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# *Refinement and Verification of Synchronized Component-based Systems*

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## Refinement and Verification of Synchronized Component-based Systems

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**Abstract:** This article deals with specification, refinement and verification approaches for systems designed with synchronized components. First of all, we define a synchronized composition of components. Transition systems are used to specify or/and to model synchronized component-based systems. Second, we give refinement semantics for these component-based systems before proposing a method to verify the refinement of a whole system from the weak refinement of its components. We also present *SynCo* (for Synchronized Component-based Systems): a tool we are implementing using our method. Third, a compositional way to verify safety properties is proposed: the unreachability of a (set of) state(s) can be efficiently ensured for a synchronized component-based system.

The different aspects of our work are illustrated on an industrial example of a wind-screen wipers system composed of a control lever, a rain sensor and two (left and right) wind-screen wipers.

**Key-words:** composition, synchronization, compositional verification, refinement, reachability analysis

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## Raffinement et vérification de systèmes à composants synchronisés

**Résumé :** Cet article traite de la spécification, du raffinement et de la vérification de systèmes conçus sous forme de composants synchronisés. Pour spécifier et/ou pour modéliser ces systèmes, nous utilisons des systèmes de transitions. Nous définissons d'abord une composition synchronisée de systèmes et donnons la sémantique du raffinement pour ce type de systèmes. Ensuite nous donnons des conditions nécessaires et suffisantes du raffinement du système complet à partir du raffinement affaibli de ses composants. Un algorithme de vérification du raffinement pour ce type de système est implanté dans *SynCo* (pour Synchronized Component-based Systems) Finalement, un algorithme de vérification compositionnelle de propriétés de sûreté est proposé.

Les différents aspects de ce travail sont illustrés par l'exemple industriel d'un contrôleur d'essuyage composé d'un levier de contrôle, d'un capteur de pluie et de deux (gauche et droite) essuie-glaces.

**Mots-clés :** composition, synchronisation, vérification compositionnelle, raffinement, vérification algorithmique, analyse d'atteignabilité

## 1 Introduction

Verification across abstraction and refinement steps is a central and important issue in formal system validation. It presents both practical and theoretical difficulties that have not yet been satisfactorily solved.

In this paper, we deal with specification and verification of component-based finite state systems supporting a top-down refinement paradigm. We suppose a specification obtained by a refinement process. Several methods, like *B* [1, 4], *TLA+* [20], *CSP2B* [12], etc. propose a refinement based development. The system specification and modelling we consider in this paper, are inspired by the syntactic and semantic concepts of the *B* refinement method which has been successfully used to specify many reactive systems. On overview, the reader can refer to case studies such as an industrial automatism [2], as well as industrial applications such as *MÉTÉOR* [5] by *Matra Transport International*, and the *SPECTRUM* project [28] by *GEC-Marconi Avionics Limited*.

In [16, 18], it has been proposed to enrich *B* specifications with dynamic properties formulated in the Propositional Linear Temporal Logic (*PLTL*). In [8], we express the refinement semantics as a relation between transition systems. In general, behavioural properties established for an abstract system model are not preserved when the system is refined to a richer level of detail. It is not the case for us: in [14], we show that our refinement relation preserves the abstract system *PLTL* properties. This way, an algorithmic verification of the refinement by model exploration can be associated with the verification of the *PLTL* properties, by model-checking.

However, it is well-known that the algorithmic verification quickly meets its limits when applied to huge systems. Therefore, we have to face the problem of combinatorial explosion during refinement since details introduced by the refinement tend to drastically increase the number of states of the systems. It is also the case while verifying properties by model-checking. Compositional approaches partially avoid this problem.

A way to have components in the *B* method is to decompose the application into separate machines. There are many works on structured development using decomposition into machines and refinement (see, for example [13, 11, 27]). Generally, *B* event systems which are closed systems can be used to describe the components. So, the interactions between components have to be described independently. This is the idea used for example in [12] or in [29].

Unlike the Schneider and Treharne's approach [26], we propose in [9] to remain in the framework of the *B* event systems. We assume that components do not share variables and we propose to specify a synchronization as pairs of events belonging

to two different components with feasibility conditions. These conditions achieve the synchronization by constraining the activation of events of a component by a predicate over the variables of another component. Moreover, during the refinement verification we take the external non-determinism into account.

In this paper, we go further to conciliate the synchronized component-based specification with the refinement verification. First, we propose to use transition systems both for specifying and for modelling synchronized component-based systems. Second, we define a refinement relation of component-based systems which is weaker than the refinement relation defined in [9]. Third, we give the conditions to ensure the refinement of the whole system from the weak refinements of its synchronized components, and vice versa. Furthermore, we propose to exploit the refinement to verify safety properties in a compositional way. The interest of this proposition is that the component-based refinement guarantees preservation of the abstract systems properties for the refined systems.

As a comparison, our goal for addressing the  $B$  event systems composition is different from the  $B$  *decomposition* one proposed by J.-R. Abrial. In [3], the event systems decomposition is based on extern shared variables and synchronized events. The main advantage of our technique is that it frees the user from the whole system design.

This paper is organised as follows. After giving preliminary notions, we define, in Section 2, the behavioural semantics of synchronized component-based systems. In Section 3, we define a refinement relation for these systems and explain our main compositionality result using for the compositional refinement verification. Then, in Section 4, we investigate how our approach is used in the context of a compositional safety property verification. Section 5 introduces a tool implementing the synchronized component refinement verification. Throughout this paper, we illustrate the use of our framework on an industrial example of a wind-screen wipers system. We end by some perspectives.

## 2 Synchronized Parallel Composition

In this section, we introduce interpreted labelled transition systems to specify and to model the behaviours of a component. We specify the synchronized behaviours of components by tuples of labels with feasibility conditions constraining activations of transitions with these labels. We provide a definition for a context-in component (i.e. a component in the context of the others). This definition is required to define the synchronized parallel composition of components under a synchronization.

Let  $Var = \{X_1, \dots, X_n\}$  be a finite set of variables with their respective domains  $\mathbb{D}_1, \dots, \mathbb{D}_n$ . Let  $AP$  be a set of atomic propositions  $ap \stackrel{\text{def}}{=} (X_i = v)$  with  $X_i \in Var$  and  $v \in \mathbb{D}_i$ . Let  $SP$  be a set of state propositions  $sp$  defined by following grammar:  $sp_1, sp_2 ::= ap \mid \neg sp_1 \mid sp_1 \vee sp_2$ .

**Definition 1 (Interpreted Labelled Transition System (LTS))**

A interpreted labelled transition system  $S$  over  $Var$  is a tuple  $\langle Q, Q_0, E, T, l \rangle$  where:

- $Q$  is a set of states,
- $Q_0 \subseteq Q$  is a set of initial states,
- $E$  is a finite set of transitions labels or actions,
- $T \subseteq Q \times E \times Q$  is a labelled transition relation, and
- $l : Q \rightarrow SP$  is an interpretation of each state on the system variables.

We define the sum of two transition systems over the same set of variables  $Var$ . Furthermore, we will show how to compute a parallel composition of synchronized components using this operator.

**Definition 2 (Sum of Two LTSs)**

Let  $S_1 = \langle Q_1, Q_{01}, E_1, T_1, l_1 \rangle$  and  $S_2 = \langle Q_2, Q_{02}, E_2, T_2, l_2 \rangle$  be two transition systems over  $Var$ . The sum of  $S_1$  and  $S_2$ , written  $S_1 \uplus S_2$ , is  $\langle Q_1 \cup Q_2, Q_{01} \cup Q_{02}, E_1 \cup E_2, T_1 \cup T_2, l_{12} \rangle$  where  $l_{12}$  is defined by:

$$l_{12}(q) = \begin{cases} l_1(q) & \text{if } q \in Q_1, \\ l_2(q) & \text{if } q \in Q_2, \end{cases}$$

Moreover,  $\forall q_1. q_1 \in Q_1, \forall q_2. q_2 \in Q_2. (l_1(q_1) = l_2(q_2) \Leftrightarrow q_1 = q_2)$ .

In order to define our synchronized parallel composition, we give the definition of a *synchronization* of  $n$  components. For that, we introduced a new transition label ‘-’ for the fictive action “skip”.

**Definition 3 (Synchronization of  $n$  Components)**

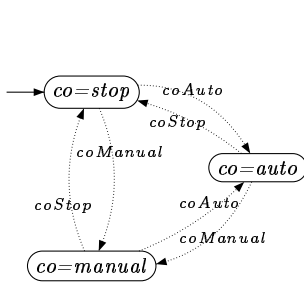
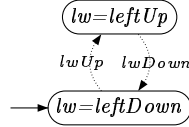
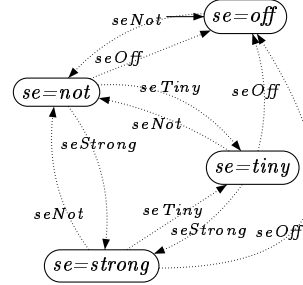
Let  $S_1, \dots, S_n$  be  $n$  components. A synchronization  $Synch$  is a set of elements ( $\alpha$  when  $p$ ) where:

- $\alpha = (e_1, \dots, e_n) \in \prod_{i=1}^n (E_i \cup \{-\})$ ,
- $p$  is a state proposition on the components variables.

To illustrate the previous definitions, we introduce the example of a car wind-screen wipers system. Consider the wipers system  $WS_A$  composed by a control lever,



a rain sensor and two (left and right) wind-screen wipers. The control lever  $CO_A$  can select the mode of the wiper system:  $co=manual$ ,  $co=auto$  or  $co=stop$ . Its behaviour is shown in Fig. 1. The left and the right wipers have the same behaviour. The transition system in Fig. 2 shows two positions for the left wiper  $LW_A$ :  $lw=leftUp$  or  $lw=leftDown$ . It is the same thing for the right wiper  $RW_A$ . The rain sensor  $SE_A$  can detect the rain amount ( $se=not$ ,  $se=tiny$  or  $se=strong$ ). Moreover, it can be off ( $se=off$ ) (see Fig. 3).

