

# Relating modal refinements, covariant-contravariant simulations and partial bisimulations<sup>\*</sup>

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**Abstract.** This paper studies the relationships between three notions of behavioural preorder that have been proposed in the literature: refinement over modal transition systems, and the covariant-contravariant simulation and the partial bisimulation preorders over labelled transition systems. It is shown that there are mutual translations between modal transition systems and labelled transition systems that preserve, and reflect, refinement and the covariant-contravariant simulation preorder. The translations are also shown to preserve the modal properties that can be expressed in the logics that characterize those preorders. A translation from labelled transition systems modulo the partial bisimulation preorder into the same model modulo the covariant-contravariant simulation preorder is also offered, together with some evidence that the former model is less expressive than the latter. In order to gain more insight into the relationships between modal transition systems modulo refinement and labelled transition systems modulo the covariant-contravariant simulation preorder, their connections are also phrased and studied in the context of institutions.

## 1 Introduction

*Modal transition systems* (MTSs) have been proposed in, e.g., [11, 12] as a model of reactive computation based on states and transitions that naturally supports a notion of *refinement* that is akin to the notion of implication in logical specification languages. (See the paper [3] for a thorough analysis of the connections between specifications given in terms of MTSs and logical specifications in the setting of a modal logic that characterizes refinement.) In an MTS, transitions come in two flavours: the *may* transitions and the *must* transitions, with the

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requirement that each must transition is also a may transition. The idea behind the notion of refinement over MTSs is that, in order to implement correctly a specification, an implementation should exhibit all the transitions that are required by the specification (these are the must transitions in the MTS that describes the specification) and may provide the transitions that are allowed by the specification (these are the may transitions in the MTS that describes the specification).

The formalism of modal transition systems is intuitive, has several variants with varying degrees of expressive power and complexity—see, e.g., the survey paper [1]—and has recently been used as a suitable model for the specification of service-oriented applications. In particular, results on the supervisory control (in the sense of Ramadge and Wonham [15]) of systems whose specification is given in that formalism have been presented in, e.g., [4, 8].

The very recent development of the notion of *partial bisimulation* in the setting of labelled transition systems (LTSs) presented in [2] has been explicitly motivated by the desire to develop a process-algebraic model within which one can study topics in the field of supervisory control. A partial bisimulation is a variation on the classic notion of bisimulation [13, 14] in which two LTSs are only required to fulfil the bisimulation conditions on a subset  $B$  of the collection of actions; transitions labelled by actions not in  $B$  are treated as in the standard simulation preorder. Intuitively, one may think of the actions in  $B$  as corresponding to the uncontrollable events—see [2, page 4]. The aforementioned paper offers a thorough development of the basic theory of partial bisimulation.

Another recent proposal for a simulation-based behavioural relation over LTSs, called the *covariant-contravariant simulation preorder*, has been put forward in [5], and its theory has been investigated further in [6]. This notion of simulation between LTSs is based on considering a partition of their set of actions into three sets: the collection of covariant actions, that of contravariant actions and the set of bivariant actions. Intuitively, one may think of the covariant actions as being under the control of the specification LTS, and transitions with such actions as their label should be simulated by any correct implementation of the specification. On the other hand, the contravariant actions may be considered as being under the control of the implementation (or of the environment) and transitions with such actions as their label should be simulated by the specification. The bivariant actions are treated as in the classic notion of bisimulation.

It is natural to wonder whether there are any relations among these three formalisms. In particular, one may ask oneself whether it is possible to offer mutual translations between specifications given in those state-transition-based models that preserve, and reflect, the appropriate notions of behavioural preorder as well as properties expressed in the modal logics that accompany them—see, e.g., [2, 3, 6]. The aim of this study is to offer an answer to this question.

In this paper, we study the relationships between refinement over modal transition systems, and the covariant-contravariant simulation and the partial bisimulation preorders over labelled transition systems. We offer mutual trans-

lations between modal transition systems and labelled transition systems that preserve, and reflect, refinement and the covariant-contravariant simulation preorder, as well as the modal properties that can be expressed in the logics that characterize those preorders. We also give a translation from labelled transition systems modulo the partial bisimulation preorder into the same model modulo the covariant-contravariant simulation preorder, together with some evidence that the former model is less expressive than the latter. Finally, in order to gain more insight into the relationships between modal transition systems modulo refinement and labelled transition systems modulo the covariant-contravariant simulation preorder, we phrase and study their connections in the context of institutions [9].

The developments in this paper indicate that the formalism of MTSs may be seen as a common ground within which one can embed LTSs modulo the covariant-contravariant simulation preorder or partial bisimilarity. Moreover, there are some interesting, and non-obvious, corollaries that one may infer from the translations we provide. See Section 5, where we use our translations to show, e.g., that checking whether two states in an LTS are related by the covariant-contravariant simulation preorder can always be reduced to an equivalent check in a setting without bivariate actions, and provide a more detailed analysis of the translations. The study of the relative expressive power of different formalisms is, however, an art as well as a science, and may yield different answers depending on the conceptual framework that one adopts for the comparison. For instance, at the level of institutions [9], we provide an institution morphism from the institution corresponding to the theory of MTSs modulo refinement into the institution corresponding to the theory of LTSs modulo the covariant-contravariant simulation preorder. However, we conjecture that there is no institution morphism in the other direction. The work presented in the study opens several interesting avenues for future research, and settling the above conjecture is one of a wealth of research questions we survey in Section 8.

