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INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

# *Transitive Closures of Semi-commutation Relations on Regular $\omega$ -Languages*

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THÈMES 4 et 3



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de recherche*





# Transitive Closures of Semi-commutation Relations on Regular $\omega$ -Languages

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**Abstract:** A semi-commutation  $R$  is a relation on a finite alphabet  $A$ . Given an infinite word  $u$  on  $A$ , we denote by  $R(u) = \{xbay \mid x \in A^*, y \in A^\omega, (a, b) \in R \text{ and } xaby = u\}$  and by  $R^*(u)$  the language  $\{u\} \cup \bigcup_{k \geq 1} R^k(u)$ . In this paper we prove that if an  $\omega$ -language  $L$  is a finite union of languages of the form  $A_0^*a_1A_1^* \dots a_kA_k^*a_{k+1}A_{k+1}^*$ , where the  $A_i$ 's are subsets of the alphabet and the  $a_i$ 's are letters, then  $R^*(L)$  is a computable regular  $\omega$ -language accepting a similar decomposition. In addition we prove the same result holds for  $\omega$ -languages which are finite unions of languages of the form  $L_0a_1L_1 \dots a_kL_ka_{k+1}L_{k+1}$ , where the  $L_i$ 's are accepted by diamond automata and the  $a_i$ 's are letters. These results improve recent works by Bouajjani, Muscholl and Touili on one hand, and by Cécé, Héam and Mainier on the other hand, by extending them to infinite words.

**Key-words:** Finite Automata, Infinite Words, Transitive Closures, Semi-commutations

## Clôtures transitives de reallions de semi-commutation sur les $\omega$ -langages réguliers

**Résumé :** Une relation de semi-commutation  $R$  est une relation sur un alphabet fini  $A$ . Etant donné un mot infini  $u$  sur  $A$ , on pose  $R(u) = \{xbay \mid x \in A^*, y \in A^\omega \text{ } (a, b) \in R \text{ and } xaby = u\}$  et  $R^*(u)$  le langage  $\{u\} \cup \cup_{k \geq 1} R^k(u)$ . Dans cet article nous montrons que si un  $\omega$ -langage  $L$  est une union finie de langages de la forme  $A_0^* a_1 A_1^* \dots a_k A_k^* a_{k+1} A_{k+1}^*$ , où les  $A_i$  sont des sous-ensembles de l'alphabet et les  $a_i$  des lettres, alors  $R^*(L)$  est un  $\omega$ -langage régulier calculable et possédant une décomposition similaire. De plus, nous prouvons que le même résultat existe pour les  $\omega$ -langages qui sont une union finie de langages de la forme  $L_0 a_1 L_1 \dots a_k L_k a_{k+1} L_{k+1}$ , où les  $L_i$  sont acceptés par des automates diamants et les  $a_i$  des lettres. Ces résultats étendent aux mots infinis des travaux récents de Bouajjani, Muscholl et Touili d'une part, et Cécé, Héam et Mainier d'autre part.

**Mots-clés :** Automates finis, mots infinis, clôtures transitives, semi-commutations

We assume a basic background in finite automata theory. For more information on automata the reader is referred to [Ber79, HU80]. We also assume that the reader is familiar with notions on finite/infinite words and languages. For precise definitions the reader could refer to [PP04].

## 1 Introduction

### 1.1 Contributions

The main purpose of the paper is to prove stability results on several classes of regular  $\omega$ -languages. More precisely, we are interested in semi-commutation relations: a semi-commutation  $R$  is a relation on a finite alphabet  $A$ . Given an infinite word  $u$  on  $A$ , we denote by  $R(u) = \{xbay \mid x \in A^*, y \in A^\omega, (a, b) \in R \text{ and } xaby = u\}$ . We denote by  $R^*(u)$  the  $\omega$ -language  $\{u\} \cup \bigcup_{k \geq 1} R^k(u)$ . By extension, for an  $\omega$ -language  $L$ , we set

$$R(L) = \bigcup_{u \in L} R(u) \quad \text{and} \quad R^*(L) = \bigcup_{u \in L} R^*(u).$$

We say that a finite automaton  $\mathcal{A}$  is a diamond automaton [MP01] if for each pair of transitions of the form  $(p, a, q), (q, b, r)$ , there exists a state  $s$  of  $\mathcal{A}$  such that  $(p, b, s)$  and  $(s, a, r)$  are transitions too. Finally, we say that a finite automaton  $\mathcal{A}$  is a partially ordered automaton [TT02] if there exists a partial order  $\leq$  on its set of states such that for each transition  $(p, a, q)$  of  $\mathcal{A}$ ,  $p \leq q$ .

The main results of this paper are as follows:

- (1) We prove that the class of  $\omega$ -languages accepted by partially ordered Büchi automata is closed under semi-commutation; i.e. if  $L$  is accepted by a partially ordered Büchi automaton then, for each semi-commutation relation  $R$ ,  $R^*(L)$  is accepted by a partially ordered Büchi automaton too.
- (2) We prove that the class of  $\omega$ -languages, called  $\omega - \text{PolC}$ , that are finite unions of  $\omega$ -languages of the form

$$L_0 a_1 L_1 \dots a_k L_k a_{k+1} L_{k+1},$$

where the  $L_i$ 's are accepted by diamond automata and the  $a_i$ 's are letters is closed under semi-commutations.

- (3) We provide an automaton based algorithm to compute  $R^*(L)$  for the two above cases.