Figure 1:  $CO_A$ Figure 2:  $LW_A$ Figure 3:  $SE_A$ 

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(lwDown,rwDown) when ((co>manual) ^ (se=off)) v ((co=auto) ^ (se=tiny)) v ((co=auto) ^ (se=strong)),
(lwUp,rwUp) when ((co>manual) ^ (se=off)) v ((co=auto) ^ (se=tiny)) v ((co=auto) ^ (se=strong)),
coManual when (lw=leftDown) ^ (rw=rightDown) ^ (co=stop) ^ (se=off),
coStop when (lw=leftDown) ^ (rw=rightDown) ^ (co>manual) ^ (se=off),
seTiny when (co=auto) ^ (lw=leftDown) ^ (rw=rightDown) ^ (se!=off),
seStrong when (co=auto) ^ (lw=leftDown) ^ (rw=rightDown) ^ (se!=off),
seNot when (co=auto) ^ (lw=leftDown) ^ (rw=rightDown) ^ (se!=off),
(coManual, seOff) when (co=auto) ^ (lw=leftDown) ^ (rw=rightDown),
(coStop, seOff) when (co=auto) ^ (lw=leftDown) ^ (rw=rightDown),
(coAuto, seNot) when (se=off) ^ (lw=leftDown) ^ (rw=rightDown)

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Figure 4: Synchronization  $csw_A$ 

A synchronization  $csw_A$  is given to describe the authorized behaviours of the complete system  $WS_A$ . For example, the left and right wipers must move together ( $(lwDown,rwDown)$  and  $(lwUp,rwUp)$ ), the rain sensor sends information only if the control lever mode is *auto* ( $seTiny$ ,  $(seStrong)$  and  $seNot$ ), the control lever mode or the rain sensor can change only if the wipers are down ( $(coManual,seOff)$ ,  $(coAuto,seNot)$ ), etc.  $csw_A$  is given in Fig. 4. For readability reason the fictive transition label '-' is not shown in  $csw_A$ .

Each component  $S_1, \dots, S_n$  is a context-free component. However, to take synchronization into account, we need to define a context-in component, i.e. a component in the context of the others under a synchronization *Synch*.

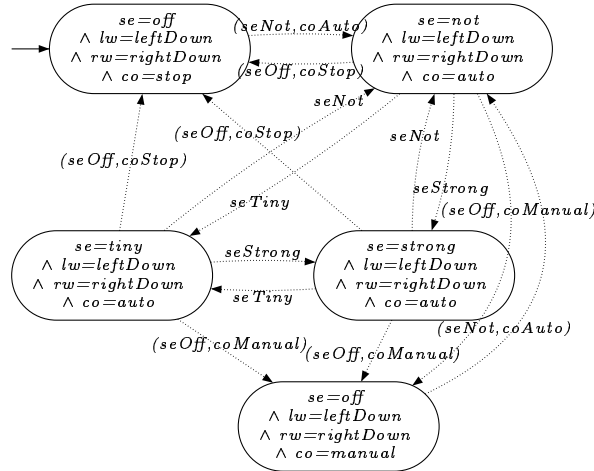
**Definition 4 (Context-in Component)**

Let  $S_1, \dots, S_n$  be  $n$  components. Let  $Synch$  be their synchronization. A context-in component  $S_i^c$  is defined by the tuple  $\langle Q_i^c, Q_{0i}^c, E_i^c, T_i^c, l_i^c \rangle$  where:

- $Q_i^c \subseteq Q_1 \times \dots \times Q_n$  with  $(q_1, \dots, q_n) \in Q_i^c$ ,
- $Q_{0i}^c \subseteq Q_{01} \times \dots \times Q_{0n}$ ,
- $E_i^c = \{(e_1, \dots, e_i, \dots, e_n) \mid ((e_1, \dots, e_i, \dots, e_n) \mathbf{when} p) \in Synch) \wedge (e_i \in E_i)\}$ ,
- $l_i^c((q_1, \dots, q_n)) = l_1(q_1) \wedge \dots \wedge l_n(q_n)$ ,
- $T_i^c \subseteq Q_i^c \times E_i^c \times Q_i^c$  with  
 $((q_1, \dots, q_n), (e_1, \dots, e_n), (q'_1, \dots, q'_n)) \in T_i^c$  iff:
  - $((e_1, \dots, e_n) \mathbf{when} p) \in Synch$ ,
  - $l_i^c((q_1, \dots, q_n)) \Rightarrow p$ , and
  - $\forall k. (k \in \{1, \dots, n\} \Rightarrow ((e_k = - \wedge q_k = q'_k) \vee (e_k \neq - \wedge (q_k, e_k, q'_k) \in T_k)))$ .

All context-in components have the same set of variables  $Var = \bigcup_{j=1}^n Var_j$ . Note that the graph representing a context-in component may be unconnected.

Figure 5 shows a representation of the context-in component  $SE_A^c$  that presents all behaviours of  $SE_A$  under  $csw_A$ . It is either simple behaviours ( $seNot$ ,  $seTiny$ ,  $seStrong$ ) or synchronized behaviours ( $(seOff, coManual)$ ,  $(seNot, coAuto)$ ). We have similar figures for the context-in components  $CO_A^c$ ,  $LW_A^c$  and  $RW_A^c$ . Remark

Figure 5:  $SE_A^c$

that  $RW_A^c$  and  $LW_A^c$  are identical. Indeed, all behaviours of  $LW_A$  and  $RW_A$  are synchronized ( $(lwDown, rwDown)$  and  $(lwUp, rwUp)$ ).

The whole system is a rearrangement of its separate parts, i.e., the components and their interactions. This arrangement is specified by a synchronized composition between components. We define a synchronized composition of  $n$  components  $S_1, \dots, S_n$  under a synchronization  $Synch$  by the sum of the  $n$  context-in components  $S_1^c, \dots, S_n^c$ .

**Definition 5 (Synchronized Composition of  $n$  Components)**

Let  $S_1, \dots, S_n$  be  $n$  components and  $Synch$  their synchronization. Let  $S_1^c, \dots, S_n^c$  be their respective context-in components. The synchronized parallel composition of  $S_1, \dots, S_n$  under  $Synch$  is defined by:

$$\parallel_{Synch}(S_1, \dots, S_n) \stackrel{def}{=} \uplus_{i=1}^n (S_i^c)$$

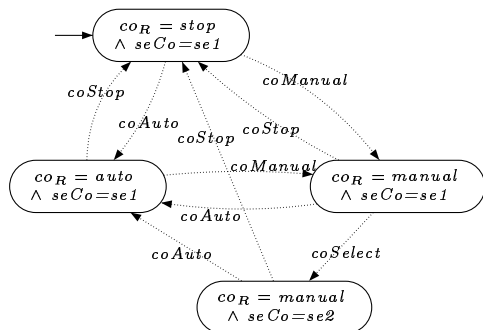
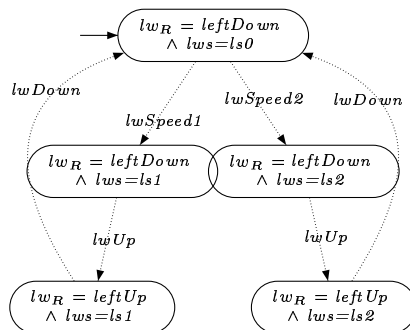
Notice that our parallel composition is more expressive than the classical synchronized product of transition systems. This is due to feasibility conditions, i.e., predicates over variables of the  $n$  components that constrain the composition. It is not a designer's task to write the context-in components nor their sum. As they can be automatically generated (thanks to Definitions 2 and 4), the designer only specifies the components and the synchronization.

Recall that the four context-in components have the same set of variables  $Var_A = \{co, lw, rw, se\}$ . The wipers system  $WS_A = \parallel_{csw_A}(CO_A, SE_A, LW_A, RW_A)$  equals to  $CO_A^c \uplus SE_A^c \uplus LW_A^c \uplus RW_A^c$ .

### 3 Synchronized Component-based Systems Refinement

In this section, we first recall the refinement semantics given in [8, 9] for classical one component transition systems. A refinement relation in the style of the Milner-Park simulation relation between abstract and concrete transition systems is given. Second, we want these semantics to fit with the synchronized component-based systems. For that we define a refinement relation between transition systems which is weaker than the refinement relation introduced in [8, 9]. Nevertheless, this weak refinement allows us to ensure the refinement of the whole system in a compositional way, unlike the refinement defined in [8, 9]. We begin by an example before giving formal definitions.

Consider a refinement of the wind-screen wipers system, still composed of four components:  $CO_R, SE_R, LW_R$  and  $RW_R$ . In  $CO_R$  the speed choice  $seCo$  is per-

Figure 6:  $CO_R$ Figure 7:  $LW_R$ 

formed in the manual mode:  $seCo=se1$  for speed 1 or  $seCo=se2$  for speed 2 (see Fig. 6). In both  $LW_R$  and  $RW_R$  the wind-screen wipers speed is taken into account. For  $LW_R$  a new variable  $lws$  (for left wiper speed) is introduced with  $\mathbb{D}(lws) = \{ls0, ls1, ls2\}$  for respectively, no speed, speed 1 or speed 2 (see Fig. 7). Idem for  $RW_A$ . In the abstract system  $SE_A$ , there are two rain levels. We observe in  $SE_R$  both limits of the tiny-rain level ( $se_R=maxTiny$ ) and the strong-rain level ( $se_R=minStrong$ ).

The authorized behaviours of the refined wipers system  $WS_R$  are described in the synchronization  $csw_R$ . We still have the old synchronized behaviours, i.e. left and right wipers must move together ( $(lwDown, rwDown)$  and  $(lwUp, rwUp)$ ), the control lever and the rain sensor change only if the wipers are down ( $coManual$ ,  $coStop$ ,  $seTiny$ ,  $seStrong$ ), etc. In addition, some of the new transitions are also synchronized. For example, the speed selection in the control lever manual mode can happen only if the wipers are down ( $coSelect$ ). The wipers change their speeds simultaneously ( $(lwSpeed1, rwSpeed1)$  and  $(lwSpeed2, rwSpeed2)$ ). In the control lever auto mode, the tiny-rain detection is synchronized with the level 1 of the wipers speeds ( $(seMaxTiny, lwSpeed1, rwSpeed1)$ ), and the strong-rain detection is synchronized with the level 2 of the wipers speeds ( $(seMinStrong, lwSpeed2, rwSpeed2)$ ).

