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THE INTERSECTION PROBLEM FOR ALPHABETIC VECTOR MONOIDS

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Abstract. – Let Σ and Γ be two vector alphabets consisting of alphabetic vectors (a_1, a_2) , where $a_1, a_2 \in A \cup \{\varepsilon\}$ for an alphabet A . We show that it is decidable whether or not $\Sigma^{\otimes} \cap \Gamma^{\otimes}$ is the trivial submonoid of the direct product $A^* \times A^*$ for the generated submonoids Σ^{\otimes} and Γ^{\otimes} . On the other hand we show that a simple version, obtained from letter-to-letter homomorphisms, of the modified Post Correspondence Problem is undecidable for alphabetic vectors.

1. INTRODUCTION

Let A be a finite alphabet. Denote by A^* the free monoid generated by A , and let $A^* \times A^* = \{(u_1, u_2) | u_i \in A^*\}$ be the direct product of A^* with itself. Each element $u = (u_1, u_2)$ is called a *vector* over A^* . For a subset $\Sigma \subseteq A^* \times A^*$ we let Σ^{\otimes} be the submonoid of $A^* \times A^*$ generated by Σ . The identity of Σ^{\otimes} is $\epsilon = (\varepsilon, \varepsilon)$, where ε is the empty word of A^* .

Further, let Σ^* denote the free monoid generated by the vectors from Σ . In this case Σ is considered to be an alphabet and hence each element $u = (u_{11}, u_{12}) \dots (u_{k1}, u_{k2})$ of Σ^* is just a word of vectors.

We shall consider the *intersection problem* for the submonoids of $A^* \times A^*$, i. e., whether or not $\Sigma^{\otimes} \cap \Gamma^{\otimes} = \{\epsilon\}$ for the submonoids Σ^{\otimes} and Γ^{\otimes} generated by the given subsets Σ and Γ of $A^* \times A^*$, respectively. The pair (Σ, Γ) is referred to as an *instance* of the intersection problem.

We observe that in general the intersection problem is undecidable, because for a pair of homomorphisms (α, β) , $\alpha, \beta : B^* \rightarrow C^*$, we choose $A = B \cup C$

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and define the generator sets as follows: $\Sigma = \{(a, \alpha(a)) \mid a \in B\}$ and $\Gamma = \{(a, \beta(a)) \mid a \in B\}$. Clearly, now $\Sigma^\otimes \cap \Gamma^\otimes \neq \{\epsilon\}$ if and only if the instance (α, β) of Post Correspondence Problem (PCP) has a solution.

We shall now restrict the instances (Σ, Γ) to cases, where the vectors are alphabetic. A vector $u = (u_1, u_2) \in A^* \times A^*$ is called *alphabetic*, if each of its components u_i is either a letter or the empty word ϵ : $u_i \in A \cup \{\epsilon\}$. In particular, the identity $\epsilon = (\epsilon, \epsilon)$ of $A^* \times A^*$ is an alphabetic vector.

Let $\Delta(A)$ denote the set of all alphabetic vectors over A^* . Notice that here $\Delta(A)^\otimes = A^* \times A^*$, because the alphabetic vectors clearly generate $A^* \times A^*$. We say that Σ^\otimes is an *alphabetic submonoid* of $A^* \times A^*$, if $\Sigma \subseteq \Delta(A)$.

Let $h_A : \Delta(A)^* \rightarrow A^* \times A^*$ be the monoid homomorphism defined by $h_A(a_1, a_2) = (a_1, a_2)$ for all $(a_1, a_2) \in \Delta(A)$. We shall write $u \equiv v$ for the words $u, v \in \Delta(A)^*$, if they produce the same element of the direct product, i. e., if $h_A(u) = h_A(v)$. Thus given two sets Σ and Γ of alphabetic vectors, the problem is to determine whether or not there exists a pair $(u, v) \in \Sigma^* \times \Gamma^*$ such that $u \equiv v$. Such a pair (u, v) will be referred to as a *solution* of the instance (Σ, Γ) .

