Checking Protocol Compatibility using Maude

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Abstract
Checking compatibility of services accessed through their behavioural interfaces is a crucial issue in Service Oriented Computing which aims at building new systems from existing software services. In this paper, we consider a model of services which takes value passing and non-observable actions into account. We propose an approach to check in a unified way several compatibility notions between two service protocols using the rewriting logic system Maude. In particular, we illustrate our approach with three widely used compatibility notions, namely opposite behaviours, unspecified receptions and deadlock freeness. These notions as well as several strategies to handle non-observable actions have been formalised and fully implemented into a prototype tool which is able to automatically detect whether two services are compatible, and return a counterexample if they are not.

Keywords: Symbolic Transition Systems, non-observable actions, compatibility, Maude.

1 Introduction

The main principle of Component Based Software Engineering (CBSE) and Service-Oriented Computing (SOC) is the reuse of existing software components or Web services\(^1\) when building new systems in order to save time and efforts. In this context, interoperability issues must be avoided and reused services have to fit with other services in the system being developed. Therefore, compatibility checking is a crucial concern to ensure whether services can interoperate successfully. However, verifying compatibility is especially difficult when the model of services takes interaction protocols into account which is essential \([20]\) to avoid erroneous behaviours or deadlock situations when executing together a set of services.

Numerous compatibility notions have already been proposed based upon several description models of service interfaces, see for instance \([23,9,20,2]\) for automata, \([4,10]\) for π-calculus, \([14,16,17]\) for Petri nets and \([1,5]\) for state machines. Most of these approaches focus on a unique compatibility notion defined with respect to a specific application area, see for instance \([17]\) for service composition, \([1,5,14]\)

\(^1\) In the remainder of this paper, we will refer to both software component and Web service using the generic term service.

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for service substitution, [10] for service choreography, etc. Compared to existing works, new contributions of our proposal are the following: (i) our model takes into account value-passing as well as non-observable or internal actions (τ actions), and considers different strategies to handle them; (ii) we propose a framework where several notions of compatibility can be checked automatically, and this framework can be extended with new compatibility notions and new strategies to handle internal actions. Note that internal actions in interface models are very important because some services can be compatible from an observable point of view, but their execution will behave erroneously due to uncontrolled internal behaviours.

Our model of service interfaces allows to specify interaction protocols (messages and their application order). Value-passing and internal actions are also considered. Our framework provides a uniform and systematic way of checking different notions of compatibility, considering different strategies to deal with internal actions. Here, we focus on three widely used compatibility notions, namely opposite behaviours [21], unspecified receptions [3,23], and deadlock freeness [2]. But other notions are already available in our framework and additional ones could be considered in the future. Moreover, we consider three different τ handling strategies, namely the strong, weak, and trace strategies introduced by Robin Milner in the context of equivalence checking in the 80s [21], and similarly, additional ones could be added to the framework as well. Note that it is important considering different strategies, since each of them makes sense depending on the objective of the compatibility check. Thus, for example, a trace strategy is well suited if one wants to compare external behaviours, whereas a weak strategy allows to detect some subtle errors when composing services. A strong strategy is required when two services must exactly match from an internal and external point of view as it is the case while substituting one service for another.

Our solution for checking protocol compatibility is independent of any specific application, and therefore can be useful for several issues, such as automatic service composition, software adaptation, service substitution, service discovery, code re-engineering, etc. Our proposal has been implemented in the rewriting logic system Maude [7]. Its powerful rewriting engine and searching capabilities open a very wide range of possibilities. Moreover, its expressivity has allowed us to implement the different notions and strategies at a very high level of abstraction, without compromising efficiency, and allowing such a flexible and extensible general framework.

The remainder of this paper is structured as follows. Section 2 formalises our model of services. Section 3 introduces some preliminaries and the notions of compatibility we use in this paper for illustration purposes. In Section 4, we present how service compatibility is checked using Maude. Section 5 presents a comparison with related approaches. Finally, Section 6 draws up some conclusions.

2 Model of Services

We assume that service interfaces are equipped both with a signature (set of required and provided operations) and a protocol represented by a Symbolic Transition System (STS). Communication between services is represented using events relative to the emission and reception of messages corresponding to operation calls. Events
Operational Semantics of one STS

A Symbolic Transition System or STS is a tuple

$$\langle s \xrightarrow{a} s' \rangle \in T$$

$$\langle s, E \rangle \xrightarrow{a} \langle s', E \rangle$$

(TAU)

where

$$m$$

stands for the message name, $$d$$ stands for the communication direction (either an emission ! or a reception ?), and $$(p_1, \ldots, p_n)$$ is either a list of data terms if the label corresponds to an emission, or a list of variables if the label is a reception.

Definition 2.1 [STS] A Symbolic Transition System or STS is a tuple $$(A, S, I, F, T)$$ where: $$A$$ is an alphabet which corresponds to the set of labels associated to transitions, $$S$$ is a set of states, $$I \subseteq S$$ is the initial state, $$F \subseteq S$$ are the final states, and $$T : S \times A \times S$$ is the transition function.

In the remainder of this paper, we describe a transition using a tuple $$(s, l, s')$$ such that $$s$$ and $$s'$$ denote the source and target states, respectively, and $$l$$ stands for the label.