### 3.1 Basic Transition Systems Refinement

Let  $SA = \langle Q_A, Q_{0A}, E_A, T_A, l_A \rangle$  be an abstract transition system over  $Var_A$  and  $SR = \langle Q_R, Q_{0R}, E_R, T_R, l_R \rangle$  a concrete transition system over  $Var_R$ . In this section, some basic definitions about transition systems refinement are given. The syntactic concepts of the refinement are the following. Refinement introduces new

transition labels, so  $E_A \subseteq E_R$ . Refinement introduces new variables and renames abstract ones, so  $Var_A \cap Var_R = \emptyset$ .

Let  $GI$  be a formula over  $SP_A \cup SP_R \cup SP'$  where  $SP_A$  is over  $Var_A$ ,  $SP_R$  is over  $Var_R$ , and  $SP' \stackrel{\text{def}}{=} \{X_A = X_R\}$  with  $X_A \in Var_A$  and  $X_R \in Var_R$  and  $\mathbb{D}(X_A) = \mathbb{D}(X_R)$ .  $GI$  is commonly known as a gluing invariant linking variables of the abstract and concrete systems. A binary relation  $\mu \subseteq Q_R \times Q_A$  allows us to express this link between the states of two transition systems [8, 9].

### Definition 6 (Gluing Relation)

Let  $GI$  be a gluing invariant between  $SR$  and  $SA$ . The states  $q_R \in Q_R$  and  $q_A \in Q_A$  are glued, written  $q_R \mu q_A$ , iff  $l_R(q_R) \wedge GI \Rightarrow l_A(q_A)$ .

$$\begin{aligned} & ((co=manual) \Leftrightarrow (co_R=manual)) \wedge ((co=stop) \Leftrightarrow ((co_R=stop) \wedge (seCo=se1))) \\ & \wedge ((co=auto) \Leftrightarrow ((co_R=auto) \wedge (seCo=se1))) \wedge (se=off) \Leftrightarrow (se_R=off) \\ & \wedge ((se=not) \Leftrightarrow (se_R=not)) \wedge ((se=strong) \Leftrightarrow ((se_R=strong) \vee (se_R=minStrong))) \\ & \wedge ((se=tiny) \Leftrightarrow ((se_R=tiny) \vee (se_R=maxTiny))) \wedge ((lw=leftDown) \Leftrightarrow (lw_R=leftDown)) \\ & \wedge ((lw=leftUp) \Leftrightarrow ((lw_R=leftUp) \wedge (lws \neq ls0))) \wedge ((rw=rightDown) \Leftrightarrow (rw_R=rightDown)) \\ & \wedge ((rw=rightUp) \Leftrightarrow ((rw_R=rightUp) \wedge (rws \neq rs0))) \end{aligned}$$

Figure 8: Gluing invariant  $GI_W$

The gluing invariant  $GI_W$  linking variables of the refined system  $WS_R$  and the abstract system  $WS_A$  is given in Fig. 8. The abstract variable  $co$  from  $CO_A$  is linked with the concrete variables  $co_R$  and  $seCo$ . If  $co=manual$  then  $co_R=manual$ , if  $co=stop$  then  $co_R=stop$  and  $seCo=se1$ , and if  $co=auto$  then  $co_R=auto$  and  $seCo=se1$ . We have the same kind of links between the variables of  $SE_A$ ,  $LW_A$ ,  $RW_A$  and respectively,  $SE_R$ ,  $LW_R$ ,  $RW_R$ .

The semantic concepts of the refinement are the following.

1. In order to describe the refinement, we keep the transitions of  $S_R$ , the labels of which are in  $E_A$  (i.e. labelled by the "old" labels) and we consider the new transitions introduced during the refinement design (i.e. labelled in  $E_R \setminus E_A$ ) as being non-observable; they are labelled by  $\tau$  and called  $\tau$ -transitions. Each portion of path containing  $\tau$ -transitions must end by a transition labelled in  $E_A$ . Therefore, the transition refinement is either a strict refinement or a stuttering refinement (see Fig. 9).
2. In order to avoid livelocks, new transitions should not take control forever. So, the paths containing infinite sequences of  $\tau$ -transitions are forbidden.
3. Moreover, new transitions should not introduce deadlocks.

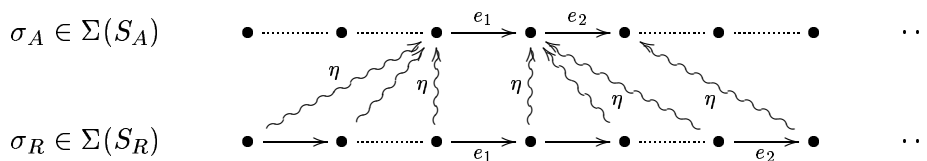


Figure 9: Path refinement

The refinement relation  $\eta$  is defined in [8, 9] as a restriction of  $\mu$  that verifies the previous concepts.

**Definition 7 (Strict Refinement Relation [8, 9])**

Let  $SA$  and  $SR$  be two transition systems, and  $e$  be a label from  $E_A$ . We define the refinement relation  $\eta$  as the greatest binary relation included into  $\mu$  and satisfying the following conditions:

**1) strict transition refinement**

$$(q_R \eta q_A \wedge q_R \xrightarrow{e} q'_R \in T_R) \Rightarrow \exists q'_A. (q_A \xrightarrow{e} q'_A \in T_A \wedge q'_R \eta q'_A),$$

**2) stuttering transition refinement**

$$(q_R \eta q_A \wedge q_R \xrightarrow{\tau} q'_R \in T_R) \Rightarrow (q'_R \eta q_A),$$

**3) lack of new deadlocks**

$$(q_R \eta q_A \wedge q_R \nrightarrow_R) \Rightarrow (q_A \nrightarrow_A)^1,$$

**4) lack of  $\tau$ -divergence**

$$q_R \eta q_A \Rightarrow \neg (q_R \xrightarrow{\tau} q'_R \xrightarrow{\tau} q''_R \xrightarrow{\tau} \dots \xrightarrow{\tau} \dots),$$

**5) external non-determinism preservation**

$$(q_A \xrightarrow{e} q'_A \in T_A \wedge q_R \eta q_A) \Rightarrow \exists q'_R, q''_R, q''_A. (q'_R \eta q_A \wedge q'_R \xrightarrow{e} q''_R \in T_R \wedge q_A \xrightarrow{e} q''_A \in T_A \wedge q''_R \eta q''_A).$$

We say that  $SR$  refines  $SA$ , written  $SR \sqsubseteq SA$ , when the conditions above are verified between the states of  $SR$  and  $SA$  i.e.  $SR \sqsubseteq SA \Leftrightarrow \forall q_R. (q_R \in Q_R \Rightarrow \exists q_A. (q_A \in Q_A \wedge q_R \eta q_A))$ .

It has been shown in [8] that  $\eta$  is a kind of  $\tau$ -simulation. It is well-known that a simulation can be computed iteratively for finite state systems. We have an algorithm based on a depth-first search enumeration of the reachability graph of the refined system. Its order is  $O(|SR|)$  where  $|SR| = |Q_R| + |T_R|$ .

<sup>1</sup>We note  $q \nrightarrow$  when  $\forall q', e. (q' \in Q \wedge e \in E \Rightarrow (q \xrightarrow{e} q') \notin T)$ .

### 3.2 Compositional Component-based Systems Refinement

In this section, the refinement semantics is fitted with synchronized component-based systems. We define a refinement relation weaker than the refinement relation presented in Section 3.1, and we clarify how  $\tau$  covers the new transition labels. Then we give a compositionality theorem allowing us to compositionally ensure the refinement of the whole system from the refinement of its components.

We have shown in [21] that  $\eta$  is too strong to verify a component-based systems refinement. The problem is that some new deadlocks in the context-in components, could cause the refinement verification of a context-in component to fail whereas the refinement of the whole system is verified. That is why, we introduce another relation, called the weak refinement relation and written  $\eta_f$ . This relation is fitted to ensure the refinement verification in this case. The relation  $\eta_f$  uses the set  $D \subseteq Q_R$  of new deadlocks which is built during the refined system exploration.

#### Definition 8 (Weak Refinement Relation)

Let  $SA$  and  $SR$  be two transition systems, and  $e$  be a label from  $E_A$ . Let  $D \subseteq Q_R$  (Initially  $D = \emptyset$ ) be the set of new deadlocks. We define the weak refinement relation  $\eta_f$  as the greatest binary relation included into  $\mu$  and satisfying the conditions **1**), **2**), **4**) and **5**) of Definition 7 and the following condition:

#### **3')** old or new deadlocks

$$(q_R \eta_f q_A \wedge q_R \nrightarrow_R) \Rightarrow ((q_A \nrightarrow_A) \vee ((q_A \xrightarrow{e} q'_A \in T_A) \Rightarrow (q_R \in D))).$$

We say that  $SR$  weakly refines  $SA$ , written  $SR \sqsubseteq_D SA$ , when the conditions above are verified between the states of  $SR$  and  $SA$  i.e.  $SR \sqsubseteq_D SA \Leftrightarrow \forall q_R. (q_R \in Q_R \Rightarrow \exists q_A. (q_A \in Q_A \wedge q_R \eta_f q_A))$ .

The relation  $\eta_f$  can be computed by an iterative algorithm with a complexity order in  $O(|SR|)$  too. It is easy to see that the strict refinement relation  $\eta$  implies the weak refinement relation  $\eta_f$  when  $D = \emptyset$ , and vice versa. Indeed, condition **3')** of Definition 8 is verified for the old deadlocks, so  $D$  remains empty.

#### Property 1

Let  $SA$  and  $SR$  be two transition systems. Let  $D \subseteq Q_R$  be the set of new deadlocks. We have  $(SR \sqsubseteq SA) \Leftrightarrow (SR \sqsubseteq_D SA \wedge D = \emptyset)$ .