Alphabetic submonoids occur in, e. g., [1], [3], [4], (see also their references for related work) where concurrent systems with a vector synchronization mechanism are studied. Such a concurrent system consists of a fixed, say n , number of sequential processes together with a control on their mutual synchronization. We shall now discuss only the simplest of these cases, $n = 2$.

The behaviour of the i -th sequential process is given as a language L_i over some alphabet A of actions. The basic units of the synchronization are alphabetic vectors which express which actions can be performed simultaneously in the system. These *synchronization vectors* form a set Σ . If Σ^* is used as the synchronization mechanism, then the valid concurrent computations of the system are those combinations (w_1, w_2) of computations $w_i \in L_i$ which have a decomposition in Σ^* : there is a $v \in \Sigma^*$ such that $h_A(v) = (w_1, w_2)$. Or, to put it differently, the set of concurrent computations is $(L_1 \times L_2) \cap \Sigma^\otimes$. If another set Γ of synchronization vectors is used, the question arises whether or not the new and the old system have common computations: is $(L_1 \times L_2) \cap (\Sigma^\otimes \cap \Gamma^\otimes)$ nontrivial? Again this question is undecidable by a reduction from PCP, even in the case that the sets L_i are regular languages. To see this, let (α, β) be a pair of homomorphisms $\alpha, \beta : B^* \rightarrow C^*$ with B and C disjoint. Let $A = B \cup C$, and set $L_1 = \{b\alpha(b) \mid b \in B\}^*$ and

$L_2 = \{b\beta(b)|b \in B\}^*$, $\Sigma = \{(b, b)|b \in B\} \cup \{(c, \epsilon), (\epsilon, c)|c \in C\}$, and $\Gamma = \{(c, c)|c \in C\} \cup \{(b, \epsilon), (\epsilon, b)|b \in B\}$. Clearly, the instance (α, β) of PCP has a solution if and only if $(L_1 \times L_2) \cap (\Sigma^{\otimes} \cap \Gamma^{\otimes}) \neq \{\epsilon\}$.

In this reduction the languages L_1 and L_2 play a crucial role. If we assume that they both are A^* , then we are asking whether or not Σ^{\otimes} and Γ^{\otimes} have a non-trivial intersection. This is the question considered in this paper.

In Section 2 we shall prove that the intersection problem is decidable for alphabetic submonoids: Given two alphabetic submonoids Σ^{\otimes} and Γ^{\otimes} of $A^* \times A^*$, the problem whether or not $\Sigma^{\otimes} \cap \Gamma^{\otimes} = \{\epsilon\}$ is decidable.

An easy consequence of this result is that PCP is decidable when restricted to instances (α, β) , where α and β are weak codings, i. e., $\alpha, \beta : X^* \rightarrow A^*$ are such that $\alpha(a), \beta(a) \in A \cup \{\epsilon\}$ for all a in X .

In Section 3 we consider the following variant of PCP: let $\alpha, \beta : X^* \rightarrow \Delta(A)^*$ be two homomorphisms that are letter-to-letter, i. e., for each letter $a \in X$, $\alpha(a)$ and $\beta(a)$ are alphabetic vectors. Let $x, y \in X$ be two distinguished *border letters*. In the *alphabetic bordered PCP* we ask whether or not there exists a word $w = xuy$ in X^* with $u \in (X \setminus \{x, y\})^*$ such that $\alpha(w) \equiv \beta(w)$. This problem is shown to be undecidable and thus contrasts with the result from Section 2.

2. THE INTERSECTION PROBLEM IS DECIDABLE

In this section we prove

THEOREM 1: *Let A be a finite alphabet. Given two alphabetic submonoids Σ^{\otimes} and Γ^{\otimes} of $A^* \times A^*$, the problem whether or not $\Sigma^{\otimes} \cap \Gamma^{\otimes} = \{\epsilon\}$ is decidable.*

Let us fix two alphabetic submonoids Σ^{\otimes} and Γ^{\otimes} of $A^* \times A^*$. We shall show that $\Sigma^{\otimes} \cap \Gamma^{\otimes} \neq \{\epsilon\}$ if and only if there is a solution (u, v) for the instance (Σ, Γ) such that the length $|u|$ of u is at most the cardinality $|\Sigma|$ of Σ .