The remainder of the paper is organized as follows. Section 2 is devoted to preliminaries. In particular, in that section, we provide all the necessary background on modal and labelled transition systems, modal refinement and the covariant-contravariant simulation preorder, and the modal logics that characterize those preorders. In Section 3, we show how one can translate LTSs modulo the covariant-contravariant simulation preorder into MTSs modulo refinement. Section 4 presents the converse translation. We discuss the mutual translations between LTSs and MTSs in Section 5. Section 6 offers a translation from LTSs modulo partial bisimilarity into LTSs modulo the covariant-contravariant simulation preorder. In Section 7, we study the relationships between modal transition systems modulo refinement and labelled transition systems modulo the covariant-contravariant simulation preorder in the context of institutions. Section 8 concludes the paper and offers a number of directions for future research that we plan to pursue.

The proofs of all the results in the paper and further developments may be found in the full version of this study, which is available at <http://www.ru.is/faculty/luca/PAPERS/mts-cc.pdf>.

## 2 Preliminaries

We begin by introducing modal transition systems, with their associated notion of (modal) refinement, and labelled transition systems modulo the covariant-contravariant simulation preorder. We refer the reader to, e.g., [3, 11, 12] and [5, 6] for more information, motivation and examples.

*Modal transition systems and refinement*

**Definition 1.** For a set of actions  $A$ , a modal transition system (MTS) is a triple  $(P, \rightarrow_{\diamond}, \rightarrow_{\square})$ , where  $P$  is a set of states and  $\rightarrow_{\diamond}, \rightarrow_{\square} \subseteq P \times A \times P$  are transition relations such that  $\rightarrow_{\square} \subseteq \rightarrow_{\diamond}$ .

An MTS is image finite iff the set  $\{p' \mid p \xrightarrow{a}_{\diamond} p'\}$  is finite for each  $p \in P$  and  $a \in A$ .

The transitions in  $\rightarrow_{\square}$  are called the *must transitions* and those in  $\rightarrow_{\diamond}$  are the *may transitions*. In an MTS, each must transition is also a may transition, which intuitively means that any required transition is also allowed.

In what follows, we often identify an MTS, or a transition system of any of the types that we consider in this paper, with its set of states. In case we wish to make clear the ‘ambient’ transition system in which a state  $p$  lives, we write  $(P, p)$  to indicate that  $p$  is to be viewed as a state in  $P$ .

The notion of (modal) refinement  $\sqsubseteq$  over MTSs that we now proceed to introduce is based on the idea that if  $p \sqsubseteq q$  then  $q$  is a ‘refinement’ of the specification  $p$ . In that case, intuitively,  $q$  may be obtained from  $p$  by possibly turning some of its may transitions into must transitions.

**Definition 2.** A relation  $R \subseteq P \times Q$  is a refinement relation between two modal transition systems if, whenever  $p R q$ :

- $p \xrightarrow{a}_{\square} p'$  implies that there exists some  $q'$  such that  $q \xrightarrow{a}_{\square} q'$  and  $p' R q'$ ;
- $q \xrightarrow{a}_{\diamond} q'$  implies that there exists some  $p'$  such that  $p \xrightarrow{a}_{\diamond} p'$  and  $p' R q'$ .

We write  $\sqsubseteq$  for the largest refinement relation.

*Example 1.* Consider the MTS  $U$  over the set of actions  $A$  with  $u$  as its only state, and transitions  $u \xrightarrow{a}_{\diamond} u$  for each  $a \in A$ . It is well known, and not hard to see, that  $u \sqsubseteq p$  holds for each state  $p$  in any MTS over action set  $A$ . The state  $u$  is often referred to as the *loosest (or universal) specification*.

**Definition 3.** Given a set of actions  $A$ , the collection of Boudol-Larsen’s modal formulae [3] is given by the following grammar:

$$\varphi ::= \perp \mid \top \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \mid [a]\varphi \mid \langle a \rangle \varphi \quad (a \in A).$$

The semantics of these formulae with respect to an MTS  $P$  and a state  $p \in P$  is defined by means of the satisfaction relation  $\models$ , which is the least relation satisfying the following clauses:

$$\begin{aligned} (P, p) &\models \top. \\ (P, p) &\models \varphi_1 \wedge \varphi_2 \text{ if } (P, p) \models \varphi_1 \text{ and } (P, p) \models \varphi_2. \\ (P, p) &\models \varphi_1 \vee \varphi_2 \text{ if } (P, p) \models \varphi_1 \text{ or } (P, p) \models \varphi_2. \\ (P, p) &\models [a]\varphi \text{ if } (P, p') \models \varphi \text{ for all } p \xrightarrow{a}_{\diamond} p'. \\ (P, p) &\models \langle a \rangle \varphi \text{ if } (P, p') \models \varphi \text{ for some } p \xrightarrow{a}_{\square} p'. \end{aligned}$$

For example, the state  $U$  from Example 1 satisfies neither the formula  $\langle a \rangle \top$  nor the formula  $[a]\perp$ . Indeed, it is not hard to see that  $U$  satisfies a formula  $\varphi$  if, and only if,  $\varphi$  is a tautology.

The following result stems from [3].

**Proposition 1.** *Let  $p, q$  be states in image-finite MTSs over the set of actions  $A$ . Then  $p \sqsubseteq q$  iff the collection of Boudol-Larsen's modal formulae satisfied by  $p$  is included in the collection of formulae satisfied by  $q$ .*

*Labelled transition systems and covariant-contravariant simulation* A labelled transition system (LTS) is just an MTS with  $\rightarrow_{\diamond} = \rightarrow_{\square}$ . In what follows, we write  $\rightarrow$  for the transition relation in an LTS.

