -> Query [ctor] .
op [ dst: _ , query: _ ] : IdInstance Query -> Request [ctor] .
```

while an `Answer` gives the boolean evaluation corresponding to a request. It can take the values true, false or `noValueYet`, when the answer to the corresponding request is currently unknown.

```
sorts ExpectedValue Answer .
subsort Bool < ExpectedValue .
op noValueYet : -> ExpectedValue .
op [ req: _, value: _ ] : Request ExpectedValue -> Answer [ctor] .
```

For example, the request `[ dst: listener1, query: isActive(Rcv)]` can be sent by node3 (which hosts `sensor1`) to node2 (which hosts `listener1`) to check whether the port `Rcv` of `listener1` is active. This corresponds to the state 9 in Figure 2. The answer `[ req: [ dst: listener1, query : isActive(Rcv)], value: true ]` is the answer which will be returned at state (10) to indicate that the port is indeed active. For more details about the remaining queries, the reader can refer to [6].

A node is specified by the identifiers of all the component instances in the assembly (used to identify the corresponding node involved in the communication), a mapping that associates the identifiers of the component instances to their nodes (i.e., an inventory), the connections between local component instances and external instances, and the local reconfiguration program to be executed on the node. A node is additionally specified by five parameters used for communication: the received answers to the previously sent requests (sent by this node), the queues of outgoing requests and answers, a history of previously sent requests (to avoid redundant messages for already pending requests) and the incoming buffer for this node. Received answers are stored as a mapping that associates requests to the value of the answer. This represents the node's vision of the status of other components. This information must be kept up to date. Note that requests are not uniquely identified, the same request can thus be sent at different points in time, and the value attached to it in `receivedAnswers` can be modified to denote updated information about other components.

```
sorts IdInstance IdInstances .
pr MAP{Request,ExpectedValue} .
pr MAP{IdInstance,Instance}
sorts Qrequest Qanswer .

op < nodeInventory: _,
     instances: _,
     connections: _,
     program: _,
     receivedAnswers: _,
     outgoingAnswers: _,
     outgoingRequests: _,
     history: _,
     buffer: _ > :
     IdInstances Map{IdInstance,Instance} Connections Program Map{Request,
         ExpectedValue} Qrequest Qrequest Requests Qanswer -> LocalConfiguration
```

For example, the description of the local configuration of node3 in state 0 is as follows:

```
eq ConfNode3 =
    < nodeInventory: sensor1,
      instances: { sensor1 ↦ instanceS1 },
      connections: { connectionSL1, connectionSL2 },
      program: programNode3,
      receivedAnswers: receivedAnswersNode3,
      outgoingAnswers: nil,
      outgoingRequests: nil,
      history: empty,
      buffer: nil >
```

where instanceS1, connectionSL1, connectionSL2 and programNode3 are the elements previously described for our use case in Sections 2 and 3.2. sensor1 is the identifier of instanceS1 and receivedAnswersNode3 is the mapping specifying the received answers of the previous requests sent by node3. Following the deployment steps that preceded the reconfiguration state 0, receivedAnswersNode3 of node3 is described as follows:

```
eq receivedAnswersNode3 =
 {
    [ dst: listener1,query: isActive(Rcv) ] ↦ true,
    [ dst: listener1,query: isConnected(connectionSL1) ] ↦ true,
    [ dst: listener1,query: isActive(Config) ] ↦ true,
    [ dst: listener1,query: isConnected(connectionSL2) ] ↦ true.
 }
```

Finally, we give the execution semantics of communication in CONCERTO-D using Maude rewrite rules, which operate on a net of local configurations of nodes. Figure 3 illustrates the communication between two nodes *x* and *y* using our communication protocol. It specifies the rules for communication presented in listings 4, 5, 6 and 7.