In order to obtain this results, we have to use the  $\sqcup_R$  operator. Given two words  $u \in A^*$  and  $v \in A^* \cup A^\omega$ , the  $R$ -shuffle of  $u$  and  $v$ , denoted  $u \sqcup_R v$ , is the set of words of the form  $u_1 v_1 \dots u_n v_n$  with  $u = u_1 \dots u_n$ ,  $v = v_1 \dots v_n$  and such that  $\alpha(u_i) \times \alpha(v_j) \subseteq R$  for all  $j < i$ . The  $R$ -shuffle operation is extended to languages  $L \subseteq A^*$  and  $K \subseteq A^*$  or  $K \subseteq A^\omega$  by

$$L \sqcup_R K = \bigcup_{u \in L, v \in K} u \sqcup_R v.$$

In this paper we obtain the following results for the  $\sqcup_R$  operator.

- (4) If  $L$  is a regular language on finite words and  $K$  is a regular  $\omega$ -language, then  $L \sqcup_R K$  is a regular  $\omega$ -language.
- (5) We provide a polynomial-time algorithm to compute  $L \sqcup_R K$ .
- (6) We prove that the classes defined in (1) and (2) are closed under the  $\sqcup_R$  operator.

Results (1-6) extend results obtained on finite words by Bouajjani et al. [BMT01, BMT07] and by Cécé et al. [CHM03] to infinite words.

## 1.2 Related Works

Regular model-checking [BG96, BW98, AJNd03] is an approach to verify infinite state systems. One represents, symbolically, sets of states by regular languages and one develops *meta-transitions* which can compute, in one step, infinite sets of successors. This amounts to compute  $R^*(L)$  for a given regular language  $L$  and a given relation  $R$  representing a subset of the transition relation  $T$  of the system. The transition relation  $T$  can be decomposed into several (sub) relations  $R_i$  (of semi-commutation or something else), each of them implying their ad-hoc techniques of computation. As most of the developed techniques are based on automata, it is more efficient and consistent to use automata during the whole computation. As explained in [BMT07], these techniques also are suitable for verifying of High-level Message Sequence Charts using both finite and infinite executions [GM05]. In this direction our works may have several applications. Moreover, diamond automata play a significant role in the translation of Büchi automata into HMSC's [MP01].

Polynomial closure of varieties of regular languages is an operation widely studied in the literature (see for example [PW97, Tho82, Brz76, BS73]). Languages on finite words accepted by partially ordered automata are called languages of level 3/2 in the Straubing-Thérien hierarchy [Str85, Thé81] which represents the current border for decidability problems and whose structure makes them suitable for verification of certain systems [ABJ98, AAB99, BMT07] [BMT01, Tou01].

Decomposable languages form a class of regular languages used for the simulation of process algebra [LS98]. It was conjectured in [Sch99] that this class was exactly the dual class of  $\omega - \text{PolC}$  for finite words. However this conjecture has been invalidated in [GP03]. Finally, looking for the maximal (positive) variety closed under an operator [BBC<sup>+</sup>06] is widely studied in the literature. One can cite the result for the shuffle operator for varieties [ES98, Per78] and for positive varieties [GP04].

The shuffle product is an operation on languages which is strongly connected to combinatorics on words and which was widely studied in the literature [Rad79, Spe86, NRR<sup>+</sup>94, PMR98, BB99].

## 1.3 Layout of the paper

After introducing the main issues of this paper and basic notations, we extend in Section 2 a result proved in [DM97] to infinite words and we prove that computing the  $R$ -closure of a

regular language reduces in some cases to the computation of the  $R$ -shuffle of these languages. Then, we provide an algorithm to compute the  $R$ -shuffle of two regular languages. Section 3 is dedicated to proving the main contributions of the paper. Finally, we conclude in Section 4 by giving some future works.

## 1.4 Background and Notations

We recall in this section notations and unusual definitions on words and automata.

Recall that a finite automaton is a 5-tuple  $\mathcal{A} = (Q, A, E, I, F)$  where  $Q$  is a finite set of states,  $A$  is the alphabet,  $E \subseteq Q \times A \times Q$  is the set of transitions,  $I \subseteq Q$  is the set of initial states and  $F \subseteq Q$  is the set of final states. If  $\mathcal{A}$  is a finite automaton,  $L(\mathcal{A})$  denotes the language accepted by  $\mathcal{A}$ . If  $C \subseteq Q$  and  $D \subseteq Q$ ,  $\mathcal{A}_{C,D}$  denotes the automaton  $(Q, A, E, C, D)$ . Moreover, for all  $p \in Q$ ,  $p \cdot_{\mathcal{A}} a = \{q \in Q \mid (p, a, q) \in E\}$ . If there is no ambiguity on  $\mathcal{A}$ ,  $p \cdot_{\mathcal{A}} a$  is also denoted  $p \cdot a$ . If  $p \cdot a = \{q\}$  is a singleton, we also write  $p \cdot a = q$ . If  $q \in p \cdot a$ , we also write  $p \rightarrow_a q$ .

A finite word  $u$  is accepted or recognized by a finite automaton  $\mathcal{A}$  if there exists a path in  $\mathcal{A}$  from an initial state to a final state labelled by  $u$ . The language of words accepted by  $\mathcal{A}$  is denoted by  $L(\mathcal{A})$ .

An infinite word  $w$  is accepted or recognized by a finite automaton  $\mathcal{A}$  if there exists an infinite path in  $\mathcal{A}$  starting from an initial states of  $\mathcal{A}$  and using infinitely many final states of  $\mathcal{A}$ . In this context, a finite automaton is commonly called a Büchi automaton. The  $\omega$ -language of  $\omega$ -word accepted by  $\mathcal{A}$  is denoted by  $L_{\omega}(\mathcal{A})$ .

If  $u$  is a finite or infinite word,  $\alpha(u)$  denotes the set of letters occurring in  $u$ . This notion is extended to languages or  $\omega$ -languages:  $\alpha(L) = \cup_{u \in L} \alpha(u)$ .