We can clearly assume that $(\epsilon, \epsilon) \notin \Sigma \cup \Gamma$, and further that $\Sigma \cap \Gamma = \emptyset$, for otherwise we can check trivially that $\Sigma^{\otimes} \cap \Gamma^{\otimes} \neq \{\epsilon\}$.

Suppose that $u \equiv v$ is a nontrivial solution for $u \in \Sigma^*$ and $v \in \Gamma^*$ with $u, v \neq \epsilon$. We let

$$u = (a_1, b_1)(a_2, b_2) \dots (a_k, b_k) \quad \text{and} \quad v = (c_1, d_1)(c_2, d_2) \dots (c_t, d_t)$$

for $(a_i, b_i) \in \Sigma$ and $(c_i, d_i) \in \Gamma$. Assume further that u is of minimal length, that is, the number $k \geq 1$ of components of u is as small as possible.

First of all we can restrict the components of u as follows:

(1) $a_1 \neq \varepsilon$. Indeed, if $a_1 = \varepsilon$, then $b_1 \neq \varepsilon$ and we can consider the generators $\Sigma^{-1} = \{(b, a) | (a, b) \in \Sigma\}$ and $\Gamma^{-1} = \{(b, a) | (a, b) \in \Gamma\}$ instead of Σ and Γ , respectively. Clearly, $\Sigma^\otimes \cap \Gamma^\otimes \neq \{\varepsilon\}$ if and only if $(\Sigma^{-1})^\otimes \cap (\Gamma^{-1})^\otimes \neq \{\varepsilon\}$.

(2) $b_1 = \varepsilon$. Indeed, if $b_1 \neq \varepsilon$, then the first decomposing vector $v_1 = (c_1, d_1)$ for v would have to be either (a_1, ε) or (ε, b_1) , since $(a_1, b_1) \in \Sigma$ and $\Sigma \cap \Gamma = \emptyset$. In the former of these cases, we may exchange Σ and Γ , and in the latter case we interchange Σ to Γ^{-1} and Γ to Σ^{-1} in order for (1) and (2) to be satisfied.

Now, since

$$h_A(u) = (a_1 a_2 \dots a_k, b_1 b_2 \dots b_k) = (c_1 c_2 \dots c_t, d_1 d_2 \dots d_t) = h_A(v),$$

there are order preserving bijections $\alpha : \{i | a_i \neq \varepsilon\} \rightarrow \{i | c_i \neq \varepsilon\}$ and $\beta : \{i | d_i \neq \varepsilon\} \rightarrow \{i | b_i \neq \varepsilon\}$ such that $a_i = c_{\alpha(i)}$ and $d_i = b_{\beta(i)}$.

Consider the word

$$w = (a_1, b_{\beta\alpha(1)}) (a_{\beta\alpha(1)}, b_{(\beta\alpha)^2(1)}) \dots (a_{(\beta\alpha)^r(1)}, b_{(\beta\alpha)^{r+1}(1)}) \dots (a_{(\beta\alpha)^{r-1}(1)}, b_{(\beta\alpha)^r(1)})$$

obtained from a_1 by repeating the functions α and β until either of them becomes undefined, i. e., until

(a) $a_{(\beta\alpha)^r(1)} = \varepsilon$, or

(b) $d_{\alpha(\beta\alpha)^r(1)} = \varepsilon$.

Notice that since α and β are order preserving bijections and $(a_1, b_1) \neq (c_1, d_1)$, the exponent r is always well-defined in above.

A pictorial representation of forming this word in Case (a) is given in figure 1.

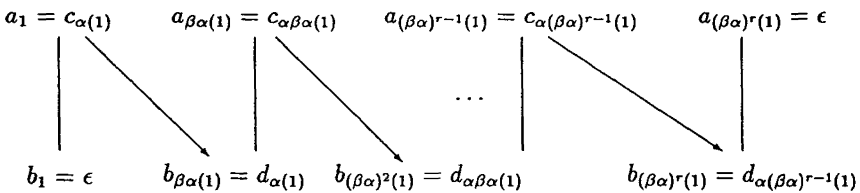


Figure 1.