Listing 4 describes the sending of a request [dst: Dst, query: Q] from node x to node y. The destination node y is determined since the identifier of the instance of the request Dst appears in the set of identifiers of the instances of node y. Therefore, sending the request implies adding to the buffer of y the tuple [req: [dst: Dst, query: Q] , value: noValueYet] where the default value

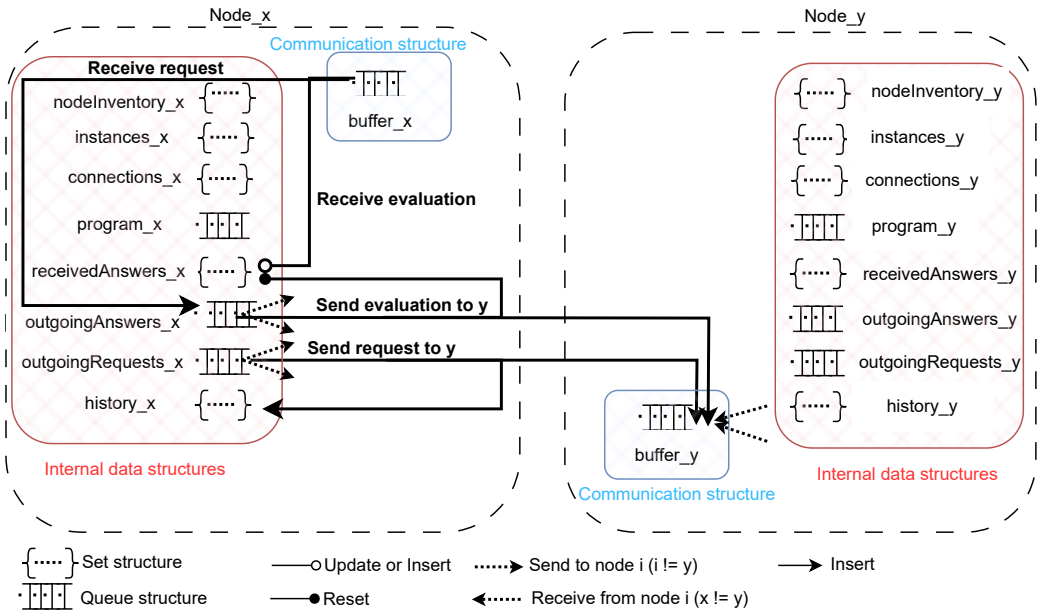


Figure 3: Communication protocol between nodes.

chosen for the request is `noValueYet`. The sent request will also be inserted in the set of the history of node `x` to avoid the request being sent multiple times.

Listing 5 describes the sending of an answer from node `x` to node `y` concerning a request `R` previously sent by `y`. The destination node `y` is chosen when the concerned request `R` is in its history of sent requests, and has not yet received in its communication buffer an answer to this request (`not InQueue(R,By)`). The value of the answer is computed on node `x` by the function `LocalEvalaution` and sent to node `y` by placing the answer in the buffer of node `y`. It is important to maintain the consistency of shared information, so requests are also used by the receiving nodes to invalidate some previously known information. For example, when a component asks (request) if a connected provide port is active, it means that its own use port may be activated soon after the answer is received. Consequently, upon replying, the node receiving the request should forget the information in its store regarding the status of that use port (of course, it should not yet assume that the use port is active). In Listing 5, this update is carried out by the function `Reset`.

Finally, listings 6 and 7 describe the semantics of receiving a message in node `x` from a remote node. Listings 6 describes the case when the retrieved message is a request on a component local to `x`. This is stated when the identifier `Dst` of the request `[dst: Dst, query: Q]` is in the set of identifiers of the components of node `x`. The request is evaluated and the answer is placed in the queue of outgoing answers. Listing 7 describes the case when the retrieved message is an answer to a request `R` previously sent by node `x` (as indicated by its presence in the history). The answered value `val` is recorded (`UpdateInsert(R, val, RcvA)`) and it replaces previous information about the result of request `R`, if any. The request `R` is removed from the history of node `x`, so that a similar request may be sent again in the future.

Listing 4: The rule to send a `Request`, that rewrites two nodes (unaffected variables are omitted).

```
1
2   rl [SendRequest] :
3   < --- [...]
4     outgoingRequests: [ dst: Dst, query: Q ] OutR,
5     history: H,
6     --- [...]