If  $R$  is a semi-commutation relation and  $u$  a finite word, we denote by  $R(u) = \{xbay \mid x \in A^*, y \in A^*, (a, b) \in R \text{ and } xaby = u\}$ . We denote by  $R^*(u)$  the language  $\{u\} \cup \cup_{k \geq 1} R^k(u)$ . By extension, for a language  $L$ , we set

$$R(L) = \cup_{u \in L} R(u) \quad \text{and} \quad R^*(L) = \cup_{u \in L} R^*(u).$$

A language (resp.  $\omega$ -language)  $L$  is  $R$ -closed if  $R^*(L) = L$ .

## 2 R-shuffle Product and Finite Automata

We first extend a result of [DM97] to infinite words.

**Proposition 1** *Let  $L_1$  be a language of finite words and  $L_2$  a language of  $\omega$ -words. One has:*

$$R^*(L_1 L_2) = R^*(L_1) \sqcup_R R^*(L_2).$$

PROOF.



$\subseteq$ : By definition of  $\sqcup_R$  one has  $L_1 L_2 \subseteq L_1 \sqcup_R L_2$ . Therefore, since  $L_1 \subseteq R^*(L_1)$  and  $L_2 \subseteq R^*(L_2)$ , one has

$$L_1 L_2 \subseteq R^*(L_1) \sqcup_R R^*(L_2). \quad (1)$$

Now let  $w \in R^*(L_1) \sqcup_R R^*(L_2)$ . We claim that  $R(w) \subseteq R^*(L_1) \sqcup_R R^*(L_2)$ . There exists  $u$  and  $v$  such that  $w \in u \sqcup_R v$ . Moreover, by definition of  $\sqcup_R$ , there exist  $u_i$ 's and  $v_i$ 's such that  $u_1 v_1 \dots u_n v_n$  with  $u = u_1 \dots u_n$ ,  $v = v_1 \dots v_n$  and such that  $\alpha(u_i) \times \alpha(v_j) \subseteq R$  for all  $j < i$ . Let  $w' \in R(w)$ . According the position of the rewriting process, following cases arise:

- The semi-commutation occurs *in*  $u_k$ : one has  $w' = u_1 v_1 \dots u_{k-1} v_{k-1} u'_k v_k u_{k+1} \dots u_n v_n$  with  $u'_k \in R(u_k)$ . Since  $\alpha(u'_k) = \alpha(u_k)$ ,  $w' \in R(u) \sqcup_R v$ . But  $u \in R^*(L_1)$ , therefore  $w' \in R^*(L_1) \sqcup_R R^*(L_2)$ .
- The semi-commutation occurs *in*  $v_k$ : similarly, one has  $w' \in R^*(L_1) \sqcup_R R^*(L_2)$ .
- The semi-commutation occurs *at the end of*  $u_k$ : one has  $w' = u_1 v_1 \dots u_{k-1} v_{k-1} u'_k v'_k u_{k+1} \dots u_n v_n$  with  $u_k = xa$ ,  $v_k = by$ ,  $u'_k = xb$ ,  $v'_k = ay$  and  $(a, b) \in R$ . In this context, set  $x_i = u_i$  and  $y_i = v_i$  for  $i < k$  and  $x_k = u'_k$  and  $y_k = v'_k$ . Let also  $x_i = u_{i+1}$  and  $y_i = v_{i+1}$  for  $i > k$ . Finally, let  $x_{k+1} = b$  and  $y_{k+1} = a$ . One has  $w' = x_1 y_1 \dots x_{n+1} y_{n+1}$ . Moreover,  $u = x_1 \dots x_{n+1}$  and  $v = y_1 \dots y_n$ . Now, one can easily check that  $\alpha(x_i) \times \alpha(y_j) \subseteq R$  for all  $j < i$ . Therefore,  $w' \in u \sqcup_R v$ . Thus  $w' \in R^*(L_1) \sqcup_R R^*(L_2)$ .
- The semi-commutation occurs *at the end of*  $v_k$ : by a similar decomposition, one has  $w' \in R^*(L_1) \sqcup_R R^*(L_2)$ , proving the claim.

Consequently  $R^*(L_1) \sqcup_R R^*(L_2)$  is  $R$ -closed. Therefore, using (1), one has

$$R^*(L_1 L_2) \subseteq R^*(R^*(L_1) \sqcup_R R^*(L_2)) = R^*(L_1) \sqcup_R R^*(L_2).$$

$\supseteq$ : By a straightforward induction, one has: for every  $u \in A^*$  and every  $v \in A^\omega$ ,

$$u \sqcup_R v \subseteq R^*(uv).$$

Obviously this inclusion can be extended to languages. Thus

$$R^*(L_1) \sqcup_R R^*(L_2) \subseteq R^*(R^*(L_1) R^*(L_2)).$$

Since  $R^*(R^*(L_1) R^*(L_2)) = R^*(L_1 L_2)$ , one has

$$R^*(L_1 L_2) \supseteq R^*(L_1) \sqcup_R R^*(L_2),$$

which concludes the proof. □

The above result may be easily extended to a finite product of languages by an obvious induction on the length of the product. Thanks to this result, we reduce the computation of  $R^*(L_1 L_2)$  to the computation of  $R^*(L_1)$ ,  $R^*(L_2)$  and of  $\sqcup - R$  operator. We are now interested in a procedure for computing  $L_1 \sqcup - R L_2$  when  $L_1$  and  $L_2$  are given by finite automata.

