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# Vector Addition System Reachability Problem (In Few Pages)

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## Abstract

The reachability problem for Vector Addition Systems (VASs) is a central problem of net theory. The general problem is known decidable by algorithms exclusively based on the classical Kosaraju-Lambert-Mayr-Sacerdote-Tenney decomposition. Recently from this decomposition, we deduced that a final configuration is not reachable from an initial one if and only if there exists a Presburger inductive invariant that contains the initial configuration but not the final one. Since we can decide if a Presburger formula denotes an inductive invariant, we deduce from this result that there exist checkable certificates of non-reachability. In particular, there exists a simple algorithm for deciding the general VAS reachability problem based on two semi-algorithms. A first one that tries to prove the reachability by enumerating finite sequences of actions and a second one that tries to prove the non-reachability by enumerating Presburger formulas. In this paper we provide the first proof of the VAS reachability problem that is not based on the classical Kosaraju-Lambert-Mayr-Sacerdote-Tenney decomposition. The new proof is based on the notion of productive sequences inspired from Hauschildt that directly provides the existence of Presburger inductive invariants.

## 1. Introduction

Vector Addition Systems (VASs) or equivalently Petri Nets are one of the most popular formal methods for the representation and the analysis of parallel processes [EN94]. The reachability problem is central since many computational problems (even outside the parallel processes) reduce to the reachability problem. Sacerdote and Tenney provided in [ST77] a partial proof of decidability of this problem. The proof was completed in 1981 by Mayr [May81] and simplified by Kosaraju [Kos82] from [ST77, May81]. Ten years later [Lam92], Lambert provided a more simplified version based on [Kos82]. This last proof still remains difficult and the upper-bound complexity of the corresponding algorithm is just known non-primitive recursive. Nowadays, the exact complexity of the reachability problem for VASs is still an open-problem. Even an elementary upper-bound complexity is open. In fact, the known general reachability algorithms are exclusively based on the Kosaraju-Lambert-Mayr-Sacerdote-Tenney (KLMST) decomposition.

Recently [Ler09] we proved thanks to the KLMST decomposition that Parikh images of languages accepted by VASs are semi-pseudo-linear, a class that extends the Presburger sets. An application of this result was provided; we proved that a final configuration is not reachable from an initial one if and only if there exists a forward inductive invariant definable in the Presburger arithmetic that contains the initial configuration but not the final one. Since we can decide if a Presburger formula denotes a forward inductive invariant, we deduce that there exist checkable certificates of non-reachability. In particular, there exists a simple algorithm for deciding the general VAS reachability problem based on two semi-algorithms. A first one that tries to prove the reachability by enumerating finite sequences of actions and a second one that tries to prove the non-reachability by enumerating Presburger formulas.

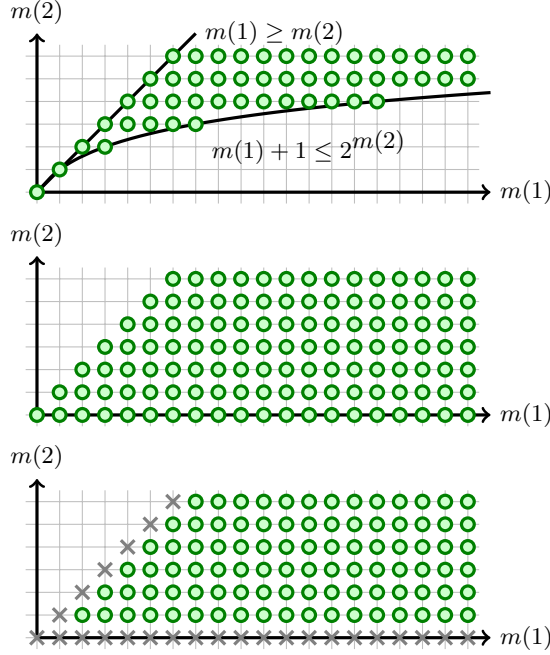
In this paper we provide a new proof of the reachability problem that is not based on the KLMST decomposition. The proof is based on the *productive sequences* inspired by Hauschildt [Hau90] and it provides directly that reachability sets are *Lambert sets*, a class of sets introduced in this paper that extend the class of Presburger sets and contained in the class of semi-pseudo-linear sets. In particular this paper provides a more precise characterization of the reachability sets of VASs.

*Outline of the paper:* Section 3 introduces the class of *Lambert sets*. Section 4 provides a sufficient condition on binary relations over  $\mathbb{N}^d$  such that there exist invariants definable in the Presburger arithmetic proving the non-reachability. Section 5 introduces the class of *Vector Addition Systems (VASs)*. Section 6 provides the definition of *productive sequences*. Finally, in Section 7 we prove that reachability sets are Lambert sets. We conclude from this result that the non-reachability problem for VAS can be solved with Presburger inductive invariants.

## 2. Notations

In the sequel  $\mathbb{N}, \mathbb{N}_{>0}, \mathbb{Z}, \mathbb{Q}, \mathbb{Q}_{>0}$  denote the set of natural numbers, positive integers, integers, rational numbers, and positive rational numbers. The  $i$ th component of a vector  $s \in X^d$  is denoted by  $s(i)$ . The addition function  $+$  and the order  $\leq$  are extended component-wise over  $\mathbb{Q}^d$ , i.e  $s \leq s'$  if  $s(i) \leq s'(i)$  for every  $i \in \{1, \dots, d\}$ . Given a function  $f : S \rightarrow S'$  we denote by  $f(X) = \{f(x) \mid x \in X\}$  for every subset  $X \subseteq S$ . In particular the sum  $S_1 + S_2$  is well defined for every  $S_1, S_2 \subseteq \mathbb{Q}^d$ . In the same way given  $T \subseteq \mathbb{Q}$  and  $S \subseteq \mathbb{Q}^d$  we let  $TS = \{ts \mid (t, s) \in T \times S\}$ . We also denote by  $s_1 + S_2$  and  $S_1 + s_2$  the sets  $\{s_1\} + S_2$  and  $S_1 + \{s_2\}$ , and we denote by  $tS$  and  $TS$  the sets  $\{t\}S$  and  $T\{s\}$ .

Given a *monoid*  $(S, \circ)$  and an element  $s \in S$ , let  $s^0$  be the neutral element and let  $s^n$  be the element in  $S$  defined for every  $n \in \mathbb{N}$  by the induction  $s^{n+1} = s^n \circ s$ . A subset  $R \subseteq S$  is called a *submonoid* of  $(S, \circ)$  if  $R$  contains the neutral element of  $(S, \circ)$



**Figure 1.** A simple monoid, a linearization  $P$ , and the interior of  $P$

and if  $r_1 \circ r_2 \in R$  for every  $r_1, r_2 \in R$ . Recall that for every  $X \subseteq S$  there exists a unique submonoid  $R$  of  $(S, \circ)$  that is minimal for the inclusion and such that  $X \subseteq R$ . This monoid is called the submonoid of  $(S, \circ)$  generated by  $X$ . A monoid  $(S, \circ)$  is said to be *finitely generated* if there exists a finite set  $X \subseteq S$  such that  $S$  is the submonoid generated by  $X$ . A *morphism* from a monoid  $(S, \circ)$  to a monoid  $(S', \circ')$  is a total function  $f : S \rightarrow S'$  such that the neutral elements  $e, e'$  of  $(S, \circ)$  and  $(S', \circ')$  satisfy  $f(e) = e'$  and such that  $f(s_1 \circ s_2) = f(s_1) \circ' f(s_2)$  for every  $s_1, s_2 \in S$ .

Given an ordered set  $(S, \sqsubseteq)$ , an element  $s \in S$  is said to be *minimal* for  $\sqsubseteq$  if for every  $s' \in S$  such that  $s' \sqsubseteq s$  we have  $s = s'$ . We denote by  $\min_{\sqsubseteq}(S)$  the set of minimal elements in  $S$ . An order  $\sqsubseteq$  over a set  $S$  is said to be *well* if for every sequence  $(s_n)_{n \in \mathbb{N}}$  of elements  $s_n \in S$  we can extract a sub-sequence that is non-decreasing for  $\sqsubseteq$ . Note that if  $(S, \sqsubseteq)$  is well-ordered then  $\min_{\sqsubseteq}(S)$  is finite and for every  $s' \in S$  there exists a minimal element  $s \in S$  such that  $s \sqsubseteq s'$ .

### 3. Lambert Sets

A subset  $M \subseteq \mathbb{N}^d$  is called a *Presburger set* if it can be denoted by a formula in the Presburger arithmetic  $\text{FO}(\mathbb{N}, +, \leq)$ . Let us recall [GS66] that a subset  $M \subseteq \mathbb{N}^d$  is Presburger if and only if it is a finite union of *linear sets*, i.e. sets of the form  $b + P$  where  $b \in \mathbb{N}^d$  and  $P$  is a finitely generated submonoid of  $(\mathbb{N}^d, +)$ . In this section we introduce the class of *simple submonoids* of  $(\mathbb{N}^d, +)$  that extends the finitely generated submonoids, and the class of *Lambert sets* defined as the finite unions of sets  $b + S$  where  $b \in \mathbb{N}^d$  and  $S$  is a simple submonoid of  $(\mathbb{N}^d, +)$ .