Our STS is a reduced version of STG (Symbolic Transition Graph) introduced in [15]. Here, guards are abstracted as $$\tau$$ transitions, which denote internal (non-observable) activity to the service. The operational semantics of one STS ($$\rightarrow_b$$) is defined with three rules (TAU, EM, REC, Figure 1).

The operational semantics of $$n$$ ($$n > 1$$) STSs ($$\rightarrow_c$$) is formalised using a synchronous communication rule (COM, Figure 2) in which value-passing and variable substitutions rely on a late binding semantics [19], and an independent evolution rule (INE, Figure 2) . $$(a_{s_1}, \ldots, a_{s_n})$$ is a set of couples $$(s_i, E_i)$$, where each couple $$(s, E)$$ is composed by an active state $$s \in S$$ and a data environment $$E$$. A data environment is a set of couples $$(x, v)$$ where $$x$$ is a variable and $$v$$ a ground value. We use a function type which returns the type of a variable or a value, and we define the environment update "$$\odot$$", and the evaluation function $$ev$$ as follows:

$$E \odot (x, v) \triangleq E(x) = v$$

$$ev(E, x) \triangleq E(x)$$

$$ev(E, f(v_1, \ldots, v_n)) \triangleq f(ev(E, v_1), \ldots, ev(E, v_n))$$

The STS formal model has been chosen because it is simple, graphical, and it can be easily derived from existing implementation platforms’ languages (see for instance [12,22,11] where such abstractions for Web services were used for verification, composition or adaptation purposes). For space reasons, in the rest of the paper, we will describe service interfaces only with their STSs. Signatures will be left implicit, yet they can be inferred from the typing of arguments (made explicit here) in STS labels.

Example. We use as running example a travel advice system which gives information for travelers. As it can be observed in Figure 3, the user interface can first log on to a server by sending its user name and password (login!). Then, it can
\[\langle s_i, E_i \rangle \xrightarrow{a^t_{uv}} \langle s'_i, E_i \rangle \quad \text{\text{type}(x) = \text{\text{type}(v)} \quad E'_j = E_j \oplus (x, e)\]

\[\{ s_1, \ldots, \langle s_i, E_i \rangle, \ldots, s_n \} \xrightarrow{a^t_{uv'}} \{ s'_1, \ldots, \langle s'_i, E'_i \rangle, \ldots, s_n \}\]

\[\frac{i, j \in \{1..n\} \quad i \neq j}{\langle s_i, E_i \rangle \xrightarrow{a^t_{uv}} \langle s'_i, E_i \rangle \quad \text{\text{type}(x) = \text{\text{type}(v)} \quad E'_j = E_j \oplus (x, e)\]

\[\{ s_1, \ldots, \langle s_i, E_i \rangle, \ldots, s_n \} \xrightarrow{a^t_{uv'}} \{ s'_1, \ldots, \langle s'_i, E'_i \rangle, \ldots, s_n \}\]

\[\{ \text{\text{as}_1}, \ldots, \langle s_i, E_i \rangle, \ldots, \text{\text{as}_n} \} \xrightarrow{a^t_{uv'}} \{ \text{\text{as}_1}, \ldots, \langle s'_i, E'_i \rangle, \ldots, \text{\text{as}_n} \}\]

\[\frac{i \in \{1..n\}}{\langle s_i, E_i \rangle \xrightarrow{\tau} \langle s'_i, E_i \rangle\]

\[\{ \text{\text{as}_1}, \ldots, \langle s_i, E_i \rangle, \ldots, \text{\text{as}_n} \} \xrightarrow{\tau} \{ \text{\text{as}_1}, \ldots, \langle s'_i, E'_i \rangle, \ldots, \text{\text{as}_n} \}\]

Fig. 2. Operational Semantics of \(n\) STSs

**Fig. 2.** Operational Semantics of \(n\) STSs

request (searchFlight!) and receive (searchFlight?) a flight identifier and price according to the wished destination and departure and return dates. Depending on its preferences (internal choice specified with \(\tau \) transitions in the user protocol), the user can either start a new flight request, ask for a hotel advice (searchHotel!), and then it receives the answer (searchHotel?), or ask for a car advice (searchCar!), get the answer (searchCar?), and then start a hotel advice request. The server service starts by receiving a user name and password (login?). Next, this service can receive and reply several flight requests until a request for a car and/or a hotel advice is received and replied.