**Proposition 2** *Let  $\mathcal{A}_1 = (Q_1, A, E_1, I_1, F_1)$  and  $\mathcal{A}_2 = (Q_2, A, E_2, I_2, F_2)$  be two finite automata on  $A$ . We define the automaton  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  by:*

- *the set of states of  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  is*

$$Q_1 \times Q_2 \times 2^A \cup Q_2$$

- *the set of initial states of  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  is*

$$I_1 \times I_2 \times \{\emptyset\},$$

- *the set of final states of  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  is  $F_2$ ,*
- *the set of transitions of  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  is*

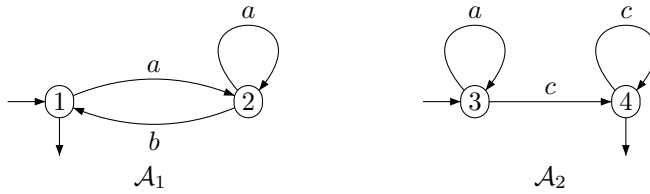
$$\begin{aligned} & \{(p, q, X) \rightarrow_a (r, q, X) \mid r \in p \cdot_{\mathcal{A}_1} a \text{ and } (a, X) \subseteq R\} \\ & \cup \{(p, q, X) \rightarrow_a (p, r, X \cup \{a\}) \mid r \in q \cdot_{\mathcal{A}_2} a\} \\ & \cup \{(p, q, X) \rightarrow_a r \mid r \in q \cdot_{\mathcal{A}_2} a, p \in F_1\} \\ & \cup E_2 \end{aligned}$$

where  $p, q, X, a$  respectively describe  $Q_1, Q_2, 2^A$  and  $A$ .

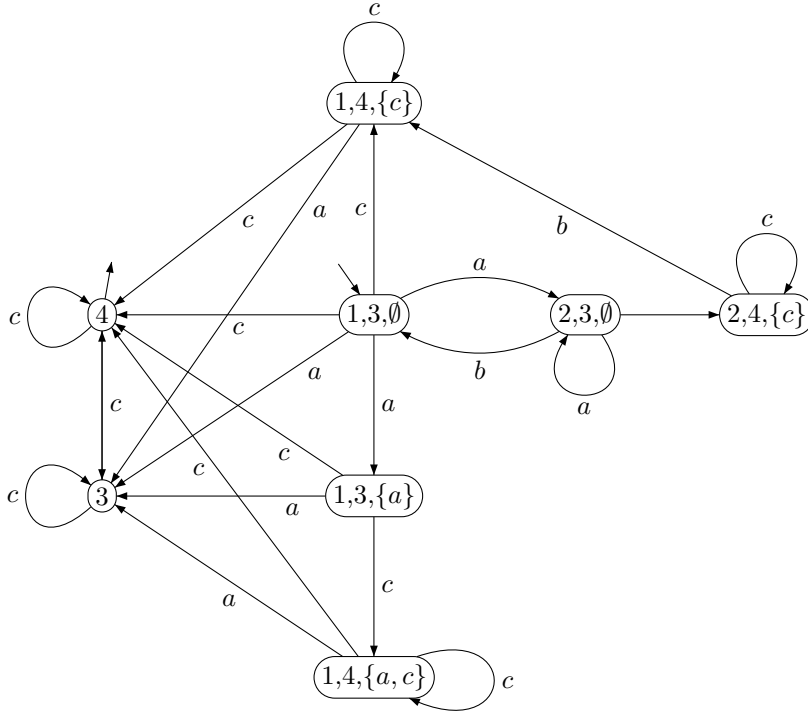
One has

$$L_\omega(\mathcal{A}_1 \sqcup_R \mathcal{A}_2) = L(\mathcal{A}_1) \sqcup_R L_\omega(\mathcal{A}_2).$$

Consider for example the two following automata:



The construction of  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  provides the following finite automaton:



Notice that in the construction, if  $(p, q, B) \rightarrow_a (r, s, D)$  is a transition, then  $B \subseteq D$ .

PROOF.

The proof will naturally be divided into two steps: we will first prove that  $L_\omega(\mathcal{A}_1 \sqcup_R \mathcal{A}_2) \subseteq L(\mathcal{A}_1) \sqcup_R L_\omega(\mathcal{A}_2)$  and second that  $L(\mathcal{A}_1) \sqcup_R L_\omega(\mathcal{A}_2) \subseteq L_\omega(\mathcal{A}_1 \sqcup_R \mathcal{A}_2)$ .

To simplify notations, set

- $\mathcal{A} = \mathcal{A}_1 \sqcup_R \mathcal{A}_2$ ,
- $G_1 = \{(p, q, X) \rightarrow_a (r, q, X) \mid r \in p \cdot_{\mathcal{A}_1} a \text{ and } (a, X) \subseteq R, p \in Q_1, q \in Q_2, X \subseteq 2^A, a \in A\}$ ,
- $G_2 = \{(p, q, X) \rightarrow_a (p, r, X \cup \{a\}) \mid r \in q \cdot_{\mathcal{A}_2} a, p \in Q_1, q \in Q_2, X \subseteq 2^A, a \in A\}$ ,
- $G_3 = \{(p, q, X) \rightarrow_a r \mid r \in q \cdot_{\mathcal{A}_2} a, p \in F_1, p \in Q_1, q \in Q_2, X \subseteq 2^A, a \in A\}$ .

Note that the set of transitions of  $\mathcal{A}$  is  $G_1 \cup G_2 \cup G_3 \cup E_2$ .