Let  $P$  be a finitely generated submonoid of  $(\mathbb{N}^d, +)$ . A vector  $v \in P$  is said to be in the *interior* of  $P$  if for any  $p \in P$  there exists  $n \in \mathbb{N}_{>0}$  such that  $nv \in p + P$ . The set of interior vectors of  $(P, +)$  is denoted by  $\text{int}(P)$ . Let  $S$  be a submonoid of  $(\mathbb{N}^d, +)$ . A *direction* of  $S$  is a vector  $v \in \mathbb{N}^d$  such that there exists  $s \in S$  satisfying  $s + \mathbb{N}v \subseteq S$ . The set of directions of  $S$

forms a submonoid of  $(\mathbb{N}^d, +)$  denoted by  $\text{dir}(S)$ . A submonoid  $S$  of  $(\mathbb{N}^d, +)$  is said to be *simple* if there exists a finitely generated submonoid  $P$  of  $(\mathbb{N}^d, +)$  such that  $S \subseteq P$  and  $\text{int}(P) \subseteq \text{dir}(S)$ . In this case  $P$  is called a *linearization* of  $S$ . A *Lambert set* is a finite union of sets of the form  $b + S$  where  $b \in \mathbb{N}^d$  and  $S$  is a simple submonoid of  $(\mathbb{N}^d, +)$ .

**Example 3.1.** The set  $S = \{m \in \mathbb{N}^2 \mid m(2) \leq m(1) \leq 2m(2) - 1\}$ , the finitely generated submonoid  $P = \{m \in \mathbb{N}^2 \mid m(2) \leq m(1)\}$  and the interior  $\text{int}(P) = \{m \in \mathbb{N}^2 \mid 0 < m(2) < m(1)\}$  are represented in Figure 1. Since  $S \subseteq P$  and  $\text{int}(P) \subseteq \text{dir}(S)$  we deduce that  $S$  is a simple submonoid and  $P$  is a linearization.

The following lemma provides a characterization of  $\text{int}(P)$ .

**Lemma 3.2.** Let  $P = \mathbb{N}p_1 + \dots + \mathbb{N}p_t$  with  $t \in \mathbb{N}_{>0}$  and  $p_j \in \mathbb{N}^d$ . We have  $\text{int}(P) = P \cap (\mathbb{Q}_{>0}p_1 + \dots + \mathbb{Q}_{>0}p_t)$ .

*Proof.* Let  $v \in P$ . Observe that if  $v$  is in the interior of  $P$ , as  $p = \sum_{j=1}^t p_j$  is in  $P$ , there exists  $n \in \mathbb{N}_{>0}$  such that  $nv \in p + P$ . Thus, there exists a sequence  $(n_j)_{1 \leq j \leq t}$  with  $n_j \in \mathbb{N}$  such that  $nv = p + \sum_{j=1}^t n_j p_j$ . We deduce that  $v = \sum_{j=1}^t \lambda_j p_j$  with  $\lambda_j = \frac{n_j+1}{n}$ . Conversely, let us assume that  $v = \sum_{j=1}^t \lambda_j p_j$  with  $\lambda_j \in \mathbb{Q}_{>0}$ . Let  $p \in P$ . There exists a sequence  $(n_j)_{1 \leq j \leq t}$  with  $n_j \in \mathbb{N}$  such that  $p = \sum_{j=1}^t n_j p_j$ . As  $\lambda_j > 0$ , there exists an integer  $n \in \mathbb{N}_{>0}$  such that  $n\lambda_j$  is an integer satisfying  $n\lambda_j \geq n_j$  for every  $j \in \{1, \dots, t\}$ . We deduce that  $nv \in p + P$ . Thus  $v$  is in the interior of  $P$ .  $\square$

In the sequel, we used the following lemma.

**Lemma 3.3.** Let  $P$  be a linearization of a simple submonoid  $S$  of  $(\mathbb{N}^d, +)$  and let  $f$  be a morphism from  $(P, +)$  to  $(\mathbb{N}^{d'}, +)$ . Then  $S' = f(S)$  is a simple submonoid of  $(\mathbb{N}^{d'}, +)$  and  $P' = f(P)$  is a linearization of  $S'$ .

*Proof.* Since  $P$  is finitely generated, there exists a finite sequence  $(p_i)_{1 \leq i \leq t}$  of vectors  $p_i \in P$  such that  $P$  is generated by  $\{p_1, \dots, p_t\}$ . As  $P'$  is generated by  $\{f(p_1), \dots, f(p_t)\}$  we deduce that  $P'$  is finitely generated. Observe that  $S' \subseteq P'$ . In order to prove that  $S'$  is a simple submonoid and  $P'$  is a linearization of  $S'$ , it is sufficient to prove that  $\text{int}(P') \subseteq \text{dir}(S')$ . So, let us consider an interior vector  $v' \in \text{int}(P')$ .

We first prove that there exists an interior vector  $v$  of  $(P, +)$  and an integer  $h \in \mathbb{N}_{>0}$  such that  $f(v) = hv'$ . Lemma 3.2 shows that there exists a sequence  $(\lambda_j)_{1 \leq j \leq t}$  with  $\lambda_j \in \mathbb{Q}_{>0}$  such that  $v' = \lambda_1 f(p_1) + \dots + \lambda_t f(p_t)$ . Let us consider  $h \in \mathbb{N}_{>0}$  such that  $h_j = h\lambda_j$  is in  $\mathbb{N}_{>0}$  for every  $j$ . Observe that  $hv' = f(v)$  with  $v = h_1 p_1 + \dots + h_t p_t$ . Lemma 3.2 shows that  $v$  is in the interior of  $(P, +)$ .

As  $v' \in P'$  and  $P' = f(P)$  there exists  $p \in P$  such that  $v' = f(p)$ . As  $v$  is in the interior of  $P$  and  $p \in P$  we deduce that  $v_n = v + np$  is in the interior of  $P$  for every  $n \in \mathbb{N}$ . As  $P$  is a linearization of  $S$ , there exists  $s_n \in S$  such that  $s_n + \mathbb{N}(v + np) \subseteq S$ . Hence  $s'_n + \mathbb{N}(h + n)v' \subseteq S'$  with  $s'_n = f(s_n)$ . We deduce that  $s' + \sum_{n=0}^{h-1} \mathbb{N}(h + n)v' \subseteq S'$  with  $s' = \sum_{n=0}^{h-1} s'_n$ . As  $\sum_{n=0}^{h-1} \mathbb{N}(h + n) = \{0\} \cup (h + \mathbb{N})$  we have proved that  $s' + hv' + \mathbb{N}v' \subseteq S'$ . Therefore  $v' \in \text{dir}(S')$  and we have proved that  $\text{int}(P') \subseteq \text{dir}(S')$ . We deduce that  $S'$  is simple and  $P'$  is a linearization of  $S'$ .  $\square$

### 4. Presburger Invariants

Let  $\rightarrow$  be a binary relation over  $\mathbb{N}^d$  denoted by a Presburger formula and let  $\rightarrow^*$  be its reflexive and transitive closure. The reach-

ability problem consists to decide if a pair  $(m, m')$  of vectors in  $\mathbb{N}^d$  satisfies  $m \xrightarrow{*} m'$ . In general this problem is undecidable since the semantics of every Minsky machine can be denoted by a Presburger binary relation  $\rightarrow$ . We introduce in this section a sufficient condition on  $\rightarrow$  such that if  $m'$  is not reachable from  $m$ , there exists a Presburger inductive invariant that contains  $m$  but not  $m'$ . In particular the reachability problem for this class is decidable.

Let  $X \subseteq \mathbb{N}^d$ . We introduce the *forward/backward one-step reachability sets*  $\text{post}(X)$  and  $\text{pre}(X)$ , and the *forward/backward reachability sets*  $\text{post}^*(X)$  and  $\text{pre}^*(X)$  as follows:

$$\begin{cases} \text{post}(X) = \{m' \in \mathbb{N}^d \mid \exists x \in X \ x \rightarrow m'\} \\ \text{post}^*(X) = \{m' \in \mathbb{N}^d \mid \exists x \in X \ x \xrightarrow{*} m'\} \\ \text{pre}(X) = \{m \in \mathbb{N}^d \mid \exists x \in X \ m \rightarrow x\} \\ \text{pre}^*(X) = \{m \in \mathbb{N}^d \mid \exists x \in X \ m \xrightarrow{*} x\} \end{cases}$$

The set  $X$  is said to be a *forward invariant* if  $\text{post}(X) \subseteq X$  and it is said to be a *backward invariant* if  $\text{pre}(X) \subseteq X$ .

In [Ler09], the reachability problem for VAS was proved by introducing the class of *semi-pseudo-linear sets*. Many geometrical results were proved in this paper that are *independent of the reachability problem*. Since every Lambert set is semi-pseudo-linear, from [Ler09], we deduce the following theorem.

**Theorem 4.1.** *Assume that for every Presburger set  $X \subseteq \mathbb{N}^d$  the following sets are Lambert sets:*

$$\text{post}^*(X) \setminus X \quad \text{pre}^*(X) \setminus X$$

*For every pair  $(M, M')$  of Presburger sets such that  $\text{post}^*(M) \cap \text{pre}^*(M') = \emptyset$ , there exists a partition of  $\mathbb{N}^d$  into a Presburger forward invariant  $I \supseteq M$  and a Presburger backward invariant  $I' \supseteq M'$ .*

Now let us consider a pair  $(m, m')$  of vectors  $m, m' \in \mathbb{N}^d$  and observe that if  $(m, m')$  is not in  $\xrightarrow{*}$  then  $\text{post}^*(M) \cap \text{pre}^*(M') = \emptyset$  with  $M = \{m\}$  and  $M' = \{m'\}$ . Since  $M, M'$  are Presburger sets, from the previous theorem we deduce that there exists a Presburger forward invariant  $I$  such that  $m \in I$  and  $m' \notin I$ .