3 Service Protocol Compatibility

We start with some definitions useful for the formalisation of service protocol compatibility that we will present in Section 3.4. Since our model considers \(\tau \) actions, the definition of different compatibility notions depends on how these non-observable actions are handled. In this paper, we consider three widely used \(\tau \) handling strategies, namely strong, weak and trace [21], and the compatibility notions can be checked with respect to each of these strategies. Moreover, we formalise the different notions of protocol compatibility using the concepts of set of global reachable states and transition compatibility.
3.1 Preliminaries

In this paper, we focus on the case of two services described using STSs $STS_i = (A_i, S_i, I_i, F_i, T_i), \ i \in \{1, 2\}$. We define a function $out_T(s)$ which returns the set of transitions going out from the state $s$ in the transition set $T$. Last, functions $reachable_T(s)$ and $reachable_{T,l}(s)$ return the set of states which can be reached from the given state $s$, and the set of states which can be reached from the given state $s$ using transitions labeled with $l$ in the transition set $T$, respectively:

- $out_T(s) = \{(s', l, s'') \mid (s', l, s'') \in T, s = s'\}$
- $reachable_T(s) = \{s_1, ..., s_m\} \cup reachable_T(s_1) \cup \ldots \cup reachable_T(s_m)$ where $s_1, ..., s_m = \{s'' \mid (s', l, s'') \in T, s = s'\}$
- $reachable_{T,l}(s) = \{s_1, ..., s_m\} \cup reachable_{T,l}(s_1) \cup \ldots \cup reachable_{T,l}(s_m)$ where $s_1, ..., s_m = \{s'' \mid (s', l', s'') \in T, s = s', l = l'\}$

Comparison of labels is useful to check whether exchanged messages are compatible or not. Formally, we define label compatibility as follows:

Definition 3.1 [Label compatibility] A label $l_1$ is compatible with a label $l_2$ if:

- $l_1 = (m_1, d_1, (p_{11}, \ldots, p_{1n})), l_2 = (m_2, d_2, (p_{21}, \ldots, p_{2n}))$ such that $m_1 = m_2$, $d_1 = d_2$, $n = m$, and $\forall k = 1, \ldots, n \quad type(p_{1k}) = type(p_{2k})$ or,
- $l_1 = \tau$ and $l_2 = \tau$,


3.2 Successor States

Given two STSs $STS_i = (A_i, S_i, I_i, F_i, T_i), \ i \in \{1, 2\}$, we define a global state as a pair of states $(s_1, s_2)$ where $s_i$ is a current state of $STS_i$. Then, the protocol compatibility will be checked for all global reachable states. Therefore, we use the auxiliary functions $successors_{TS}((s_1, s_2))$ and $reachable_{TS}((s_1, s_2))$ which respectively provide the set of global states that can be reached, in one step, from a current global state $(s_1, s_2)$, and the set of all global reachable states for two STSs, where $TS$ stands for the considered $\tau$ handling strategy, namely strong, weak or trace, etc. Note that both $successors_{TS}((s_1, s_2))$ and $reachable_{TS}((s_1, s_2))$ sets are obtained by application of the COM and INE rules given in Figure 2.

In our approach, the successor states function depends on the different ways of dealing with $\tau$ actions. In the following, we present the successor states function for the strong, weak and trace strategies.

We start by defining the strong successor states, in which every label held by a transition going out from a state of one service must be matched with a label hold by a transition going out from a state of the other service, even for $\tau$ actions.

Definition 3.2 [Strong Successor States] The set of global states which are strongly reachable, in one step, from a current global state $(s_1, s_2)$ is defined as follows:

$successors_{strong}((s_1, s_2)) = \{(s_1', s_2') \mid (s_1, l_1, s_1') \in T_1, (s_2, l_2, s_2') \in T_2$ such that $l_1$ and $l_2$ are compatible}
We define now the \textit{weak successor states}. As far as \(\tau\) actions are concerned, we require that each \(\tau\) action is matched by zero or more \(\tau\) actions.

\textbf{Definition 3.3} [Weak Successor States] The set of global states which are \textit{weakly} reachable, in one step, from a current global state \((s_1, s_2)\) is defined as follows:

\[ \text{successors}_{\text{weak}}((s_1, s_2)) = \{(s'_1, s'_2) \mid (s_1, l_1, s'_1) \in T_1, (s_2, l_2, s'_2) \in T_2, l_1 \neq \tau \} \]

\[ \cup \{(s'_1, s'_2) \mid s'_1 \in \text{reachable}_{T_1}(s_1), \text{and} \text{reachable}_{T_1}(s'_1) = \emptyset \text{ or } \exists (s'_1, l_1, s''_1) \in T_1 \text{ such that } l_1 \neq \tau \} \]

\[ \cup \{(s_1, s'_2) \mid s'_2 \in \text{reachable}_{T_2}(s_2), \text{and} \text{reachable}_{T_2}(s'_2) = \emptyset \text{ or } \exists (s'_2, l_2, s''_2) \in T_2 \text{ such that } l_2 \neq \tau \} \]

A weaker definition of successor states consists in determining the set of global states that can be reached from the current one, in one step, by execution of the same traces. By doing so, \(\tau\) actions are just not considered in the service protocols.