We have to clarify how  $\tau$  covers new transition labels when we deal with synchronized component-based systems. Indeed, we want to avoid the refinement verification failure when an old transition and a new one are synchronized. The problem is then to decide whether this synchronized transition has to be covered by  $\tau$  or not.

Our approach is the following. On the one hand, the old transition label must be saved if it is a label of the component being considered. On the other hand, the transition must be kept out if its label is not a label of the considered component. We define a context-in  $\tau$ -component to be a context-in component covered by  $\tau$ . The first step of Definition 9 deletes some transitions and their labels, and the second step covers by  $\tau$  the remaining transition labels.

**Definition 9 (Context-in  $\tau$ -component)**

Let  $SA_1, SA_2, SR_1$  and  $SR_2$  be four components. Let  $SR_1^c$  be a context-in component. The context-in  $\tau$ -component  $SR_1^\tau$  is the tuple  $\langle Q_{R1}^\tau, Q_{R01}^\tau, E_{R1}^\tau, T_{R1}^\tau, l_{R1}^\tau \rangle$  where:

- $Q_{R1}^\tau = Q_{R1}^c$ ,
- $Q_{R01}^\tau = Q_{R01}^c$ ,
- $l_{R1}^\tau((q_1, q_2)) = l_{R1}^c((q_1, q_2))$ ,
- $T_{R1}^\tau = T_{R1}^c \setminus \{((q_1, q_2), (e_1, e_2), (q'_1, q'_2)) \mid ((q_1, q_2), (e_1, e_2), (q'_1, q'_2)) \in T_{R1}^c \wedge e_1 \in E_{R1} \setminus E_{A1} \wedge e_2 \in E_{A2}\}$ ,
- $E_{R1}^\tau = E_{R1}^c \setminus \{(e_1, e_2) \mid (e_1, e_2) \in E_{R1}^c \wedge e_1 \in E_{R1} \setminus E_{A1} \wedge e_2 \in E_{A2}\}$ .

Then, the elements of  $E_{R1}^\tau$  are covered as follows<sup>2</sup>:

- if  $(e_1, -) \in E_{R1}^\tau$  and  $e_1 \in E_{R1} \setminus E_{A1}$  then  $(e_1, -) \setminus \tau$ ,
- if  $(e_1, e_2) \in E_{R1}^\tau$ ,  $e_1 \in E_{R1} \setminus E_{A1}$  and  $e_2 \in E_{R2} \setminus E_{A2}$  then  $(e_1, e_2) \setminus \tau$ ,
- if  $(e_1, e_2) \in E_{R1}^\tau$ ,  $e_1 \in E_{A1}$  and  $e_2 \in E_{R2} \setminus E_{A2}$  then  $(e_1, e_2) \setminus (e_1, -)$ .

Our first result is a compositional refinement verification theorem. This theorem links the separate context-in components weak refinements with the component-based system refinement. It is based on deadlocks reduction. A state inducing a new deadlock in a component does not induce a deadlock in the whole system if there exists another component in which this state is not a deadlock state.

**Definition 10 (New Deadlocks Reduction)**

Let  $SA_1, SA_2, SR_1$  and  $SR_2$  be four components such that  $SR_1^\tau \sqsubseteq_{D_1} SA_1^c$  and  $SR_2^\tau \sqsubseteq_{D_2} SA_2^c$ . Let  $Synch$  and  $Synch'$  be two respective synchronizations. The set  $D_{1,2} \subseteq Q_{R1}^\tau \cup Q_{R2}^\tau$  of states producing new deadlocks during the weak refinement of  $SR_1 \parallel_{Synch'} SR_2$  is defined by:

$$D_{1,2} \stackrel{def}{=} (D_1 \cap D_2) \cup (D_1 \setminus Q_{R2}^\tau) \cup (D_2 \setminus Q_{R1}^\tau)$$

We can compute the set  $D_{1,\dots,n}$  containing the new deadlocks during the weak refinement verification of  $\parallel_{Synch'}(SR_1, \dots, SR_n)$ . It is an associative computation:

---

<sup>2</sup>We note  $e_1 \setminus e_2$  the relabelling of  $e_1$  by  $e_2$ .



$D_{1,\dots,n} = D_{(1,\dots,n-1),n} = D_{1,(2,\dots,n)}$ . Then, *Property 1* allows us to decide the strict refinement of the whole system.

**Theorem 1 (Refinement of a Synchronized Component-based System)**

Let  $SA_1, \dots, SA_n$ , and  $SR_1, \dots, SR_n$  be  $n$  abstract and refined components. Let  $Synch$  and  $Synch'$  be two respective synchronizations.

$$\begin{aligned} \|_{Synch'}(SR_1, \dots, SR_n) \sqsubseteq \|_{Synch}(SA_1, \dots, SA_n) \text{ iff} \\ - \forall i. 1 \leq i \leq n \Rightarrow SR_i^r \sqsubseteq_{D_i} SA_i^c \\ - D_{1,\dots,n} = \emptyset \end{aligned}$$

A proof is given in [19].

This theorem provides a compositional refinement verification algorithm. This algorithm is based on the computation of the relation  $\eta_f$  for each context-in component  $SR_i^r$  which complexity order is  $O(|SR_i^r|)$ . The complexity of this refinement algorithm is  $O(|SR_1^r| + \dots + |SR_n^r|)$  but it can be iteratively computed. The greatest memory space used by this algorithm computation is  $\max_{i=1}^n(|SR_i^r|)$ , at most.

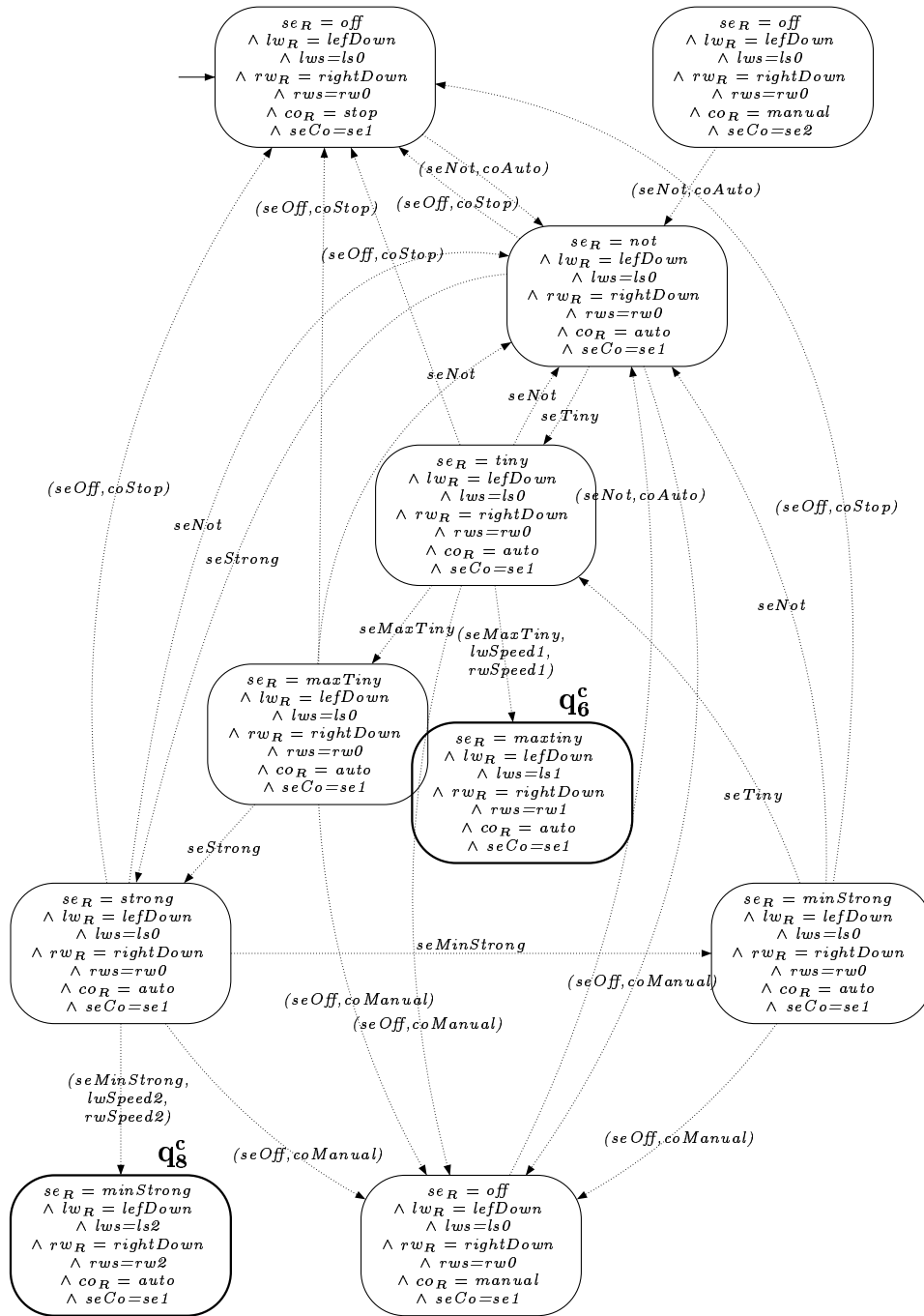
For our example, we built the refined context-in components. Figure 10 shows the refined context-in component  $SE_R^c$ . This context-in component only describes behaviours of  $SE_R$  under  $csw_R$  that are either old transitions (*seNot*, *seTiny*, *seStrong* or (*seOff*, *coStop*), (*seNot*, *coAuto*)) or new transitions (*seMaxTiny*, *seMinStrong* or (*seMaxTiny*, *lwSpeed1*, *rwSpeed1*), (*seMinStrong*, *lwSpeed2*, *rwSpeed2*)).

By Definition 5, we have  $WS_R = CO_R^c \uplus SE_R^c \uplus LW_R^c \uplus RW_R^c$  over the set of variables  $Var_R = \{co_R, seCo, lw_R, lws, rw_R, rws, se_R\}$ . The weak refinement is verified for each context-in component. We have  $SE_R^c \sqsubseteq_{D_{SE}} SE_A^c$  where the set  $D_{SE}$  contains two new deadlocks  $q_6^c$  and  $q_8^c$  (see Fig. 10). By Definition 10, we reduce  $D_{SE}$  and we show that  $D_{CO,SE,LW,RW}$  is empty. By Theorem 1, we conclude that the wipers system  $WS_R$  refines  $WS_A$ .

