# SETS OF UNIVERSAL SEQUENCES FOR THE SYMMETRIC GROUP AND ANALOGOUS SEMIGROUPS

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ABSTRACT. A *universal sequence* for a group or semigroup $S$ is a sequence of words $w_1, w_2, \ldots$ such that for any sequence $s_1, s_2, \ldots \in S$, the equations $w_i = s_i$, $i \in \mathbb{N}$, can be solved simultaneously in $S$. For example, Galvin showed that the sequence $\{a^{-1}(a^iba^{-i})b^{-1}(a^ib^{-1}a^{-i})ba : i \in \mathbb{N}\}$ is universal for the symmetric group $\text{Sym}(X)$ when $X$ is infinite, and Sierpiński showed that $(a^2b^3(abab^3)^{n+1}ab^2ab^3)_{n\in\mathbb{N}}$ is universal for the monoid $X^X$ of functions from the infinite set $X$ to itself.

In this paper, we show that under some conditions, the set of universal sequences for the symmetric group on an infinite set $X$ is independent of the cardinality of $X$. More precisely, we show that if $Y$ is any set such that $|Y| \geq |X|$, then every universal sequence for $\text{Sym}(X)$ is also universal for $\text{Sym}(Y)$. If $|X| > 2^{\aleph_0}$, then the converse also holds. It is shown that an analogue of this theorem holds in the context of inverse semigroups, where the role of the symmetric group is played by the symmetric inverse monoid. In the general context of semigroups, the full transformation monoid $X^X$ is the natural analogue of the symmetric group and the symmetric inverse monoid. If $X$ and $Y$ are arbitrary infinite sets, then it is an open question as to whether or not every sequence that is universal for $X^X$ is also universal for $Y^Y$. However, we obtain a sufficient condition for a sequence to be universal for $X^X$ which does not depend on the cardinality of $X$. A large class of sequences satisfy this condition, and hence are universal for $X^X$ for every infinite set $X$.

## 1. Introduction

Let $F$ be a free group, let $w \in F$, and let $G$ be a group. We say that the word $w$ is *group universal* for $G$ if for all $g \in G$ there exists a group homomorphism $\phi : F \longrightarrow G$ such that $(w)\phi = g$. Perhaps one of the most well-known examples is that of Oré [21] who showed that every element of the symmetric group $\text{Sym}(X)$ on an infinite set $X$ is a commutator. In other words, for all $p \in \text{Sym}(X)$, there exists $a, b \in \text{Sym}(X)$ such that $p = a^{-1}b^{-1}ab$. More generally, every element is a commutator in any Polish group with a comeagre conjugacy class [15]. There are many such groups in addition to the symmetric group; for example, the automorphism group of the countable random graph; see [15] for further examples.

Something much stronger than Óre's Theorem holds for the symmetric group: any word $w$, which is not a proper power of another word, in any free group $F$ is group universal for $\text{Sym}(X)$. Silberger [24], Droste [6], and Mycielski [20] proved some special cases of this theorem, the proof of which was completed by Lyndon [16] and Dougherty and Mycielski [4]. Droste and Truss [5] proved that certain classes of words are group universal for the automorphism group of the countably infinite random graph.

Roughly speaking, if $w$ is a group universal word for $G$, then the equation $w = g$ can be solved for all $g \in G$. It is natural to extend this to solving simultaneous equations. If $F$ is a free group and $w_1, w_2, \ldots \in F$, then given any sequence $g_1, g_2, \ldots \in G$, is it possible to find a homomorphism $\phi : F \longrightarrow G$ such that $(w_i)\phi = g_i$ for all $i \in \mathbb{N}$? The sequence $w_1, w_2, \ldots \in F$ is *group universal* for $G$ if such a homomorphism exists for all $g_1, g_2, \ldots \in G$. In [11], Galvin showed that $(a^{-1}(a^nba^{-n})b^{-1}(a^nb^{-1}a^{-n})ba)_{n\in\mathbb{N}}$ is universal for the symmetric group on an infinite set. Truss [26] showed that Galvin's proof works essentially unchanged for the groups of homeomorphisms of the Cantor space, the rationals $\mathbb{Q}$, and the irrationals $\mathbb{R} \setminus \mathbb{Q}$. If $G$ is a group, and $a, b \in G$, then the *commutator* $a^{-1}b^{-1}ab$ is denoted $[a, b]$ and the *conjugate* $a^{-1}ba$ is denoted $b^a$. In [14], the present authors showed that

$$\left(\prod_{i=3n(n-1)}^{3n(n+1)-1} [a^{b^{-8i-1}}, a^{b^{8i+2}c}]^{f^2} \cdot [a^{b^{-8i-3}}, a^{b^{8i+4}c}]^{f^4} \cdot [a^{b^{-8i-5}}, a^{b^{8i+6}c}]^{f^3} \cdot [a^{b^{-8i-7}}, a^{b^{8i+8}c}]^{f^5}\right)_{n\in\mathbb{N}}$$

is a universal sequence for the group $\operatorname{Aut}(\mathbb{Q}, \leq)$ of order-automorphisms of the rationals $\mathbb{Q}$, and that there exists a universal sequence for $\operatorname{Aut}(\mathbb{Q}, \leq)$ over a 2-letter alphabet. In [7], Droste and Shelah consider a more general notion of universality than that defined here. As a special case, it follows from the result in [7] that if $X$ and $Y$ are sets such that $|X|, |Y| > 2^{\aleph_0}$, then a finite sequence is universal, in our sense, for $\operatorname{Sym}(X)$ if and only if it is universal for $\operatorname{Sym}(Y)$. In Corollary 3.2, we extend this result to infinite universal sequences.

Let $A$ be a finite set, called an *alphabet*, and let $A^+$ denote the *free semigroup* consisting of all of the non-empty words over $A$ with multiplication being simply the concatenation of words.

**Definition 1.1.** Let $S$ be a semigroup and let $A$ be any alphabet. Then a sequence of words $w_1, w_2, \ldots \in A^+$ is *semigroup universal* for $S$ if for any sequence $s_1, s_2, \ldots \in S$ there exists a homomorphism $\phi : A^+ \longrightarrow S$ such that $(w_n)\phi = s_n$ for all $n \in \mathbb{N}$.

Suppose that $G$ is a group. Since the free semigroup on a finite alphabet $A$ is a subsemigroup of the free group on $A$, it follows that every semigroup universal sequence for $G$ is also a group universal sequence for $G$. On the other hand, every group universal sequence over $A$ for $G$ is a semigroup universal sequence for $G$ over $A \cup A^{-1}$. So, broadly speaking, the notion of semigroup universal sequences includes the corresponding notion for groups, and as such we will restrict ourselves to considering only semigroup universal sequences.

The existence of a universal sequence over a finite alphabet for a semigroup $S$ implies that $S$ has several further properties. For instance, if $S$ is such a semigroup and $X$ is any generating set for $S$, then there exists an $n \in \mathbb{N}$ such that every element of $S$ can be given as a product over $X$ of length at most $n$. This is known as the *Bergman property* after Bergman's seminal paper [2]; see also [17, 19]. A group $G$ with the Bergman property automatically satisfies Serré's properties (FA) and (FH); see [15]. There are, of course, many groups which have no universal sequences. For example, since every group with a universal sequence has property (FA), any group with $\mathbb{Z}$ as a homomorphic image has no universal sequences (see also Corollary 2.4(i)).

The question of whether a universal sequence exists for a given semigroup has a long history, which predates Óre's Theorem [21]. In 1934, Sierpiński [22] showed that $(ab^{n-1}cd^{n-1})_{n\in\mathbb{N}}$ is a universal sequence for the semigroup of continuous functions on the closed unit interval $[0, 1]$ in $\mathbb{R}$, and in 1935, [23] showed that $(a^2b^3(abab^3)^{n+1}ab^2ab^3)_{n\in\mathbb{N}}$ is universal for the semigroup $X^X$ of functions from the infinite set $X$ to itself where the operation is composition of functions. Several further universal sequences are known for $X^X$ when $X$ is infinite, such as $(aba^{n+1}b^2)_{n\in\mathbb{N}}$; see Banach [1].

It was shown in [19] that every countable subset of the semigroup consisting of all surjective functions on an infinite set is contained in a finitely generated subsemigroup, but that this semigroup has no universal sequences. Some recent results include [8, Theorem 31], [9, Theorem 37], and [10, Theorem 6.1]. See [19] and the references therein for further background on universal sequences for semigroups.

In the context of clones of polymorphisms, the natural equivalent of words are *terms*. In [18], McNulty gave a sufficient condition for such a sequence of terms to be universal. A special case of our main result in Section 4 and of McNulty's result, is Corollary 4.4. Taylor [25] showed that the question of whether or not a term is universal for the clone of polymorphisms is undecidable.

Given that a universal sequence for a given semigroup $S$ exists, it is natural to attempt to classify all of the universal sequences for $S$. For instance, given that universal words for the symmetric group $\operatorname{Sym}(X)$ on any infinite set $X$ are completely classified, we might ask for a classification of universal sequences for $\operatorname{Sym}(X)$. We do not provide such a classification, but in Section 3, we show that if $X$ is any infinite set and $Y$ is any set containing $X$, then every sequence that is universal for the symmetric group $\operatorname{Sym}(X)$ on $X$ is universal for $\operatorname{Sym}(Y)$. The converse holds when $|X|$ is greater than $2^{\aleph_0}$. We also show that the analogous results hold for the symmetric inverse monoids.