## 5. Vector Addition Systems

A *vector addition system* is a couple  $\mathcal{V} = (A, d, \delta)$  where  $A$  is a non-empty finite set,  $d \in \mathbb{N}_{>0}$  is the *dimension*,  $\delta : A \rightarrow \mathbb{Z}^d$  is a total function called the *displacement function*. A vector in  $\mathbb{N}^d$  is called a *marking*. The displacement function  $\delta$  is extended over words in  $A^*$  by  $\delta(\sigma) = \sum_{j=1}^k \delta(a_j)$  for every word  $\sigma = a_1 \dots a_k$  with  $a_j \in A$  and  $k \in \mathbb{N}$ . A word  $\sigma$  is said to be *fireable from a marking*  $m$  if for every prefix  $w$  of  $\sigma$  the vector  $m + \delta(w)$  is non-negative. In this case we write  $m \xrightarrow{\sigma} m'$  where  $m' = m + \delta(\sigma)$ . The *one-step reachability binary relation*  $\rightarrow$  over  $\mathbb{N}^d$  is defined by  $m \rightarrow m'$  if there exists  $a \in A$  such that  $m \xrightarrow{a} m'$ .

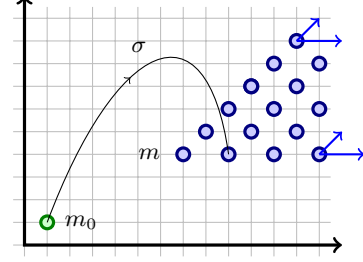
The following proposition shows that Theorem 4.1 can be applied if we prove that  $\text{post}^*(\{m_0\}) \cap (m + R)$  is a Lambert set for every  $m_0, m \in \mathbb{N}^d$  and for every finitely generated submonoids  $R$  (see Figure 2).

**Proposition 5.1.** *Assume that for every VAS  $\mathcal{V}$ , for every markings  $m_0, m$ , and for every finitely generated submonoid  $R$  the following set is a Lambert set:*

$$\text{post}^*(\{m_0\}) \cap (m + R)$$

*Then for every VAS  $\mathcal{V}$  and for every Presburger sets  $X, Y$  the following sets are Lambert sets:*

$$\text{post}^*(X) \cap Y \quad \text{pre}^*(X) \cap Y$$



**Figure 2.** A word  $\sigma$  fireable from  $m_0$  that reaches a marking in  $m + R$ .

*Proof.* In order to clarify the notations, let us denote by  $\text{post}_{\mathcal{V}}^*(X)$  and  $\text{pre}_{\mathcal{V}}^*(X)$  the sets  $\text{post}^*(X)$  and  $\text{pre}^*(X)$  associated to the one-step binary relation of a VAS  $\mathcal{V}$ . Since  $\text{pre}_{\mathcal{V}}^*(X)$  is equal to  $\text{post}_{-\mathcal{V}}^*(X)$  where  $-\mathcal{V} = (A, d, -\delta)$ , we just have to prove that  $\text{post}_{\mathcal{V}}^*(X) \cap Y$  is a Lambert set for every Presburger sets  $X, Y \subseteq \mathbb{N}^d$  and for every VAS  $\mathcal{V}$ . As a Presburger set is a finite union of linear sets, it is sufficient to prove that  $\text{post}_{\mathcal{V}}^*(m_0 + R_0) \cap (m + R)$  is a Lambert set for every  $m_0, m \in \mathbb{N}^d$  and for every finitely generated submonoids  $R_0, R$  of  $(\mathbb{N}^d, +)$ . Since  $R_0$  is finitely generated, there exists a finite sequence  $r_1, \dots, r_k$  of vectors  $r_j \in \mathbb{N}^d$  such that  $R_0$  is the submonoid generated by  $\{r_1, \dots, r_k\}$ . Let us consider a sequence  $(b_1, \dots, b_k)$  of distinct elements disjoint of  $A$  and let  $A' = A \cup \{b_1, \dots, b_k\}$ . We introduce the extension  $\delta'$  of  $\delta$  over  $A'$  defined by  $\delta'(b_j) = r_j$ . Now just observe that  $\text{post}_{\mathcal{V}}^*(m_0 + R_0) = \text{post}_{\mathcal{V}'}^*(\{m_0\})$  where  $\mathcal{V}' = (A', d, \delta')$ .  $\square$

## 6. Finite Decomposition

Let us consider two markings  $m_0, m \in \mathbb{N}^d$  and a finitely generated submonoid  $R$  (see Figure 2). We introduce the set  $\Sigma_{m_0, m, R}$  of words  $\sigma \in A^*$  fireable from  $m_0$  and such that  $m_0 + \delta(\sigma) \in m + R$ .

**Definition 6.1** (Inspired by Hauschildt [Hau90]). *Let  $\sigma = a_1 \dots a_k$  be a word in  $\Sigma_{m_0, m, R}$  with  $a_j \in A$  for every  $j$ . A sequence  $\pi = (w_j)_{0 \leq j \leq k}$  of words  $w_j \in A^*$  is said to be productive for  $(m_0, \sigma, R)$  if the following conditions hold:*

- The word denoted by  $\sigma^\pi = w_0 a_1 w_1 \dots a_k w_k$  is fireable from  $m_0$ , and
- The partial sums  $\delta(w_0) + \dots + \delta(w_j)$  are non-negative for every  $j \in \{0, \dots, k\}$ , and
- The total sum denoted by  $\delta(\pi) = \sum_{j=0}^k \delta(w_j)$  is in  $R$ .

We denote by  $\Pi_{m_0, \sigma, R}$  the set of productive sequences.

**Example 6.2.** *Let  $\pi = (w_j)_{0 \leq j \leq k}$  be a productive sequence for  $(m_0, \sigma, R)$ . We introduce the partial sums  $r_j = \delta(w_0) + \dots + \delta(w_j)$  for each  $j$ . Figure 3 describes a part of the execution of  $\sigma^\pi$  from  $m_0$ .*

In this section we prove that  $\delta(\Pi_{m_0, \sigma, R}) = \{\delta(\pi) \mid \pi \in \Pi_{m_0, \sigma, R}\}$  is a submonoid of  $(R, +)$  and there exists a finite set  $\Sigma \subseteq \Sigma_{m_0, m, R}$  such that the following *finite decomposition* holds:

$$\text{post}^*(\{m_0\}) \cap (m + R) = \bigcup_{\sigma \in \Sigma} m_0 + \delta(\sigma) + \delta(\Pi_{m_0, \sigma, R})$$

In particular we reduce the problem of proving that  $\text{post}^*(\{m_0\}) \cap (m + R)$  is a Lambert set to prove that  $\delta(\Pi_{m_0, \sigma, R})$  is a simple submonoid.

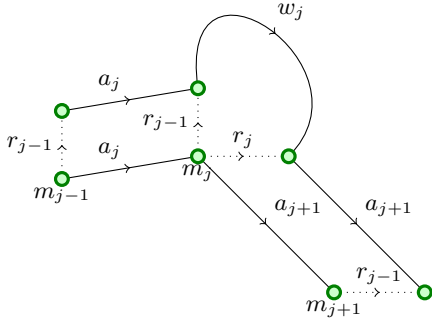


Figure 3. The effect of a productive sequence.

We consider the total function  $\circ$  defined over  $\Pi_{m_0, \sigma, R} \times \Pi_{m_0, \sigma, R}$  by  $\pi \circ \pi' = (w_j w'_j)_{0 \leq j \leq k}$  where  $\pi = (w_j)_{0 \leq j \leq k}$  and  $\pi' = (w'_j)_{0 \leq j \leq k}$ . The following lemma shows that  $(\Pi_{m_0, \sigma, R}, \circ)$  is a monoid with the neutral element  $(\epsilon)_{0 \leq j \leq k}$ . Since  $\delta(\pi \circ \pi') = \delta(\pi) + \delta(\pi')$  we deduce that  $\delta(\Pi_{m_0, \sigma, R})$  is a submonoid of  $(R, +)$ .