The refinement relation provides a formal framework for verifying system properties. When the refinement is verified, most properties that have been verified on the abstract system are preserved on the refined one.

## 4 Compositional Property Verification

In this section, we propose a method to verify a class of safety properties on synchronized component-based systems. These properties can be expressed as the unreachability of a set of states. If this set is not reachable in the abstract system, then the


 Figure 10:  $SE_R^c$

refinement relation ensures the unreachability of the corresponding set in the refined system.

Since we introduce new details in the refinement, the abstract system is usually small in number of states while the refined system is likely to be very large. We want to exploit the refinement approach enriched by a component paradigm. It allows us to avoid the model-checking blow-up by verifying safety properties in a compositional way.

The method we propose here is based on Definition 5. The idea is to verify the reachability among the context-in components  $S_i^c$  instead of exploring the whole system  $\parallel_{Synch}(S_1, \dots, S_n)$ . Actually, the state space and the transition relation of a context-in component are less important than the entire system ones. We reduce the number of possible behaviours during the system exploration, and, consequently, we postpone the state space explosion problem.

Let  $\parallel_{Synch}(S_1, \dots, S_n)$  be a synchronized parallel composition under *Synch*. The reachability problem for  $\parallel_{Synch}(S_1, \dots, S_n)$  is the following decision problem.

**Input:**  $n$  context-in components  $S_1^c, \dots, S_n^c$  and a target state  $q_t^c$  s.t.  $q_t^c \in \bigcup_{i=1}^n Q_i^c$ .  
**Reachability problem (RP):** Determine whether  $q_t^c$  is in  $\{q^c \mid q^c \in \bigcup_{i=1}^n Q_i^c \wedge \exists q_0^c. (q_0^c \in \bigcup_{i=1}^n Q_{0i}^c \wedge \exists w. (w \in (\bigcup_{i=1}^n E_i^c)^* \wedge (q_0^c, w, q^c) \in (\bigcup_{i=1}^n T_i^c)^*))\}$ , where  $(\bigcup_{i=1}^n T_i^c)^*$  is the reflexive and transitive closure of the transition relation  $\bigcup_{i=1}^n T_i^c$ .

### Theorem 2 (RP for a Synchronized Component-based System)

There exists an algorithm to decide the reachability problem for a synchronized component-based system  $\parallel_{Synch}(S_1, \dots, S_n)$  whose complexity order is in  $O(|S_1^c| + \dots + |S_n^c|)$ .

In practice, to verify the reachability of a target state  $q_t^c$  in a context-in component, we apply the backward-reachability analysis from  $q_t^c$ . During this exploration, the set  $Q_D$  of the deadlock states is built. If no initial state is reachable, we choose another context-in component, and, often, a new target state among the deadlock states (in  $Q_D$ ), in order to continue the reachability analysis from this state. We can choose a new target, since the state  $q_t^c$  is reachable from this new state. We stop when either an initial state  $q_0^c \in \bigcup_{i=1}^n Q_{0i}^c$  is reached or exploration of all possible choices is already done.

The verification algorithm below formally presents the compositional reachability analysis.

**Algorithm 1 (Compositional Reachability)**

```

1  Input                                     23
2   $(Q_0^c = \bigcup_{i=1}^n Q_{0i}^c)$  (*Initial state space*) 24
3   $q_i^c \in \bigcup_{i=1}^n Q_{0i}^c$  (*Target state*) 25
4   $CI \subseteq \{S_1^c, \dots, S_n^c\}$  (*A set of context-in compo-ts*) 26
5  Result                                     27
6   $reach: boolean$  (*true if  $q_i^c$  is reachable*) 28
7  Variables                                   29
8   $Q_D^c, Q_{ND}^c, Q_{suc}^c, Q_{pre}^c \subseteq \bigcup_{i=1}^n Q_{0i}^c$  30
9   $S_i^c \in CI$                                   31
10  $(q_i^c \in \bigcup_{i=1}^n Q_{0i}^c)$                        32
11  $tested \subseteq \bigcup_{i=1}^n Q_{0i}^c \times \{S_1^c, \dots, S_n^c\}$  33
12  $end, possible, deadlock: boolean$            34
13 Begin                                       35
14  $Q_D^c := \{q_i^c\}$                              36
15  $end := false$                                  37
16  $reach := false$                                38
17 WHILE ( $end = false$ ) DO                   39
18   Choice ( $Q_D^c, CI, tested, possible, q_i^c, S_i^c$ ) 40
19   IF ( $possible = false$ ) DO                 41
20      $end := true$                                42
21   ELSE                                       42
22      $tested := tested \cup \{(q_i^c, S_i^c)\}$  43
23      $deadlock := false$                          24
24      $Q_{suc}^c := \{q_i^c\}$                        25
25      $Q_{pre}^c := \{\}$                            26
26     WHILE ( $deadlock = false$ ) DO           27
27       Predecessors ( $Q_{suc}^c, S_i^c, Q_{pre}^c, Q_{ND}^c$ ) 28
28        $Q_D^c := Q_D^c \cup Q_{ND}^c$                  29
29       IF ( $Q_{pre}^c = \{\}$ ) DO                 30
30          $deadlock := true$                        31
31       ELSE                                    32
32         IF ( $Q_0^c \cap Q_{pre}^c \neq \{\}$ ) DO     33
33            $deadlock := true$                      34
34         end := true                             35
35          $reach := true$                            36
36       ELSE                                    37
37          $Q_{suc}^c := Q_{pre}^c$                      38
38       FI                                       39
39     FI                                       40
40   ENDWHILE                                   41
41 FI                                       42
42 ENDWHILE                                   42
43 End                                       43

```

This algorithm uses the following procedures.

- Predecessors(Input:  $Q_{suc}^c, S_i^c$ , Output:  $Q_{pre}^c, Q_{ND}^c$ ),
- Choice(Input:  $Q_D^c, CI, tested, possible, q_i^c, S_i^c$ ).

The first procedure computes  $Q_{pre}^c$  in  $S_i^c$ , i.e., the set of predecessors of  $Q_{suc}^c$ . The states in  $Q_{suc}^c$  without predecessors are put in a set  $Q_{ND}^c$  of new deadlocks. Formally we have  $Q_{pre}^c \stackrel{\text{def}}{=} \{q^c \mid (q^c, \alpha, q^{c'}) \in T_i^c \wedge q^{c'} \in Q_{suc}^c\}$ . The second procedure chooses, among both states in  $Q_D^c$  and context-in components in  $CI$ , the most convenient and not tested yet pair  $(q_i^c, S_i^c)$ . To be efficient, this choice has to be based on some heuristics. For example, the strong dependency analysis of [22] between components can be used for an efficient reachability analysis of their synchronized composition.

This compositional reachability algorithm becomes very interesting when combined with the refinement verification approach. Indeed, all the components in the context are computed during the refinement verification.

**Theorem 3 (Correctness of Algorithm 1)**

Algorithm 1 eventually terminates and indicates whether the target state is reachable ( $reach = true$ ) or not ( $reach = false$ ).

*Proof idea.* The computation in the loop **WHILE** ( $deadlock = false$ ) (lines 26-42) stops. The predecessors computation stops either when an initial state is reached (line 33), or when there are no predecessors (line 30). The computation of the loop **WHILE** ( $end = false$ ) (lines 17-42) eventually terminates. The variable  $end$  becomes  $true$  since either an initial state is reached (line 34), or there is no other choice for a pair of a context-in component and a deadlock state (line 20). The only

possibility to have the variable *reach* equal to *true* (line 35) is to reach an initial state.

For our running wind-screen wipers example, we want some states to be forbidden. For instance, states where the wipers system can move only one of the wind-screen wipers, must be unreachable. Then we exploit the refinement to ensure this property for the refined system.

Consider  $q_t^c$ , a state such that  $l(q_t^c) \stackrel{\text{def}}{=} (lw = \text{leftDown} \wedge rw = \text{rightUp} \wedge co = \text{manual} \wedge se = \text{off})$ . We want to ensure the unreachability of the state  $q_E^c$ , written  $\square(\neg q_t^c)$  in *PLTL*. By Algorithm 1, it is possible to show that  $q_t^c$  is not reachable in the abstract system  $WS_A$ . As the system  $WS_R$  refines the system  $WS_A$  (as explained in Section 3), the refined system states corresponding to  $q_t^c$  by the gluing invariant  $GI_W$  are unreachable too.