The question of describing universal words for $X^X$, and whether or not such words depend on the cardinality of $X$, is Problem 27 in [3]. As a partial result in the direction of solving this problem in Section 4, we give a natural sufficient condition under which a sequence over a 2-letter alphabet is universal for $X^X$. A special case of this condition is any sequence of distinct words $w_1, w_2, \dots$ where no $w_i$ is a subword of any $w_j$, $i \neq j$, and no proper prefix of any $w_i$ is a suffix of any $w_j$. We will show in Proposition 2.5 that the apparent restriction to 2-letter alphabets is, in fact, not a restriction at all.

## 2. Preliminaries

In this section, we present some preliminary material about semigroups and universal sequences. Throughout the paper we use the convention that a countable set can be finite or infinite.

A *monoid* is a semigroup $M$ with an identity, that is an element $1_M \in M$ such that $1_M m = m 1_M = m$ for all $m \in M$. A *submonoid* of a monoid $M$ is a subsemigroup containing the identity $1_M$ of $M$. Any semigroup can be made into a monoid by adjoining an identity as follows. If $S$ is a semigroup and $1_S \notin S$, define an operation on $S^1 = S \cup \{1_S\}$ which extends the operation of $S$ by $s1_S = 1_S s = s$ for all $s \in S^1$. The set $S^1$ with this operation is a monoid. An element $0_S$ of a semigroup $S$ is called a *zero* if $0_S s = s0_S = 0_S$ for all $s \in S$. A zero can be adjoined to a semigroup $S$ in much the same way as an identity; we denote this by $S^0$. The *free monoid* $A^*$ is obtained from $A^+$ by adjoining an identity $\varepsilon$, usually referred to as the *empty word*. If $w = a_1 \cdots a_n$ is a word in $A^*$ and $i, j \in \{1, \ldots, n\}$ are such that $i \leq j$, then $a_1 \cdots a_{i-1}$ is a *prefix* of $w$, $a_{j+1} \cdots a_n$ is a *suffix* of $w$, and $a_i \cdots a_j$ is a *subword* of $w$. The empty word $\varepsilon$ is a prefix and a suffix of every word. The *free groups* are the free objects in the category of groups, see, for example, [13, Chapter I, Section 9].

The analogue of the symmetric group in the context of semigroups is the *full transformation monoid* $X^X$ consisting of all functions from the set $X$ to $X$ under composition of functions. Every semigroup is isomorphic to a subsemigroup of some full transformation monoid; see [12, Theorem 1.1.2].

An *inverse semigroup* is a semigroup $S$ such that for all $x \in S$ there exists a unique $x^{-1} \in S$ such that $xx^{-1}x = x$ and $x^{-1}xx^{-1} = x^{-1}$. A *partial permutation* on a set $X$ is a bijection $f : A \longrightarrow B$ between subsets $A$ and $B$ of $X$. The set $A$ is called the *domain* of $f$ and is denoted $\operatorname{dom}(A)$; the set $B$ is called the *range* and is denoted $\operatorname{ran}(B)$. If $f : X \longrightarrow Y$ is a partial permutation and $Z \subseteq X$, then the *restriction* of $f$ to $Z$ is the partial permutation $f|_Z : Z \longrightarrow Y$ defined by $(z)f|_Z = (z)f$ for all $z \in Z$. Under the usual composition of binary relations, the set $I(X)$ of all partial permutations on $X$ is an inverse semigroup; $I(X)$ will be referred to as the *symmetric inverse monoid* on $X$. The Wagner-Preston Representation Theorem [12, Theorem 5.1.7] states that every inverse semigroup is isomorphic to an inverse subsemigroup of $I(X)$ for some set $X$. There exist free objects in the category of inverse semigroups, which are called the *free inverse semigroups*; see [12, Section 5.10] for more details. It is possible to define the notion of an inverse semigroup universal sequence, which is analogous to the notions defined above for groups and semigroups. Semigroup and inverse semigroup universal sequences can be compared in the same way as group and semigroup universal sequences were in the introduction. More precisely, if $S$ is an inverse semigroup, then the free semigroup on a finite alphabet $A$ is a subsemigroup of the free inverse semigroup on $A$. Hence every semigroup universal sequence for $S$ is also an inverse semigroup universal sequence for $S$. On the other hand, every inverse semigroup universal sequence over $A$ for $S$ is a semigroup universal sequence for $S$ over $A \cup A^{-1}$. So, in some sense, semigroup universal sequences encompass group and inverse semigroup universal sequences, and as such we will only consider semigroup universal sequences in the remainder of this paper. For the sake of brevity we may refer to semigroup universal sequences as simply *universal sequences*.

We conclude this section with some observations about universal sequences and the nature of semigroups with a universal sequence over a finite alphabet.

The existence of a universal sequence for any semigroup $S$, immediately implies the existence of $2^{\aleph_0}$ universal sequences for $S$, by permuting the terms, or taking subsequences.

**Proposition 2.1.** *Let $S$ be a semigroup and let $\alpha > 0$ be some cardinal number. Then a sequence is universal for $S$ if and only if it is universal for $S^\alpha$.*

*Proof.* The case when $\alpha$ is countably infinite is [14, Proposition 2.1(ii)], and we note that the proof given in [14] also works for arbitrary cardinals both infinite and finite. ☐

The next proposition shows that universal sequences are preserved by surjective homomorphisms.

**Proposition 2.2.** *Let $S$ and $T$ be semigroups, let $\zeta : S \longrightarrow T$ be a surjective homomorphism, and let $A$ be any alphabet. If $w_1, w_2, \ldots \in A^+$ is universal for $S$, then $w_1, w_2, \ldots$ is universal for $T$.*

*Proof.* Let $t_1, t_2, \ldots \in T$ be arbitrary. Then there exists a homomorphism $\phi : A^+ \longrightarrow S$ such that $(w_i)\phi \in (t_i)\zeta^{-1}$ for all $i \in \mathbb{N}$. Hence $\phi\zeta : A^+ \longrightarrow T$ is a homomorphism and $(w_i)\phi\zeta = t_i$ for all $i$, and so $w_1, w_2, \ldots$ is universal for $T$. ☐

Next, we show that a semigroup for which there exists a universal sequence over a finite alphabet must be at least of cardinality continuum.

**Proposition 2.3.** *If $S$ is a semigroup, $|S| > 1$, and there exists a universal sequence for $S$ over finite alphabet, then $|S| \geq 2^{\aleph_0}$.*

*Proof.* Let $(w_1, w_2, \ldots)$ be a universal sequence for $S$ over some finite alphabet $A$. Suppose that $s_1, s_2, \ldots, t_1, t_2, \ldots \in S$ are such that there exists $i \in \mathbb{N}$ such that $s_i \neq t_i$. Then there exist homomorphisms $\phi_s, \phi_t : A^+ \longrightarrow S$ such that $(w_n)\phi_s = s_n$ and $(w_n)\phi_t = t_n$ for all $n \in \mathbb{N}$. Since $(w_i)\phi_s = s_i \neq t_i = (w_i)\phi_t$, it follows that $\phi_s \neq \phi_t$. There are $|S|^{\aleph_0}$ distinct sequences of elements of $S$, each of which gives rise to a distinct homomorphism from $A^+$ to $S$ by the above. Hence there are at least $|S|^{\aleph_0}$ distinct homomorphisms from $A^+$ to $S$.

On the other hand, any homomorphism from $A^+$ to $S$ is determined by its values on the set $A$, and hence there are at most $|S|^{|A|}$ such homomorphisms. Therefore $|S|^{|A|} \geq |S|^{\aleph_0} \geq 2^{\aleph_0}$ and since $A$ is finite, it follows that $|S| \geq 2^{\aleph_0}$. ☐

**Corollary 2.4.** *Let $S$ be a semigroup. Then the following hold:*

(i) *if $S$ has a non-trivial homomorphic image of cardinality less than $2^{\aleph_0}$, then $S$ has no universal sequences over any finite alphabets;*
(ii) *if $S$ can be partitioned into an ideal and a subsemigroup, then $S$ has no universal sequences over any finite alphabets;*
(iii) *if $S$ is non-empty, then the semigroup obtained from $S$ by adjoining an identity, or a zero, has no universal sequences over a finite alphabet.*

*Proof.* **(i).** By Proposition 2.2, any sequence over any alphabet that is universal for $S$ is also universal for every homomorphic image of $S$. Thus, by Proposition 2.3, $S$ has no infinite universal sequences over any finite alphabet.

**(ii).** The partition of $S$ into an ideal and a subsemigroup defines a congruence on $S$, and so $S$ has a homomorphic image of size 2. This part then follows by part (i).