**Definition 4.** *Let  $P$  and  $Q$  be two LTSs over the set of actions  $A$ , and let  $\{A^r, A^l, A^{bi}\}$  be a partition of  $A^3$ . An  $(A^r, A^l)$ -simulation (or just a covariant-contravariant simulation when the partition of the set of actions  $A$  is understood from the context) between  $P$  and  $Q$  is a relation  $R \subseteq P \times Q$  such that, whenever  $p R q$ , we have:*

- For all  $a \in A^r \cup A^{bi}$  and all  $p \xrightarrow{a} p'$ , there exists some  $q \xrightarrow{a} q'$  with  $p' R q'$ .
- For all  $a \in A^l \cup A^{bi}$  and all  $q \xrightarrow{a} q'$ , there exists some  $p \xrightarrow{a} p'$  with  $p' R q'$ .

We will write  $p \lesssim_{cc} q$  if there exists a covariant-contravariant simulation  $R$  such that  $p R q$ .

The actions in the set  $A^r$  are sometimes called *covariant*, those in  $A^l$  are *contravariant* and the ones in  $A^{bi}$  are *bivariant*. When working with covariant-contravariant simulations, we shall sometimes refer to the triple  $(A^r, A^l, A^{bi})$  as the *signature* of the corresponding LTS.

*Example 2.* Assume that  $a \in A^r$  and  $b \in A^l$ . Consider the LTSs described by the CCS [13] terms  $p = a + b$ ,  $q = a$  and  $r = b$ . Then  $r \lesssim_{cc} p \lesssim_{cc} q$ , but none of the converse relations holds.

**Definition 5.** *Covariant-contravariant modal logic has almost the same syntax as the one for modal refinement:*

$$\varphi ::= \perp \mid \top \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \mid [b]\varphi \mid \langle a \rangle \varphi \quad (a \in A^r \cup A^{bi}, b \in A^l \cup A^{bi}).$$

*The semantics differs for the modal operators, since we interpret formulae over ordinary LTSs:*

<sup>3</sup> Note that any of the sets  $A^r$ ,  $A^l$  and  $A^{bi}$  may be empty.

$$\begin{aligned} (P, p) \models [b]\varphi & \text{ if } (P, p') \models \varphi \text{ for all } p \xrightarrow{b} p'. \\ (P, p) \models \langle a \rangle \varphi & \text{ if } (P, p') \models \varphi \text{ for some } p \xrightarrow{a} p'. \end{aligned}$$

For example, both  $p$  and  $q$  from Example 2 satisfy the formula  $\langle a \rangle \top$ , while  $r$  does not. On the other hand,  $q$  satisfies the formula  $[b]\perp$ , but neither  $p$  nor  $r$  do.

The following result stems from [6].

**Proposition 2.** *Let  $p, q$  be states in image-finite LTSs with the same signature. Then  $p \lesssim_{cc} q$  iff the collection of covariant-contravariant modal formulae satisfied by  $p$  is included in the collection of covariant-contravariant modal formulae satisfied by  $q$ .*

### 3 From covariant-contravariant simulations to modal refinements

We are now ready to begin our study of the connections between MTSs modulo refinement and LTSs modulo the covariant-contravariant simulation preorder. First we show that, perhaps surprisingly, LTSs modulo  $\lesssim_{cc}$  may be translated into MTSs modulo  $\sqsubseteq$ . Such a translation preserves, and reflects, those preorders and the satisfaction of modal formulae.

**Definition 6.** *Let  $P$  be an LTS with the set of actions  $A$  partitioned into  $A^r$ ,  $A^!$ , and  $A^{bi}$ . The MTS  $\mathcal{M}(P)$  is constructed as follows:*

- The set of actions of  $\mathcal{M}(P)$  is  $A$ .
- The set of states of  $\mathcal{M}(P)$  is the same as the one of  $P$  plus a new state  $u$ .
- For each transition  $p \xrightarrow{a} p'$  in  $P$ , add a may transition  $p \xrightarrow{a}_{\diamond} p'$  in  $\mathcal{M}(P)$ .
- For each transition  $p \xrightarrow{a} p'$  in  $P$  with  $a \in A^r \cup A^{bi}$ , add a must transition  $p \xrightarrow{a}_{\square} p'$  in  $\mathcal{M}(P)$ .
- For each  $a$  in  $A^r$  and state  $p$ , add the transition  $p \xrightarrow{a}_{\diamond} u$  to  $\mathcal{M}(P)$ , as well as transitions  $u \xrightarrow{a}_{\diamond} u$  for each action  $a \in A$ .

The following proposition essentially states that the translation  $\mathcal{M}$  is correct.

**Proposition 3.** *Let  $P$  and  $Q$  be two LTSs with the same signature, and let  $p \in P$  and  $q \in Q$ . Then  $(P, p) \lesssim_{cc} (Q, q)$  iff  $(\mathcal{M}(P), p) \sqsubseteq (\mathcal{M}(Q), q)$ .*

**Definition 7.** *Let us extend  $\mathcal{M}$  to translate formulae over the modal logic that characterizes the covariant-contravariant simulation preorder to the modal logic for modal transition systems by simply defining  $\mathcal{M}(\varphi) = \varphi$ .*

**Proposition 4.** *If  $P$  is an LTS and  $\varphi$  is a formula of the logic that characterizes covariant-contravariant simulation, then for each  $p \in P$ :*

$$(P, p) \models \varphi \iff (\mathcal{M}(P), p) \models \mathcal{M}(\varphi).$$

## 4 From modal refinements to covariant-contravariant simulations

We now show that MTSs modulo  $\sqsubseteq$  may be translated into LTSs modulo  $\lesssim_{cc}$ . As the one studied in the previous section, our translation preserves, and reflects, those preorders and the satisfaction of modal formulae.