Now, by the definitions of the bijections α and β ,

$$w = (c_\alpha(1), d_\alpha(1)) (c_{\alpha\beta\alpha}(1), d_{\alpha\beta\alpha}(1)) \dots (c_{\alpha(\beta\alpha)^{r-1}}(1), d_{\alpha(\beta\alpha)^{r-1}}(1)),$$

and hence $w \in \Gamma^*$.

We shall first consider Case (a). For this define

$$w_a = (a_1, \varepsilon)(a_{\beta\alpha}(1), b_{\beta\alpha}(1)) \dots (a_{(\beta\alpha)^{r-1}}(1), b_{(\beta\alpha)^{r-1}}(1)) \dots (\varepsilon, b_{(\beta\alpha)^r}(1)).$$

We have $w_a \in \Sigma^*$ and, moreover, $\omega_a \equiv w$. Thus in this case $h_A(w_a) \in \Sigma^\otimes \cap \Gamma^\otimes$ gives also a solution.

By the minimality assumption for u , it follows that $u = w_a$, and hence that $\alpha(i) = i$ and $\beta(i) = i + 1$, i. e.,

$$\begin{aligned} u &= (a_1, \varepsilon) (a_2, b_2) \dots (a_{k-1}, b_{k-1}) (\varepsilon, b_k), \\ v &= (a_1, b_2) (a_2, b_3) \dots (a_{k-1}, b_k) \end{aligned}$$

for nonempty letters $a_i, b_i \in A$.

Similarly, in Case (b) for the word

$$\begin{aligned} w_b &= (a_1, \varepsilon) (a_{\beta\alpha}(1), b_{\beta\alpha}(1)) \\ &\dots (a_{(\beta\alpha)^{r-1}}(1), b_{(\beta\alpha)^{r-1}}(1)) (a_{(\beta\alpha)^r}(1), b_{(\beta\alpha)^r}(1)), \end{aligned}$$

we have $h_A(w_b) \in \Sigma^\otimes \cap \Gamma^\otimes$. In this case, we obtain that

$$\begin{aligned} u &= (a_1, \varepsilon) (a_2, b_2) \dots (a_{k-1}, b_{k-1}) (a_k, b_k), \\ v &= (a_1, b_2) (a_2, b_3) \dots (a_{k-1}, b_k) (a_k, \varepsilon) \end{aligned}$$

for nonempty letters $a_i, b_i \in A$.

In both of these cases it is easy to see that if $u = w_1 \cdot (a_i, b_i) \cdot w_2 \cdot (a_j, b_j) \cdot w_3$, where $(a_i, b_i) = (a_j, b_j)$ for some indices i, j with $i < j$, then $w_1 (a_i, b_i) w_3$ provides another solution. We deduce from this that a minimal solution u has length at most the cardinality of the alphabet Σ . This shows that it is decidable whether or not $\Sigma^\otimes \cap \Gamma^\otimes = \{\epsilon\}$, and hence Theorem 1 is proved.

3. UNDECIDABILITY OF ALPHABETIC BORDERED PCP

In the proof of the undecidability of the alphabetic bordered PCP we use the following modification of Post's Correspondence Problem.

Let $\alpha, \beta : X^* \rightarrow X^*$ be two nonerasing homomorphisms for an alphabet X . We shall say the pair (α, β) is a *bordered instance*, if there are two special letter $c, d \in X$ such that for $B = X \setminus \{c, d\}$,

$$\begin{aligned} \alpha(c), \beta(c) \in c \cdot B^* \quad \text{and} \quad \alpha(d), \beta(d) \in B^* \cdot d, \\ \alpha(a), \beta(a) \in B^* \quad (a \in B). \end{aligned}$$

LEMMA: *It is undecidable whether or not there exists a word $w \in B^*$ such that $\alpha(cwd) = \beta(cwd)$ for a given bordered instance (α, β) of homomorphisms.*

The proof is standard, see [2] and omitted here.