\textbf{Definition 3.4} [Trace Successor States] The set of global states which are \textit{trace} reachable, in one step, from a current global state \((s_1, s_2)\) is defined as follows:

\[ \text{successors}_{\text{trace}}((s_1, s_2)) = \{(s'_1, s'_2) \mid (s_1, l_1, s'_1) \in T_1, (s_2, l_2, s'_2) \in T_2, l_1 \neq \tau \text{ and such that } l_1 \text{ and } l_2 \text{ are compatible} \}

\[ \cup \bigcup_{(s_1, l_1, s''_1) \in T_1} \text{successors}_{\text{trace}}((s'_1, s'_2)) \]

\[ \cup \bigcup_{(s_2, l_2, s''_2) \in T_2} \text{successors}_{\text{trace}}((s'_1, s'_2)) \]

\textbf{Example.} We focus on small parts of our running example to illustrate how the successor states can be obtained for the strong, weak and trace strategies. Let us consider the global state \((u_1, s_1)\):

\[ \text{successors}_{\text{strong}}((u_1, s_1)) = \text{successors}_{\text{weak}}((u_1, s_1)) = \text{successors}_{\text{trace}}((u_1, s_1)) = \{(u_2, s_2)\} \]

Since there is no \(\tau\) action hold by a transition going out from \(u_1\) and \(s_1\), we obtain the same set of global states reachable, in one step, from \((u_1, s_1)\) according to any \(\tau\) strategy.

Now, let us consider the global state \((u_4, s_4)\):

\[ \text{successors}_{\text{strong}}((u_4, s_4)) = \emptyset \]

\[ \text{successors}_{\text{weak}}((u_4, s_4)) = \{(u_2, s_4), (u_5, s_4), (u_7, s_4)\} \]

\[ \text{successors}_{\text{trace}}((u_4, s_4)) = \{(u_3, s_3), (u_6, s_3), (u_8, s_3)\} \]

As it can be observed in Figure 3, all the transitions going out from \(u_4\) hold \(\tau\) actions, namely \[\{(u_4, \tau, u_2), (u_4, \tau, u_5), (u_4, \tau, u_7)\}\], while all actions hold by the transitions outgoing from \(s_4\) are different to \(\tau\), namely \[\{(s_4, \text{searchFlight} \downarrow \text{dis} : \text{string}, \text{dep} : \text{tdate}, \text{ret} : \text{tdate}, s_3), (s_1, \text{searchHotel} \downarrow \text{dep} : \text{tdate}, \text{ret} : \text{tdate}, \text{cat} : \text{string}, s_0), (s_4, \text{searchCar} \downarrow \text{d1} : \text{date}, \text{d2} : \text{date}, \text{type} : \text{string}, s_0)\}\]. By application
of the strong successor states definition, the τ actions at \( u_4 \) do not match with any action at \( s_1 \), and none of the expected receptions at \( s_4 \) can be emitted at \( u_4 \). Hence, there is no global state that can be strongly reachable from \((u_4, s_4)\). Considering the definition of weak successor states, the τ actions at state \( u_4 \) are skipped because all the transitions going out from this state are labeled with τ. Therefore, the set of global states weakly reachable, in one step, from \((u_4, s_4)\) is \( \{(u_2, s_4), (u_5, s_4), (u_7, s_4)\} \) since \( \text{reachable}_{\text{weak}}(u_2) = \emptyset, \text{reachable}_{\text{weak}}(u_5) = \emptyset \) and \( \text{reachable}_{\text{weak}}(u_7) = \emptyset \). Finally, following the trace successor states definition, as it is shown in Figure 3, the set of global states \( \{(u_3, s_3), (u_6, s_3), (u_8, s_3)\} \) can be reached, in one step, from \((u_4, s_4)\) using traces of compatible labels.

In order to obtain the set of all global reachable states for two STSs starting from an initial global state \((s_1, s_2)\), we present the following definition:

\[
\text{reachable}_{\text{TS}}((s_1, s_2)) = \{(s_1, s_2)\} \cup \bigcup_{(s'_1, s'_2) \in \text{successors}_{\text{TS}}((s_1, s_2))} \text{reachable}_{\text{TS}}((s'_1, s'_2))
\]

### 3.3 Transition Compatibility

As successor states, compatibility of transitions going out from a global state \((s_1, s_2)\) depends on how τ actions are handled. Transition compatibility consists in checking if the sent (respectively, received) messages at a state \( s_1 \) could be received (respectively, sent) at another state \( s_2 \) and vice versa. To do so, we took inspiration from the equivalence notions stated by Milner [21] to present the following definitions:

**Definition 3.5** [Strong Transition Compatibility] Given a global state \((s_1, s_2)\), \(\text{comp-em-rec}_{\text{strong}}((s_1, s_2)) = \text{true} \) iff \( \forall (s_i, l_i, s'_j) \in T_i, \text{ with } i \in \{1, 2\}, \exists (s_j, l_j, s'_j) \in T_j, \text{ with } j = i \mod 2 + 1, \text{ such that } l_i \text{ and } l_j \text{ are compatible} \).

**Definition 3.6** [Weak Transition Compatibility] Given a global state \((s_1, s_2)\), \(\text{comp-em-rec}_{\text{weak}}((s_1, s_2)) = \text{true} \) iff:

- \( \forall (s_i, l_i, s'_j) \in T_i, \text{ with } i \in \{1, 2\}, l_i \neq \tau, \exists (s_j, l_j, s'_j) \in T_j, \text{ with } j = i \mod 2 + 1, \text{ such that } l_i \text{ and } l_j \text{ are compatible} \), and
- \( \forall (s_i, \tau, s''_j) \in T_i, \text{ with } i \in \{1, 2\}, \text{ comp-em-rec}_{\text{weak}}((s''_j, s_j)) = \text{true} \), and \( \forall (s_j, \tau, s''_j) \in T_j, \text{ with } j = i \mod 2 + 1, \text{ comp-em-rec}_{\text{weak}}((s_i, s''_j)) = \text{true} \).