**Definition 8.** *Let  $M$  be an MTS with set of actions  $A$ . The LTS  $\mathcal{C}(M)$ , with signature  $A^r = \{\text{cv}(a) \mid a \in A\}$ ,  $A^l = \{\text{ct}(a) \mid a \in A\}$  and  $A^{bi} = \emptyset$ , is constructed as follows:*

- The set of states of  $\mathcal{C}(M)$  is the same as that of  $M$ .
- For each transition  $p \xrightarrow{a}_{\diamond} p'$  in  $M$ , add  $p \xrightarrow{\text{ct}(a)} p'$  to  $\mathcal{C}(M)$ .
- For each transition  $p \xrightarrow{a}_{\square} p'$  in  $M$ , add  $p \xrightarrow{\text{cv}(a)} p'$  to  $\mathcal{C}(M)$ .

Observe that the LTSs obtained as a translation of an MTS have the following properties:

1.  $A^{bi} = \emptyset$  and
2. there is a bijection  $h : A^r \rightarrow A^l$  such that if  $p \xrightarrow{a} p'$  with  $a \in A^r$  then  $p \xrightarrow{h(a)} p'$ .

The following proposition essentially states that the translation  $\mathcal{C}$  is correct.

**Proposition 5.** *Let  $P$  and  $Q$  be two MTSs with the same action set, and let  $p \in P$  and  $q \in Q$ . Then  $(P, p) \sqsubseteq (Q, q)$  iff  $(\mathcal{C}(P), p) \lesssim_{cc} (\mathcal{C}(Q), q)$ .*

**Definition 9.** *Let us extend  $\mathcal{C}$  to translate formulae over the modal logic for modal transition systems with set of actions  $A$  to the modal logic that characterizes covariant-contravariant simulation with signature  $A^r = \{\text{cv}(a) \mid a \in A\}$ ,  $A^l = \{\text{ct}(a) \mid a \in A\}$  and  $A^{bi} = \emptyset$ .*

- $\mathcal{C}(\perp) = \perp$ .
- $\mathcal{C}(\top) = \top$ .
- $\mathcal{C}(\varphi \wedge \psi) = \mathcal{C}(\varphi) \wedge \mathcal{C}(\psi)$ .
- $\mathcal{C}(\varphi \vee \psi) = \mathcal{C}(\varphi) \vee \mathcal{C}(\psi)$ .
- $\mathcal{C}(\langle a \rangle \varphi) = \langle \text{cv}(a) \rangle \mathcal{C}(\varphi)$ .
- $\mathcal{C}([a] \varphi) = [\text{ct}(a)] \mathcal{C}(\varphi)$ .

**Proposition 6.** *If  $P$  is an MTS and  $\varphi$  a modal formula, then for each  $p \in P$ :*

$$(P, p) \models \varphi \iff (\mathcal{C}(P), p) \models \mathcal{C}(\varphi).$$

## 5 Discussion of the translations

In Sections 3–4, we saw that it is possible to translate back and forth between the world of LTSs modulo the covariant-contravariant simulation preorder and MTSs modulo refinement. The translations we have presented preserve, and reflect, the preorders and the relevant modal formulae. There are, however, some interesting, and non-obvious, corollaries that one may infer from the translations.

To begin with, assume that  $P$  and  $Q$  are two LTSs with the same signature with  $A^{bi} \neq \emptyset$ . Let  $p \in P$  and  $q \in Q$  be such that  $(P, p) \lesssim_{cc} (Q, q)$ . By Proposition 3, we know that this holds exactly when  $(\mathcal{M}(P), p) \sqsubseteq (\mathcal{M}(Q), q)$ . Using Proposition 5, we therefore have that checking whether  $(P, p) \lesssim_{cc} (Q, q)$  is equivalent to verifying whether  $(\mathcal{C}(\mathcal{M}(P)), p) \lesssim_{cc} (\mathcal{C}(\mathcal{M}(Q)), q)$ . Note now that  $A^{bi}$  is empty in the signature for the LTSs  $\mathcal{C}(\mathcal{M}(P))$  and  $\mathcal{C}(\mathcal{M}(Q))$ . Therefore checking whether two states are related by the covariant-contravariant simulation preorder can always be reduced to an equivalent check in a setting without bivariate actions.

It is also natural to wonder whether there is any relation between a state  $p$  in an LTS  $P$  and the equally-named state in  $\mathcal{C}(\mathcal{M}(P))$ . Similarly, one may wonder whether there is any relation between a state  $p$  in an MTS  $P$  and the equally-named state in  $\mathcal{M}(\mathcal{C}(P))$ . In both cases, we are faced with the difficulty that the transition systems resulting from the compositions of the translations are over actions of the form  $\{\text{cv}(a), \text{ct}(a) \mid a \in A\}$  whereas the original systems had transitions labelled by actions in  $A$ . In order to overcome this difficulty, let  $\rho : \{\text{cv}(a), \text{ct}(a) \mid a \in A\} \rightarrow A$  be the renaming that, for each  $a \in A$ , maps both  $\text{cv}(a)$  and  $\text{ct}(a)$  to  $a$ . For any transition system  $P$  over the set of actions  $\{\text{cv}(a), \text{ct}(a) \mid a \in A\}$ , we write  $\rho(P)$  for the transition system that is obtained from  $P$  by renaming the label of each transition in  $P$  as indicated by  $\rho$ .