## 5 *SynCo*: a Tool Verifying the Synchronized Component-based Systems Refinement

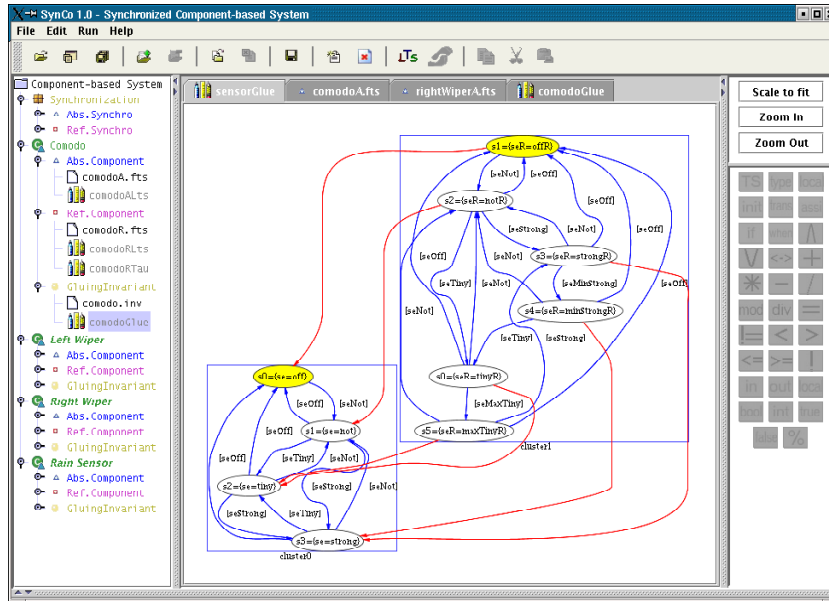


Figure 11: The tool *SynCo*

Theorem 1 in Section 3 gives the required conditions to ensure the strict refinement of a whole system from the weak refinements of its synchronized components, and vice versa. This way, we have an algorithm to verify the strict refinement of a synchronized component-based system. The most important advantage of this refinement verification is that it is not necessary to build the whole system to verify the refinement.

```

Transition System
type CONTROLR = {stopR, autoR, manualR}
type SELECTR = {se1, se2}
local coR : CONTROLR
local seCo : SELECT
Initially (coR = stopR)  $\wedge$  (seCo = se1)
Transition coStop :
enable (coR != stopR) ;
assign coR := stopR, seCo := se1
Transition coAuto :
enable (coR != autoR) ;
assign coR := autoR, seCo := se1
Transition coManual :
enable (coR = stopR)  $\vee$  (coR = autoR) ;
assign coR := manualR, seCo := se1
Transition coSelect :
enable (coR = manualR)  $\wedge$  (seCo = se1) ;
assign seCo := se2

```

Figure 12:  $CO_R$  in STeP

We are developing *SynCo* (for *Synchronized Component-based System Analyser*)<sup>3</sup>; a tool implementing with Java the synchronized component refinement verification (Figure 11 show a capture of its interface). We specify the components as transition systems using the STeP's Fair Transition Systems syntax [23, 10]. Each transition is specified with its activation condition (**enable**) and its assignments (**assign**). Figure 12 gives the STeP specification of the component  $CO_R$ .

The context-in components are built automatically from both STeP and synchronization specifications. Each component or each context-in component can be visualised as an automaton using the Java package *Grappa* from the toolkit *Graphviz*<sup>4</sup>.

Theorem 1 is implemented in *SynCo* to verify the refinement of a synchronized component-based system. We compute the relation  $\eta_f$  for each context-in  $\tau$ -component using a kind of depth-first search enumeration of the reachability graph of this context-in  $\tau$ -component. Then, we conclude about the refinement of the whole system. Figure 11 shows the relation  $\eta_f$  between a refined component and an abstract component.

The refinement verification of a simple system can be done with *SynCo* too. We assume that the simple system is the one component of a synchronized component-based system. Obviously, the new deadlocks set is empty by Property 1.

With this tool the refinement verification of the wind-screen wipers system and of an industrial robot has been done. Thanks to *SynCo* we can measure the efficiency of our method. Tables 13 and 14 give the results of our tests. For the wind-screen wipers system  $WS_R$  both the states and the transitions are decreased by a third between the whole system and the greatest context-in component (see Fig. 13). We

<sup>3</sup>*SynCo* home page: <http://lifc.univ-fcomte.fr/~lanoix/synco.html>

<sup>4</sup>Graphviz official page: <http://www.research.att.com/sw/tools/graphviz>

	$CO_R^c$	$SE_R^c$	$LW_R^c$	$RW_R^c$	$WS_R$
$ Q_R $	8	10	18	18	20
$ T_R $	17	25	20	20	47
$ SR $	25	35	38	38	67

Figure 13: The wipers system

	$CL_R^c$	$LI_R^c$	$HA_R^c$	$RO_R$
$ Q_R $	19	13	19	25
$ T_R $	21	13	20	40
$ SR $	40	26	39	65

Figure 14: The robot

have similar results in Fig. 14 for the industrial robot  $RO_R$  moving pieces thanks to a clip  $CL_R$ , a handle  $HA_R$  and a lift  $LI_R$ . We plan to test *SynCo* on more complex examples.

## 6 Conclusion and Perspectives

Compositional design and refinement paradigms are very convenient to specify and to verify large embedded reactive systems such as automatic trains, car driving assistance systems or communication protocols. In this paper, we propose a technique to take advantages of both paradigms. This technique is based on a specific notion of refinement relation defined in the style of Milner-Park simulation relation between concrete and abstract finite transition systems.

The contributions of this paper are the following. On the one hand, we want the refinement paradigm to be compatible with the compositional specification. For that, we propose a new compositional specification method that allows us to ensure the refinement of the whole system from the refinement of its context-in components, and vice versa. Although context-in components seem comparable with the whole system, they are generally smaller than the whole system. On the other hand, we want to avoid the model-checking blow-up by verifying a class of safety properties in a compositional way. For that, we give an algorithm to ensure the unreachability of a set of states of a synchronized component-based system. Moreover, this algorithm is very interesting when combined with the compositional refinement verification algorithm.

A tool that implements the compositional refinement verification has been implemented in Java. This tool, *SynCo*, allows us to measure the efficiency of our approach, and to test it to real industrial examples. We are currently working on extending this tool to incorporate the compositional reachability algorithm. In addition, we are going to use the strong dependency analysis of [22] as heuristics to efficiently choose a pair  $(q_i^c, S_i^c)$ . As far as we know, other compositional tools also implement a reachability compositional verification (see for instance [15, 22]). How-

ever, they were designed for a very different purpose than *SynCo* and, thus, do not implement compositional refinement verification.

One of the consequences of the composition theorem in [25] is the limitation of the compositional verification. It has been shown that the composition theorem fails for very simple parallel operators if there is a property expressing that "there is a path such that all the nodes of the path have a property  $p$ ". Moreover, we have established in [14] that the strict refinement relation preserves the abstract system *PLTL* properties, i.e. safety and liveness properties because of Conditions 3) and 4) of Definition 7. This preservation partially avoids the combinatorial explosion problem. Indeed, a property proof on an abstract system can be reused as a hypothesis for its verification on the refined system. That is why we are interested in a compositional verification of *PLTL* properties.

More generally, we are going to use the works on property preservation [14], modular verification [24, 17], and dynamic property refinement [6, 7] in the framework of the component-based system specification and refinement presented in this paper. We hope this will allow us to verify a large spectrum of properties in a compositional way.

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## A Proof of Theorem 1

We prove that  $SR_1 \parallel_{Synchron_R} SR_2 \sqsubseteq SA_1 \parallel_{Synchron_A} SA_2 \quad [R]$  iff  $\begin{cases} SR_1^T \sqsubseteq_{D_1} SA_1^c, & [a] \\ SR_2^T \sqsubseteq_{D_2} SA_2^c, & [b] \\ D_{12} = \emptyset. & [c] \end{cases}$

It can be extended to  $n$  components.

For that, we show that items [a], [b] and [c] imply [R] (see Section A.1). Then, we show that [R] implies [a], [b] and [c] (see Section A.2).

Let  $Q_R^c$  be the state set of  $SR_1 \parallel_{Synchron_R} SR_2$ , and  $Q_A^c$  the state set of  $SA_1 \parallel_{Synchron_A} SA_2$ . By Definition 2, we have  $Q_R^c = Q_{R1}^c \cup Q_{R2}^c$  and  $Q_A^c = Q_{A1}^c \cup Q_{A2}^c$ .

### A.1 $[a] \wedge [b] \wedge [c] \Rightarrow [R]$

Let  $M \stackrel{\text{def}}{=} \{(q_R^c, q_A^c) \mid ((q_R^c \in Q_{R1}^c \wedge q_A^c \in Q_{A1}^c) \vee (q_R^c \in Q_{R2}^c \wedge q_A^c \in Q_{A2}^c)) \wedge q_R^c \eta_f q_A^c\}$ .

We show that  $M$  verifies the conditions of the refinement relation  $\eta$  (Definition 7) using Lemmas 1, 2, 3, 4 and 5.

By [c] we have  $D_{12} = \emptyset$ . As  $D_{12} = (D_1 \cap D_2) \cup (D_1 \setminus Q_{R2}^c) \cup (D_2 \setminus Q_{R1}^c)$  (Definition 10), we have [c'] :  $(D_1 \cap D_2 = \emptyset) \wedge (D_1 \setminus Q_{R2}^c = \emptyset) \wedge (D_2 \setminus Q_{R1}^c = \emptyset)$ .

### Lemma 1 (Strict Transition Refinement Condition)

Assume that  $q_R^c \xrightarrow{\alpha} q_R^{c'}$  and  $\alpha \in E_{R1}^c \cup E_{R2}^c$ ; we must prove that there exists  $q_A^{c'}$  such that  $q_A^c \xrightarrow{\alpha} q_A^{c'}$  and  $q_R^{c'} \eta q_A^{c'}$ .

*Proof on the form of  $\alpha$ . There are three cases.*

-  $\alpha = (e_1, -)$ . By Definition 4, we have  $(q_R^c, (e_1, -), q_R^{c'}) \in T_{R1}^c$ ,  $q_R^c \in Q_{R1}^c$  and  $q_R^{c'} \in Q_{R1}^c$ . Since  $SR_1^T \sqsubseteq SA_1^c$ , we obtain that there exists  $q_A^c$  such that  $q_A^c \in Q_{A1}^c$  and  $q_R^c \eta q_A^c$ . By condition 1 for  $SR_1^T \sqsubseteq SA_1^c$ , there exists  $q_A^{c'}$  such that  $q_A^{c'} \in Q_{A1}^c$ ,  $q_A^c \xrightarrow{(e_1, -)} q_A^{c'}$  and  $q_R^{c'} \eta q_A^{c'}$ . The states  $q_A^c$  and  $q_A^{c'}$  belong to  $Q_A^c$  because of  $Q_A^c = Q_{A1}^c \cup Q_{A2}^c$ .