**Lemma 6.3.** *The sequence  $\pi \circ \pi'$  is in  $\Pi_{m_0, \sigma, R}$  for every  $\pi, \pi' \in \Pi_{m_0, \sigma, R}$ .*

*Proof.* Let us consider  $\pi = (w_j)_{0 \leq j \leq k}$  and  $\pi' = (w'_j)_{0 \leq j \leq k}$  in  $\Pi_{m_0, \sigma, R}$  and let  $\pi'' = (w''_j)_{0 \leq j \leq k}$  with  $w''_j = w_j w'_j$  for every  $j$ . We introduce the partial sums  $r_j = \delta(w_0) + \dots + \delta(w_j)$ ,  $r'_j = \delta(w'_0) + \dots + \delta(w'_j)$ , and  $r''_j = \delta(w''_0) + \dots + \delta(w''_j)$ . Observe that  $r''_j = r_j + r'_j$  which is a non-negative vector and  $r''_k = r_k + r'_k$  which is a vector in  $R$  since  $r_k, r'_k \in R$ . Let us prove that  $\sigma^{\pi''}$  is fireable from  $m_0$ . A prefix  $u$  of this word has the form  $w_0 w'_0 a_1 \dots w_{j-1} w'_{j-1} a_j w$  where  $w$  is either a prefix of  $w_j$  or  $w$  is a word of the form  $w = w_j w'$  where  $w'$  is a prefix of  $w'_j$ . In the first case  $m_0 + \delta(u) = r'_{j-1} + m_0 + \delta(v)$  with  $v = w_0 a_1 \dots w_{j-1} a_j w$ . Since  $v$  is a prefix of  $\sigma^\pi$  that is fireable from  $m_0$  we deduce that  $m_0 + \delta(v)$  is non-negative. Therefore  $m_0 + \delta(u)$  is non-negative. In the second case  $m_0 + \delta(u) = r_j + m_0 + \delta(v')$  with  $v' = w'_0 a_1 \dots w'_{j-1} a_j w'$ . Since  $v'$  is a prefix of  $\sigma^{\pi'}$  that is fireable from  $m_0$  we deduce that  $m_0 + \delta(v')$  is non-negative. Therefore  $m_0 + \delta(u)$  is non-negative. We have proved that  $\sigma^{\pi''}$  is fireable from  $m_0$ . Thus  $\pi'' \in \Pi_{m_0, \sigma, R}$ .  $\square$

We introduce the order  $\leq_R$  over  $R$  defined by  $r \leq_R r'$  if  $r' \in r + R$ .

**Lemma 6.4.**  *$(R, \leq_R)$  is a well-ordered set.*

*Proof.* Since  $R$  is finitely generated, there exists a finite sequence  $(r_j)_{1 \leq j \leq t}$  of vectors  $r_j \in R$  such that  $R = \mathbb{N}r_1 + \dots + \mathbb{N}r_t$ . In particular there exists a total function  $f : R \rightarrow \mathbb{N}^t$  that maps every vector  $r \in R$  onto a sequence  $f(r) = (n_j)_{1 \leq j \leq t}$  such that  $r = \sum_{j=1}^t n_j r_j$ . From Dickson's Lemma,  $(\mathbb{N}^t, \leq)$  is well-ordered. We deduce that  $(R, \leq_R)$  is well-ordered since for every  $r, r' \in R$  if  $f(r) \leq f(r')$  then  $r \leq_R r'$ .  $\square$

We introduce a well-order  $\sqsubseteq_{m_0, m, R}$  over  $\Sigma_{m_0, m, R}$  as follows. We first consider the infinite set  $H = A \times \mathbb{N}^d$  ordered by  $(a, x) \preceq (a', x')$  if and only if  $a = a'$  and  $x \leq x'$ . From Dickson's Lemma, the order  $\leq$  over  $\mathbb{N}^d$  is well. As  $A$  is finite, we deduce that  $(H, \preceq)$  is a well-ordered set. We introduce the order  $\preceq^*$  over the words

in  $H^*$  defined by  $u \preceq^* u'$  where  $u = h_1 \dots h_k$  with  $h_j \in H$  if there exists a sequence  $(h'_j)_{1 \leq j \leq k}$  with  $h_j \preceq h'_j$  and a sequence  $(u_j)_{0 \leq j \leq k}$  of words  $u_j \in H^*$  such that  $u' = u_0 h'_1 u_1 \dots h'_k u_k$ . From Higman's Lemma, the order  $\preceq^*$  is a well-order over  $H^*$ . Next, we associate to every couple  $(m_0, \sigma)$  where  $m_0 \in \mathbb{N}^d$  and  $\sigma \in A^*$  is a word fireable from  $m_0$ , the word  $u_{m_0, \sigma} \in H^*$  defined by the following equality where  $m_j = m_0 + \delta(a_1 \dots a_j)$ :

$$u_{m_0, \sigma} = (a_1, m_1) \dots (a_k, m_k)$$

The set  $\Sigma_{m_0, m, R}$  is equipped with the order  $\sqsubseteq_{m_0, m, R}$  defined by  $\sigma \sqsubseteq_{m_0, m, R} \sigma'$  if and only if  $u_{m_0, \sigma} \preceq^* u_{m_0, \sigma'}$  and  $(m_0 + \delta(\sigma) - m) \leq_R (m_0 + \delta(\sigma') - m)$ . Since  $(H^*, \preceq^*)$  and  $(R, \leq_R)$  are well-ordered sets, we deduce that  $(\Sigma_{m_0, m, R}, \sqsubseteq_{m_0, m, R})$  is also a well-ordered set.

**Lemma 6.5.** *For every  $\sigma, \sigma' \in \Sigma_{m_0, m, R}$  we have  $\sigma \sqsubseteq_{m_0, m, R} \sigma'$  if and only if there exists  $\pi \in \Pi_{m_0, \sigma, R}$  such that  $\sigma' = \sigma^\pi$ .*

*Proof.* We associate to every word  $u = (a_1, m_1) \dots (a_k, m_k)$  with  $(a_j, m_j) \in H$  the word  $w = a_1 \dots a_k$  called the *label* of  $u$ . Let  $\sigma, \sigma' \in \Sigma_{m_0, m, R}$ . We introduce the sequence  $(a_j)_{1 \leq j \leq k}$  such that  $\sigma = a_1 \dots a_k$  and the marking  $m_j = m_0 + \delta(a_1 \dots a_j)$ .

Let us first assume that there exists  $\pi = (w_j)_{0 \leq j \leq k}$  in  $\Pi_{m_0, \sigma, R}$  such that  $\sigma' = \sigma^\pi$  and let us prove that  $\sigma \sqsubseteq_{m_0, m, R} \sigma'$ . We introduce the partial sum  $r_j = \delta(w_0) + \dots + \delta(w_j)$  where  $j \in \{-1, \dots, k\}$ . We also introduce the vector  $m'_j = m_j + r_{j-1}$  for every  $j \in \{0, \dots, k\}$ . Since  $\sigma^\pi$  is fireable from  $m_0$ , we have:

$$m'_0 \xrightarrow{w_0 a_1} m'_1 \dots m'_{k-1} \xrightarrow{w_{k-1} a_k} m'_k \xrightarrow{w_k} (m_k + \delta(\pi))$$

We deduce that  $u_{m_0, \sigma'} = h_0(a_1, m'_1)h_1 \dots (a_k, m'_k)h_k$  where  $h_j$  is obtained from the intermediate markings in  $m'_j \xrightarrow{w_j} (m'_j + \delta(w_j))$ . As  $m'_j \geq m_j$  we deduce that  $u_{m_0, \sigma} \preceq^* u_{m_0, \sigma'}$ . Moreover, as  $\delta(\pi) \in R$  we have proved that  $m_0 + \delta(\sigma') \in m_0 + \delta(\sigma) + R$ . Therefore  $\sigma \sqsubseteq_{m_0, m, R} \sigma'$ .

Conversely, let us assume that  $\sigma \sqsubseteq_{m_0, m, R} \sigma'$  and let us prove that there exists  $\pi \in \Pi_{m_0, \sigma, R}$  such that  $\sigma' = \sigma^\pi$ . Observe that  $u_{m_0, \sigma} = (a_1, m_1) \dots (a_k, m_k)$ . Since  $u_{m_0, \sigma} \preceq^* u_{m_0, \sigma'}$ , there exists a sequence  $(m'_j)_{1 \leq j \leq k}$  of standard markings  $m'_j \geq m_j$  and a sequence  $(h_j)_{0 \leq j \leq k}$  of words in  $H^*$  such that:

$$u_{m_0, \sigma'} = h_0(a_1, m'_1)h_1 \dots (a_k, m'_k)h_k$$

Let us consider the sequence  $\pi = (w_j)_{0 \leq j \leq k}$  where  $w_j$  is the label of  $h_j$ . By definition of  $u_{m_0, \sigma'}$ , we have the following relations where  $\delta(\pi) = \sum_{j=0}^k \delta(w_j)$ :

$$m'_0 \xrightarrow{w_0 a_1} m'_1 \dots m'_{k-1} \xrightarrow{w_{k-1} a_k} m'_k \xrightarrow{w_k} (m_k + \delta(\pi))$$

As  $m'_j \geq m_j$  we deduce that  $\delta(w_0) + \dots + \delta(w_{j-1})$  is non-negative for every  $j \in \{1, \dots, k\}$ . Moreover as  $m_0 + \delta(\sigma') \in m_0 + \delta(\sigma) + R$ , we get  $\delta(\pi) \in R$ . We have proved that  $\pi \in \Pi_{m_0, \sigma, R}$  and  $\sigma' = \sigma^\pi$ .  $\square$

Now, we can prove the main theorem of this section.

**Theorem 6.6.** *The set  $\Sigma = \min_{\sqsubseteq_{m_0, m, R}}(\Sigma_{m_0, m, R})$  is finite and it satisfies:*

$$\text{post}^*(\{m_0\}) \cap (m + R) = \bigcup_{\sigma \in \Sigma} m_0 + \delta(\sigma) + \delta(\Pi_{m_0, \sigma, R})$$

*Proof.* As  $(\Sigma_{m_0, m, R}, \sqsubseteq_{m_0, m, R})$  is a well-ordered set, we deduce that  $\Sigma$  is finite and we have the following equality:

$$\Sigma_{m_0, m, R} = \bigcup_{\sigma \in \Sigma} \{\sigma' \in \Sigma_{m_0, m, R} \mid \sigma \sqsubseteq_{m_0, m, R} \sigma'\}$$



From Lemma 6.5 we get the following equality:

$$\Sigma_{m_0, m, R} = \bigcup_{\sigma \in \Sigma} \{\sigma^\pi \mid \pi \in \Pi_{m_0, \sigma, R}\}$$

In particular by applying  $\delta$ , since  $m_0 + \delta(\Sigma_{m_0, m, R})$  is equal to  $\text{post}^*(\{m_0\}) \cap (m + R)$  and  $\delta(\sigma^\pi) = \delta(\sigma) + \delta(\pi)$ , we get the theorem.  $\square$

## 7. Simple Monoids

In this section we prove that the monoid  $(\delta(\Pi_{m_0, \sigma, R}), +)$  is simple.