**(iii).** Let $S^1 = S \cup \{1\}$ and $S^0 = S \cup \{0\}$ be the semigroups obtained by adjoining an identity and a zero to $S$, respectively. Then $\{1\}$ is a subsemigroup, and $S$ is an ideal, of

$S^1$. Similarly, $S$ is a subsemigroup, and $\{0\}$ is an ideal, of $S^0$. In either case, this part follows by part (ii). □

Part (iii) of the previous corollary shows that we may not, and so we do not, assume without loss of generality that every semigroup is a monoid.

If our ultimate goal is to classify all of the universal sequences for a given semigroup $S$, then the next result shows that, in some sense, it suffices to classify all of the universal sequences for $S$ over an alphabet with as few letters as possible.

**Proposition 2.5** (cf. Problem 27 in [3])**.** *Let $S$ be a semigroup such that there exists a universal sequence for $S$ over a finite alphabet, and let $A$ be such an alphabet of minimum cardinality. If $B$ is an alphabet and $|B| \geq |A|$, then there exists a function $\phi : (B^+)^{\mathbb{N}} \longrightarrow (A^+)^{\mathbb{N}}$ such that $(w_1, w_2, \ldots) \in (B^+)^{\mathbb{N}}$ is universal universal for $S$ if and only if $(w_1, w_2, \ldots)\phi \in (A^+)^{\mathbb{N}}$ is universal for $S$.*

*Proof.* By assumption, there exists a universal sequence $(w_1, w_2, \ldots) \in (A^+)^{\mathbb{N}}$ for $S$. If $(u_1, u_2 \ldots)$ is a sequence over $B = \{b_1, \ldots, b_n\}$, then for every $m \in \mathbb{N}$ we define $v_m \in (A^+)^{\mathbb{N}}$ to be the word obtained by replacing every occurrence of every letter $b_j$ in $u_m \in B^+$ by the word $w_j \in A^+$. We define $\phi$ by $(u_1, u_2, \ldots)\phi = (v_1, v_2, \ldots)$.

If $(u_1, u_2, \ldots)$ is universal for $S$ over $B$, then for any choice of $s_1, s_2, \ldots \in S$ there is a homomorphism $\Phi : B^+ \longrightarrow S$ such that $(u_i)\Phi = s_i$ for all $i$. Since $(w_1, w_2, \ldots)$ is universal there is a homomorphism $\Psi : A^+ \longrightarrow S$ such that $(w_j)\Psi = (b_j)\Phi$ for all $j \in \{1, \ldots, n\}$. Then $(v_i)\Psi = (u_i)\Phi = s_i$ for all $i$, and so $(v_1, v_2, \ldots)$ is universal also.

On the other hand, if $(v_1, v_2, \ldots)$ is universal, then for every choice of $s_1, s_2, \ldots \in S$ there is a homomorphism $\Phi : A^+ \longrightarrow S$ such that $(v_i)\Phi = s_i$ for all $i$. If $\Psi : B^+ \longrightarrow S$ is the natural homomorphism extending $(b_j)\Psi = (w_j)\Phi$ for all $j$, then $(u_i)\Psi = (v_i)\Phi = s_i$ for all $i$, and thus $(u_1, u_2, \ldots)$ is universal. □

## 3. The role of $|X|$ for universal sequences in $\text{Sym}(X)$ and $I(X)$

In this section, we consider a class of semigroups which includes the symmetric groups and inverse symmetric monoids on arbitrary infinite sets. In particular, let $\alpha$ be either an arbitrary infinite cardinal or 0, and let $X$ be any set. Then we denote by $I(X, \alpha)$ the inverse subsemigroup of $I(X)$ consisting of all the partial permutations $f$ of $X$ such that $|X \setminus \text{dom}(f)|, |X \setminus \text{ran}(f)| \leq \alpha$. Note that $I(X, 0) = \text{Sym}(X)$, the symmetric group on $X$, and that $I(X, \alpha)$ is the whole of $I(X)$ for any $\alpha \geq |X|$.

The main theorem of this section is the following.

**Theorem 3.1.** *Let $X$ and $Y$ be sets, and let $\alpha$ be any infinite cardinal number or 0. Then the following hold:*

(i) *if $\aleph_0 \leq |X| < |Y|$ and $\alpha \in \{0, |Y|\}$, then every sequence that is universal over a countable alphabet for $I(X, \alpha)$ is universal for $I(Y, \alpha)$;*
(ii) *if $2^{\aleph_0} < |X| < |Y|$, $\alpha < |X|$ or $\alpha = |Y|$, and $|X|$ is a regular cardinal, then every sequence that is universal over a countable alphabet for $I(Y, \alpha)$ is universal for $I(X, \alpha)$.*

Before proceeding with the proof of Theorem 3.1 we give two immediate corollaries for the symmetric group and the symmetric inverse monoid.

**Corollary 3.2.** *Let $X$ and $Y$ be infinite sets such that $|X| < |Y|$. Then the following hold:*

(i) *every sequence that is universal over a countable alphabet for* $\mathrm{Sym}(X)$ *is universal for* $\mathrm{Sym}(Y)$*;*

(ii) *if $2^{\aleph_0} < |X|$, then every sequence that is universal over a countable alphabet for* $\mathrm{Sym}(Y)$ *is universal for* $\mathrm{Sym}(X)$*.*

*In particular, if $2^{\aleph_0} < |X| \leq |Y|$, then the universal sequences over a countable alphabet for* $\mathrm{Sym}(X)$ *coincide with those for* $\mathrm{Sym}(Y)$*.*

*Proof.* Part (i) follows immediately from Theorem 3.1(i), when $\alpha = 0$.

For part (ii), it suffices to show that the regularity condition in part (ii) of Theorem 3.1 can be removed. Let $w_1, w_2, \ldots$ be a universal sequence for $\mathrm{Sym}(Y)$, let $\lambda$ denote the successor cardinal of $2^{\aleph_0}$, and let $Z$ be any set of cardinality $\lambda$. Then $\lambda$ is a regular cardinal, and so Theorem 3.1(ii) implies that $w_1, w_2, \ldots$ is universal for $\mathrm{Sym}(Z)$. Therefore since $|X| \geq \lambda = |Z|$, it follows from part (i) that $w_1, w_2, \ldots$ is universal for $\mathrm{Sym}(X)$. □

The proof of the next corollary is analogous to that of Corollary 3.2, if $\alpha = |Y|$ and we observe that $I(X, \alpha) = I(X)$ and $I(Y, \alpha) = I(Y)$.

**Corollary 3.3.** *Let $X$ and $Y$ be infinite sets such that $|X| < |Y|$. Then the following hold:*

(i) *every sequence that is universal over a countable alphabet for $I(X)$ is universal for $I(Y)$;*

(ii) *if $2^{\aleph_0} < |X|$, then every sequence that is universal over a countable alphabet for $I(Y)$ is universal for $I(X)$.*

*In particular, if $2^{\aleph_0} < |X|$, then the universal sequences over a countable alphabet for $I(X)$ coincide with those for $I(Y)$.*

We now proceed to the proof of Theorem 3.1.

*Proof of Theorem 3.1.* **(i).** Let $w_1, w_2, \ldots$ be a universal sequence for $I(X, \alpha)$ over some countable alphabet $A$, and let $s_1, s_2, \ldots \in I(Y, \alpha)$ be arbitrary. By Proposition 2.1, it follows that $w_1, w_2, \ldots$ is also universal for $I(X, \alpha)^{|Y|}$.

We define $S$ to be the inverse semigroup generated by $\{s_1, s_2, \ldots\}$. Then $S$ is countable and the sets $\{(z)s : s \in S^1\}$, where $z \in Y$, partition $Y$ into $|Y|$ many countable sets. We refer to these sets as the *blocks* of $S$ on $Y$. Define a partition $\{X_y : y \in Y\}$ of $Y$ such that each $X_y$ is a union of blocks and $|X_y| = |X|$, this is possible since the blocks are countable and $X$ is infinite. For every $y \in Y$, let $\mu_y : X_y \longrightarrow X$ be any bijection. It follows that $f : S \longrightarrow I(X, \alpha)^{|Y|}$ defined by $(s)f = (\mu_y^{-1} s \mu_y)_{y \in Y}$ is an injective homomorphism.

Define a map $g : I(X, \alpha)^{|Y|} \longrightarrow I(Y)$ by

$$((b_y)_{y \in Y})g = \bigcup_{y \in Y} \mu_y b_y \mu_y^{-1}.$$

Since the sets $X_y$ partition $Y$, $((b_y)_{y\in Y})g$ is a well-defined partial permutation of $Y$. We will show that if $\alpha$ is either $|Y|$ or 0, then, in fact, $g$ is contained in $I(Y,\alpha)$. If $\alpha$ is $|Y|$, then $I(Y,\alpha)=I(Y)$, as required. Suppose that $\alpha=0$. Then for every $(b_y)_{y\in Y}\in I(X,\alpha)^{|Y|}$ and every $y\in Y$

$$|X_y \setminus \operatorname{dom}(\mu_y b_y \mu_y^{-1})| = |X\setminus \operatorname{dom}(b_y)| = 0$$

and similarly

$$|X_y \setminus \operatorname{ran}(\mu_y b_y \mu_y^{-1})| = |X\setminus \operatorname{ran}(b_y)| = 0.$$

Hence the domain and range of $((b_y)_{y\in Y})g$ are both $Y$, and so $((b_y)_{y\in Y})g\in I(Y,\alpha)$. Hence $g: I(X,\alpha)^{|Y|}\longrightarrow I(Y,\alpha)$ is a homomorphism, and $(s)fg=s$ for all $s\in S$.