We now prove

THEOREM 2: *The alphabetic bordered PCP is undecidable.*

Let then (α, β) be a bordered instance of homomorphisms as above. Set $X = \{a_1, a_2, \dots, a_N\}$, where $a_1 = c$, $a_N = d$ and $B = \{a_2, \dots, a_{N-1}\}$. Define

$$M = \max\{|\alpha(a_i)|, |\beta(a_i)| \mid i = 1, 2, \dots, N\},$$

and write $\alpha(a_i) = \alpha_{i1}\alpha_{i2} \dots \alpha_{iM}$ and $\beta(a_j) = \beta_{j1}\beta_{j2} \dots \beta_{jM}$, where $\alpha_{ij}, \beta_{ij} \in X \cup \{\varepsilon\}$ and $\alpha_{11} = c = \beta_{11}$, $\alpha_{NM} = d = \beta_{NM}$. Clearly, we may assume that $M > 1$.

Further, let

$$\begin{aligned} D_1 &= \{[i, j] \mid 1 \leq i \leq N, 1 \leq j \leq M\}, \\ D_2 &= \{[i, j], [i, 1, k] \mid 1 \leq i, k \leq N, 2 \leq j \leq M\} \end{aligned}$$

be two new alphabets. Our basic alphabet for the components of the vectors will be $A = X \cup D_1$. Define two homomorphisms $\alpha_1, \beta_1 : D_2^* \rightarrow \Delta(A)^*$ as follows:

$$\begin{aligned} \alpha_1([1, 1, 1]) &= (\alpha_{11}, \varepsilon), \\ \alpha_1([i, 1, k]) &= (a_{i1}, [k, M]), \quad (i \neq 1), \\ \alpha_1([i, j]) &= (\alpha_{ij}, [i, j-1]), \quad ((i, j) \neq (1, 1)), \end{aligned}$$

and

$$\begin{aligned} \beta_1([i, 1, k]) &= (\beta_{i1}, [i, 1]), \\ \beta_1([i, j]) &= (\beta_{ij}, [i, j]), \quad ((i, j) \neq (N, M)), \\ \beta_1([N, M]) &= (\beta_{NM}, \varepsilon). \end{aligned}$$

Clearly, both of these homomorphisms map letters to alphabetic vectors, *i. e.*, they are letter-to-letter homomorphisms.

Consider the instance (α_1, β_1) with border letters $[1, 1, 1]$ and $[N, M]$, and define for each word $w = a_1 a_{i_1} \dots a_{i_m} a_N \in cB^*d$, the word $\tau(w) = u_1 u_{i_1} \dots u_{i_m} u_N$, where

$$u_1 = [1, 1, 1] [1, 2] \dots [1, M], \quad u_N = [N, 1, i_m] [N, 2] \dots [N, M]$$

$$u_{i_j} = [i_j, 1, i_{j-1}] [i_j, 2] \dots [i_j, M].$$

We observe that

$$\alpha_1(u_1) \equiv (\alpha(a_1), [1, 1] \dots [1, M-1]),$$

$$\beta_1(u_1) \equiv (\beta(a_1), [1, 1] \dots [1, M]),$$

$$\alpha_1(u_{i_j}) \equiv (\alpha(a_{i_j}), [i_{j-1}, M] [i_j, 1] \dots [i_j, M-1]),$$

$$\beta_1(u_{i_j}) \equiv (\beta(a_{i_j}), [i_j, 1] [i_j, 2] \dots [i_j, M]),$$

$$\alpha_1(u_N) \equiv (\alpha(a_N), [i_m, M] \dots [N, 1], [N, M-1]),$$

$$\beta_1(u_N) \equiv (\beta(a_N), [N, 1] [N, 2] \dots [N, M-1]).$$

From these it is now straightforward to show that for all $u \in cB^*d$, $\alpha(u) = \beta(u)$ if and only if $\alpha_1(\tau(u)) \equiv \beta_1(\tau(u))$. Moreover, if v is a solution to the instance (α_1, β_1) of the alphabetic bordered PCP, then one can easily construct a word $u \in cB^*d$ such that $v = \tau(u)$. This proves Theorem 2.

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