7   > ,
8   < nodeInventory: (Dst, Ids),
9     ---[...]
10    buffer: B >
11   =>
12  < --- [...]
13    outgoingRequests: OutR,
14    history: ([ dst: Dst, query: Q ], H),
15    --- [...]
16  > ,
17  < nodeInventory: (Dst, Ids),
18    --- [...]
19    buffer: append(B, [ req: [dst: Dst, query: Q] , value: noValueYet ]) >
```

4 Related work

CONCERTO and CONCERTO-D can be considered as component models, such as defined in Component-Based Software Engineering (CBSE). As explained in [6, 9] CONCERTO, and by extension CONCERTO-D, differ from usual component models by modeling the life cycle of components instead of modeling the functional code of components. For this reason, both CONCERTO and CONCERTO-D are more comparable to DevOps approaches. Only one other component model can be compared to CONCERTO: Aeolus [10]. However, Aeolus is more limited than CONCERTO in terms of parallelism and concurrency. As for CONCERTO, and unlike CONCERTO-D, Aeolus is a centralized model, and it has been formalized manually.

Regarding DevOps approaches for deployments, a few contributions have studied a decentralized approach. In [15, 25] each component of the application expresses its dependencies with the other components in a central plan, distributed to the corresponding nodes, deploying their part of the application. Deployment executions are then coordinated between the nodes according to their dependencies. Here, the execution is decentralized as in CONCERTO-D. In [24], an extension of the DevOps tool Pulumi is presented to handle both the computation and execution of deployment and update programs in a decentralized manner. However, the three approaches above, and almost all DevOps tools, lack formal specifications: their language is defined by a unique implementation and informal documentation.

To our knowledge, there are only two DevOps contributions that offer formal semantics of their system configuration languages: SMARTFROG [2] a tool no longer maintained, and μPUPPET [14] a subset of PUPPET. The semantics of SMARTFROG is a denotational semantics of a *compiler* for a core SMARTFROG fragment. From the high-level language SF, which handles features such as inheritance, composition, references, etc., the compilation process produces a store, basically a tree of attribute-value pairs. These trees are also the abstractions for system states in SMARTFROG's semantics. The authors wrote three implementations (in Scala, Haskell, and OCaml) of the compiler guided by the semantics

Listing 5: The (conditional) rule to send an `Answer`

```
crl [SendAnswer] :
< --- [...]
  instances: I,
  connections: C,
  program: P,
  receivedAnswers: RcvA,
  outgoingAnswers: R OutA,
  --- [...]
> ,
< --- [...]
  history: (R, H),
  buffer: B >
 =>
< --- [...]
  instances: I,
  connections: C,
  program: P,
  receivedAnswers: Reset(RcvA, ResetId(C, R, LocalEvaluation(R, I, C, P))),
  outgoingAnswers: OutA ,
  --- [...]
> ,
< --- [...]
  history: H,
  buffer: append(B, [ req: R, value: LocalEvaluation(R, I, C, P) ]) >
if ( not InQueue(R, B) ) .
```

but not proved correct w.r.t. to the formal semantics (which is not mechanized). These implementations were randomly tested and a few implementation errors were found. They were also tested against the production compiler: it allowed them to find both a misunderstanding of the semantics of SMARTFROG and bugs in the production compiler. The semantics of μPUPPET is a small-step operational semantics. An implementation of a μPUPPET compiler exists, guided by the semantics but not proved correct w.r.t. the formal semantics, which is also not mechanized. The output of the compiler is a catalog, i.e., a structure close to the stores' output by SMARTFROG's compiler. A catalog is also an abstraction for a system state. To help debug μPUPPET manifests, Fu [13] also proposed an analysis of provenance [7] based on the μPUPPET operational semantics. In both cases, the formal semantics is not an executable artifact as is our proposal.