The set  $\mathbb{Z}$  is extended with an additional element  $\infty \notin \mathbb{Z}$  and we denote by  $\mathbb{Z}_\infty$  and  $\mathbb{N}_\infty$ , respectively, the sets  $\mathbb{Z} \cup \{\infty\}$  and  $\mathbb{N} \cup \{\infty\}$ . The total-order  $\leq$  over  $\mathbb{Z}$  is extended over  $\mathbb{Z}_\infty$  by  $z \leq \infty$  for every  $z \in \mathbb{Z}_\infty$ . The total-order  $\leq$  is extended into an order  $\leq$  over  $\mathbb{Z}_\infty^d$  defined component-wise by  $v \leq v'$  if  $v(i) \leq v'(i)$  for every  $i \in \{1, \dots, d\}$ . The addition function is extended into a total function  $+: \mathbb{Z}_\infty \times \mathbb{Z}_\infty \rightarrow \mathbb{Z}_\infty$  defined by  $z + \infty = \infty = \infty + z$  for every  $z \in \mathbb{Z}_\infty$ . This function is also extended component-wise. The multiplication is extended over  $\mathbb{N}_\infty$  by  $\infty n = \infty = n \infty$  if  $n \neq 0$  and  $\infty 0 = 0 = 0 \infty$ .

A vector in  $\mathbb{N}_\infty^d$  is called an *extended marking*. A word  $\sigma$  is said to be *fireable from an extended marking*  $m$  if for every prefix  $w$  of  $\sigma$  the vector  $m + \delta(w)$  is non-negative. In this case we write  $m \xrightarrow{\sigma} m'$  where  $m' = m + \delta(\sigma)$ .

A graph (labelled by  $A$ ) is a couple  $G = (Q, E)$  where  $Q$  is a non-empty set of *states* and  $E \subseteq Q \times A \times Q$  is a set of *edges*. The graph  $G$  is said to be *finite* if  $Q$  and  $E$  are both finite. A *path* in  $G$  is a word  $p = e_1 \dots e_k$  of  $k \in \mathbb{N}$  edges  $e_j \in E$  such that there exists a sequence  $(q_j)_{0 \leq j \leq k}$  of states  $q_j \in Q$  and a sequence  $(a_j)_{1 \leq j \leq k}$  of element  $a_j \in A$  such that  $e_j = (q_{j-1}, a_j, q_j)$  for every  $j \in \{1, \dots, k\}$ . In this case the word  $\sigma = a_1 \dots a_k$  is unique and it is called the label of  $p$ . The path  $p$  is also denoted by  $q_0 \xrightarrow{\sigma}_G q_k$  and it is called a path from  $q_0$  to  $q_k$  labelled by  $\sigma$ . We denote by  $\|p\|: E \mapsto \mathbb{N}$  the *Parikh image* of  $p$  defined for every  $e \in E$  by  $\|p\|(e)$  is the number of occurrences of  $e$  in  $p$ . When  $q_0 = q_k$ , the path is called a *cycle*. The graph  $G$  is said to be *strongly connected* if for every pair  $(q, q') \in Q \times Q$  there exists a path from  $q$  to  $q'$ .

Let  $G = (Q, E)$  be a graph and let  $f: E \rightarrow \mathbb{N}$  be a total function. We introduce the graph  $G_f = (Q_f, E_f)$  defined by the set of edges  $E_f = \{e \in E \mid f(e) > 0\}$  and the  $Q_f$  such that  $Q_f$  is the minimal for the inclusion subset of  $Q$  such that  $E_f \subseteq Q_f \times A \times Q_f$ . The graph  $G_f$  is said to be *induced* by  $(G, f)$ . We say that a total function  $f: E \rightarrow \mathbb{N}$  satisfies the *Kirchhoff laws of  $G$*  if for every  $q \in Q$  the following equality holds:

$$\sum_{e \in E \cap (\{q\} \times A \times Q)} f(e) = \sum_{e \in E \cap (Q \times A \times \{q\})} f(e)$$

Let us recall that a total function  $f: E \rightarrow \mathbb{N}$  is the Parikh image of a cycle if and only if  $f$  satisfies the Kirchhoff laws and the graph  $G_f$  is finite and strongly connected.

The tuple  $(m_0, \sigma, R)$  is fixed in this section and the set  $\Pi_{m_0, \sigma, R}$  is simply denoted by  $\Pi$ . We introduce the sequence  $(a_j)_{1 \leq j \leq k}$  of elements  $a_j \in A$  such that  $\sigma = a_1 \dots a_k$ , and the sequence  $(m_j)_{0 \leq j \leq k}$  of markings  $m_j = m_0 + \delta(a_1 \dots a_j)$ .

Let us consider a productive sequence  $\pi = (w_j)_{0 \leq j \leq k}$  and let us introduce the partial sums  $r_j = \delta(w_0) + \dots + \delta(w_j)$  for every  $j$ . Based on Figures 4 and 5, we introduce the  $j$ th intermediate markings of  $\pi$  and its  $j$ th intermediate edges. A vector  $q_j \in \mathbb{N}^d$  is said to

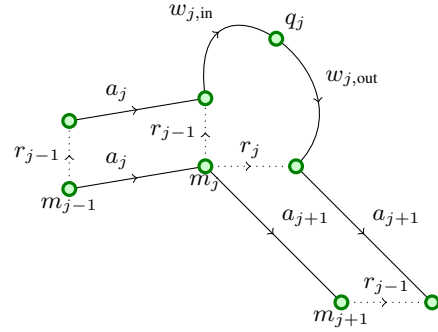


Figure 4. A  $j$ th intermediate marking  $q_j$ .

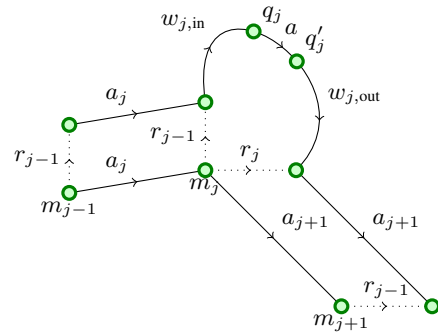


Figure 5. A  $j$ th intermediate edge  $(q_j, a, q'_j)$ .

be a  $j$ th intermediate marking of  $\pi$  if there exist  $w_{j,\text{in}}, w_{j,\text{out}} \in A^*$  such that  $w_j = w_{j,\text{in}} w_{j,\text{out}}$  and such that the following relation holds:

$$(m_j + r_{j-1}) \xrightarrow{w_{j,\text{in}}} q_j \xrightarrow{w_{j,\text{out}}} (m_j + r_j)$$

A couple  $(q_j, a, q'_j)$  where  $q_j, q'_j \in \mathbb{N}^d$  and  $a \in A$  is said to be a  $j$ th intermediate edge of  $\pi$  if there exist  $w_{j,\text{in}}, w_{j,\text{out}} \in A^*$  such that  $w_j = w_{j,\text{in}} a w_{j,\text{out}}$  and such that the following relation holds:

$$(m_j + r_{j-1}) \xrightarrow{w_{j,\text{in}}} q_j \xrightarrow{a} q'_j \xrightarrow{w_{j,\text{out}}} (m_j + r_j)$$

We consider the set  $Q_j$  of  $j$ th intermediate marking and the set  $E_j$  of  $j$ th intermediate edges for at least one productive sequence  $\pi \in \Pi$ . We introduce the (infinite) graph  $G_j = (Q_j, E_j)$ .

We are interested in folding  $G_j$  into a finite graph. We introduce for each  $j \in \{0, \dots, k\}$  the set  $I_j$  of integers  $i \in \{1, \dots, d\}$  such that  $\{q_j(i) \mid q_j \in Q_j\}$  is infinite. We introduce the vector  $v_j \in \{0, \infty\}^d$  such that  $v_j(i) = \infty$  if and only if  $i \in I_j$ . By construction, the set  $\tilde{Q}_j = Q_j + v_j$  is a finite set of extended markings. In the sequel we denote by  $\tilde{q}_j$  the extended marking  $q_j + v_j$ . We also introduce the set  $\tilde{E}_j = \{(\tilde{q}_j, a, \tilde{q}'_j) \mid (q_j, a, q'_j) \in E_j\}$ . We introduce the finite graph  $\tilde{G}_j = (\tilde{Q}_j, \tilde{E}_j)$ .