Let  $w \in L_\omega(\mathcal{A})$ . By definition, there exists an infinite path  $m$  in  $\mathcal{A}$  labelled by  $w$ , starting from an initial state of  $\mathcal{A}$  and using infinitely many final states of  $\mathcal{A}$ . By construction, all transitions of  $G_1$  and  $G_2$  are between states of  $Q_1 \times Q_2 \times 2^A$ , all transitions of  $G_3$  starts from a states of  $Q_1 \times Q_2 \times 2^A$  and ends in a state of  $Q_2$ , and all transitions of  $E_2$  are between states of  $Q_2$ . Thus, since initial states of  $\mathcal{A}$  are in  $Q_1 \times Q_2 \times 2^A$  and final states of  $\mathcal{A}$  are in  $Q_2$ , the path  $m$  can be decomposed into:

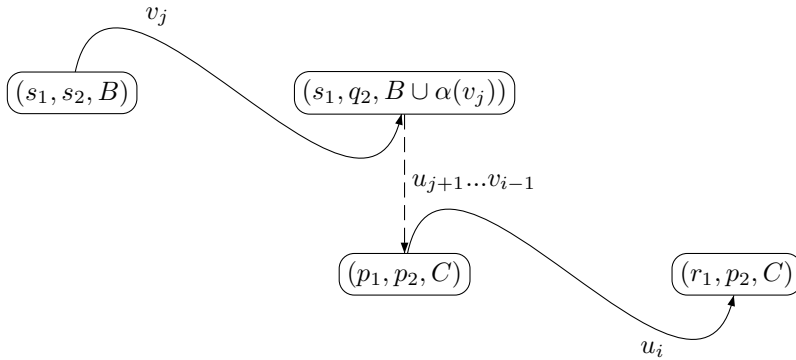
$$m = m_{\text{finite}}, t, m_\omega$$

where the path  $m_{\text{finite}}$  is a finite path using only transitions of  $G_1$  and  $G_2$ ,  $t \in G_3$  and  $m_\omega$  is an infinite path using only transitions of  $E_2$ .

In turn, the finite path  $m_{\text{finite}}$  can be decomposed into:

$$m_{\text{finite}} = m_1, m_2, m_3, \dots, m_k$$

such that each  $m_{2i+1}$  ( $0 \leq i \leq (k-1)/2$ ) only uses transitions of  $G_1$  and each  $m_{2i}$  ( $1 \leq i \leq k/2$ ) only uses transitions of  $G_2$  (some of them may be empty). Now, let us denote by  $u_{i+1}$  the label of  $m_{2i+1}$  and  $v_i$  the label of  $m_{2i}$ . By construction, the label of  $m_{\text{finite}}$  is  $u_1 v_1 u_2 \dots u_r v_r$  ( $r = k/2$  if  $k$  is even and  $r = (k-1)/2$  if  $k$  is odd). We claim that for all  $1 \leq j < i \leq r$ ,  $\alpha(u_i) \times \alpha(v_j) \subseteq R$ . Indeed, let  $1 \leq j < i \leq r$ . Assume that  $u_i$  or  $v_j$  is empty. Then  $\alpha(u_i) \times \alpha(v_j) = \emptyset \subseteq R$ . Assume now that  $u_i$  and  $v_j$  are both non-empty. Let  $(s_1, s_2, B)$  be the first state of  $m_{2j}$ . Since  $m_{2j}$  only uses transitions of  $G_2$  the last state of  $m_{2j}$  is of the form  $(s_1, q_2, B \cup \alpha(v_j))$ . Let  $(p_1, p_2, C)$  the first state of  $m_{2i+1}$ . Since  $m_{2i+1}$  only uses transitions of  $G_1$ , its last state is of the form  $(r_1, p_2, C)$ .



By construction  $C = B \cup \alpha(v_j v_{j+1} \dots v_{i-1})$ . Moreover, since the path  $m_{2i+1}$  only uses transitions of  $G_1$ , each letter  $a \in \alpha(u_i)$  has to satisfy  $\{a\} \times C \subseteq R$ . It follows that

$$\alpha(u_i) \times \alpha(v_j) \subseteq R, \quad (2)$$

proving the claim.

Now since  $m = m_{\text{finite}} t m_\omega$  and since  $t \in G_3$ , the last state of  $m_{\text{finite}}$  is of the form  $(p, q, D)$  with  $p \in F_1$ . Consequently,

$$u_1 u_2 \dots u_r \in L(\mathcal{A}_1). \quad (3)$$

Now let  $v$  be the label of  $t, m_\omega$ . By construction, the path  $m_2, m_4, \dots, m_{2r}, t, m_\omega$  is labelled by  $v_0 v_1 \dots v_r v$  and is a word of  $L_\omega(\mathcal{A}_2)$ . Consequently, and by (2) and (3),  $w \in L(\mathcal{A}_1) \sqcup_R L_\omega(\mathcal{A}_2)$ , proving the first step of the proof.

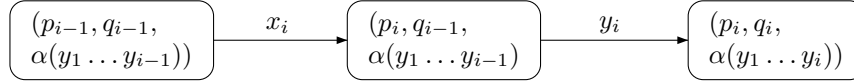
Now we can prove that  $L(\mathcal{A}_1) \sqcup_R L_\omega(\mathcal{A}_2) \subseteq L(\mathcal{A})$ . Let  $z$  be in  $L(\mathcal{A}_1) \sqcup_R L_\omega(\mathcal{A}_2)$ . By definition there exist  $x_1, y_1, \dots, x_{n-1}, y_{n-1}, x_n \in A^*$ ,  $y_n \in A^\omega$ , such that  $x_1 x_2 \dots x_n \in L(\mathcal{A}_1)$ ,  $y_1 y_2 \dots y_n \in L_\omega(\mathcal{A}_2)$  and for all  $1 \leq i \leq n$  and for all  $1 \leq j < i \leq n$ ,  $\alpha(x_i) \times \alpha(y_j) \subseteq R$ . Since  $x_1 x_2 \dots x_n \in L(\mathcal{A}_1)$ , there exist  $p_0, p_1, \dots, p_n \in Q_1$  such that

- $p_0 \in I_1$ ,
- $p_n \in F_1$ ,
- for all  $i \in \{1, \dots, n\}$ , there exists a path in  $\mathcal{A}_1$  from  $p_{i-1}$  to  $p_i$  labelled by  $x_i$ .