### Proposition 7.

1. Let  $P$  be an MTS and let  $p \in P$ . Then  $(\rho(\mathcal{M}(\mathcal{C}(P))), p) \sqsubseteq (P, p)$ .
2. Let  $P$  be an LTS and let  $p \in P$ . Then  $(P, p) \lesssim_{cc} (\rho(\mathcal{C}(\mathcal{M}(P))), p)$ .
3. In general,  $(P, p) \sqsubseteq (\rho(\mathcal{M}(\mathcal{C}(P))), p)$  does not hold for an MTS  $P$  and a state  $p \in P$ , nor does  $(\rho(\mathcal{C}(\mathcal{M}(P))), p) \lesssim_{cc} (P, p)$  for an LTS  $P$  and a state  $p \in P$ .

**Definition 10.** Let  $P$  be an LTS with the set of actions partitioned into  $A^r$  and  $A^l$ . The LTS  $\bar{P}$  is obtained from  $P$  by renaming every  $a \in A^r$  as  $\text{cv}(a)$  and every  $a \in A^l$  as  $\text{ct}(a)$ .

**Proposition 8.** Let  $P$  be an LTS over a set of actions  $A^r \cup A^l$  and let  $Q$  be an MTS over the same actions. Then the following statements hold.

1. If a relation  $R$  is a covariant-contravariant simulation between  $\bar{P}$  and  $\mathcal{C}(Q)$  then  $R$  is a refinement between  $\mathcal{M}(P)$  and  $Q$ .
2. If  $(\bar{P}, p) \lesssim_{cc} (\mathcal{C}(Q), q)$  then  $(\mathcal{M}(P), p) \sqsubseteq (Q, q)$ , for all states  $p \in P$  and  $q \in Q$ .
3. The converse implication of the above statement fails.



## 6 Partial bisimulation

The partial bisimulation preorder has been recently proposed in [2] as a suitable behavioural relation over LTSs for studying the theory of supervisory control [15] in a concurrency-theoretic framework. Formally, the notion of partial bisimulation is defined over LTSs with a set of actions  $A$  and a so-called *bisimulation set*  $B \subseteq A$ . The LTSs considered in [2] also include a termination predicate  $\downarrow$  over states. For the sake of simplicity, since its role is orthogonal to our aims in this paper, instead of extending MTSs and their refinements or covariant-contravariant simulations with such a predicate, we simply omit it in what follows.

**Definition 11.** *A partial bisimulation with bisimulation set  $B$  between two LTSs  $P$  and  $Q$  is a relation  $R \subseteq P \times Q$  such that, whenever  $p R q$ :*

- For all  $a \in A$ , if  $p \xrightarrow{a} p'$  then there exists some  $q \xrightarrow{a} q'$  with  $p' R q'$ .
- For all  $b \in B$ , if  $q \xrightarrow{b} q'$  then there exists some  $p \xrightarrow{b} p'$  with  $p' R q'$ .

We write  $p \lesssim_B q$  if  $p R q$  for some partial bisimulation with bisimulation set  $B$ .

It is easy to see that partial bisimulation with bisimulation set  $B$  is a particular case of covariant-contravariant simulation.

**Proposition 9.** *Let  $P$  be an LTS. A relation  $R$  is a partial bisimulation with bisimulation set  $B$  iff it is a covariant-contravariant simulation when the LTS  $P$  has signature  $A^r = A \setminus B$ ,  $A^l = \emptyset$  and  $A^{bi} = B$ . Therefore,  $p \lesssim_B q$  iff  $p \lesssim_{cc} q$  with respect to that partition of  $A$ , for each  $p, q \in P$ .*

As a corollary of the above proposition, we immediately obtain the following result, to the effect that, instead of the modal logic used in [2] to characterize the partial bisimulation preorder with bisimulation set  $B$ , one can use the simpler, negation-free logic for the covariant-contravariant simulation preorder.

**Corollary 1.** *Let  $p, q$  be states in some image-finite LTS. Then  $p \lesssim_B q$  iff the collection of formulae in Definition 5 over signature  $A^r = A \setminus B$ ,  $A^l = \emptyset$  and  $A^{bi} = B$  satisfied by  $p$  is included in the collection of formulae satisfied by  $q$ .*

Note also that, as a corollary of Proposition 9, the translations of LTSs and formulae defined in Section 3 can be applied to embed LTSs modulo the partial bisimulation preorder into modal transition systems modulo refinement. In this case, however, there is an easier transformation that does not require the extra state  $u$ .

**Definition 12.** *Let  $P$  be an LTS over a set of actions  $A$  with a bisimulation set  $B \subseteq A$ . The MTS  $\mathcal{N}(P)$  is constructed as follows:*

- The set of states is that of  $P$ .
- For each transition  $p \xrightarrow{a} p'$  in  $P$ , add a may transition  $p \xrightarrow{a}_{\diamond} p'$  in  $\mathcal{N}(P)$ .
- For each transition  $p \xrightarrow{b} p'$  in  $P$  with  $b \in B$ , add a must transition  $p \xrightarrow{b}_{\square} p'$  in  $\mathcal{N}(P)$ .