**Lemma 7.1.** *The graph  $\tilde{G}_j$  is strongly connected and for every productive sequence  $\pi = (w_j)_{0 \leq j \leq k}$  in  $\Pi$  and for every  $j \in \{0, \dots, k\}$ , we have:*

$$\tilde{m}_j \xrightarrow{w_j}_{\tilde{G}_j} \tilde{m}_j$$

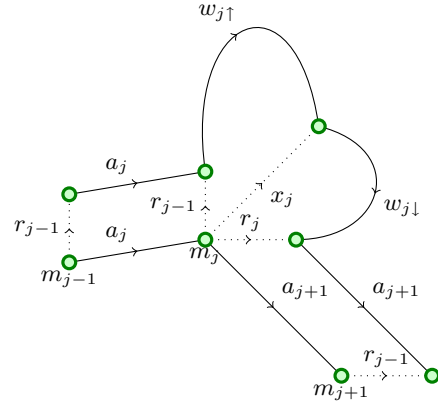
*Proof.* Let us consider a productive sequence  $\pi = (w_j)_{0 \leq j \leq k}$  in  $\Pi$ . We introduce the partial sum  $r_j = \delta(w_0) + \dots + \delta(w_j)$ . Let  $n \in \mathbb{N}$ . Since  $(\Pi, \circ)$  is a monoid, the productive sequence  $\pi^n$  is well defined. We deduce that  $\sigma^{\pi^n}$  is fireable from  $m_0$ . Hence the vectors  $m_0 + \delta(w_0^n a_1 \dots w_{j-1}^n a_j)$  and  $m_0 + \delta(w_0^n a_1 \dots w_{j-1}^n a_j w_j^n)$  are both non negative. Since these vectors are respectively equal to  $m_j + nr_{j-1}$  and  $m_j + nr_j$  we deduce that  $r_{j-1}(i) > 0$  or  $r_j(i) > 0$  implies  $i \in I_j$ . Therefore  $m_j + r_{j-1} + v_j = \tilde{m}_j$  and  $m_j + r_j + v_j = \tilde{m}_j$ . Since  $(m_j + r_{j-1}) \xrightarrow{w_j} (m_j + r_j)$  and immediate induction provides  $\tilde{m}_j \xrightarrow{w_j} \tilde{m}_j$ . We also deduce that for every  $\tilde{q}_j \in \tilde{Q}_j$  there exists a path in  $\tilde{G}_j$  from  $\tilde{m}_j$  to  $\tilde{q}_j$  and a path from  $\tilde{q}_j$  to  $\tilde{m}_j$ . Thus  $\tilde{G}_j$  is strongly connected,  $\square$

We consider the set  $\bar{\Pi}$  of sequences  $\bar{\pi} = (\bar{w}_j)_{0 \leq j \leq k}$  of words  $\bar{w}_j \in A^*$  such that  $\bar{m}_j \xrightarrow{\bar{w}_j} \bar{m}_j$ , the partial sums  $\delta(\bar{w}_0) + \dots + \delta(\bar{w}_j)$  are non-negative for every  $j \in \{0, \dots, k\}$ , and the total sum denoted by  $\delta(\bar{\pi}) = \sum_{j=0}^k \delta(\bar{w}_j)$  is in  $R$ . A sequence  $\bar{\pi} \in \bar{\Pi}$  is called a *weak-productive sequence*. The previous lemma shows that  $\Pi$  is the set of weak-productive sequences  $\bar{\pi} \in \bar{\Pi}$  such that  $\sigma^{\bar{\pi}}$  is fireable from  $m_0$ . In order to transform a weak-productive sequence into a productive sequence, we introduce the mixed-productive sequences.

We consider the set  $\Theta$  of sequences  $\theta = (w_{j\uparrow}, w_{j\downarrow})_{0 \leq j \leq k}$  where  $w_{j\uparrow}, w_{j\downarrow} \in A^* \times A^*$  are such that  $\pi = (w_j)_{0 \leq j \leq k}$ , with  $w_j = w_{j\uparrow} w_{j\downarrow}$ , is in  $\Pi$  and such that partial sums  $x_j = \delta(w_0) + \dots + \delta(w_{j-1}) + \delta(w_{j\uparrow})$  are non-negative for every  $j \in \{0, \dots, k\}$ . A sequence  $\theta \in \Theta$  is called a *mixed-productive sequence* and the vector  $x_j$  is called the  $j$ th increase of  $\theta$  (See Figure 6). We introduce the total function  $\circ$  defined over  $\Theta \times \Theta$  by  $\theta \circ \theta' = (w_{j\uparrow} w'_{j\uparrow}, w_{j\downarrow} w'_{j\downarrow})_{0 \leq j \leq k}$  where  $\theta = (w_{j\uparrow}, w_{j\downarrow})_{0 \leq j \leq k}$  and  $\theta' = (w'_{j\uparrow}, w'_{j\downarrow})_{0 \leq j \leq k}$ . The following lemma shows that  $(\Theta, \circ)$  is a monoid. In particular the mixed-productive sequence  $\theta^n$  is well defined for every  $n \in \mathbb{N}$ .

**Lemma 7.2.** *We have  $\theta \circ \theta' \in \Theta$  for every  $\theta, \theta' \in \Theta$ .*

*Proof.* Let  $\theta = (w_{j\uparrow}, w_{j\downarrow})_{0 \leq j \leq k}$  and  $\theta' = (w'_{j\uparrow}, w'_{j\downarrow})_{0 \leq j \leq k}$ . We introduce  $w''_{j\uparrow} = w_{j\uparrow} w'_{j\uparrow}$  and  $w''_{j\downarrow} = w'_{j\downarrow} w_{j\downarrow}$ . We have  $\theta \circ \theta' = \theta''$  with  $\theta'' = (w''_{j\uparrow}, w''_{j\downarrow})_{0 \leq j \leq k}$ . We introduce the words  $w_j = w_{j\uparrow} w_{j\downarrow}$ ,  $w'_j = w'_{j\uparrow} w'_{j\downarrow}$ , and  $w''_j = w''_{j\uparrow} w''_{j\downarrow}$ , the sequences  $\pi = (w_j)_{0 \leq j \leq k}$ ,  $\pi' = (w'_j)_{0 \leq j \leq k}$ , and  $\pi'' = (w''_j)_{0 \leq j \leq k}$ , the partial sums  $r_j = \delta(w_0) + \dots + \delta(w_j)$ ,  $r'_j = \delta(w'_0) + \dots + \delta(w'_j)$ , and  $r''_j = \delta(w''_0) + \dots + \delta(w''_j)$ , and the  $j$ th increases  $x_j = \delta(w_0) + \dots + \delta(w_{j-1}) + \delta(w_{j\uparrow})$ ,  $x'_j = \delta(w'_0) + \dots + \delta(w'_{j-1}) + \delta(w'_{j\uparrow})$ , and  $x''_j = \delta(w''_0) + \dots + \delta(w''_{j-1}) + \delta(w''_{j\uparrow})$ . We observe that  $r''_j = r_j + r'_j$  and  $x''_j = x_j + x'_j$  are non-negative for every  $j \in \{0, \dots, k\}$ , and  $r''_k = r_k + r'_k \in R$ . Thus, in order to prove that  $\theta$  is in  $\Theta$ , it just remains to prove that  $\sigma^{\pi''}$  is fireable from  $m_0$ . A prefix  $u$  of this word has the form  $u = w''_0 a_1 w''_1 \dots w''_{j-1} a_j w$  where  $w$  is either a prefix of  $w_{j\uparrow}$ , or a word of the form  $w_{j\uparrow} w'_j$  where  $w'$  is a prefix of  $w'_j$ , or a word of the form  $w_{j\uparrow} w'_j w$  where  $w$  is a prefix of  $w_{j\downarrow}$ . We divide the proof in these three cases. If  $w$  is a prefix of  $w_{j\uparrow}$  then  $m_0 + \delta(u) = r'_{j-1} + m_0 + \delta(v)$  with  $v = w_0 a_1 \dots w_{j-1} a_j w$ . Since  $v$  is a prefix of  $\sigma^{\pi'}$  that is fireable from  $m_0$  we deduce that  $m_0 + \delta(v)$  is non negative. Thus  $m_0 + \delta(u)$  is non-negative. If  $w$  is a word of the form  $w_{j\uparrow} w'$  where  $w'$  is a prefix of  $w'_j$  then  $m_0 + \delta(u) = x_j + m_0 + \delta(v')$  with  $v' = w'_0 a_1 \dots w'_{j-1} a_j w'$ . Since  $v'$  is a prefix of  $\sigma^{\pi'}$  that is fireable from  $m_0$  we deduce that  $m_0 + \delta(v')$  is non-negative. Thus  $m_0 + \delta(u)$  is non-negative. If  $w$  is a word of the form  $w_{j\uparrow} w'_j w$  where  $w$  is a prefix of  $w_{j\downarrow}$  then  $m_0 + \delta(u) = r'_j + m_0 + \delta(v)$



**Figure 6.** The effect of a mixed-productive sequence.

with  $v = w_0 a_1 \dots w_{j-1} a_j w_{j\uparrow} w$ . Since  $v$  is a prefix of  $\sigma^{\pi}$  that is fireable from  $m_0$  we deduce that  $m_0 + \delta(v)$  is non-negative. Therefore  $m_0 + \delta(u)$  is non-negative. We have proved that  $\sigma^{\pi''}$  is fireable from  $m_0$ . Therefore  $\theta'' \in \Theta$ .  $\square$

Let  $x_j$  be the  $j$ th increase of a mixed-productive sequence  $\theta \in \Theta$ . The mixed-productive sequence  $\theta^n$  shows that  $m_j + nx_j \in Q_j$  for every  $n \in \mathbb{N}$ . We deduce that  $x_j(i) > 0$  implies  $i \in I_j$ . A mixed-productive sequence  $\theta$  is said to be *strong* if for every  $j \in \{0, \dots, k\}$ , its  $j$ th increase  $x_j$  satisfies  $x_j(i) > 0$  if and only if  $i \in I_j$ .