Since  $y_1 y_2 \dots y_n \in L_\omega(\mathcal{A}_2)$ , there exist  $q_0, q_1, \dots, q_n \in Q_2$  such that

- $q_0 \in I_2$ ,
- $q_n \in F_2$ ,
- for all  $i \in \{1, \dots, n-1\}$ , there exists a path in  $\mathcal{A}_2$  from  $q_{i-1}$  to  $q_i$  labelled by  $y_i$ .
- there exists an infinite path in  $\mathcal{A}_2$  from  $q_{n-1}$  visiting infinitely many often  $q_n$ .

For all  $i \in \{1, \dots, n-1\}$ , let us denote by  $t_i$  the word  $y_1 \dots y_i$ . Moreover, let  $t_0 = \varepsilon$ . We claim that for all  $i \in \{1, \dots, n\}$ , there exist a path in  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  labelled by  $x_i$  from  $(p_{i-1}, q_{i-1}, \alpha(t_{i-1}))$  to  $(p_i, q_{i-1}, \alpha(t_{i-1}))$  and for all  $i \in \{1, \dots, n-1\}$ , a path in  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  labelled by  $y_i$  from  $(p_i, q_{i-1}, \alpha(t_{i-1}))$  to  $(p_i, q_i, \alpha(t_i))$ .



Let  $i$  be in  $\{1, \dots, n\}$ . Since for all  $j$  such that  $1 \leq j < i$ ,  $\alpha(x_i) \times \alpha(y_j) \subseteq R$ , one has  $\alpha(x_i) \times \alpha(t_{i-1}) \subseteq R$ . Thus, by definition of  $p_{i-1}, p_i, q_{i-1}$  and by construction of  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$ , there exists a path in  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  labelled by  $x_i$  from  $(p_{i-1}, q_{i-1}, \alpha(t_{i-1}))$  to  $(p_i, q_{i-1}, \alpha(t_{i-1}))$ . Furthermore, by definition of  $q_{i-1}, p_i, q_i$  and by construction of  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$ , there exists a path in  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  labelled by  $y_i$  from  $(p_i, q_{i-1}, \alpha(t_{i-1}))$  to  $(p_i, q_i, \alpha(t_i))$ , proving the claim.

Now, let  $a$  be the first letter of  $y_n$  and set  $y_n = ay'_n$ . By definition of  $q_{n-1}$  and  $q_n$  there exists a state  $q'_n \in Q_2$  such that  $(q_{n-1}, a, q_n) \in E_2$  and such that there exists an infinite path from  $q'_n$  labelled by  $y'_n$  and visiting infinitely many often  $q'_n$ . Since  $p_n$  is final in  $\mathcal{A}_1$ , there exists in  $\mathcal{A}$  a transition from  $(p_n, q_{n-1}, \alpha(y_1 \dots y_{n-1}))$  to  $q'_n$  labelled by  $a$ . Consequently,

there exists an infinite path in  $\mathcal{A}$  from  $(p_n, q_{n-1}, \alpha(y_1 \dots y_{n-1}))$  labelled by  $y_n$  and visiting infinitely many often  $q_n$ . It results that  $z \in L(\mathcal{A})$ , which concludes the proof.  $\square$

### 3 Permutation Rewriting and Polynomial Closure of Commutative Regular Languages

In this section the main stability results of the paper are proved.

A regular language on finite words is commutative if and only if its minimal automaton is a diamond automaton. It is obvious that all languages and  $\omega$ -languages accepted by diamond automata are  $R$ -closed for all semi-commutation relations.

The class  $\text{PolC}$  (polynomial closure of commutative regular languages) is composed of finite union of languages of the form  $L_0 a_0 L_1 a_1 \dots a_k L_k$  where the  $a_i$ 's are letters and the  $L_i$ 's are commutative regular languages.

One has the following result [CHM03].

**Theorem 3** *The class  $\text{PolC}$  is closed under semi-commutation.*

Recall that  $\omega - \text{PolC}$  is the class of  $\omega$ -languages which are a finite union of languages of the form

$$L_0^* a_1 L_2 \dots a_{k-1} L_{k-1} a_k L_k$$

where the  $a_i$ 's are letters of  $A$  and the  $L_i$ 's ( $i < k$ ) are commutative regular languages and  $L_k$  is accepted by a diamond Büchi automaton.

Following results in [BMT07], we also introduce the following class of regular  $\omega$ -languages which is the infinite words version of APC or of languages of level 3/2 in Straubing's hierarchy [Thé81, Str85].

**Proposition 4** *Let  $L$  be a regular  $\omega$ -language. The following propositions are equivalent:*

- (1)  *$L$  is a finite union of languages of the form*

$$A_0^* a_1 A_2^* \dots a_{k-1} A_{k-1}^* a_k A_k^\omega$$

*where the  $a_i$ 's are letters of  $A$  and the  $A_i$ 's are subsets of  $A$ .*

- (2)  *$L$  is recognized by a partially ordered Büchi automaton.*

*This class of  $\omega$ -languages is called  $\omega$ -alphabetic pattern constraints and is denoted  $\omega\text{-APC}$ .*

The proof is obvious and left to the reader.

**Theorem 5** *The classes  $\omega\text{-APC}$  and  $\omega - \text{PolC}$  are closed under semi-commutations.*

The proof of Theorem 5 is obtained thanks to the sequence of lemmas below.

**Lemma 6** Let  $\mathcal{A} = (Q, A, E, I, F)$  be a finite automaton,  $L_1, L_2$  be two languages on  $A$  and  $R$  a semi-commutation relation over  $A$ . The following equality holds:

$$L_1 L_2 \sqcup_R L(\mathcal{A}) = \cup_{q \in Q} ((L_1 \sqcup_R (L(\mathcal{A}_{I,q}) \cap B^*)) ((L_2 \cap C^*) \sqcup_R L_\omega(\mathcal{A}_{q,F})))$$

where the union is taken for all subsets  $B$  and  $C$  of  $A$  such that  $C \times B \subseteq R$ .