Since $w_1,w_2,\ldots$ is a universal sequence for $I(X,\alpha)^{|Y|}$, there exists a homomorphism $\phi: A^+\longrightarrow I(X,\alpha)^{|Y|}$ such that $(w_n)\phi=(s_n)f$ for all $n$, and so $\phi\circ g: A^+\longrightarrow I(Y,\alpha)$ is a homomorphism and $(w_n)\phi\circ g=(s_n)fg=s_n$, as required.

**(ii).** Let $w_1,w_2,\ldots$ be a universal sequence for $I(Y,\alpha)$ over some countable alphabet $A$, and let $s_1,s_2,\ldots\in I(X,\alpha)$ be arbitrary.

As in part (i) we denote the inverse subsemigroup of $I(X,\alpha)$ generated by $\{s_1,s_2,\ldots\}$ by $S$, and let $\Omega$ be the set of blocks of $S$ on $X$. We define an equivalence relation $\sim$ on $\Omega$ as follows: for $U,V\in\Omega$ we write $U\sim V$ if there is a bijection $\phi:U\longrightarrow V$ such that $s_n\circ\phi=\phi\circ s_n$ for all $n\in\mathbb{N}$. In other words, $U\sim V$ if and only if the inverse semigroup $S$ has the same action on $U$ and $V$, up to relabelling the points.

If $U\in\Omega$, then $|U|\leq\aleph_0$ and since $|X|>\aleph_0$, it follows that $|\Omega|=|X|$. Since a countable semigroup has at most $\aleph_0^{\aleph_0}=2^{\aleph_0}$ distinct (partial) actions on a given countable set, it follows that there are at most $2^{\aleph_0}$ equivalence classes of $\sim$. Since $|\Omega|=|X|>2^{\aleph_0}$ and $|X|$ is a regular cardinal, $\Omega$ cannot be written as a union of $2^{\aleph_0}$ sets of cardinality strictly less than $|X|$. Hence there exists an equivalence class $E$ of $\sim$ such that $|E|=|X|$.

For a fixed $U\in E$, we define $Y'$ to be the disjoint union of $Y\times U$ and $X$ and also for each $n$ we define $t_n: Y'\longrightarrow Y'$ by

$$(x)t_n=\begin{cases}(x)s_n & x\in X\\ (y,(z)s_n) & x=(y,z)\in Y\times U.\end{cases}$$

Obviously $t_n$ is a partial permutation, and we will show that $t_n\in I(Y',\alpha)$. There are two cases to consider, when $\alpha=|Y|$ and when $\alpha<|X|$. If $\alpha=|Y|$, then $I(Y',\alpha)$ consists of all partial permutations on $Y'$, and so $t_n\in I(Y',\alpha)$. The other case is significantly more complicated.

**Claim 3.4.** If $\alpha<|X|$, then $t_n\in I(Y',\alpha)$ for all $n\in\mathbb{N}$.

*Proof.* We define

$$Z=\bigcup_{s\in S}\big(X\setminus\operatorname{dom}(s)\big)\cup\big(X\setminus\operatorname{ran}(s)\big).$$

Since $Z$ is a countable union of sets with cardinality at most $\alpha$, $|Z|\leq\alpha$.

If $V,W\in E$ and $V\cap Z\neq\varnothing$, then we will show that $W\cap Z\neq\varnothing$ also. Since $V,W\in E$, there exists a bijection $\phi: V\longrightarrow W$ such that $s_n\phi=\phi s_n$ for all $n\in\mathbb{N}$. Suppose that $x\in V\cap Z$. Then by the definition of $Z$ there exists $m\in\mathbb{N}$ such that $x\notin\operatorname{dom}(s_m)$ or

$x \notin \text{ran}(s_m)$. If $x \notin \text{dom}(s_m)$, then $x \notin \text{dom}(s_m\phi) = \text{dom}(\phi s_m)$. But $x \in \text{dom}(\phi) = V$, and so $(x)\phi \notin \text{dom}(s_m)$. In other words, $(x)\phi \in W \cap Z$, which is consequently non-empty. The case that $x \notin \text{ran}(s_m)$ is dual.

So, if $V \cap Z \neq \varnothing$ for some $V \in E$, then $W \cap Z \neq \varnothing$ for all $W \in E$. Hence since elements of $E$ are pairwise disjoint it follows that

$$\alpha < |X| = |E| \leq |\bigcup_{V \in E} V \cap Z| \leq |Z| \leq \alpha$$

a contradiction. Hence $V \cap Z = \varnothing$, or equivalently,

$$V \subseteq \bigcap_{s \in S} \text{dom}(s) \cap \text{ran}(s),$$

for all $V \in E$. Hence if $s \in S$, then $s|_U : U \longrightarrow U$ is surjective, and since every element of $I(X, \alpha)$ is injective, $s$ is a permutation of $U$. Since, in this case, $s_n$ is a permutation of $U$, it follows that $Y' \setminus \text{dom}(t_n) = X \setminus \text{dom}(s_n)$ for all $n \in \mathbb{N}$. In particular, $t_n \in I(Y', \alpha)$ for all $n \in \mathbb{N}$, as required. □

Since $w_1, w_2, \ldots \in A^+$ is universal for $I(Y, \alpha)$ and $|Y| = |Y'|$, it follows that $w_1, w_2, \ldots$ is universal for $I(Y', \alpha)$ also. Thus there is a homomorphism $\Phi : A^+ \longrightarrow I(Y', \alpha)$ such that $(w_n)\Phi = t_n$ for all $n \in \mathbb{N}$. We define $X' = \{(x)f : x \in X,\ f \in (A^+)\Phi\} \cup X \subseteq Y'$. Since $(A^+)\Phi$ is countable and $|X| > \aleph_0$, it follows that $|X'| = |X|$.

Let $T$ be the inverse subsemigroup of $I(Y', \alpha)$ generated by $\{t_1, t_2, \ldots\}$ and let $\Omega'$ be the set of blocks of $T$ acting on $X' \setminus X$. Since $|E| = |X|$ and $|\Omega'| \leq |X|$, there exists a bijection $b : E \longrightarrow \Omega' \cup E$. We will show that for every $V \in E$ there exists $\phi_V : V \longrightarrow (V)b$ such that $t_n\phi_V = \phi_V t_n$ for all $n \in \mathbb{N}$. If $(V)b \in E$, then this follows immediately from the definition of $E$ and since $t_n|_X = s_n$. Suppose that $(V)b \in \Omega'$. If $(x, y) \in (V)b \subseteq X' \setminus X \subseteq Y' \setminus X = Y \times U$, then

$$(V)b = \{(x, (y)s) : s \in S\} = \{x\} \times U$$

since $U$ is a block of the action of $S$ on $X$. Since $U, V \in E$, there exists bijection $\phi : V \longrightarrow U$ such that $\phi s_n = s_n\phi$ for all $n \in \mathbb{N}$. Define $\phi_V : V \longrightarrow \{x\} \times U$ so that $(a)\phi_V = (x, (a)\phi)$. Since $\phi$ is a bijection, so too is $\phi_V$. If $n \in \mathbb{N}$ and $a \in V$ are arbitrary, then

$$(a)\phi_V t_n = (x, (a)\phi)t_n = (x, (a)\phi s_n) = (x, (a)s_n\phi) = (a)s_n\phi_V = (a)t_n\phi_V.$$

We define $\psi : X \longrightarrow X'$ by

$$\psi = \bigcup_{V \in E} \phi_V \cup 1_{X \setminus \bigcup_{W \in E} W}.$$

Note that $\psi$ is injective, $\text{dom}(\psi) = X$, and $\text{ran}(\psi) = \big(\bigcup_{W \in E}(W)b\big) \cup \big(X \setminus \bigcup_{W \in E} W\big) = X'$. Hence $\psi$ is a bijection. We will show that $\psi t_n = s_n\psi$ for all $n \in \mathbb{N}$. Suppose that $x \in X$. Then either $x \notin V$ for all $V \in E$ or $x \in V$ for some $V \in E$. In the first case, $(x)\psi t_n = (x)t_n = (x)s_n$ and since $(x)s_n \notin V$ for all $V \in E$, it follows that $(x)\psi t_n = (x)s_n = (x)s_n\psi$, as required. In the second case, $(x)\psi t_n = (x)\phi_V t_n = (x)t_n\phi_V = (x)s_n\phi_V$, and since $(x)s_n \in V$, $(x)s_n\phi_V = (x)s_n\psi$.