**Definition 3.7** [Trace Transition Compatibility] Given a global state \((s_1, s_2)\), \(\text{comp-em-rec}_{\text{trace}}((s_1, s_2)) = \text{true} \) iff:

- \( \forall (s_i, l_i, s'_j) \in T_i, \text{ with } i \in \{1, 2\}, l_i \neq \tau, \exists (s_j, l_j, s'_j) \in T_j, \text{ with } j = i \mod 2 + 1, \text{ such that } l_i \text{ and } l_j \text{ are compatible} \), and
- \( \forall (s_i, \tau, s''_j) \in T_i, \text{ with } i \in \{1, 2\}, \exists (s, l, s') \in T_i, l = \tau, \text{ such that } s \in \text{reachable}_{\text{trace}}(s_i) \text{ then } \exists (s'_j, s'_j) \in \text{successors}_{\text{trace}}((s_1, s_2)) \text{ where } s'_j = s' \).

**Example.** Figure 4 shows a part of our running example. Considering the global state \((u_4, s_4)\), \(\text{comp-em-rec}_{\text{TS}}((u_4, s_4))\) returns \text{false} if TS is strong or weak, and \text{true} if TS is trace. Since there are transition labels at \( u_4 \) (respectively at \( s_4 \))
which do not match with transition labels at $s_4$ (respectively at $u_4$), $\text{com-em-rec}_{\text{strong}}(u_4, s_4) = false$. By application of the weak transition compatibility notion, $\text{com-em-rec}_{\text{weak}}(u_4, s_4) = true$ iff:

$$\text{com-em-rec}_{\text{weak}}(u_2, s_4) = true \text{ and } \text{com-em-rec}_{\text{weak}}(u_5, s_4) = true \text{ and } \text{com-em-rec}_{\text{weak}}(u_7, s_4) = true.$$

Let us focus on $(u_2, s_4)$. The transition label $(\text{searchCar} ? d1 : \text{date}, d2 : \text{date}, \text{type} : \text{string})$ at $s_4$ does not match with any transition label at $u_2$, and thus $\text{com-em-rec}_{\text{weak}}((u_2, s_4)) = false$. Therefore, $\text{com-em-rec}_{\text{weak}}((u_4, s_4)) = false$. Last, by skipping the transitions holding $\tau$ actions at $u_4$, we always have traces of compatible labels starting from $(u_4, s_4)$. Hence, $\text{com-em-rec}_{\text{trace}}((u_4, s_4)) = true$.

### 3.4 Formalising Some Service Compatibility Notions

Various notions of service compatibility exist [4,17,14,15] setting different requirements on how services are compatible. There is no standard or unique service compatibility notion, all of them are useful for different application domains. For illustration purposes, we focus here on three widely used notions, namely opposite behaviours, unspecified receptions and deadlock freeness.

**Opposite behaviours.** The strongest and most intuitive compatibility notion is that of opposite behaviours. In this paper, our definition of opposite behaviours compatibility is inspired from the bisimilarity concept originally stated by Milner [21]. Here, the opposite behaviours compatibility consists in the fact that when one service can send a message, then the other service must be willing to receive that message, and when one service is waiting to receive a message, then the other service must be sending that message. Hence, for any $\tau$ handling strategy $TS$, we formalise the opposite behaviours compatibility notion as follows:

Two STSs $STS_i = (A_i, S_i, I_i, F_i, T_i), i = \{1, 2\}$, are opposite behaviours compatible if and only if for each global state $(s_1, s_2) \in \text{reachable}_{TS}((I_1, I_2))$:

- $\text{comp-em-rec}_{TS}((s_1, s_2)) = true$, and
- if $s_1 \in F_1$ ($s_2 \in F_2$, respectively) then $s_2 \in F_2$ ($s_1 \in F_1$, respectively).

**Example.** Considering our running example, as we have explained in the previous section, $\text{com-em-rec}_{TS}((u_4, s_4)) = false$ if $TS$ is strong or weak. Then, the user and server protocols are not opposite behaviours compatible with respect to the strong and weak strategies. However, these protocols are opposite behaviours compatible according to the trace strategy. For the user and server protocols, we can check that for each trace global reachable state $(u_i, s_j)$ from $(u_1, s_1)$ $\text{com-em-rec}_{\text{trace}}((u_i, s_j)) = true$. We can easily also check the second condition given in the opposite behaviours definition.

**Unspecified receptions.** One compatibility notion which is less restrictive than opposite behaviours is that of unspecified receptions. Here, our unspecified receptions definition is close to that given in [3,23] which consider that two service protocols are compatible even if one service can receive a message that cannot be sent by the other service, i.e. additional receptions, and this works in both directions. However,
this definition requires that if one service can send a message at a reachable state, then that emission must be willing to be received by the other service. By doing so, it is also possible that one protocol holds an emission that will not be received by its partner as long as the state from which this emission goes out is unreachable during an established interaction.