**Proposition 10.**  *$R$  is a partial bisimulation with bisimulation set  $B$  between  $P$  and  $Q$  iff  $R^{-1}$  is a refinement between  $\mathcal{N}(Q)$  and  $\mathcal{N}(P)$ .*

*Remark 1.* In the special case  $B = \emptyset$ , the partial bisimulation preorder is just the standard simulation preorder. Therefore, letting  $0$  denote a one-state LTS with no transitions,  $0 \lesssim_B p$  for each state  $p$  in any LTS  $P$ . Since  $B = \emptyset$ , all the modal transition systems  $\mathcal{N}(P)$  that result from the translation of an LTS  $P$  will have no must transitions; for such modal transition systems,  $\mathcal{N}(P) \sqsubseteq 0$  always holds. Indeed, in that case  $\sqsubseteq$  coincides with the inverse of the simulation preorder over MTSs.

The drawback of the direct transformation presented in Definition 12, as compared to that in Section 3, is that it does not preserve the satisfiability of modal formulae. The problem lies in the fact that, while the existential modality  $\langle a \rangle$  allows any transition with  $a \in A$  in the partial bisimulation framework, it requires a must transition in the setting of MTSs.

As we have seen, it is easy to express partial bisimulations as a special case of covariant-contravariant simulations. It is therefore natural to wonder whether the converse also holds. We shall present some indications that the partial bisimulation framework is strictly less expressive than both modal refinements and covariant-contravariant simulations.

Let us assume, by way of example, that the set of actions  $A$  is partitioned into  $A^r = \{a\}$  and  $A^l = \{b\}$ —so the set of bivariate actions is empty. In this setting, there cannot be a translation  $\mathcal{T}$  from LTSs modulo  $\lesssim_{cc}$  into LTSs modulo  $\lesssim_B$  that satisfies the following natural conditions (by abuse of notation, we identify an LTS  $P$  with a specific state  $p$ ):

1. For all  $p$  and  $q$ ,  $p \lesssim_{cc} q \iff \mathcal{T}(p) \lesssim_B \mathcal{T}(q)$ .
2.  $\mathcal{T}$  is a homomorphism with respect to  $+$ , that is,  $\mathcal{T}(p + q) = \mathcal{T}(p) + \mathcal{T}(q)$ , where  $+$  denotes the standard notion of nondeterministic composition of LTSs from CCS [13]. (Intuitively, this compositionality requirement states that the translation is based on ‘local information’.)
3. There is an  $n$  such that  $\mathcal{T}(b^n)$  is not simulation equivalent to  $\mathcal{T}(0)$ , where  $b^n$  denotes an LTS consisting of  $n$  consecutive  $b$ -labelled transitions.

Indeed, observe that, by condition 2,

$$\mathcal{T}(p) = \mathcal{T}(p + 0) = \mathcal{T}(p) + \mathcal{T}(0) \quad \text{for each } p,$$

and therefore  $\mathcal{T}(p) + \mathcal{T}(0) \lesssim_B \mathcal{T}(p)$ . This means that  $\mathcal{T}(0) \lesssim \mathcal{T}(p)$  for each  $p$ , where  $\lesssim$  is the simulation preorder. In particular,  $\mathcal{T}(0) \lesssim \mathcal{T}(\perp)$  where  $\perp$  is the process consisting of a  $b$ -labelled loop with one state, which is the least element with respect to  $\lesssim_{cc}$ .

Note now that  $\perp \lesssim_{cc} b^{n+1} \lesssim_{cc} b^n \lesssim_{cc} 0$  for each  $n > 0$ . Therefore, by condition 1,

$$\mathcal{T}(\perp) \lesssim_B \mathcal{T}(b^{n+1}) \lesssim_B \mathcal{T}(b^n) \lesssim_B \mathcal{T}(0) \quad \text{for each } n > 0.$$

Hence,

$$\mathcal{T}(\perp) \lesssim \mathcal{T}(b^n) \lesssim \mathcal{T}(0) \lesssim \mathcal{T}(\perp) \quad \text{for each } n > 0.$$

This yields that, for each  $n > 0$ ,  $\mathcal{T}(b^n)$  is simulation equivalent to  $\mathcal{T}(0)$ , which contradicts condition 3. (Note that we have only used the soundness of the transformation  $\mathcal{T}$ .)

This indicates strongly that any  $\mathcal{T}$  that is compositional with respect to  $+$  and is sound, in the sense of condition 1, would have to be very odd indeed, if it exists at all. Modulo simulation equivalence, such a translation would have to conflate a non-well-founded descending chain of LTSs into a point modulo simulation equivalence.

We end this section with a companion result.

**Proposition 11.** *Assume that  $a \in A^r$  and  $b \in A^l$ . Suppose furthermore that  $B = \emptyset$ . Then there is no translation  $\mathcal{T}$  from LTSs modulo  $\lesssim_{cc}$  into LTSs modulo  $\lesssim_B$  that satisfies conditions 1 and 2 above.*

## 7 Institutions and institution morphisms

In order to gain more insight into the relationships between modal transition systems modulo refinement and labelled transition systems modulo the covariant-contravariant simulation preorder, we will now study their connections at a more abstract level in the context of institutions [9]. When compared at the level of institutions it turns out that the correspondence between these models is, in a sense, not one-to-one.