Define $\Lambda : A^+ \longrightarrow I(X,\alpha)$ by $(w)\Lambda = \psi(w)\Phi|_{X'}\psi^{-1}$ for all $w \in A^+$. By the definition of $X'$, the partial permutation $(w)\Phi$ maps $X'$ to $X'$, and so $(w)\Lambda$ is a partial permutation of $X$. Also

$$|X \setminus \operatorname{dom}((w)\Lambda)| = |X' \setminus \operatorname{dom}((w)\Phi)| \leq |Y' \setminus \operatorname{dom}((w)\Phi)| \leq \alpha$$

and similarly $|X \setminus \operatorname{ran}((w)\Lambda)| \leq \alpha$. Hence $(w)\Lambda \in I(X,\alpha)$. Finally, let $u, v \in A^+$. Then

$$(uv)\Lambda = \psi(u)\Phi|_{X'}1_{X'}(v)\Phi|_{X'}\psi^{-1} = \psi(u)\Phi|_{X'}\psi^{-1}\psi(v)\Phi|_{X'}\psi^{-1} = \Lambda(u)\Lambda(v),$$

and so $\Lambda$ is a homomorphism. Furthermore,

$$(w_n)\Lambda = \psi\ (w_n)\Phi\ \psi^{-1} = \psi t_n \psi^{-1} = s_n$$

and hence $w_n$ is universal for $I(X,\alpha)$. □

We conclude the section with an open question.

**Question 3.5.** Can the assumption that $|X| > 2^{\aleph_0}$ be removed from Theorem 3.1?

## 4. A sufficient condition for the universality of sequences for $X^X$

In this section, we give a sufficient condition for a sequence over a 2-letter alphabet to be universal for $X^X$ for any infinite $X$. This might be seen as a small step towards obtaining a description of the set of all universal sequences for $X^X$, if such a description exists; and towards resolving the following open question, which was the original motivation behind the results in this section.

**Question 4.1.** Let $X$ and $Y$ be infinite sets. Is the set of universal sequences for $X^X$ equal to the set of universal sequences for $Y^Y$?

Throughout this section, we denote by $A$ a fixed alphabet $\{a, b\}$. Let $\mathbf{w} = (w_1, w_2, \ldots)$ be a sequence of elements of $A^+$, and let $S$ be a submonoid of $A^*$ such that:

(1) if $w_n = svuvs'$ where $s, s' \in S$, and $u, v \in A^*$, then $v \in S$;
(2) if $w_m = svt$ and $w_n = t'vs'$, $m \neq n$, where $s, s' \in S$ and $t, t', v \in A^*$, then $v \in S$;
(3) if $w_n = svt$ where $s, t, v \in A^*$ and $sv, vt \in S$, then $w_n \in S$;

where $m, n \in \mathbb{N}$. For every sequence $\mathbf{w}$ of elements of $A^+$ there is at least one submonoid of $A^*$ satisfying these conditions, namely $A^*$ itself.

We will show that for every sequence $\mathbf{w}$ in $A^+$ there exists a least submonoid of $A^*$ with respect to containment satisfying (1), (2), and (3). It can be shown that an arbitrary intersection of submonoids satisfying these three conditions, also satisfies the conditions. However, we opt instead to give a construction of this least submonoid, which we will make use of later.

We define $S_0 = \langle \varepsilon \rangle$ where $\varepsilon$ denotes the empty word, which is the identity element of $A^*$. For some $n \geq 0$, suppose that we have defined a submonoid $S_n$ of $A^*$. We define

$$\begin{aligned} X_n &= \{v \in A^* : w_i = svuvs' \text{ for some } i \in \mathbb{N}, s, s' \in S_n \text{ and } u \in A^*\}; \\ Y_n &= \{v \in A^* : w_i = svt, w_j = t'vs' \text{ for some distinct } i, j \in \mathbb{N}, s, s' \in S_n \text{ and } t, t' \in A^*\}; \\ Z_n &= \{w_i \in A^* : w_i = svt \text{ for some } i \in \mathbb{N} \text{ and } s, v, t \in A^* \text{ so that } sv, vt \in S_n\}. \end{aligned}$$

and set $S_{n+1} = \langle S_n, X_n, Y_n, Z_n\rangle$. We define $S_{\mathbf{w}} = \bigcup_{n\in\mathbb{N}} S_n$. Since $S_0 \leq S_1 \leq S_2 \leq \ldots$ by definition, $S_{\mathbf{w}}$ is a submonoid of $A^*$.

The next proposition is a straightforward consequence of the construction of $S_{\mathbf{w}}$.

**Proposition 4.2.** *Let $\mathbf{w} = (w_1, w_2, \ldots)$ be an arbitrary sequence of elements of $A^+$. Then $S_{\mathbf{w}}$ is the least submonoid of $A^*$ satisfying conditions (1), (2), and (3).*

The main result of this section is the following.

**Theorem 4.3.** *Let $\mathbf{w} = (w_1, w_2, \ldots)$ be a sequence of words in $A^+$ such that $w_n \notin S_{\mathbf{w}}$ for all $n \in \mathbb{N}$. Let $p_n, s_n, u_n \in A^*$ be such that $w_n = p_n u_n s_n$, and $p_n$ and $s_n$ are respectively the longest prefix and the longest suffix of $w_n$ so that $p_n, s_n \in S_{\mathbf{w}}$. Suppose that $u_n$ is a subword of $w_m$ if and only if $n = m$ and that $u_n$ is not a subword of $p_n$ for all $n$. Then $(w_1, w_2, \ldots)$ is a semigroup universal sequence for $X^X$, where $X$ is any infinite set.*

As a corollary to Theorem 4.3 we obtain the following result.

**Corollary 4.4.** *Let $X$ be an infinite set and let $w_1, w_2, \ldots \in A^+$ be such that no proper prefix of $w_n$ is a suffix of any $w_m$ and $w_n$ is not a subword of $w_m$, $m \neq n$. Then $(w_1, w_2, \ldots)$ is a universal sequence for $X^X$.*

*Proof.* It follows from the construction of $S_{\mathbf{w}}$ where $\mathbf{w} = (w_1, w_2, \ldots)$, that $X_1 = Y_1 = Z_1 = \varnothing$. Hence $S_{\mathbf{w}} = \langle\varepsilon\rangle$, and so we are done by Theorem 4.3. □

Examples of sequences satisfying the hypothesis of Corollary 4.4 are $(aba^{n+1}b^2)_{n\in\mathbb{N}}$ and $(a^2b^3(abab^3)^{n+1}ab^2ab^3)_{n\in\mathbb{N}}$ of Banach and Sierpiński mentioned in the introduction. There are further sequences satisfying the hypothesis of Theorem 4.3 but not that of Corollary 4.4. For example, it can be show that if $w_n = aba(ab)^{n+1}bab \in A^+$ for all $n \in \mathbb{N}$, then $(w_1, w_2, \ldots)$ satisfies the hypothesis of Theorem 4.3, even though $ab$ is both a prefix and a suffix.

Before presenting the proof of Theorem 4.3 we prove a technical result about $S_{\mathbf{w}}$.

**Lemma 4.5.** *Let $\mathbf{w} = (w_1, w_2, \ldots)$ be an arbitrary sequence of elements of $A^+$ such that $a, b \notin S_{\mathbf{w}}$. Then either $w_1, w_2, \ldots \in aA^*b$ and $S_{\mathbf{w}} \subseteq aA^*b \cup \{\varepsilon\}$; or $w_1, w_2, \ldots \in bA^*a$ and $S_{\mathbf{w}} \subseteq bA^*a \cup \{\varepsilon\}$.*

*Proof.* We begin by showing that $w_n \in aA^*b$ for all $n \in \mathbb{N}$ or $w_n \in bA^*a$ for all $n \in \mathbb{N}$. Suppose that $w_m \in aA^*$ and $w_n \in A^*a$ for some $m, n \in \mathbb{N}$. Then, by condition (2), $a \in S_{\mathbf{w}}$, which contradicts the assumption of the lemma. Hence if there exists $m \in \mathbb{N}$ such that $w_m \in aA^*$, then $w_n \in A^*b$ for all $n \in \mathbb{N}$. Similarly, if $w_m \in bA^*$, then $w_n \in A^*a$ for all $n \in \mathbb{N}$. Hence together these imply that $w_n \in aA^*b$ for all $n \in \mathbb{N}$ or $w_n \in bA^*a$ for all $n \in \mathbb{N}$, as required. Assume without loss of generality that $w_n \in aA^*b$ for all $n \in \mathbb{N}$. Since $S_0 = \{\varepsilon\}$, it suffices to show that $X_n \cup Y_n \cup Z_n \subseteq aA^*b \cup \{\varepsilon\}$ for all $n \in \mathbb{N}$. Suppose that $n \in \mathbb{N}$ is arbitrary.