Khebbeb et al. also use Maude to formalize adaptation in the Cloud [17] and at the edge [16]. The motivation and approach are however very different from our work. There is no reconfiguration language: the goal is to automatically adapt resources depending on the load of the Cloud system. On the one hand, this work considers the provisioning and de-provisioning of virtual machines, an aspect we do not consider. On the other hand, their concept of service is very simplistic: a service is something that processes requests (and only the number of requests is formalized) and there are no connections between services. Their rewrite rules implement pre-defined elasticity strategies. While they perform model-checking on a small example (3 services, 1 VM, and 2 Fog nodes) [16], they neither provide any information about the number of states, nor the time required for the verification. In its complexity, our

Listing 6: The rule for receiving a request

```
rl [ReceiveRequest] :
 < nodeInventory: (Dst, Ids),
   --- [...]
   outgoingAnswers: OutA,
   --- [...]
   buffer: [ req: [dst: Dst, query: Q], value: val ] B >
  =>
< nodeInventory: (Dst, Ids),
  --- [...]
  outgoingAnswers: append(OutA,[dst: Dst, query: Q]),
  buffer: B >
```

Listing 7: The rule for receiving an answer

```
 rl [ReceiveAnswer] :
< --- [...]
  receivedAnswers: RcvA,
  --- [...]
  history: (R, H),
  buffer: [ req: R, value: val ] B >
    =>
< --- [...]
  receivedAnswers: UpdateInsert(R, val, RcvA),
  --- [...]
  history: H,
  buffer: B >
```

proposal is closer to work that models APIs for e.g., [26]. As Yu et al., to analyze interesting enough case studies, we will need to optimize the model-checking by implementing partial order reduction [12].

5 Conclusion

In this paper, we have proposed a formalization in Maude of the decentralized reconfiguration language CONCERTO-D, an extension of the centralized reconfiguration language CONCERTO [6]. In CONCERTO-D each node is responsible for a local reconfiguration program that may require some coordination with reconfiguration programs on other nodes (through their connected component instances). CONCERTO-D automatically manages the necessary communications between nodes via asynchronous communications, which involve nodes communicating by exchanging messages through buffers.

In future work, we plan to use the mechanical formalization of CONCERTO-D presented in this paper as follows. First, we plan on proving properties of the CONCERTO-D model itself (e.g., verifying that component progress is guaranteed if port requirements are eventually satisfied, or verifying that transitions and places correctly describes a partial order on the execution of reconfiguration tasks) to ensure that the model behaves as intended. Second, thanks to CONCERTO-D, CONCERTO could be transformed into a choreographic language (as defined in [1]). In a choreographic approach CON-

CERTO would be the choreography language. A compilation process would then automatically generate the CONCERTO-D programs (i.e., local projections) on the nodes, and guarantee that required communications between nodes will be performed when required. The formalization may be used to prove that the set of CONCERTO-D programs yielded by that process simulates the original centralized CONCERTO program. Verifying the generic properties mentioned above may require the use of interactive theorem proving (ITP). There are ongoing efforts to develop a dedicated interactive theorem prover for Maude [11] or to translate Maude specifications into existing ITP languages [23]. Automated methods such as parametric or symbolic model checking may also be used. Maude has been used in conjunction with SMT solvers to perform parametric model-checking [3].

References

[1] Davide Ancona, Viviana Bono, Mario Bravetti, Joana Campos, Giuseppe Castagna, Pierre-Malo Deniélou, Simon J. Gay, Nils Gesbert, Elena Giachino, Raymond Hu, Einar Broch Johnsen, Francisco Martins, Viviana Mascardi, Fabrizio Montesi, Rumyana Neykova, Nicholas Ng, Luca Padovani, Vasco T. Vasconcelos & Nobuko Yoshida (2016): *Behavioral Types in Programming Languages*. *Foundations and Trends in Programming Languages* 3, doi:10.1561/2500000031.

[2] Paul Anderson & Herry Herry (2016): *A Formal Semantics for the SmartFrog Configuration Language*. *J. Netw. Syst. Manag.*, doi:10.1007/s10922-015-9351-y.