-  $\alpha = (-, e_2)$ . By Definition 4, we have  $(q_R^c, (-, e_2), q_R^{c'}) \in T_{R2}^c$ ,  $q_R^c \in Q_{R2}^c$  and  $q_R^{c'} \in Q_{R2}^c$ . Since  $SR_2^T \sqsubseteq SA_2^c$ , we obtain that there exists  $q_A^c$  such that  $q_A^c \in Q_{A2}^c$  and  $q_R^c \eta q_A^c$ . By condition 1 for  $SR_2^T \sqsubseteq SA_2^c$ , there exists  $q_A^{c'}$  such that  $q_A^{c'} \in Q_{A2}^c$ ,  $q_A^c \xrightarrow{(-, e_2)} q_A^{c'}$  and  $q_R^{c'} \eta q_A^{c'}$ . The states  $q_A^c$  and  $q_A^{c'}$  belong to  $Q_A^c$  because of  $Q_A^c = Q_{A1}^c \cup Q_{A2}^c$ .

-  $\alpha = (e_1, e_2)$ . By Definition 4, we have  $(q_R^c, (e_1, e_2), q_R^{c'}) \in T_{R1}^c$ ,  $q_R^c \in Q_{R1}^c$  and  $q_R^{c'} \in Q_{R1}^c$ . Since  $SR_1^T \sqsubseteq SA_1^c$ , we obtain that there exists  $q_A^c$  such that  $q_A^c \in Q_{A1}^c$

and  $q_R^c \eta q_A^c$ . By condition 1 for  $SR_1^r \sqsubseteq SA_1^c$ , there exists  $q_A^{c'}$  such that  $q_A^{c'} \in Q_{A1}^c$ ,  $q_A^c \xrightarrow{(e_1, -)} q_A^{c'}$  and  $q_R^c \eta q_A^{c'}$ . The states  $q_A^c$  and  $q_A^{c'}$  belong to  $Q_A^c$  because of  $Q_A^c = Q_{A1}^c \cup Q_{A2}^c$ .

**Lemma 2 (Stuttering Transition Refinement Condition)**

Assume that  $q_R^c \xrightarrow{\tau} q_R^{c'}$ ; we must show that  $q_R^c \eta q_A^c$ .

*Proof on the form of labels covered by  $\tau$ . There are three cases.*

- $(e'_1, -) \setminus \tau$ . By Definition 4, we have  $(q_R^c, (e'_1, -) \setminus \tau, q_R^{c'}) \in T_{R1}^c$ ,  $q_R^c \in Q_{R1}^c$  and  $q_R^{c'} \in Q_{R1}^c$ . Since  $SR_1^r \sqsubseteq SA_1^c$ , there exists  $q_A^c$  such that  $q_A^c \in Q_{A1}^c$  and  $q_R^c \eta q_A^c$ . By condition 2 for  $SR_1^r \sqsubseteq SA_1^c$ , we obtain that  $q_R^{c'} \eta q_A^c$ .
- $(-, e'_2) \setminus \tau$ . by Definition 4, we have  $(q_R^c, (-, e'_2) \setminus \tau, q_R^{c'}) \in T_{R2}^c$ ,  $q_R^c \in Q_{R2}^c$  and  $q_R^{c'} \in Q_{R2}^c$ . Since  $SR_2^r \sqsubseteq SA_2^c$ , there exists  $q_A^c$  such that  $q_A^c \in Q_{A2}^c$  and  $q_R^c \eta q_A^c$ . By condition 2 for  $SR_2^r \sqsubseteq SA_2^c$ , we obtain that  $q_R^{c'} \eta q_A^c$ .
- $(e'_1, e'_2) \setminus \tau$ . By Definition 4, we have  $(q_R^c, (e'_1, e'_2) \setminus \tau, q_R^{c'}) \in T_{R1}^c$ ,  $q_R^c \in Q_{R1}^c$  and  $q_R^{c'} \in Q_{R1}^c$ . Since  $SR_1^r \sqsubseteq SA_1^c$ , there exists  $q_A^c$  such that  $q_A^c \in Q_{A1}^c$  and  $q_R^c \eta q_A^c$ . By condition 2 for  $SR_1^r \sqsubseteq SA_1^c$ , we obtain that  $q_R^{c'} \eta q_A^c$ .

**Lemma 3 (Lack of New Deadlocks Condition)**

Assume that  $q_R^c \dashv\vdash$ ; we must prove that  $q_A^c \dashv\vdash$ .

*Proof on the structure of the state set. There are three cases.*

- $q_R^c \in Q_{R1}^c \setminus Q_{R2}^c$ . As we have  $q_R^c \eta_f q_A^c$ , condition 3 in  $SR_1^r \sqsubseteq_{D_1} SA_1^c$  gives:
  - either  $q_A^c \dashv\vdash$  and we are done,
  - or  $q_A^c \xrightarrow{e}_A q_A^{c'}$  and  $q_R^c \in D_1$ . As  $q_R^c \notin Q_{R2}^c$ , we have a contradiction with  $D_1 \setminus Q_{R2}^c = \emptyset$ .
- $q_R^c \in Q_{R2}^c \setminus Q_{R1}^c$ . As we have  $q_R^c \eta_f q_A^c$ , condition 3 in  $SR_2^r \sqsubseteq_{D_2} SA_2^c$  gives:
  - either  $q_A^c \dashv\vdash$  and we are done,
  - or  $q_A^c \xrightarrow{e}_A q_A^{c'}$  and  $q_R^c \in D_2$ . As  $q_R^c \notin Q_{R1}^c$ , we have a contradiction with  $D_2 \setminus Q_{R1}^c = \emptyset$ .
- $q_R^c \in Q_{R1}^c \cap Q_{R2}^c$ . As we have  $q_R^c \eta_f q_A^c$ , condition 3 in  $SR_1^r \sqsubseteq_{D_1} SA_1^c$  gives:
  - either  $q_A^c \dashv\vdash$  and we are done,
  - or  $q_A^c \xrightarrow{e}_A q_A^{c'}$  and  $q_R^c \in D_1$ .

Moreover, condition 3 in  $SR_2^r \sqsubseteq_{D_2} SA_2^c$  gives:

- either  $q_A^c \dashv\vdash$  and we are done,
- or  $q_A^c \xrightarrow{e}_A q_A^{c'}$ ,  $q_R^c \in D_1$  and  $q_R^c \in D_2$ . We have a contradiction with  $D_1 \cap D_2 = \emptyset$ .

**Lemma 4 (Lack of  $\tau$ -divergence Condition)**

We must prove that there is no  $(q_R^c \xrightarrow{\tau} q_R^{c'} \xrightarrow{\tau} q_R^{c''} \xrightarrow{\tau} \dots \xrightarrow{\tau} \dots)$  in  $M$ .

*Proof by contradiction.* We suppose that  $(q_R \xrightarrow{\tau} q_R^{c'} \xrightarrow{\tau} q_R^{c''} \xrightarrow{\tau} \dots \xrightarrow{\tau} \dots)$  exists.

- $q_R^c, q_R^{c'}, q_R^{c''}, \dots \in Q_{R1}^c$ . We have a contradiction with condition 4 for  $SR_1^c \sqsubseteq SA_1^c$ .
- $q_R^c, q_R^{c'}, q_R^{c''}, \dots \in Q_{R2}^c$ . We have a contradiction with condition 4 for  $SR_2^c \sqsubseteq SA_2^c$ .
- $\exists i. (q_R^{c(i)} \in Q_{R1}^c \wedge q_R^{c(i+1)} \in Q_{R2}^c)$ . Inconsistence with condition 3 for  $SR_1^c \sqsubseteq SA_1^c$ .

**Lemma 5 (Non-determinism Preservation Condition)**

Assume that  $q_A^c \xrightarrow{\alpha} q_A^{c'}$ ; we must show that there exists  $q_R^{c'}$ ,  $q_R^{c''}$  and  $q_A^{c''}$  such that  $q_R^{c'} \eta q_A^c$ ,  $q_R^{c'} \xrightarrow{\alpha} q_R^{c''}$ ,  $q_A^c \xrightarrow{\alpha} q_A^{c''}$ , and  $q_R^{c''} \eta q_A^{c''}$ .

*Proof on the form of  $\alpha$ .* There are three cases.

-  $\alpha = (e_1, -)$ . By Definition 4, we have  $(q_A^c, (e_1, -), q_A^{c'}) \in T_{A1}^c$ ,  $q_A^c \in Q_{A1}^c$  and  $q_A^{c'} \in Q_{A1}^c$ . Since  $SR_1^c \sqsubseteq SA_1^c$ , there exists  $q_R^c$  such that  $q_R^c \in Q_{R1}^c$  and  $q_R^c \eta q_A^c$ . By condition 5 for  $SR_1^c \sqsubseteq SA_1^c$ , we obtain that there exist  $q_R^{c'}$ ,  $q_R^{c''}$  and  $q_A^{c''}$  such that  $q_R^{c'} \eta q_A^c$ ,  $q_R^{c'} \xrightarrow{\alpha} q_R^{c''}$ ,  $q_A^c \xrightarrow{\alpha} q_A^{c''}$  and  $q_R^{c''} \eta q_A^{c''}$ .

-  $\alpha = (-, e_2)$ . By Definition 4, we have  $(q_A^c, (-, e_2), q_A^{c'}) \in T_{A2}^c$ ,  $q_A^c \in Q_{A2}^c$  and  $q_A^{c'} \in Q_{A2}^c$ . Since  $SR_2^c \sqsubseteq SA_2^c$ , there exists  $q_R^c$  such that  $q_R^c \in Q_{R2}^c$  and  $q_R^c \eta q_A^c$ . By condition 5 for  $SR_2^c \sqsubseteq SA_2^c$ , we obtain that there exist  $q_R^{c'}$ ,  $q_R^{c''}$  and  $q_A^{c''}$  such that  $q_R^{c'} \eta q_A^c$ ,  $q_R^{c'} \xrightarrow{\alpha} q_R^{c''}$ ,  $q_A^c \xrightarrow{\alpha} q_A^{c''}$  and  $q_R^{c''} \eta q_A^{c''}$ .