If $x \in X_n$, then there exists $m \in \mathbb{N}$ such that $w_m = sxuxs'$ for some $s, s' \in S_n$ and $u, v \in A^*$. If $x \in A^*a$, then since $w_m \in aA^*b$ there exists $q \in A^*$ such that $w_m = aqas'$. Hence $a \in S_{\mathbf{w}}$ by (1), a contradiction. Hence $x \in A^*b$, and, by symmetry, $x \in aA^*$, as required. Suppose that $y \in Y_n$. Then there exist distinct $m, k \in \mathbb{N}$ such that $w_m = syt = aq$

and $w_k = t'ys'$ where $s, s' \in S_n$ and $q, v, t, t' \in A^*$. If $y \in A^*a$, then $w_k = q'as'$ for some $q' \in A^*$ and so $a \in S_{\mathbf{w}}$ by (2), a contradiction. Hence $y \in A^*b$ and by symmetry $y \in aA^*$. By the definition $Z_n$ is a subset of $\{w_n : n \in \mathbb{N}\}$, and so by assumption $Z_n \subseteq aA^*b$. □

**Lemma 4.6.** *If* $\mathbf{w} = (w_1, w_2, \ldots)$ *is a sequence of words in* $A^+$ *such that* $w_n \notin S_{\mathbf{w}}$ *for all* $n \in \mathbb{N}$*, then* $w_n = p_n u_n s_n$ *where* $u_n \in A^+$*, and* $p_n$ *and* $s_n$ *are the longest prefix and suffix, respectively, of* $w_n$ *belonging to* $S_{\mathbf{w}}$*, for all* $n \in \mathbb{N}$*.*

*Proof.* Suppose there exists $n \in \mathbb{N}$ such that $w_n = stv$, $p_n = st$, and $s_n = tv$ for some $s, v \in A^+$ and $t \in A^*$. Then $w_n \in S_{\mathbf{w}}$ by (3), which contradicts the assumption. □

*Proof of Theorem 4.3.* First suppose that $a \in S_{\mathbf{W}}$. We consider three cases: there is $n \in \mathbb{N}$ such that $b$ does not appear in $w_n$; $b$ appears at least twice in at least one $w_n$; and for all $n \in \mathbb{N}$ the letter $b$ appears exactly once. In the first case, $w_n = a^i \in S_{\mathbf{w}}$ for some $i \geq 1$, a contradiction. In the second case, $w_n = a^i buba^j$ for some $i, j \geq 0$ and some $u \in A^*$. Then $b \in S_{\mathbf{w}}$ by (1), and so $S_{\mathbf{w}} = A^*$, a contradiction. In the final case, $w_n = a^{i_n} ba^{j_n}$ for some $i_n, j_n \geq 0$ and all $n \in \mathbb{N}$. Then $b \in S_{\mathbf{w}}$ by (2), again a contradiction. Therefore $a \notin S_{\mathbf{w}}$ and the symmetric argument shows that $b \notin S_{\mathbf{w}}$. For the rest of the proof we assume that $a, b \notin S_{\mathbf{w}}$. By Lemma 4.5 we may assume that $w_1, w_2, \ldots \in aA^*b$ and $S_{\mathbf{w}} \subseteq aA^*b \cup \{\varepsilon\}$.

Denote by $F(A)$ the free group with $A$ being the set of generators. Let $Y$ be any set such that $|Y| = |X|$. Since $F(A)$ is countable and $Y$ is infinite, we may assume that $X$ is the set of eventually constant sequences over $F(A) \cup Y$ such that the first element is in $F(A)$. For convenience write the sequences from right to left, namely

$$X = \{(\ldots, x_1, x_0) : x_0 \in F(A),\ x_i \in F(A) \cup Y \text{ for } i \geq 1, \text{ and there is } K \in \mathbb{N} \text{ such that } x_K = x_k \text{ for all } k \geq K\}.$$

We proceed by proving a series of claims.

**Claim 4.7.** $u_n \in aA^*b$ for all $n \in \mathbb{N}$.

*Proof.* Let $n, m \in \mathbb{N}$ be distinct. Suppose that $u_n \in bA^*$. Then $u_n = bu$ for some $u \in A^*$, thus $w_n = p_n bus_n$. Since $w_m \in aA^*b$ there is some $v \in A^*$ such that $w_m = avb$, and so condition (2) implies that $b \in S_{\mathbf{w}}$, a contradiction. Hence $u_n \in aA^*$ and by symmetry $u_n \in A^*b$. □

By construction $S_{\mathbf{w}}$ is generated by $G = \bigcup_{n \in \mathbb{N}} X_n \cup Y_n \cup Z_n$, a set of subwords of words in $\mathbf{w}$. Let $G_n$ be the set of all words in $G$ of length at most $n$. Recall that we say that a generating set $T$ is irredundant if $v$ is not an element of the monoid generated by $T \setminus \{v\}$ for every $v \in T$. Let $T_1 = G_1$. Then $T_1$ is irredundant. For some $n \in \mathbb{N}$, suppose that we defined $T_n$ such that $T_n$ is an irredundant generating set for the monoid generated by $G_n$ and if $n \geq 2$ then $T_{n-1} \subseteq T_n \subseteq G_n$. Since $S_{\mathbf{w}}$ is free and $G_{n+1}$ is finite, there is an irredundant generating set $T_{n+1}$ for the monoid generated by $G_{n+1}$ such that $T_n \subseteq T_{n+1} \subseteq G_{n+1}$. Therefore such $T_n$ exists for all $n \in \mathbb{N}$. Let $T = \bigcup_{n \in \mathbb{N}} T_n$. Then it is routine to verify that $T$ is an irredundant generating set for $S_{\mathbf{w}}$. We note that $T$ only needs to be a monoid generating set, and so we may assume that $\varepsilon \notin T$.

**Claim 4.8.** For each $v \in T$, there are $t, t' \in S_{\mathbf{w}}$ and $n, m \in \mathbb{N}$ such that $tv$ is a prefix of $p_n$, and $vt'$ is a suffix of $s_m$.

*Proof.* Let $X_k$, $Y_k$, and $Z_k$ be as in the construction of $S_{\mathbf{w}}$. Note that $Z_n = \varnothing$ for all $n \in \mathbb{N}$, as otherwise there exists $w_m \in Z_n \subseteq S_{\mathbf{w}}$ for some $m \in \mathbb{N}$. Hence $T \subseteq \bigcup_{n \in \mathbb{N}} X_n \cup Y_n$.

Suppose $v \in T \cap X_k$ for some $k \in \mathbb{N}$. Then $w_n = tvuvt'$ for some $n \in \mathbb{N}$, $t, t' \in S_k$, and $u \in A^*$. Hence $tv, vt' \in S_{\mathbf{w}}$, and so it then follows from the maximality of $p_n$ and $s_n$ that $tv$ is a prefix of $p_n$, and $vt'$ is a suffix of $s_n$. If $v \in T \cap Y_k$ for some $k \in \mathbb{N}$, then $w_n = qvt$ and $w_m = t'vq'$ for some $n, m \in \mathbb{N}$, $t, t' \in A^*$, and $q, q' \in S_k$. Hence $tv, vt' \in S_{\mathbf{w}}$, and so $tv$ is a prefix of $p_n$, and $vt'$ is a suffix of $s_m$. □

**Claim 4.9.** For all $v \in T$ and all $n \in \mathbb{N}$, a prefix of $v$ is not a suffix of $u_n$, and a suffix of $v$ is not a prefix of $u_n$.

*Proof.* Let $v \in T$ and $n \in \mathbb{N}$ be arbitrary. By Claim 4.8 there are $t, t' \in S_{\mathbf{w}}$ such that $tv$ is a prefix of $p_m$ and $vt'$ is a suffix of $s_k$ for some $m, k \in \mathbb{N}$. Then there is $r \in A^*$ so that $w_m = tvru_ms_m$. Suppose that $q$ is a non-trivial prefix of $v$ which is also a suffix of $u_n$. First, consider the case where $m = n$. Then $q \in S_{\mathbf{w}}$ by (1) as $w_m = tqhqs_m$ for some $h \in A^*$. If $m \neq n$, then, since $w_m = tvru_ms_m$ and $w_n = p_nu_ns_n$ where $t, s_n \in S_{\mathbf{w}}$, it follows from (2) that $q \in S_{\mathbf{w}}$. Hence in both cases $q \in S_{\mathbf{w}}$, which contradicts the maximality of $s_n$.

The case where $q$ is non-trivial suffix of $v$ which is a prefix of $u_n$ follows in an almost identical way, using $w_k = p_ku_kr'vt'$ for some $r', t' \in A^*$. □

**Claim 4.10.** For every $v, v' \in T$, if a non-trivial prefix $q$ of $v$ is a suffix of $v'$, then $q = v = v'$.

*Proof.* Let $v, v' \in T$ be arbitrary. Suppose that $v = qr$ and $v' = r'q$ for some $r, r' \in A^*$ and $q \in A^+$. By Claim 4.8 there are $t, t' \in S_{\mathbf{w}}$ and $n, m \in \mathbb{N}$ such that $tv$ is a prefix of $p_n$, and $v't'$ is a suffix of $s_m$. If $n = m$ then there is $x \in A^*$ such that $w_n = tvxv't' = tqrxr'qt'$, and so $q \in S_{\mathbf{w}}$ by (1) since $t, t' \in S_{\mathbf{w}}$. If $n \neq m$, then $w_n = tvx = tqrx$ and $w_m = x'v't' = x'r'qt'$ for some $x, x' \in A^*$. Since $t, t' \in S_{\mathbf{w}}$, (2) implies that $q \in S_{\mathbf{w}}$. Hence $q \in S_{\mathbf{w}}$ in both cases.