[3] Jaime Arias, Kyungmin Bae, Carlos Olarte, Peter Csaba Ölveczky, Laure Petrucci & Fredrik Rømming (2023): *Symbolic analysis and parameter synthesis for time Petri nets using Maude and SMT solving*. In: *International Conference on Applications and Theory of Petri Nets and Concurrency*, Springer, pp. 369–392, doi:10.1007/978-3-031-33620-1_20.

[4] Maverick Chardet, Hélène Coullon & Christian Pérez (2020): *Predictable Efficiency for Reconfiguration of Service-Oriented Systems with Concerto*. In: *20th IEEE/ACM International Symposium on Cluster, Cloud and Internet Computing (CCGrid)*, IEEE, doi:10.1109/CCGrid49817.2020.00-59.

[5] Maverick Chardet, Hélène Coullon, Christian Pérez, Dimitri Pertin, Charlène Servantie & Simon Robillard (2020): *Enhancing Separation of Concerns, Parallelism, and Formalism in Distributed Software Deployment with Madeus*. hal: hal-02737859.

[6] Maverick Chardet, Hélène Coullon & Simon Robillard (2021): *Toward safe and efficient reconfiguration with Concerto*. *Sci. Comput. Program.*, doi:10.1016/j.scico.2020.102582. hal: hal-03103714.

[7] James Cheney, Laura Chiticariu & Wang Chiew Tan (2009): *Provenance in Databases: Why, How, and Where*. *Found. Trends Databases*, doi:10.1561/1900000006.

[8] Manuel Clavel, Francisco Durán, Steven Eker, Santiago Escobar, Patrick Lincoln, Narciso Martı-Oliet, José Meseguer, Rubén Rubio & Carolyn Talcott (2024): *Maude manual (version 3.4)*. Available at `https://maude.lcc.uma.es/maude-manual/`.

[9] Hélène Coullon, Ludovic Henrio, Frédéric Loulergue & Simon Robillard (2023): *Component-Based Distributed Software Reconfiguration: A Verification-Oriented Survey*. *ACM Comput. Surv.*, doi:10.1145/3595376.

[10] Roberto Di Cosmo, Jacopo Mauro, Stefano Zacchiroli & Gianluigi Zavattaro (2014): *Aeolus: a Component Model for the Cloud*. *Information and Computation*, doi:10.1016/j.ic.2014.11.002.

[11] F Durán, S Escobar, J Meseguer & J Sapina (2024): *An Inductive Theorem Prover for Maude Equational Theories*.

[12] Azadeh Farzan & José Meseguer (2006): *Partial Order Reduction for Rewriting Semantics of Programming Languages*. In: *Workshop on Rewriting Logic and its Applications (WRLA)*, *ENTCS* 176, Elsevier, doi:10.1016/J.ENTCS.2007.06.008.

[13] Weili Fu (2019): *Semantics and provenance of configuration programming language μPuppet*. Ph.D. thesis, University of Edinburgh, UK. Available at `https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.798916`.

[14] Weili Fu, Roly Perera, Paul Anderson & James Cheney (2017): *muPuppet: A Declarative Subset of the Puppet Configuration Language*. In: *31st European Conference on Object-Oriented Programming (ECOOP)*, LIPIcs, doi:10.4230/LIPIcs.ECOOP.2017.12.

[15] Herry Herry, Paul Anderson & Michael Rovatsos (2013): *Choreographing configuration changes*. In: *9th International Conference on Network and Service Management (CNSM 2013)*, doi:10.1109/CNSM.2013.6727828.

[16] Khaled Khebbeb, Nabil Hameurlain & Faiza Belala (2020): *A Maude-Based rewriting approach to model and verify Cloud/Fog self-adaptation and orchestration*. *J. Syst. Archit.*, doi:10.1016/J.SYSARC.2020.101821.

[17] Khaled Khebbeb, Nabil Hameurlain, Faiza Belala & Hamza Sahli (2019): *Formal modelling and verifying elasticity strategies in cloud systems*. *IET Softw.* 13(1), doi:10.1049/IET-SEN.2018.5030.