**Proposition 7.3.** *There exists a strong mixed-productive sequence.*

*Proof.* Since the mixed-productive sequences are composable by  $\circ$  and the  $j$ th increase of  $\theta \circ \theta'$  is equal to  $x_j + x'_j$  where  $x_j, x'_j$  are the  $j$ th increases of  $\theta, \theta'$ , it is sufficient to prove that for every  $j \in \{0, \dots, k\}$  and for every  $i \in I_j$ , there exists a mixed-productive sequence  $\theta$  such that the  $j$ th increase  $x_j$  satisfies  $x_j(i) > 0$ . So, let us fix  $j \in \{0, \dots, k\}$  and  $i \in I_j$ .

Since the set  $\{q_j(i) \mid q_j \in Q_j\}$  is infinite, there exists an infinite sequence in  $Q_j$  such that the  $i$ th component is strictly increasing. As  $\leq$  is a well order over  $\mathbb{N}^d$ , we can extract from this sequence a subsequence that is non-decreasing for  $\leq$ . We have proved that there exist  $q_j, q'_j \in Q_j$  such that  $q_j \leq q'_j$  and  $q_j(i) < q'_j(i)$ . By definition of  $Q_j$ , there exists a productive sequence  $\pi = (w_j)_{0 \leq j \leq k}$  in  $\Pi$  and a decomposition of  $w_j$  into  $w_j = w_{j,\text{in}} w_{j,\text{out}}$  such that the following relation holds where  $r_{j-1}$  and  $r_j$  are the partial sums  $\delta(w_0) + \dots + \delta(w_{j-1})$  and  $\delta(w_0) + \dots + \delta(w_j)$ :

$$(m_j + r_{j-1}) \xrightarrow{w_{j,\text{in}}} q_j \xrightarrow{w_{j,\text{out}}} (m_j + r_j)$$

Symmetrically there exists a productive sequence  $\pi' = (w'_j)_{0 \leq j \leq k}$  in  $\Pi$  and a decomposition of  $w'_j$  into  $w'_j = w'_{j,\text{in}} w'_{j,\text{out}}$  such that the following relation holds where  $r'_{j-1}$  and  $r'_j$  are the partial sums  $\delta(w'_0) + \dots + \delta(w'_{j-1})$  and  $\delta(w'_0) + \dots + \delta(w'_j)$ :

$$(m_j + r'_{j-1}) \xrightarrow{w'_{j,\text{in}}} q'_j \xrightarrow{w'_{j,\text{out}}} (m_j + r'_j)$$

Since  $r_j, r'_j, r_{j-1}, r'_{j-1}$  are non negative and  $q'_j \geq q_j$ , we observe that the following relations hold:

$$\begin{aligned} (m_j + r_{j-1} + r'_{j-1}) &\xrightarrow{w'_{j,\text{in}}} (q'_j + r_{j-1}) = (q_j + r_{j-1} + q'_j - q_j) \\ &\xrightarrow{w_{j,\text{out}}} (m_j + r_j + r_{j-1} + q'_j - q_j) \\ &\xrightarrow{w_{j,\text{in}}} (q'_j + r_j) \\ &\xrightarrow{w'_{j,\text{out}}} (m_j + r_j + r'_j) \end{aligned}$$

Let us consider the sequence  $\theta = (w_{t\uparrow}, w_{t\downarrow})_{0 \leq t \leq k}$  defined by:

$$\begin{aligned} w_{t\uparrow} &= \begin{cases} w_{t,\text{in}}w_{t,\text{out}} & \text{if } t \neq j \\ w'_{j,\text{in}}w_{j,\text{out}} & \text{if } t = j \end{cases} \\ w_{t\downarrow} &= \begin{cases} w'_{t,\text{in}}w'_{t,\text{out}} & \text{if } t \neq j \\ w_{j,\text{in}}w'_{j,\text{out}} & \text{if } t = j \end{cases} \end{aligned}$$

Observe that the vector  $x_t = \delta(w_0) + \dots + \delta(w_{t-1}) + \delta(w_{t\uparrow})$  is equal to  $r_t + r'_{t-1}$  if  $t \neq j$  and it is equal to  $r_j + r_{j-1} + (q'_j - q_j)$  if  $t = j$ . In particular  $x_t$  is non-negative for every  $t \in \{0, \dots, k\}$  and  $x_j(i) > 0$ . We have proved that  $\theta$  is a mixed-productive sequence with a  $j$ th increase  $x_j$  such that  $x_j(i) > 0$ .  $\square$

**Lemma 7.4.** *For every weak-productive sequence  $\bar{\pi} = (\bar{w}_j)_{0 \leq j \leq k}$  in  $\bar{\Pi}$ , there exists a mixed-productive sequence  $\theta = (w_{j\uparrow}, w_{j\downarrow})_{0 \leq j \leq k}$  such that for every  $n \in \mathbb{N}$  the following sequence  $\pi_n$  is in  $\Pi$ :*

$$\pi_n = (w_{j\uparrow}\bar{w}_j^n w_{j\downarrow})_{0 \leq j \leq k}$$

*Proof.* Let us consider a strong mixed-productive sequence  $\theta = (w_{j\uparrow}, w_{j\downarrow})_{0 \leq j \leq k}$  and let  $x_j$  be the  $j$ th increase of  $\theta$ . Since  $\theta$  is strong we deduce that  $\infty x_j = v_j$  and in particular  $\tilde{m}_j = m_j + \infty x_j$ . As  $\tilde{m}_j \xrightarrow{\bar{w}_j} \tilde{c}_j \tilde{m}_j$  we deduce that  $\bar{w}_j$  is fireable from  $\tilde{m}_j$ . Hence, there exists an integer  $h_j \in \mathbb{N}$  such that  $\bar{w}_j$  is fireable from  $m_j + h_j x_j$ . Let us consider  $h \in \mathbb{N}$  such that  $h_j \leq h$  for every  $j \in \{0, \dots, k\}$ . By replacing  $\theta$  by  $\theta^h$ , we can assume without loss of generality that  $h = 1$  and in particular  $\bar{w}_j$  is fireable from  $m_j + x_j$  for every  $j \in \{0, \dots, k\}$ .

We introduce the productive sequence  $\pi = (w_j)_{0 \leq j \leq k}$  where  $w_j = w_{j\uparrow}w_{j\downarrow}$  for every  $j \in \{0, \dots, k\}$  and the sequence  $\pi_n = (w_{j\uparrow}\bar{w}_j^n w_{j\downarrow})_{0 \leq j \leq k}$  where  $n \in \mathbb{N}$ . We are interested in proving that  $\pi_n \in \Pi$ . The case  $n = 0$  is immediate since  $\pi_0 = \pi$ . So we can assume that  $n \geq 1$ . We consider the partial sums  $p_j = \delta(\bar{w}_0) + \dots + \delta(\bar{w}_j)$  and  $r_j = \delta(w_0) + \dots + \delta(w_j)$  associated to the sequences  $\bar{\pi}$  and  $\pi$ . Note that the partial sums of  $\pi_n$  are equal to  $r_j + np_j$  which is non-negative. Moreover  $\delta(\pi_n) = \delta(\pi) + n\delta(\bar{\pi})$  which is in  $R$  since  $(R, +)$  is a monoid and  $\delta(\pi), \delta(\bar{\pi}) \in R$ . In order to prove that  $\pi_n \in \Pi$  it is sufficient to prove that  $\sigma^{\pi_n}$  is fireable from  $m_0$ . A prefix  $u$  of this word is a word of the form  $u = w_0\uparrow\bar{w}_0^n w_0\downarrow a_1 \dots w_{j-1}\uparrow\bar{w}_{j-1}^n w_{j-1}\downarrow a_j v$  where  $v$  is either a prefix of  $w_{j\uparrow}$ , or  $v$  is a word of the form  $v = w_{j\uparrow}\bar{w}_j^t \bar{w}$  where  $t \in \{0, \dots, n-1\}$  and  $\bar{w}$  is a prefix of  $\bar{w}_j$ , or  $v$  is a word of the form  $v = w_{j\uparrow}\bar{w}_j^n w$  where  $w$  is a prefix of  $w_{j\downarrow}$ . We prove that  $m_0 + \delta(u)$  is non-negative by dividing the proof in three cases. In the first case, if  $v$  is a prefix of  $w_{j\uparrow}$  then  $m_0 + \delta(u) = np_{j-1} + m_0 + \delta(u')$  with  $u' = w_0 a_1 w_1 \dots a_j v$ . Since  $u'$  is a prefix of  $\sigma^\pi$  that is fireable from  $m_0$ , we deduce that  $m_0 + \delta(u')$  is non-negative. Thus  $m_0 + \delta(u)$  is non-negative. In the second case, we have  $v = w_{j\uparrow}\bar{w}_j^t \bar{w}$  where  $t \in \{0, \dots, n-1\}$  and  $\bar{w}$  is a prefix of  $\bar{w}_j$ . We have  $m + \delta(u) = tp_j + (n-t)p_{j-1} + m_j + x_j + \delta(\bar{w})$ . As  $\bar{w}_j$  is fireable from  $m_j + x_j$ , we deduce that  $m_j + x_j + \delta(\bar{w})$  is non-negative. Therefore  $m + \delta(u)$  is non-negative. In the last case, we have  $v = w_{j\uparrow}\bar{w}_j^n w$  where  $w$  is a prefix of  $w_{j\downarrow}$ . In this case