Since $v \in T$, by Claim 4.8 there are $n, m \in \mathbb{N}$, $l, l' \in S_{\mathbf{w}}$ so that $lv$ is a prefix of $p_n$ and $vl'$ is a suffix of $s_m$. As in the previous paragraph, if $n = m$ then there is $x \in A^*$ such that $w_n = lvxvl' = lqrxqrl'$, and so $r \in S_{\mathbf{w}}$ by (1) since $lq, l' \in S_{\mathbf{w}}$. If $n \neq m$, then $w_n = lvx = lqrx$ and $w_m = x'v'l' = x'qrl'$ for some $x, x' \in A^*$. Since $lq, l' \in S_{\mathbf{w}}$, (2) implies that $r \in S_{\mathbf{w}}$. Hence $r \in S_{\mathbf{w}}$ in both cases. Since $T$ is irredundant, $q, r \in S_{\mathbf{w}}$, and $qr \in T$, it follows that $r = \varepsilon$. The same argument for $v'$ implies that $r' = \varepsilon$, and so $q = v = v'$. □

Let $f_1, f_2, \ldots \in X^X$. We will construct a homomorphism $\Phi : A^+ \to X^X$ such that $(w_n)\Phi = f_n$ for all $n \in \mathbb{N}$. In order to do that we will require the following auxiliary functions $\alpha, \beta, \gamma \in X^X$ defined as follows:

$$(\ldots, x_1, x_0)\alpha = (\ldots, x_0, a) \qquad \text{and} \qquad (\ldots, x_1, x_0)\beta = (\ldots, x_0, b).$$

If $x_{i-1} \ldots x_0 = v \in T$ for some $i \geq 1$, $x_j \in A^+$ for all $j \in \{0, \ldots i-1\}$, and $x_i \in F(A)$, we define

$$(\ldots, x_1, x_0)\gamma = (\ldots, x_{i+1}, x_iv)$$

and otherwise define $(\dots, x_1, x_0)\gamma = (\dots, x_1, x_0)$.

Suppose there are $i, i' \in \mathbb{N}$, such that $i \geq i'$, $x_{i-1}\dots x_0 = v$, and $x_{i'-1}\dots x_0 = v'$ for some $v, v' \in T$, and so that $x_j \in A^+$ for all $j \in \{0, \dots, i-1\}$. Then $v'$ is a suffix of $v$. By Claim 4.10 this is only possible if $v = v'$. Hence $\gamma$ is well-defined. Let $\Psi : A^+ \longrightarrow X^X$ be the canonical homomorphism induced by $(a)\Psi = \alpha$ and $(b)\Psi = \beta \circ \gamma$. We will later use $\Psi$ to define the required $\Phi$.

**Claim 4.11.** For $v \in aA^*$ such that no prefix of $v$ is a suffix of a word in $T$, there are $z_1, \dots, z_k \in A^+$ such that $z_1 \dots z_k = v$ and $(\dots, x_1, x_0)\left((v)\Psi\right) = (\dots, x_1, x_0, z_1, \dots, z_k)$ for every $(\dots, x_1, x_0) \in X$.

*Proof.* Let $v \in aA^*$ be such that no prefix of $v$ is a suffix of a word in $T$, and let $v = y_1 \dots y_m$ for some $m \in \mathbb{N}$ and $y_1, \dots, y_m \in A$. Then $y_1 = a$, and so $(\dots, x_1, x_0)\alpha = (\dots, x_1, x_0, y_1)$ for all $(\dots, x_1, x_0) \in X$. Suppose that for some $i \in \{1, \dots, m-2\}$ there are $j \in \mathbb{N}$ and $z_1, \dots, z_j \in A^+$ such that $(\dots, x_1, x_0)\left((y_1 \dots y_i)\Psi\right) = (\dots, x_1, x_0, z_1, \dots, z_j)$ for every $(\dots, x_1, x_0) \in X$ and $y_1 \dots y_i = z_1 \dots z_j$.

There are two cases to consider, either $y_{i+1} = a$, or $y_{i+1} = b$. Suppose that $y_{i+1} = a$. Since $\Psi$ is a homomorphism, $(\dots, x_1, x_0)\left((y_1 \dots y_{i+1})\Psi\right) = (\dots, x_1, x_0, z_1, \dots, z_j, a)$ for all $(\dots, x_1, x_0) \in X$ and $z_1 \dots z_j a = y_1 \dots y_{i+1}$. Hence the condition is satisfied. If $y_{i+1} = b$, since $\Psi$ is a homomorphism, $(\dots, x_1, x_0)\left((y_1 \dots y_{i+1})\Psi\right) = (\dots, x_1, x_0, z_1, \dots, z_j, b)\gamma$ for all $(\dots, x_1, x_0) \in X$ and $z_1 \dots z_j b = y_1 \dots y_{i+1}$. Since $y_1 \dots y_{i+1}$ is a prefix of $v$, by the assumption it cannot be a suffix of any word in $T$. Thus $z_1 \dots z_j b \notin T$ and if $x_0, \dots, x_t \in A^+$ then $x_t \dots x_0 z_1 \dots z_j b \notin T$ for all $t \in \mathbb{N}$. Hence either $\gamma$ acts as the identity on $(\dots, x_1, x_0, z_1, \dots, z_j, b)$, or there is $k > 1$ such that $z_k \dots z_j b \in T$. In the later case

$$\begin{aligned}(\dots, x_1, x_0)\left((y_1 \dots y_{i+1})\Psi\right) &= (\dots, x_1, x_0, z_1, \dots, z_j, b)\gamma \\ &= (\dots, x_1, x_0, z_1, \dots, z_{k-1} z_k \dots z_j b).\end{aligned}$$

Since $z_1 \dots z_j b = y_1 \dots y_{i+1}$, the inductive hypothesis is satisfied in both cases. Hence the claim holds by induction. □

**Claim 4.12.** Let $v \in S_{\mathbf{w}}$. Then $(\dots, x_1, x_0)\left((v)\Psi\right) = (\dots, x_1, x_0 v)$ for all $(\dots, x_1, x_0) \in X$ and $(v)\Psi$ is a bijection.

*Proof.* Let $v \in T$. Then $v \in aA^*b$ as $S_{\mathbf{w}} \subseteq aA^*b \cup \{\varepsilon\}$, and so $v = v'b$ for some $v' \in aA^*$. By Claim 4.10 any proper prefix of $v$, and hence any prefix of $v'$, is not a suffix of any word in $T$. Hence by Claim 4.11 there exists $j \in \mathbb{N}$ and $z_1, \dots, z_j \in A^+$ such that $(\dots, x_1, x_0)\left((v')\Psi\right) = (\dots, x_1, x_0, z_1, \dots, z_j)$ for all $(\dots, x_1, x_0) \in X$ and $z_1 \dots z_j = v'$. Since $v = z_1 \dots z_j b$, $\Psi$ is a homomorphism, and $x_0 \in F(A)$, it follows that

$$(\dots, x_1, x_0)\left((v)\Psi\right) = (\dots, x_1, x_0, z_1, \dots, z_j, b)\gamma = (\dots, x_1, x_0 v). \tag{4.1}$$

Suppose that $(\dots, x_1, x_0 v) = (\dots, x_1', x_0' v)$ where $x_i, x_i' \in F(A) \cup Y$ for all $i, i' \geq 1$ and $x_0, x_0' \in F(A)$. Then $x_i = x_i'$ for all $i \geq 1$ and $x_0 v = x_0' v$. Since $x_0 v$ and $x_0' v$ are both elements of the free group $F(A)$ it follows that $x_0 = x_0'$. Hence $(v)\Psi$ is injective by (4.1). Let $(\dots, x_1, x_0) \in X$. Then $(\dots, x_1, x_0 v^{-1})\left((v)\Psi\right) = (\dots, x_1, x_0)$, so $(v)\Psi$ is surjective, and hence bijective on $X$. Therefore, we are done, as $T$ is a generating set for $S_{\mathbf{w}}$. □

In order to define the required $\Phi$, we need a final auxiliary function $\delta \in X^X$, defined as follows. If there exists $n, i \in \mathbb{N}$, $i > 0$, such that $x_{i-1} \cdots x_0 = u_n$, $x_0, \ldots, x_{i-1} \in A^+$, and $x_i \in F(A)$, then we define

$$(\ldots, x_1, x_0)\delta = (\ldots, x_{i+1}, x_i p_n^{-1}) f_n \circ (s_n)\Psi^{-1}$$

and we define $(\ldots, x_1, x_0)\delta = (\ldots, x_1, x_0)$ otherwise. Note that $(s_n)\Psi^{-1}$ is defined by Claim 4.12. Suppose there are $i, i', n, n' \in \mathbb{N}$, $i \geq i'$ such that $x_{i-1} \ldots x_0 = u_n$ and $x_{i'-1} \ldots x_0 = u_{n'}$ where $x_j \in A^+$ for all $j \in \{0, \ldots, i-1\}$ and $x_i, x_{i'} \in F(A)$. Then $u_{n'}$ is a suffix of $u_n$. On the other hand, if $n' \neq n$, then $u_{n'}$ is not a subword of $w_n$ (by assumption in the statement of the theorem) and hence not of $u_n$ either. Hence $n = n'$, and so $i = i'$, and $\delta$ is well-defined.