PROOF. Let  $q \in Q$  and  $u \in ((L_1 \sqcup_R (L(\mathcal{A}_{I,q}) \cap B^*)) ((L_2 \cap C^*) \sqcup_R L_\omega(\mathcal{A}_{q,F})))$ , with  $C \times B \subseteq R$ . Then  $u$  can be decomposed into:

$$u = x_1 y_1 \dots x_n y_n z_1 t_1 \dots z_k t_k$$

such that

- (1)  $x_1 \dots x_n \in L_1, y_1 \dots y_n \in L(\mathcal{A}_{I,q}) \cap B^*$ ,
- (2) for all  $1 \leq j < i \leq n, \alpha(x_i) \times \alpha(y_j) \subseteq R$ ,
- (3)  $z_1 \dots z_k \in L_2 \cap C^*, t_1 \dots t_k \in L(\mathcal{A}_{q,F})$ ,
- (4) for all  $1 \leq j < i \leq k, \alpha(z_i) \times \alpha(t_j) \subseteq R$ ,

Since  $C \times B \subseteq R$  and by (1) and (3), for all  $1 \leq i \leq n$  and for all  $1 \leq j \leq k, \alpha(z_j) \times \alpha(y_i) \subseteq R$ . Consequently and by (2) and (4),  $u \in L_1 L_2 \sqcup_R L_\omega(\mathcal{A})$ .

Conversely, let  $u \in L_1 L_2 \sqcup_R L_\omega(\mathcal{A})$ . By definition of the R-shuffle, there exist  $x_1, \dots, x_{n-1}, y_1, \dots, y_n \in A^*$  and  $x_n \in A^\omega$  such that

- (5)  $u = y_1 x_1 \dots y_n x_n$
- (6) for all  $1 \leq j < i \leq n, \alpha(x_j) \times \alpha(y_i) \subseteq R$ ,
- (7)  $x_1 \dots x_n \in L_\omega(\mathcal{A})$ ,
- (8)  $y_1 \dots y_n \in L_1 L_2$ .

Statement (8) implies that there is  $1 \leq k \leq n$  such that  $y_k$  may be decomposed into  $y_k = st$ , with  $s, t \in A^*$  and  $y_1 \dots y_{k-1} s \in L_1$  and  $ty_{k+1} \dots y_n \in L_2$ . Statement (7) implies that there exists a state  $q$  such that  $x_1 \dots x_k \in L(\mathcal{A}_{I,q})$  and  $x_{k+1} \dots x_n \in L_\omega(\mathcal{A}_{q,F})$ . Now, by (5) and (6),

$$y_1 x_1 y_2 \dots x_{k-1} y_{k-1} s \in L_1 \sqcup_R (L(\mathcal{A}_{I,q}) \cap \alpha(x_1 \dots x_{k-1})^*)$$

and

$$tx_{k+1} y_{k+1} \dots y_n x_n \in (L_2 \cap \alpha(ty_{k+1} \dots y_n)^*) \sqcup_R L(\mathcal{A}_{q,F})$$

By (6),  $\alpha(x_1 \dots x_k) \times \alpha(ty_{k+1} \dots y_n) \subseteq R$ , which concludes the proof.  $\square$

**Lemma 7** *Let  $\mathcal{A}_1 = (Q_1, A, E_1, I_1, F_1)$  and  $\mathcal{A}_2 = (Q_2, A, E_2, I_2, F_2)$  be two finite automata and  $R$  a semi-commutation relation over  $A$ . If  $\mathcal{A}_1$  and  $\mathcal{A}_2$  are diamond automata, then  $L_\omega(\mathcal{A}_1 \sqcup_R \mathcal{A}_2) \in \omega - \text{PolC}$ .*

PROOF. Let  $\mathcal{A} = (Q, A, E, I, F)$  be the trim automaton obtained from  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$ . For all subsets  $B$  of  $\alpha(L(\mathcal{A}_2))$ , we denote by  $Q_B$  the subset  $\{(q_1, q_2, B) \mid q_1 \in Q_1, q_2 \in Q_2\}$  of  $Q$  and by  $E_B$  the subset  $E \cap Q_B \times A \times Q_B$  of  $E$ .

Let  $t = ((p, q, C), a, (p', q', D)) \in E \setminus \cup_{B \subseteq A} E_B$ . We claim that there is no loop in  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  using  $t$ : since  $C \subsetneq D$  all states accessible from  $(p', q', D)$  are of the form  $(r, s, B)$ , with  $D \subseteq B$ .

Each successful path  $m$  in  $\mathcal{A}_1 \sqcup_R \mathcal{A}_2$  can be decomposed into:

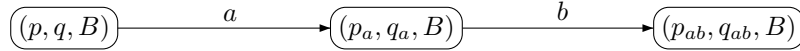
$$m = m_0, t_1, m_1, t_2, \dots, t_n, m_n, t, m_\omega$$

with  $t_i \in E \setminus \cup_{B \subseteq A} E_B$  and  $m_i$  only using transitions of  $E_{B_i}$ , for all  $0 \leq i \leq n$ . Using the above claim, we have  $n \leq |E \setminus \cup_{B \subseteq A} E_B|$ . Consequently,  $L(\mathcal{A}_1 \sqcup_R \mathcal{A}_2)$  is a finite union of languages of the form:

$$L_0 a_1 L_1 a_2 \dots a_n L_n a L$$

where the  $a_i$ 's are letters and the  $L_i$ 's are accepted by finite automata whose graphs of transitions are  $(Q_{B_i}, E_{B_i})$ ,  $a$  is the label of  $t$  and  $L$  is accepted by finite automata whose graphs of transitions  $(Q_2, E_2)$ .