Two STSs $STS_i = (A_i, S_i, I_i, F_i, T_i)$, $i \in \{1, 2\}$, are unspecified receptions compatible if and only if for each global state $(s_1, s_2) \in \text{reachable}_{STS}((I_1, I_2))$:

- $\text{comp-em-rec}_{STS}((s_1, s_2)) = \text{true}$, and if $s_1 \in F_1$ ($s_2 \in F_2$, respectively) then $s_2 \in F_2$ ($s_1 \in F_1$, respectively), or
- $\exists (s_i, l_i, s'_j) \in T_i$, with $i = \{1, 2\}$, $l_i = (m_i, ?, pl)$, $\not\exists (s_j, l_j, s'_j) \in T_j$, with $j = i \mod 2 + 1$, such that $l_i$ and $l_j$ are compatible.

Example. In our travel advice running example, the user and server protocols are unspecified receptions incompatible according to the strong strategy since at the global state $(u_4, s_4)$ there are transition labels, different to receptions, at $u_4$ (respectively $s_4$) which do not match with transition labels at $s_4$ (respectively $u_4$). However, both protocols are unspecified receptions compatible with respect to weak and trace strategies because for all global reachable states $(u_i, s_j)$, if there is a transition label $l$ at $u_i$ (respectively $s_j$) which cannot be matched with a transition label at $s_j$ (respectively $u_i$) thus $l$ is a reception. For instance, let us consider the global reachable state $(u_7, s_4)$ in Figure 5. At state $s_4$, there are two additional receptions, namely $(\text{searchCar}\?, d1 : \text{date}, d2 : \text{date}, \text{type} : \text{string})$ and $(\text{searchFlight}\?, \text{dis} : \text{string}, \text{dep} : \text{tdate}, \text{ret} : \text{tdate})$, that do not match with the emission at $u_7$.

Deadlock freeness. This notion is less restrictive than the two previous ones. It considers that two service protocols are compatible if and only if, starting from their initial states, they can always evolve until reaching a final global state. In order to formalise our deadlock freeness compatibility, we took inspiration from [2].

Two STSs $STS_i = (A_i, S_i, I_i, F_i, T_i)$, $i \in \{1, 2\}$, are deadlock freeness compatible if and only if for each global state $(s_1, s_2) \in \text{reachable}_{STS}((I_1, I_2))$:

- $(s_1, s_2) \in (F_1 \times F_2)$, or
- $\text{successors}_{STS}((s_1, s_2)) \neq \emptyset$. 

![Fig. 4. Strong and Weak Incompatible Emissions Receptions at $(u_4, s_4)$](image-url)
Example. Going back to the travel advice system, the user and server are incompatible with respect to the strong strategy since there exists no global strongly reachable state from \((u_4, s_4)\), and \(u_4\) and \(s_4\) are not final states. Nevertheless, these two protocols are deadlock free compatible according to the weak and trace strategies because, starting from their initial states, for each weak (or trace) global reachable state \((u_i, s_i)\) successors \(TS((u_i, s_i)) \neq \emptyset\) until reaching a final global state, where \(TS\) is weak or trace.

3.5 Compatibility Checking

We now present a protocol compatibility definition \(UPC\) for two given protocols described using STSs, a compatibility notion \(CN\) and a \(\tau\) handling strategy \(TS\). This definition enables one to check if two service protocols, described using STSs, are compatible with respect to \(CN\) and \(TS\), and reports a counterexample \(CE\) if they are not.

\[
UPC : \{STS_1, STS_2\} \times CN \times TS \rightarrow <\ Boolean, CE >
\]

4 Encoding into Maude and Tool Support

In this Section, we respectively present a short introduction to Maude, the Maude encoding of our compatibility checking framework, and the prototype tool that automates the compatibility verification.

4.1 Maude Overview

Maude \([6,8,7]\) is a high-level language and a high-performance interpreter and compiler in the OBJ \([13]\) algebraic specification family that supports membership equational logic and rewriting logic specification and programming of systems. Thus, Maude integrates an equational style of functional programming with rewriting logic computation. In this section we provide an informal description of those Maude features necessary for understanding the paper; the interested reader is referred to \([8,7]\) for more details.

Maude’s underlying equational logic is membership equational logic \([18]\), a Horn logic whose atomic sentences are equalities \(t = t’\) and membership assertions of the form \(t : S\), stating that a term \(t\) has sort \(S\). Such a logic extends order-
sorted equational logic, and supports sorts, sort relations, subsort polymorphic
overloading of operators, and the definition of partial functions with equationally
defined domains.

In Maude, there are three different types of modules: functional, system and
object-oriented modules. We focus here on functional modules (see [8,7] for addi-
tional information). For example, the following Maude functional module defines
the natural numbers (with sorts \texttt{Nat} of natural numbers and \texttt{NzNat} of nonzero
natural numbers), using the Peano notation, with the zero (0) and successor (\texttt{s}_)
operators as constructors (note the \texttt{ctor} attribute). Then, the addition operation
(\texttt{+_}) is defined, being its behaviour specified by two equational axioms. The op-
erators \texttt{s}_ and \texttt{+_} are defined using \texttt{mixfix} syntax (underscores indicate places for
arguments).