**Definition 13.** *The institution  $\mathcal{I}_{cc} = (\mathbf{Sign}_{cc}, \text{sen}_{cc}, \mathbf{Mod}_{cc}, \models_{cc})$ , associated to the logic for the covariant-contravariant simulation preorder, is defined as follows.*

- $\mathbf{Sign}_{cc}$  has as objects triples  $(A, B, C)$  of pairwise disjoint sets and morphisms  $f : A \cup B \cup C \longrightarrow A' \cup B' \cup C'$  with  $f(A) \subseteq A'$ ,  $f(B) \subseteq B'$ , and  $f(C) \subseteq C'$ .
- $\text{sen}_{cc}(A, B, C)$  is the set of formulae in the logic characterizing the covariant-contravariant simulation preorder, with  $A$  the set of covariant actions,  $B$  the set of contravariant actions, and  $C$  the set of bivariate actions.  $\text{sen}(f)(\varphi)$  is obtained from  $\varphi$  by replacing each action  $a$  with  $f(a)$ .
- $\mathbf{Mod}_{cc}(A, B)$  is the category of LTS over the set of actions  $A \cup B \cup C$ , with a distinguished state; a morphism from  $(P, p)$  to  $(Q, q)$  is a covariant-contravariant simulation  $R$  such that  $(p, q) \in R$ .

Now, if  $f : A \cup B \cup C \longrightarrow A' \cup B' \cup C'$ , then

$$\mathbf{Mod}_{cc}(f) : \mathbf{Mod}_{cc}(A', B', C') \longrightarrow \mathbf{Mod}_{cc}(A, B, C)$$

maps  $P$  to  $P|_f$  and  $R : P \longrightarrow Q$  to  $R_f : P|_f \longrightarrow Q|_f$ , where:

- The set of states of  $P|_f$  is the same as that of  $P$ , and the distinguished state remains the same.

- $p \xrightarrow{a} p'$  in  $P|_f$  if  $p \xrightarrow{f(a)} p'$  in  $P$ .
  - $R|_f$  coincides with  $R$ .
- $(P, s) \models_{cc} \varphi$  if  $(P, s) \models \varphi$  using the notion of satisfaction associated to the logic for the covariant-contravariant simulation preorder given in Definition 5.

**Proposition 12.**  $\mathcal{I}_{cc}$  is an institution.

**Definition 14.** The institution  $\mathcal{I}_{mts} = (\mathbf{Sign}_{mts}, sen_{mts}, \mathbf{Mod}_{mts}, \models_{mts})$ , associated to the logic for refinement over modal transition systems, is defined as follows.

- $\mathbf{Sign}_{mts}$  is the category of sets.
- $sen_{mts}(A)$  is the set of formulae over  $A$  in the logic presented in Definition 3. The formula  $sen_{mts}(f)(\varphi)$  is obtained from  $\varphi$  by replacing each action  $a$  with  $f(a)$ .
- $\mathbf{Mod}_{mts}(A)$  is the category of MTSs over the set of labels  $A$ , with a distinguished state. A morphism from  $(M, m)$  to  $(N, n)$  is a refinement  $R$  such that  $(m, n) \in R$ .  
If  $f : A \rightarrow B$  in  $\mathbf{Sign}_{mts}$ , then  $\mathbf{Mod}_{mts}(f) : \mathbf{Mod}_{mts}(B) \rightarrow \mathbf{Mod}_{mts}(A)$  maps an MTS  $M$  to  $M|_f$  and a morphism  $R$  to  $R|_f$ , where:
  - $M|_f$  has the same set of states as  $M$  and the same distinguished state.
  - $p \xrightarrow{a}_{\diamond} p'$  in  $M|_f$  if  $p \xrightarrow{f(a)}_{\diamond} p'$  in  $M$ .
  - $p \xrightarrow{a}_{\square} p'$  in  $M|_f$  if  $p \xrightarrow{f(a)}_{\square} p'$  in  $M$ .
  - $R|_f$  coincides with  $R$ .
- $\models_{mts}$  is the notion of satisfaction presented in Definition 3.

**Proposition 13.**  $\mathcal{I}_{mts}$  is an institution.

As the following result shows, one can translate  $\mathcal{I}_{mts}$  into  $\mathcal{I}_{cc}$  using an institution morphism. (The intuition for institution morphisms is that they are truth preserving translations from one logical system into another.)

**Proposition 14.**  $(\Phi, \alpha, \beta) : \mathcal{I}_{mts} \rightarrow \mathcal{I}_{cc}$  is an institution morphism, where:

- $\Phi : \mathbf{Sign}_{mts} \rightarrow \mathbf{Sign}_{cc}$  maps  $A$  to the triple  $(cv(A), ct(A), \emptyset)$ , with:
  - $cv(A) = \{cv(a) \mid a \in A\}$  and
  - $ct(A) = \{ct(a) \mid a \in A\}$ .
For  $f : A \rightarrow B$ , we define  $\Phi(f)(cv(a)) = cv(f(a))$  and  $\Phi(f)(ct(a)) = ct(f(a))$ .
- The natural transformation  $\alpha : sen_{cc} \circ \Phi \Rightarrow sen_{mts}$  translates a formula  $\varphi$  in  $sen_{cc}(cv(A), ct(A), \emptyset)$  as follows:
  - $\alpha(\top) = \top$ ,  $\alpha(\perp) = \perp$ .
  - $\alpha(\varphi_1 \wedge \varphi_2) = \alpha(\varphi_1) \wedge \alpha(\varphi_2)$ .
  - $\alpha(\varphi_1 \vee \varphi_2) = \alpha(\varphi_1) \vee \alpha(\varphi_2)$ .
  - $\alpha(\langle cv(a) \rangle \varphi) = \langle a \rangle \alpha(\varphi)$ .
  - $\alpha([\text{ct}(a)] \varphi) = [a] \alpha(\varphi)$ .

- The natural transformation  $\beta : \mathbf{Mod}_{mts} \Rightarrow \mathbf{Mod}_{cc} \circ \Phi$  maps an MTS  $(M, s)$  in  $\mathbf{Mod}_{mts}(A)$  to  $(\mathcal{C}(M), s)$ , and a morphism  $R$  to itself.