-  $\alpha = (e_1, e_2)$ . By Definition 4, we have  $(q_A^c, (e_1, e_2), q_A^{c'}) \in T_{A1}^c$ ,  $q_A^c \in Q_{A1}^c$  and  $q_A^{c'} \in Q_{A2}^c$ . Since  $SR_1^c \sqsubseteq SA_1^c$ , there exists  $q_R^c$  such that  $q_R^c \in Q_{R1}^c$  and  $q_R^c \eta q_A^c$ . By condition 5 for  $SR_1^c \sqsubseteq SA_1^c$ , we obtain that there exist  $q_R^{c'}$ ,  $q_R^{c''}$  and  $q_A^{c''}$  such that  $q_R^{c'} \eta q_A^c$ ,  $q_R^{c'} \xrightarrow{\alpha} q_R^{c''}$ ,  $q_A^c \xrightarrow{\alpha} q_A^{c''}$  and  $q_R^{c''} \eta q_A^{c''}$ .

## A.2 $[R] \Rightarrow [a] \wedge [b] \wedge [c]$

Property 1 gives immediately  $D_{12} = \emptyset [c]$  and  $SR_1 \parallel_{\text{Synch}} SR_2 \sqsubseteq_{D_{12}} SA_1 \parallel_{\text{Synch}} SA_2 [R']$ . We show that  $[R']$  implies  $[a]$  and  $[b]$ .

Let  $M_1 \stackrel{\text{def}}{=} \{(q_{R1}^c, q_{A1}^c) \mid (q_{R1}^c \in Q_{R1}^c \wedge q_{A1}^c \in Q_{A1}^c)\}$   
 and  $M_2 \stackrel{\text{def}}{=} \{(q_{R2}^c, q_{A2}^c) \mid (q_{R2}^c \in Q_{R2}^c \wedge q_{A2}^c \in Q_{A2}^c)\}$  be two sets  
 with  $\forall q_R^c. (q_R^c \in Q_{R1}^c \cup Q_{R2}^c \Rightarrow \exists q_A^c. (q_A^c \in Q_{A1}^c \cup Q_{A2}^c \wedge q_R^c \eta_f q_A^c))$ .

We show that  $M_1$  verifies the conditions of Definition 8 using Lemmas 6, 7, 8, 9 and 10. The proof is the same for  $M_2$ .

As  $D_{12} = \emptyset$ , we always have  $[c'] : (D_1 \cap D_2 = \emptyset) \wedge (D_1 \setminus Q_{R2}^c = \emptyset) \wedge (D_2 \setminus Q_{R1}^c = \emptyset)$ .

### Lemma 6 (Strict Transition Refinement Condition)

Assume that  $q_{R1}^c \xrightarrow{\alpha} q_{R1}'^c$ ; we must prove that there exists  $q_{A1}'^c$  such that  $q_{A1}^c \xrightarrow{\alpha} q_{A1}'^c$  and  $q_{R1}'^c \eta q_{A1}'^c$ .

*Proof on the form of  $\alpha$ . There are three cases.*

-  $\alpha = (e_1, -)$  or  $\alpha = (e_1, e_2)$ . By Definition 4, we have  $q_{R1}^c \in Q_{R1}^c$  and  $q_{R1}'^c \in Q_{R1}^c$ . Since  $q_{R1}^c \eta_f q_{A1}^c$  for the whole system, we obtain that there exist  $q_{A1}^c$  and  $q_{A1}'^c$  such that  $q_{A1}^c, q_{A1}'^c \in Q_A^c$ ,  $q_{A1}^c \xrightarrow{\alpha} q_{A1}'^c$  and  $q_{R1}'^c \eta q_{A1}'^c$ . By Definition 4, we have  $q_{A1}^c$  and  $q_{A1}'^c$  belonging to  $Q_{A1}^c$ . We conclude that  $(q_{R1}^c, q_{A1}^c) \in M_1$ .

-  $\alpha = (-, e_2)$ . Impossible because of Definition 4.

### Lemma 7 (Stuttering Transition Refinement Condition)

Assume  $q_{R1}^c \xrightarrow{\tau} q_{R1}'^c$ ; we must prove that  $q_{R1}'^c \eta q_{A1}^c$ .

*Proof on the form of labels covered by  $\tau$ . There are three cases.*

-  $(e_1', -) \setminus \tau$  or  $(e_1', e_2') \setminus \tau$ . By Definition 4, we have  $q_{R1}^c \in Q_{R1}^c$  and  $q_{R1}'^c \in Q_{R1}^c$ . Since  $q_{R1}^c \eta_f q_{A1}^c$  for the whole system, we obtain that there exists  $q_{A1}^c$  such that  $q_{A1}^c \in Q_A^c$  and  $q_{R1}'^c \eta q_{A1}^c$ .

- If  $q_{A1}^c \in Q_{A1}^c$ , we conclude that  $(q_{R1}^c, q_{A1}^c) \in M_1$ .

- If  $q_{A1}^c \in Q_{A2}^c \setminus Q_{A1}^c$ , then  $(q_{R1}^c, q_{A1}^c) \notin M_1$  and we are done.

-  $(-, e_2') \setminus \tau$ . Impossible because of Definition 4.

**Lemma 8 (Old or New Deadlocks Condition)**

Assume that  $q_{R1}^c \not\rightarrow$  with  $q_{R1}^c \in Q_{R1}^c$ ; we must prove that either  $q_{A1}^c \not\rightarrow$  or  $\exists q_{A1}^{c'}.(q_{A1}^c \xrightarrow{e} q_{A1}^{c'} \text{ and } q_{R1}^c \in D_1)$ .

- Suppose that  $q_{R1}^c$  is a deadlock for  $SR_1 \parallel_{Synchron} SR_2$ . As we have  $q_{R1}^c \eta_f q_{A1}^c$  for the whole system, we have two cases:

- either  $q_{A1}^c \not\rightarrow$ ;
- If  $q_{A1}^c \in Q_{A1}^c$ , we conclude that  $(q_{R1}^c, q_{A1}^c) \in M_1$ .
- If  $q_{A1}^c \in Q_{A2}^c \setminus Q_{A1}^c$ , then  $(q_{R1}^c, q_{A1}^c) \notin M_1$  and we are done.
- or  $\exists q_{A1}^{c'}.(q_{A1}^c \xrightarrow{e} q_{A1}^{c'} \wedge q_{R1}^c \in D_{12})$ . Impossible since  $D_{12} = \emptyset$ .

- Suppose that  $q_{R1}^c$  is not a deadlock for  $SR_1 \parallel_{Synchron} SR_2$ . Since  $q_{R1}^c \not\rightarrow$  for  $SR_1$ , then  $q_{R1}^c \xrightarrow{e} q_{R1}^{c'}$  for  $SR_2$ . Then we have  $q_{R1}^c \in Q_{R2}^c$ . We have  $q_{R1}^c \eta_f q_{A1}^c$  for the whole system and:

- either  $q_{A1}^c \not\rightarrow$ ;
- If  $q_{A1}^c \in Q_{A1}^c$  we conclude that  $(q_{R1}^c, q_{A1}^c) \in M_1$ .
- If  $q_{A1}^c \in Q_{A2}^c \setminus Q_{A1}^c$  then  $(q_{R1}^c, q_{A1}^c) \notin M_1$  and we are done.
- or  $\exists q_{A1}^{c'}.(q_{A1}^c \xrightarrow{e} q_{A1}^{c'})$ ;
- If  $q_{A1}^c \in Q_{A1}^c$ , we verify  $D_1 \setminus Q_{R2}^c = \emptyset$  because of  $q_{R1}^c \in Q_{R2}^c$  and we conclude that  $(q_{R1}^c, q_{A1}^c) \in M_1$ .
- If  $q_{A1}^c \in Q_{A2}^c \setminus Q_{A1}^c$ , then  $(q_{R1}^c, q_{A1}^c) \notin M_1$  and we are done.

**Lemma 9 (Lack of  $\tau$ -divergence Condition)**

We must prove that there is no  $(q_{R1}^c \xrightarrow{\tau} q_{R1}^{c'} \xrightarrow{\tau} q_{R1}^{c''} \xrightarrow{\tau} \dots \xrightarrow{\tau} \dots)$  in  $M_1$ .

*Proof by contradiction.* We suppose that  $(q_{R1}^c \xrightarrow{\tau} q_{R1}^{c'} \xrightarrow{\tau} q_{R1}^{c''} \xrightarrow{\tau} \dots \xrightarrow{\tau} \dots)$  exists.

Since  $q_{R1}^c, q_{R1}^{c'}, q_{R1}^{c''}, \dots \in Q_{R1}^c$ , we have a  $\tau$ -divergence for the whole system.

**Lemma 10 (Non-determinism Preservation Condition)**

Assume that  $q_{A1}^c \xrightarrow{\alpha} q_{A1}^{c'}$ ; we must show that there exist  $q_{R1}^{c'}$ ,  $q_{R1}^{c''}$  and  $q_{A1}^{c''}$  such that  $q_{R1}^{c'} \eta_f q_{A1}^c$ ,  $q_{R1}^{c'} \xrightarrow{\alpha} q_{R1}^{c''}$ ,  $q_{A1}^c \xrightarrow{\alpha} q_{A1}^{c''}$ , and  $q_{R1}^{c''} \eta_f q_{A1}^{c''}$ .

*Proof on the form of  $\alpha$ .* There are three cases.

-  $\alpha = (e_1, -)$  or  $\alpha = (e_1, e_2)$ . By Definition 4, we have  $q_{A1}^c \in Q_{A1}^c$  and  $q_{A1}^{c'} \in Q_{A1}^c$ . Since  $q_{R1}^c \eta_f q_{A1}^c$  for the whole system, we obtain that there exist  $q_{R1}^{c'}$ ,  $q_{R1}^{c''}$  and  $q_{A1}^{c''}$  such that  $q_{R1}^{c'} \eta_f q_{A1}^c$ ,  $q_{R1}^{c'} \xrightarrow{\alpha} q_{R1}^{c''}$ ,  $q_{A1}^c \xrightarrow{\alpha} q_{A1}^{c''}$  and  $q_{R1}^{c''} \eta_f q_{A1}^{c''}$ . By Definition 4, we conclude that  $q_{R1}^{c'}$  and  $q_{R1}^{c''}$  belong to  $Q_{R1}^c$ , and that  $q_{A1}^{c''}$  belongs to  $Q_{A1}^c$ . We conclude that  $(q_{R1}^c, q_{A1}^c) \in M_1$ .

-  $\alpha = (-, e_2)$ . Impossible because of Definition 4.





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