[18] Vincent Lostanlen, Antoine Bernabeu, Jean-Luc Béchennec, Mikaël Briday, Sébastien Faucou & Mathieu Lagrange (2021): *Energy Efficiency is Not Enough:Towards a Batteryless Internet of Sounds*. In: *16th International Audio Mostly Conference*, doi:10.1145/3478384.3478408.

[19] Peter Csaba Ölveczky (2017): *Designing Reliable Distributed Systems*. Springer, doi:10.1007/978-1-4471-6687-0.

[20] Antoine Omond, Hélène Coullon, Issam Raïs & Otto Anshus (2023): *Leveraging Relay Nodes to Deploy and Update Services in a CPS with Sleeping Nodes*. In: *16th IEEE International Conference on Cyber, Physical and Social Computing (CPSCom)*, IEEE. hal: hal-04372320.

[21] Antoine Omond, Issam Raïs & Hélène Coullon (2023): *Evaluating the energy consumption of adaptation tasks for a CPS in the Arctic Tundra*. In: *19th IEEE International Conference on Green Computing and Communications (GreenCom)*, IEEE. hal: hal-04372340.

[22] Jolan Philippe, Antoine Omond, Hélène Coullon, Charles Prud'Homme & Issam Raïs (2024): *Fast Choreography of Cross-DevOps Reconfiguration with Ballet: A Multi-Site OpenStack Case Study*. In: *IEEE International Conference on Software Analysis, Evolution and Reengineering (SANER)*, IEEE. hal: hal-04457484.

[23] Rubén Rubio & Adrián Riesco (2022): *Theorem proving for Maude specifications using Lean*. In: *International Conference on Formal Engineering Methods*, Springer, pp. 263–280, doi:10.1007/978-3-031-17244-1_16.

[24] Daniel Sokolowski, Pascal Weisenburger & Guido Salvaneschi (2021): *Automating Serverless Deployments for DevOps Organizations*. In: *29th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering (ESEC/FSE)*, doi:10.1145/3468264.3468575.

[25] Karoline Wild, Uwe Breitenbücher, Kálmán Képes, Frank Leymann & Benjamin Weder (2020): *Decentralized Cross-organizational Application Deployment Automation: An Approach for Generating Deployment Choreographies Based on Declarative Deployment Models*. In: *Advanced Information Systems Engineering (CAiSE)*, Springer, doi:10.1007/978-3-030-49435-3_2.

[26] Geunyeol Yu, Seunghyun Chae, Kyungmin Bae & Sungkun Moon (2024): *Formal Specification of Trusted Execution Environment APIs*. In: *Fundamental Approaches to Software Engineering*, Springer Nature Switzerland, doi:10.1007/978-3-031-57259-3_5.

Towards Formal Verification of Attested TLS: Potential Replay Attacks on RA-TLS*

Muhammad Usama Sardar[1], Arto Niemi[2], Hannes Tschofenig[3] and Thomas Fossati[4]

[1] TU Dresden, Germany
muhammad_usama.sardar@tu-dresden.de
[2] Huawei Technologies, Helsinki, Finland
arto.niemi@huawei.com
[3] University of Applied Sciences Bonn-Rhein-Sieg and Siemens, Germany
Hannes.Tschofenig@siemens.com
[4] Linaro, Lausanne, Switzerland
thomas.fossati@linaro.org

Abstract. Transport Layer Security (TLS) is a widely used protocol for secure channel establishment. However, it lacks any inherent mechanism for validating the security state of the endpoint software and its platform. To overcome this limitation, there have been recent proposals to combine remote attestation and TLS, named as attested TLS. The most common attested TLS protocol for confidential computing is Intel's RA-TLS, which is used in multiple open-source industrial projects. By using the state-of-the-art symbolic security analysis tool ProVerif, we found a potential issue in RA-TLS, namely attestation evidence can be replayed from an old session without the verifier noticing. We finally reflect on the challenges and lessons learned in the formalization process, including the discovery of crucial issues in the earlier formalization of TLS.

Keywords: Formal analysis · Transport Layer Security (TLS) · Remote Attestation (RA) · Symbolic Security Analysis · ProVerif.

* funded by DFG grant 389792660 as part of TRR 248 – CPEC.