\begin{verbatim}
fmod MY-NAT is
  sort NzNat Nat.
  subsort NzNat < Nat.
  op 0 : -> Nat [ctor].
  op s : Nat -> NzNat [ctor].
  op + : Nat Nat -> Nat [assoc comm id: 0].
  vars M N : Nat.
  eq s M + s N = s (M + N).
endfm
\end{verbatim}

If an equational specification is confluent, terminating, and sort-decreasing, then
it can be executed. Computation in a functional module is accomplished by using
the equations as simplification rules from left to right until a canonical form is
reached. Some equations, like the one expressing the commutativity of a binary
operator, are not terminating, but nonetheless they are supported by means of
operator attributes, so that Maude performs simplification \textit{modulo} the equational
theories provided by such attributes, that can be associative (\texttt{assoc}), commutativity
(\texttt{comm}), and identity (\texttt{id}). The above properties must therefore be understood in
the more general context of simplification \textit{modulo} such equational theories.

In Maude, specifications may be generic, that is, they may be defined with
other specifications as parameters. The requirements that a datatype must satisfy
are described by \textit{theories}. Parameterized modules are instantiated by means of
\textit{views}. A view shows how a particular module satisfies a theory, by mapping sorts
and operations in the theory to sorts and operations in the target module, in such
a way that the induced axioms are provable in the target module.

4.2 Maude Encoding

In this section, we will overview the different Maude modules (see Figure 6) used
to encode our approach:

\textbf{STS Specification}. A module called \texttt{STS} specifies the service model. STSs are
represented as objects of the form:

\begin{verbatim}
< Oid : STS | is : State, fss : Set{State}, ts : Set{Transition} >.
\end{verbatim}

An \texttt{STS} object has an identifier (\texttt{Oid}), a type (\texttt{STS}), and an attribute set which
consists of an initial state (\texttt{is}), a set of final states (\texttt{fss}), and a set of transitions
(\texttt{ts}). A transition is a tuple of the form \texttt{St1 \sim L \rightarrow St2} where \texttt{St1} and \texttt{St2} are,
respectively, the source and target states, and \texttt{L} is the label. A label is either a \tau
Durán, Ouederni and Salaün

Compatibility Notion

Strategy

Weak Trace Strong

STS uses

Unspecified receptions

Deadlock freeness

Opposite behaviours

uses

uses

uses

Fig. 6. Diagram of Maude Modules

(T) or a tuple of the form $M \ d \ (PRS)$, where $M$ is the message name, $d$ stands for the direction being $?$ or $!$, and $PRS$ denotes the parameter list.

**Tau Strategies.** Two operations successors and comp-em-rec encode the successors$_{\sigma}$ and $\text{comp-em-rect}_{\sigma}$ functions, respectively, in three Maude modules called STRONG, WEAK and TRACE, respectively. For space reasons, we cannot give all the Maude specifications implementing these functions. For instance, Figure 7 shows the encoding of the successors$_{\text{trace}}$ function. The successors operation explores two STS objects (first and third arguments in line 1) starting from a global state (second and forth arguments in line 1) in order to return the set of global states ($\text{Set} \{\text{Pair} \{\text{State}, \text{State}\}\}$) reachable, in one step, from the current one using traces of compatible labels. Regarding the label compatibility, the expressions $\text{St}_1 - M \ d_1 \ (PRS_1) \rightarrow \text{St}_1'$ and $\text{St}_2 - M \ d_2 \ (PRS_2) \rightarrow \text{St}_2'$ in lines 8-9 require that the two transition labels at $\text{St}_1$ and $\text{St}_2$ have the same name and opposite directions such that $d_1 = \overline{d}_2$. Then, the compatible-parameters($PRS_1, PRS_2$) call checks if both parameter lists $PRS_1$ and $PRS_2$ have identical type lists (same types in the same order).

**Compatibility Notions.** The opposite behaviours, unspecified receptions and deadlock freeness compatibility notions presented in Section 3.4 are specified into three operations opposite-behaviours, unspecified-receptions and deadlock-freeness, respectively. Each of these operations evaluates the compatibility of two STSs at all reachable global states with respect to a $\tau$ strategy. For instance, Figure 8 shows the specification of the opposite behaviours compatibility notion. In the very first step, the opposite-behaviours operation (line 1) accepts as arguments two STS objects and returns a tuple consisting of a Boolean value and a counterexample ($\text{Tuple} \{\text{Bool}, \text{Tuple} \{\text{List} \{\text{Transition}\}\}\}$). Then, in order to check the protocol compatibility at all global reachable states using a recursive execution, an auxiliary opposite-behaviours operation (lines 8-10) is called. As it is shown in line 13, the auxiliary opposite-behaviours operation calls the comp-em-rec operation for each global reachable state ($\text{St}_1, \text{St}_2$). Depending on the returned Boolean value, it might be possible to recursively call (lines 14-15) the opposite-behaviours operation for each global state in $SPS$, *i.e.*, the
Maude Encoding of Successors Function wrt the Trace Strategy

eq successors( O : ats | ts : S1 + M ? (PRS1) -> St1', TS ), AtS >, St1, St1', St2') = successors( O : ats | ts : TS, AtS >, St1, St1', St2').

eq successors( O : ats | ts : S1 + M ? (PRS2) -> St2', TS' ), AtS' >, St2) = empty.

if compatible-parameters(PRS1, PRS2).

eq successors( O : ats | ts : S1 + M ? (PRS2) -> St2', TS' ), AtS' >, St2).

if compatible-parameters(PRS1, PRS2).

eq successors( O : ats | ts : TS, AtS >, St1).

eq successors( O : ats | ts : TS, AtS' >, St2).

eq successors( O : ats | ts : TS', AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

eq successors( O : ats | ts : TS'), AtS' >, St2).