By Lemma 1, it remains to prove that the  $L_i$ 's are commutative languages and that  $L$  is accepted by a diamond automaton. Since  $\mathcal{A}_2$  is a diamond automaton,  $L$  is accepted by a diamond automaton. Now, let  $B \subseteq A$ , we prove that the monoid of transitions generated by  $(Q_B, E_B)$  is commutative. Let  $r = (p, q, B)$ ,  $r_a = (p_a, q_a, B)$  and  $r_{ab} = (p_{ab}, q_{ab}, B)$  be three states of  $Q_B$  such that there exist transitions  $t_a = (r, a, r_a)$  and  $t_{ab} = (r_a, b, r_{ab})$  in  $E_B$ .



With the notation of the proof of Proposition 2, the following cases occur:

- $t_a, t_{ab} \in G_1$ . Since  $\mathcal{A}_1$  is minimal and since  $L(\mathcal{A}_1)$  is commutative, the transition monoid of  $\mathcal{A}_1$  is commutative. Thus there exists  $p_b$  in  $Q_1$  such that  $p \cdot b = p_b$  and  $p_b \cdot a = p_{ab}$ . Moreover, since  $t_a$  and  $t_b$  belong to  $G_1$ ,  $\{a\} \times B \subseteq R$  and  $\{b\} \times B \subseteq R$ . Consequently,  $(r, b, (p_b, q, B))$  and  $((p_b, q, B), a, r_{ab})$  are in  $G_1 \cap E_B$ . It follows that  $r_{ab} \in r \cdot ba$ .
- $t_a, t_{ab} \in G_2$ . By a similar argument on  $\mathcal{A}_2$ , one has  $r_{ab} \in r \cdot ba$ .
- $t_a \in G_1, t_{ab} \in G_2$ . Thus  $q_a = q$  and  $p_{ab} = p_a$ . Consequently  $(r, b, (p, q_{ab}, B)) \in G_2 \cap E_B$  and  $((p, q_{ab}, B), a, r_{ab}) \in G_1 \cap E_B$ . It follows that  $r_{ab} \in r \cdot ba$ .
- $t_a \in G_2, t_{ab} \in G_1$ . By a similar argument on  $\mathcal{A}_2$ , one has  $r_{ab} \in r \cdot ba$ .



Consequently  $r \cdot ab \subseteq r \cdot ba$ . Since the roles of  $a$  and  $b$  are symmetric,  $r \cdot ba \subseteq r \cdot ab$ . Therefore, the monoid of transitions generated by  $(Q_B, E_B)$  is commutative, which concludes the proof.  $\square$

**Lemma 8** *Let  $K$  be a language of  $\text{PolC}$  and  $\mathcal{A}$  a diamond automaton. Then  $K \sqcup_R L(\mathcal{A})$  belongs to  $\omega - \text{PolC}$ .*

PROOF. For each regular language  $K$  and each  $\omega$ -language  $L$ , one has: if  $\varepsilon \in K$ , then  $KL = L \cup_{a \in A} (Ka^{-1})aL$ , and if  $\varepsilon \notin K$ , then  $KL = \cup_{a \in A} (Ka^{-1})aL$ , with  $Ka^{-1} = \{v \in A^* \mid va \in K\}$ . Moreover, since the class of languages accepted by diamond automata forms a variety of regular languages, if  $Ka^{-1}$  is accepted by a diamond automaton too.

Now Lemma can be proved by a direct trivial induction using Lemma 7.  $\square$

The same proof works for the following lemma.

**Lemma 9** *Let  $K$  be an APC language and  $L$  a language of the form  $B^\omega$ , where  $B \subseteq A$ . Then  $K \sqcup_R L$  belongs to  $\omega\text{-APC}$ .*

One can now prove Theorem 5.

PROOF. Let  $R$  be a semi-commutation relation.

We just give the proof for  $\omega - \text{PolC}$  languages. The same proof works for  $\omega\text{-APC}$ .

Since for all sets  $H$  and  $I$  of  $A^\omega$ ,  $R^*(H \cup I) = R^*(H) \cup R^*(I)$ , we only have to prove the result for languages of the form  $L = L_0 a_1 L_1 \dots a_k L_k a_{k+1} L_{k+1}$ , where the  $L_i$ 's are accepted by diamond automata and the  $a_i$ 's are letters.

Now, by Proposition 1, one has

$$R^*(L) = R^*(L_0 a_1 L_1 \dots a_k L_k a_{k+1}) \sqcup_R L_{k+1}.$$

Using Theorem 3, one has  $R^*(L_0 a_1 L_1 \dots a_k L_k a_{k+1})$  belongs to  $\text{PolC}$ , and we conclude by Lemma 8.  $\square$

## 4 Conclusion

The results presented in this paper improve recent works by Bouajjani, Muscholl and Touili on one hand, and by Cécé, Héam and Mainier on the other hand, by extending them to infinite words.

We intend to investigate practical applications of this work, particularly for HMSC's formal verification. As far as we know, several connected theoretical problems remains open: are the classes  $\omega\text{-APC}$ ,  $\omega - \text{PolC}$  and  $\text{PolC}$  decidable (the class  $\text{APC}$  is decidable [Arf91]). Another difficult related problem is, given a language of  $\omega - \text{PolC}$ , to decompose it into a finite union of products of languages accepted by diamond automata. The same problem faces for  $\text{PolC}$ , while an inefficient algorithm exists for  $\text{APC}$ . This kind of problems generally requires deep semi-groups theory arguments, see [Pin87, Pin94] for instance.

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