$m_0 + \delta(u) = np_j + m_0 + \delta(u')$  with  $u' = w_0 a_1 \dots w_{j-1} a_j w_{j\uparrow} w$ . As  $u'$  is a prefix of  $\sigma^\pi$  that is fireable from  $m_0$ , we deduce that  $m_0 + \delta(u')$  is non-negative. Therefore  $m_0 + \delta(u)$  is non-negative. We have proved that  $\sigma^{\pi_n}$  is fireable from  $m_0$ . Therefore  $\pi_n \in \Pi$ .  $\square$

By  $F_j$  we denote the set of total functions  $f_j : \tilde{E}_j \rightarrow \mathbb{N}$  that satisfy the Kirchhoff laws of  $\tilde{G}_j$ . We extend  $\delta$  over  $F_j$  by the following equality:

$$\delta(f_j) = \sum_{\tilde{e}=(\tilde{q}, a, \tilde{q}') \in \tilde{E}_j} f_j(\tilde{e}) \delta(a)$$

We introduce the set  $F$  of sequences  $f = (f_j)_{0 \leq j \leq k}$  of elements  $f_j \in F_j$  such that the partial sums  $\delta(f_0) + \dots + \delta(f_j)$  are non-negative for every  $j \in \{0, \dots, k\}$  and such that the total sum denoted by  $\delta(f) = \sum_{j=0}^k \delta(f_j)$  satisfies  $\delta(f) \in R$ . Let us consider the order  $\sqsubseteq$  over  $F$  defined by  $f \sqsubseteq f'$  if  $f_j \leq f'_j$  for every  $j$  and  $\delta(f) \leq_R \delta(f')$ . Since  $(F_j, \leq)$  and  $(R, \leq_R)$  are well ordered sets, we deduce that  $(F, \sqsubseteq)$  is well ordered. In particular  $\min_{\sqsubseteq}(F \setminus \{0\})$  is finite. The following lemma shows that  $(F, +)$  is finitely generated.

**Lemma 7.5.** *The monoid  $(F, +)$  is generated by  $\min_{\sqsubseteq}(F \setminus \{0\})$ .*

*Proof.* Let us denote by  $F'$  the submonoid of  $(F, +)$  generated by  $\min_{\sqsubseteq}(F \setminus \{0\})$  and assume by contradiction that  $F$  is not included in  $F'$ . Since  $(F, \sqsubseteq)$  is a well ordered set and  $F \setminus F'$  is non empty, there exists a sequence  $f \in \min(F \setminus F')$ . Since  $0 \in F'$  we deduce that  $f \neq 0$ . As  $(F, \sqsubseteq)$  is a well ordered set, there exists  $f' \in \min_{\sqsubseteq}(F \setminus \{0\})$  such that  $f' \sqsubseteq f$ . In particular  $f' \in F'$ . Let us introduce the sequence  $f'' = f - f'$ . Since  $f \sqsubseteq f'$  we deduce that  $f'' \in F$ . Observe that if  $f'' = 0$  then  $f = f'$  and we get the contradiction  $f \in F'$ . If  $f' \neq 0$ , from  $f'' \sqsubseteq f$  and  $f'' \neq f$  we deduce by minimality of  $f$  that  $f'' \in F'$ . From  $f = f' + f''$  we get the contradiction  $f \in F'$ . Thus  $F \subseteq F'$ . Since  $F' \subseteq F$  we have proved the equality  $F = F'$ .  $\square$

Since  $F$  is generated by this set, we deduce that  $(F, +)$  is a finitely generated monoid. We associate to every weak-productive sequence  $\bar{\pi} = (\bar{w}_j)_{0 \leq j \leq k}$  the sequence  $f = (f_j)_{0 \leq j \leq k}$  where  $f_j$  is the Parikh image of the cycle  $\tilde{m}_j \xrightarrow{\bar{w}_j} \tilde{c}_j \tilde{m}_j$ . Observe that  $f \in F$  since  $\delta(f_j) = \delta(\bar{w}_j)$ . In the sequel, the sequence  $f$  is denoted by  $\|\bar{\pi}\|$  and the total function  $f_j$  by  $\|\bar{\pi}\|_j$ .

**Lemma 7.6.** *For every  $f$  interior to  $(F, +)$ , there exists a weak-productive sequence  $\bar{\pi} \in \bar{\Pi}$  such that  $f = \|\bar{\pi}\|$ .*

*Proof.* Let us consider  $f = (f_j)_{0 \leq j \leq k}$  a function interior to  $(F, +)$ . Let us first prove that  $f_j(\tilde{e}) > 0$  for every  $\tilde{e} \in \tilde{E}_j$ . Let  $\tilde{e} \in \tilde{E}_j$ . By definition of  $\tilde{E}_j$ , there exists  $\pi \in \Pi$  such that  $\|\pi\|_j(\tilde{e}) > 0$ . Since  $f$  is in the interior of  $F$  and  $\|\pi\| \in F$ , there exists an integer  $n \in \mathbb{N}_{>0}$  such that  $nf \in \|\pi\| + F$ . In particular  $nf_j(\tilde{e}) \geq \|\pi\|_j(\tilde{e})$ . We have proved that  $f_j(\tilde{e}) > 0$  for every  $\tilde{e} \in \tilde{E}_j$ . In particular the graph induced by  $(\tilde{G}_j, f_j)$  is the finite strongly connected graph  $\tilde{G}_j$ . Therefore  $f_j$  is the Parikh image of a cycle  $\tilde{m}_j \xrightarrow{\bar{w}_j} \tilde{c}_j \tilde{m}_j$ . Let  $\bar{\pi} = (\bar{w}_j)_{0 \leq j \leq k}$ . From  $\delta(\bar{w}_j) = \delta(f_j)$  we deduce that  $\bar{\pi} \in \bar{\Pi}$ .  $\square$

**Proposition 7.7.** *The monoid  $(\|\Pi\|, +)$  is simple and  $F$  is a linearization.*

*Proof.* Observe that  $\|\Pi\| \subseteq F$ . Next, let us consider an interior function  $f \in F$ . Lemma 7.6 proves that there exists a weak-productive sequence  $\bar{\pi} = (\bar{w}_j)_{0 \leq j \leq k}$  such that  $f = \|\bar{\pi}\|$ .



From Lemma 7.4, there exists a mixed-productive sequence  $\theta = (w_{j\uparrow}, w_{j\downarrow})_{0 \leq j \leq k}$  such that for every  $n \in \mathbb{N}$  the following sequence  $\pi_n$  is in  $\Pi$ :

$$\pi_n = (w_{j\uparrow} \bar{w}_j^n w_{j\downarrow})_{0 \leq j \leq k}$$

Observe that  $\|\pi_n\| = \|\pi\| + nf$  where  $\pi = (w_{j\uparrow} w_{j\downarrow})_{0 \leq j \leq k}$ . We are done.  $\square$

From Lemma 3.3, since  $\delta$  is a morphism from  $(F, +)$  to  $(R, +)$ , we deduce that  $\delta(\|\Pi\|)$  is simple and  $\delta(F)$  is a linearization. As  $\delta(\|\Pi\|) = \delta(\Pi)$ , we get the following theorem:

**Theorem 7.8.** *The monoid  $(\delta(\Pi_{m_0, \sigma, R}), +)$  is simple.*

From Theorem 7.8, Theorem 6.6 and Proposition 5.1 we deduce the following main theorem of this paper.

**Theorem 7.9.** *For every Presburger sets  $X, Y \subseteq \mathbb{N}^d$  the following sets are Lambert sets:*

$$\text{post}^*(X) \cap Y \quad \text{pre}^*(X) \cap Y$$

## 8. Conclusion

We deduce that the following algorithm decides the reachability problem.

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1 Reachability(  $m, \mathcal{V}, m'$  )
2    $k \leftarrow 0$ 
3   repeat forever
4     for each word  $\sigma \in A^k$ 
5       if  $m \xrightarrow{\sigma} m'$ 
6         return "reachable"
7     for each Presburger formula  $\psi(x)$  of length  $k$ 
8       if  $\psi(m)$  and  $\neg\psi(m')$  are true and
9          $\psi(x) \wedge y = x + \delta(a) \wedge \neg\psi(y)$  unsat  $\forall a \in \Sigma$ 
10        return "unreachable"
11     $k \leftarrow k + 1$ 

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The correctness is immediate and the termination is guaranteed by Theorem 7.9 and Theorem 4.1. This algorithm is the *very first one* that does not require the classical KLMST decomposition. Even though the termination proof is not based on the KLMST decomposition, the complexity of the algorithm is still open. In fact, the complexity depends on the minimal size of a word  $\sigma \in \Sigma^*$  such that  $m \xrightarrow{\sigma} m'$  if  $m \xrightarrow{*} m'$ , and the minimal size of a Presburger formula  $\psi(x)$  denoting a forward invariant  $I$  such that  $m \in I$  and  $m' \in I$  otherwise. We left as an open question the problem of computing lower and upper bounds for these sizes. Note that the VAS exhibiting a large (Ackermann size) but finite reachability set given in [MM81] does not directly provide an Ackermann lower-bound for these sizes since inductive separators can overapproximate reachability sets.

We also left as an open question the problem of adapting the *Counter Example Guided Abstract Refinement* approach [CGJ<sup>+</sup>00] to obtain an algorithm for the VAS reachability problem with termination guarantee. In practice, such an algorithm should be more efficient than the previously given enumeration-based algorithm.

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