Let $\Phi$ be the canonical homomorphism induced by $(a)\Phi = \alpha$ and $(b)\Phi = \beta \circ \gamma \circ \delta$.

**Claim 4.13.** If $v \in S_{\mathbf{w}}$, then $(v)\Phi = (v)\Psi$.

*Proof.* Suppose that $v = y_1 \ldots y_m \in T$ where $y_i \in A$ for all $i \in \{1, \ldots, m\}$. Since $S_{\mathbf{w}} \subseteq aA^*b \cup \{\varepsilon\}$, it follows that $y_1 = a$, and so $(y_1)\Phi = \alpha = (y_1)\Psi$. Suppose $(y_1 \ldots y_i)\Phi = (y_1 \ldots y_i)\Psi$ for some $i \in \{1, \ldots, m-1\}$. Then $(y_1 \ldots y_{i+1})\Phi = (y_1 \ldots y_i)\Psi \circ (y_{i+1})\Phi$.

If $y_{i+1} = a$, then $(y_{i+1})\Phi = (y_{i+1})\Psi$, and so the inductive hypothesis is satisfied. Suppose that $y_{i+1} = b$, then $(y_{i+1})\Phi = (y_{i+1})\Psi \circ \delta$, and so $(y_1 \ldots y_{i+1})\Phi = (y_1 \ldots y_{i+1})\Psi \circ \delta$. If $i + 1 < m$, then $y_1 \ldots y_{i+1}$ is a proper prefix of $v$. By Claim 4.10 for any $j \in \{1, \ldots, i+1\}$ the proper prefix $y_1 \ldots y_j$ of $v$ is a not a suffix of any word in $T$. Since $y_1 \ldots y_{i+1} \in aA^*$, by Claim 4.11 there exists $j \in \mathbb{N}$ and $z_1, \ldots, z_j \in A^+$ such that $z_1 \ldots z_j = y_1 \ldots y_{i+1}$ and $(\ldots, x_1, x_0)\left((y_1 \ldots y_{i+1})\Psi\right) = (\ldots, x_1, x_0, z_1, \ldots, z_j)$ for all $(\ldots, x_1, x_0) \in X$. If $i + 1 = m$, then $y_1 \ldots y_{i+1} = v \in S_{\mathbf{w}}$, and so $(\ldots, x_1, x_0)\left((y_1 \ldots y_{i+1})\Psi\right) = (\ldots, x_1, x_0 y_1 \ldots y_{i+1})$ for all $(\ldots, x_1, x_0) \in X$ by Claim 4.12. Hence in any case there are $z_0, \ldots, z_j \in A^+$ such that $z_0 \ldots z_j = y_1 \ldots y_{i+1}$ and for all $(\ldots, x_1, x_0) \in X$

$$(\ldots, x_1, x_0)\left((y_1 \ldots y_{i+1})\Psi\right) = (\ldots, x_1, x_0 z_0, z_1, \ldots, z_j). \tag{4.2}$$

We will show that $\delta$ acts as the identity on $(\ldots, x_1, x_0)\left((y_1 \ldots y_{i+1})\Psi\right)$ for all $(\ldots, x_1, x_0) \in X$. Fix $(\ldots, x_1, x_0) \in X$, and let $z_0, \ldots, z_j \in A^+$ be as in (4.2). Suppose that there are $k \geq 1$ and $n \in \mathbb{N}$ such that $x_{k-1}, \ldots, x_1, x_0 z_0 \in A^+$, $x_k \in F(A)$, and $x_{k-1} \ldots x_0 z_0 \ldots z_j = u_n$. Then $z_0 \ldots z_j = y_1 \ldots y_{i+1}$ is both a prefix of $v$ and a suffix of $u_n$, contradicting Claim 4.9. If $k > 0$ and $z_k \ldots z_j = u_n$, then $u_n$ is a subword of $v$ for some $n \in \mathbb{N}$. By Claim 4.8 there are $t \in S_{\mathbf{w}}$ and $m \in \mathbb{N}$ such that $tv$ is a prefix of $p_m$, and so $u_n$ is a subword of $p_n$, contradicting by the hypothesis of the theorem. Hence $\delta$ acts as identity on $(\ldots, x_1, x_0 z_0, z_1, \ldots, z_j)$, and so the inductive hypothesis is satisfied and by induction, that is $(v)\Phi = (v)\Psi$ for all $v \in T$. Since $T$ is a generating set for $S_{\mathbf{w}}$, it follows that $(v)\Phi = (v)\Psi$ for all $v \in S_{\mathbf{w}}$. □

**Claim 4.14.** $(u_n)\Phi = (u_n)\Psi \circ \delta$ for all $n \in \mathbb{N}$.

*Proof.* Let $n \in \mathbb{N}$, and let $u_n = y_1 \ldots y_m$ where $y_1, \ldots, y_m \in A$. We will now show that $(y_1 \ldots y_{m-1})\Phi = (y_1 \ldots y_{m-1})\Psi$. Since $y_1 = a$, it follows that $(y_1)\Phi = \alpha = (y_1)\Psi$. Suppose $(y_1 \ldots y_i)\Phi = (y_1 \ldots y_i)\Psi$ for some $i \in \{1, \ldots, m-2\}$. Then $(y_1 \ldots y_{i+1})\Phi = (y_1 \ldots y_i)\Psi \circ (y_{i+1})\Phi$. If $y_{i+1} = a$, then $(y_{i+1})\Phi = (y_{i+1})\Psi$, and so the inductive hypothesis is satisfied.

Suppose $y_{i+1} = b$. Then $(y_{i+1})\Phi = (y_{i+1})\Psi \circ \delta$. Hence $(y_1 \dots y_{i+1})\Phi = (y_1 \dots y_{i+1})\Psi \circ \delta$. By Claim 4.9, for every $j \in \{1, \dots, i+1\}$ the proper prefix $y_1 \dots y_j$ of $u_n$ is not a suffix of any word in $T$. By Claim 4.7, $y_1, \dots y_j \in aA^*$, and so by Claim 4.11 there exists $j \in \mathbb{N}$ and $z_1, \dots, z_j \in A^+$ such that $(\dots, x_1, x_0)\left((y_1 \dots y_{i+1})\Psi\right) = (\dots, x_1, x_0, z_1, \dots, z_j)$ for all $(\dots, x_1, x_0) \in X$ and $z_1 \dots z_j = y_1 \dots y_{i+1}$.

Suppose that $z_k \dots z_j = u_t$ for some $k \in \{1, \dots, j\}$ and $t \in \mathbb{N}$. Then $u_t$ is a subword of $u_n$, and so of $w_n$. Hence $t = n$ by the hypothesis of the theorem, and thus $u_n$ is a proper subword of $u_n$, which is a contradiction. Suppose that $u_t = x_k \dots x_0 z_1 \dots z_j$ for some $k \geq 0$ and $t \in \mathbb{N}$ such that $x_0, \dots, x_k \in A^+$. Then $z_1 \dots z_j$ is a prefix of $u_n$ and a suffix of $u_t$, and so $z_1 \dots z_j \in S_{\mathbf{w}}$ by the definition of $S_{\mathbf{w}}$, which contradicts the choice of $u_n$. So $\delta$ acts as the identity on $(\dots, x_1, x_0, z_1, \dots, z_j)$. Hence the inductive hypothesis is satisfied, and by induction $(y_1 \dots y_{m-1})\Phi = (y_1 \dots y_{m-1})\Psi$. Finally, $(u_n)\Phi = (u_n)\Psi \circ \delta$, as $y_m = b$. □

Let $n \in \mathbb{N}$. It follows from Claim 4.12, Claim 4.13, Claims 4.14, and the fact that $\Phi$ is a homomorphism, that for all $(\dots, x_1, x_0) \in X$

$$\begin{aligned}(\dots, x_1, x_0)(w_n)\Phi &= (\dots, x_1, x_0)\left((p_n)\Psi \circ (u_n)\Psi \circ \delta \circ (s_n)\Psi\right) \\ &= (\dots, x_1, x_0 p_n)\left((u_n)\Psi \circ \delta \circ (s_n)\Psi\right).\end{aligned}$$

It follows from Claims 4.7, 4.9 and 4.11 that there are $z_1, \dots, z_k \in A^+$ such that $z_1 \dots z_k = u_n$ and

$$\begin{aligned}(\dots, x_1, x_0)(w_n)\Phi &= (\dots, x_1, x_0 p_n)\left((u_n)\Psi \circ \delta \circ (s_n)\Psi\right) \\ &= (\dots, x_1, x_0 p_n, z_1, z_2, \dots, z_k)\delta \circ (s_n)\Psi.\end{aligned}$$

Finally, by the definition of $\delta$

$$\begin{aligned}(\dots, x_1, x_0)(w_n)\Phi &= (\dots, x_1, x_0 p_n, z_1, z_2, \dots, z_k)\delta \circ (s_n)\Psi \\ &= (\dots, x_1, x_0) f_n \circ (s)\Psi^{-1} \circ (s)\Psi \\ &= (\dots, x_1, x_0) f_n.\end{aligned}$$

Therefore $(w_n)\Phi = f_n$, and since $n$ was arbitrary, $(w_1, w_2, \dots)$ is a universal sequence. □

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