Fig. 7. Maude Encoding of Successors Function wrt the Trace Strategy

set of global states that can be reached from (St1, St2). In the case in which the
comp-em-rec operation returns false, the auxiliary get-counterexample operation
returns a couple of transition sequences starting from the initial states until reaching
the incompatibility source. The recursive call can stop if the current global
reachable state (St1, St2) has previously been visited (line 17) in order to avoid an
infinite execution in the case of looping protocols.

Compatibility Checking. A module COMPATIBILITY{TSNOTION} implements the
compatibility definition. The parameter TSNOTION refers to a compatibility notion
(opposite behaviours, unspecified receptions or deadlock freeness) encoded into a
module called NOTION{STRATEGY}, according to a τ strategy (strong, weak or trace)
taken as a parameter.

4.3 Tool Support

The compatibility checking framework that we have presented in the previous
sections has been fully implemented into a prototype tool (see Figure 9 for an
Fig. 9. Compatibility Checking Process

Overview). The STS Maude specifications are automatically generated using our script STS2Maude implemented in Python. In order to check the protocol compatibility, we call the Maude’s \texttt{reduce} command for the operation which implements the chosen compatibility notion (e.g., opposite-behaviours), and the $\tau$ handling strategy. A Boolean value and a counterexample are returned indicating whether two STSs are compatible according to the checked compatibility notion and identifying the incompatibility source, respectively.

So far, our prototype tool has been validated on more than 75 examples, which range from small examples to real-world ones. The largest example of our database consists of two services where each one consists of more than 85 states and around 90 transitions. The maximum computation time for this example was about 7 seconds, and that was needed to check the trace deadlock freeness compatibility.

5 Related Work

During the last 25 years, compatibility has been intensively studied as a main issue in Software Engineering. Let us survey some key related works in this area. [3,23] have formally defined a compatibility notion for software components using an automata-based formalism. Their compatibility notion consists of checking two protocol properties, namely unspecified receptions and deadlock. More recently, [1,5] have used a Finite State Machine (FSM) model to formalise a compatibility notion for Web services which aims to check whether one service can substitute another service. In [1], the authors adopt an asymmetric relation, namely simulation, for determining if a new version of a service behaviour simulates a previous one. [5] gives a restrictive notion of behavioural compatibility saying that each trace in one Web service must also be preserved in another Web service. In [16,17,14], the authors rely on bisimulation algorithms to define the compatibility of Web services which are described using Petri nets. As regards process algebra, [4] and [10] have proposed a compatibility notion based on the $\pi$-calculus to ensure the successful composition of Software components and Web services, respectively. Bordeaux et al. [2] were the first who survey several compatibility notions. However, the Labeled Transition System (LTS) model presented in [2] does not consider value-passing and
internal behaviour, and no tool support exists.

To sum up, there are few compatibility approaches [4,14,17] which take into account \( \tau \) actions, and those that deal with them only use one of the possible strategies. Most of the previous works [3,5,2,1,17,14] consider models where value-passing is not taken into account. In addition, only a few proposals [1,5] have at their disposal an implementation to automatically check the proposed compatibility notions. Compared to these works, we consider a formal interface model which takes into account both non-observable actions and value-passing. Moreover, we propose a framework which enables to check, in a unified manner, several compatibility notions, and therefore make our proposal useful for many possible application domains. Our solution also deals with the subtleties of \( \tau \) actions, and we have implemented several \( \tau \) strategies to handle them properly. Since our proposal relies on an encoding into Maude, the compatibility check is fully automated. Last, the prototype tool that we implemented goes beyond the check of protocol compatibility since it is able to return a counterexample.

6 Concluding Remarks

In this paper we have presented a unified way to check different protocol compatibility notions using the rewriting logic system Maude. The compatibility notions presented in this paper deal with the subtlety of \( \tau \) actions in service protocols. Our proposal is completely implemented into a prototype tool which enables a fully automated check of different compatibility notions with respect to the different \( \tau \) handling strategies. Our prototype tool checks whether two protocols are compatible, but also returns a counterexample to identify the incompatibility source.

As regards future work, we first plan to extend our approach to check compatibility for \( n \) (\( n > 2 \)) service protocols. We also aim at including more compatibility notions as well as more \( \tau \) strategies, and to propose a methodology to make easier the extension of our approach with these new definitions. As far as possible applications are concerned, we would like to rely on our compatibility checking techniques in order to measure similarity of service protocols. Similarity goes farther than “Boolean” compatibility by detecting existing mismatches, and measuring the degree of compatibility of two (or more) protocols. Finally, we would like to propose a high-level language to enable a user to define his own compatibility notion, and some encoding techniques that would automatically generate the Maude code needed to verify this compatibility.

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