The import of the above result is that MTSs modulo refinement and its accompanying modal logic can be ‘translated in a truth preserving fashion’ into LTSs modulo the covariant-contravariant simulation preorder and its companion modal logic. It is natural to ask oneself whether one can consider  $\mathcal{I}_{mts}$  a ‘substitution’ of  $\mathcal{I}_{cc}$ . There are several related notions of substitution that have in common the requirement that the functor  $\beta$ , which is used to translate the models between the institutions, is an equivalence of categories.

Recall that an object in a category is weakly final if any other object has at least one arrow into it.

**Proposition 15.**  $\mathbf{Mod}_{cc}(A, B, \emptyset)$  has weakly final objects but  $\mathbf{Mod}_{mts}(A)$  does not.

In other words, in the absence of bivariant actions, there is a universal implementation in the setting of LTSs modulo the covariant-contravariant simulation preorder. Within that framework, there is also a universal specification, namely the LTS  $(I, s)$  where  $I$  is the LTS with a single state  $s$  and transitions  $s \xrightarrow{b} s$  for every  $b \in B$ . On the other hand, there is a universal specification with respect to modal refinements, namely the MTS  $U$  from Example 1, but no universal implementation.

**Proposition 16.** *There is no embedding from  $\mathcal{I}_{mts}$  into  $\mathcal{I}_{cc}$ .*

A natural question to ask is whether there is an embedding from  $\mathcal{I}_{cc}$  into  $\mathcal{I}_{mts}$ . The following proposition answers this question negatively.

**Proposition 17.** *There exists no embedding from  $\mathcal{I}_{cc}$  into  $\mathcal{I}_{mts}$ .*

We conjecture that there is not even an institution morphism from  $\mathcal{I}_{cc}$  to  $\mathcal{I}_{mts}$ . (Compare with Proposition 14.)

## 8 Conclusions and future work

In this paper we have studied the relationships between three notions of behavioural preorders that have been proposed in the literature: refinement over modal transition systems, and the covariant-contravariant simulation and the partial bisimulation preorders over labelled transition systems. We have provided mutual translations between modal transition systems and labelled transition systems that preserve, and reflect, refinement and the covariant-contravariant simulation preorder, as well as the the modal properties that can be expressed in the logics that characterize those preorders. We have also offered a translation from labelled transition systems modulo the partial bisimulation preorder into the same model modulo the covariant-contravariant simulation preorder, together with some evidence that the former model is less expressive than the

latter. Finally, in order to gain more insight into the relationships between modal transition systems modulo refinement and labelled transition systems modulo the covariant-contravariant simulation preorder, we have also phrased and studied their connections in the context of institutions.

The work presented in the study opens several interesting avenues for future research. Here we limit ourselves to mentioning a few research directions that we plan to pursue in future work.

First of all, it would be interesting to study the relationships between the LTS-based models we have considered in this article and variations on the MTS model surveyed in, for instance, [1]. In particular, the third author recently contributed in [7] to the comparison of several refinement settings, including modal and mixed transition systems. The developments in that paper offer a different approach to the comparison and application of the formalisms studied in this article.

In [6], three of the authors gave a ground-complete axiomatization of the covariant-contravariant simulation preorder over the language BCCS [13]. It would be interesting to see whether the translations between MTSs and LTSs we have provided in this paper can be used to lift that axiomatization result, as well as results on the nonexistence of finite (in)equational axiomatizations, to the setting of modal transition systems modulo refinement, using the BCCS-like syntax for MTSs given in [3]. We also intend to study whether our translations can be used to obtain characteristic-formula constructions [3, 10, 16] for one model from extant results on the existence of characteristic formulae for the other.

The existence of characteristic formulae allows one to reduce checking the existence of a behavioural relation between two processes to a model checking question. Conversely, the main result from [3] offers a complete characterization of the model checking questions of the form  $(M, m) \models \varphi$ , where  $M$  is an MTS and  $\varphi$  is a formula in the logic for MTSs considered in this paper, that can be reduced to checking for the existence of a refinement between  $(M_\varphi, m_\varphi)$  and  $(M, m)$ , where  $(M_\varphi, m_\varphi)$  is an MTS with a distinguished state that ‘graphically represents’ the formula  $\varphi$ . In future work, we plan to offer a characterization of the logical specifications that can be ‘graphically represented’ by LTSs modulo the covariant-contravariant simulation preorder and partial bisimilarity. Such characterizations may shed further light on the relative expressive power of the two formalisms and may give further evidence of the fact that LTSs modulo the covariant-contravariant simulation preorder are, in some suitable formal sense, more expressive than LTSs modulo partial bisimilarity.

From the theoretical point of view, it would also be satisfying to settle our conjecture that there is no institution morphism from  $\mathcal{I}_{cc}$  to  $\mathcal{I}_{mts}$ .

Last, but not least, the development of the notion of partial bisimulation in [2] has been motivated by the desire to develop a process-algebraic model within which one can study topics in the field of *supervisory control* [15]. Recently, MTSs have been used as a suitable model for the specification of service-oriented applications, and results on the supervisory control of systems whose specification is given in that formalism have been presented in, e.g., [4, 8]. It is a very interesting

area for future research to study whether the mutual translations between MTSS modulo refinement and LTSs modulo the covariant-contravariant simulation preorder can be used to transfer results on supervisory control from MTSS to LTSs. One may also wish to investigate directly the adaptation of the supervisory control theory of Ramadge and Wonham to the enforcement of specifications given in terms of LTSs modulo the covariant-contravariant simulation preorder.

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