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The Frobenius problem for homomorphic embeddings of languages into the integers

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Abstract Let S be a map from a language $\mathcal{L}$ to the integers satisfying $\mathrm{S}(vw) = \mathrm{S}(v) + \mathrm{S}(w)$ for all $v, w \in \mathcal{L}$. The classical Frobenius problem asks whether the complement of $\mathrm{S}(\mathcal{L})$ in the natural numbers will be infinite or finite, and in the latter case the value of the largest element in this complement. This is also known as the 'coin-problem', and $\mathcal{L}$ is the full language consisting of all words over a finite alphabet. We solve the Frobenius problem for the golden mean language, any Sturmian language and the Thue-Morse language. We also consider two-dimensional embeddings.

1 Introduction

The Frobenius problem is also known as the 'coin problem'. Since the value of a coin can only be positive, we will consider exclusively embeddings into the natural numbers $\mathbb{N} = \{1, 2, 3, \dots\}$. Let $\mathcal{L}$ be a language, i.e., a factor-closed subset of the free semigroup generated by a finite alphabet under the concatenation operation.

A homomorphism of $\mathcal{L}$ into the natural numbers is a map $\mathrm{S} : \mathcal{L} \to \mathbb{N}$ satisfying

$$\mathrm{S}(vw) = \mathrm{S}(v) + \mathrm{S}(w), \quad \text{for all } v, w \in \mathcal{L}.$$

The two main questions to be asked about the image set $\mathrm{S}(\mathcal{L})$ are

(Q1) Is the complement $\mathbb{N} \setminus \mathrm{S}(\mathcal{L})$ finite or infinite?

(Q2) If the complement of $\mathrm{S}(\mathcal{L})$ is finite, then what is the largest element in this set?

These two questions are known as the Frobenius problem in the special case that $\mathcal{L}$ is the full language consisting of *all* words over a finite alphabet. In this case they have been posed as a problem (with solution) for an alphabet $\{a, b\}$ of cardinality 2 by James Joseph Sylvester in 1884 [15]: $\mathbb{N} \setminus \mathrm{S}(\mathcal{L})$ is finite if and only if $\mathrm{S}(a)$ and $\mathrm{S}(b)$ are relatively prime, in which case its largest element is

$$\mathrm{S}(a)\mathrm{S}(b) - \mathrm{S}(a) - \mathrm{S}(b).$$

In this paper we will also restrict ourselves to the two symbol case: alphabet $\{a, b\}$.

In Section 2 we prove that for the golden mean language ("no bb") the set $\mathbb{N} \setminus \mathrm{S}(\mathcal{L})$ is finite when $\mathrm{S}(a)$ and $\mathrm{S}(b)$ are relatively prime, with largest element

$$\mathrm{S}(a)^2 + \mathrm{S}(a)\mathrm{S}(b) - 3\mathrm{S}(a) - \mathrm{S}(b).$$

Our main interest is however not in sofic languages[1], but in languages with low complexity (slow growth of the number of subwords of length n), where the complement of $\mathrm{S}(\mathcal{L})$ can be infinite.

In Section 3 we analyse the case of Sturmian languages, and show that for the Fibonacci language a 0–∞ law holds: either the complement is empty or it has infinite cardinality.

In Section 4 we show that for any homomorphism S the image of the Thue-Morse language will consist of a union of 5 arithmetic sequences.

In Section 5 we consider two-dimensional embeddings, which behave quite differently.

We usually suppose that $\gcd(\mathrm{S}(a), \mathrm{S}(b)) = 1$. First of all this is not a big loss since automatically the complement will have infinite cardinality if this is not the case. Secondly, if r divides both $\mathrm{S}_1(a)$ and $\mathrm{S}_1(b)$ for some homomorphism S_1, then

$$\mathrm{S}_1(\mathcal{L}^n) = r^n \mathrm{S}_2(\mathcal{L}^n), \quad \text{for } n = 1, 2, \ldots, \text{ where } \mathrm{S}_2(a) = \frac{\mathrm{S}_1(a)}{r}, \mathrm{S}_2(b) = \frac{\mathrm{S}_1(b)}{r}.$$

Here, and throughout the paper, we write $\mathcal{L}^n$ for the set of words of length n in a language $\mathcal{L}$—not to be confused with the n-fold concatenation of $\mathcal{L}$.

Our work is related to the work on *abelian complexity*, see, e.g., [3], [13], [8]. See Lemma 3.1 for such a connection.

Our work is also related to the notion of *additive complexity*, see [14] and [2]. The *additive complexity* of an infinite word w over a finite set of integers (see [2]) is the function $n \to \phi^+(w, n)$ that counts the number of distinct sums obtained by summing n consecutive symbols of w. Let $\mathcal{L}_w$ be the language of all words occurring in the infinite word w. Then the additive complexity is $\phi^+(w, n) = \mathrm{Card}\{\mathrm{S}(u) : u \in \mathcal{L}_w^n\}$, where S is the identity map on the alphabet of w. Here we do, and may, assume that the alphabet of w is a subset of $\mathbb{N}$.

We finally mention that homomorphisms S from a language to the natural numbers already occur in the 1972 paper [4, Section 6] in the context of the Fibonacci language, where they are called *weights*.

2 Homomorphic images of the golden-mean language

The golden mean language is the language $\mathcal{L}_{\mathrm{GM}}$ consisting of all words over $\{a, b\}$ in which bb does not occur as a subword. Now if S satisfies $\mathrm{S}(a) = 1$ or $\mathrm{S}(b) = 1$, then it is easily seen that $\mathrm{S}(\mathcal{L}_{\mathrm{GM}}) = \mathbb{N}$, so for these homomorphisms the golden mean and the full language both map to $\mathbb{N}$. One could say they both have Frobenius number 0. In general however, the Frobenius number will increase substantially. If we take S defined by

$$\mathrm{S}(a) = 100, \; \mathrm{S}(b) = 3,$$

[1]Regular languages, or equivalently, languages defined by the labelling of paths of an automaton, see [10, Section 1.5]

then the Frobenius number of the full language under S is $300 - 100 - 3 = 197$, and the Frobenius number of $\mathrm{S}(\mathcal{L}_{\mathrm{GM}})$ is equal to 9997. For arbitrary homomorphisms the solution of the Frobenius problem for the golden mean language is given by the following, where we write $\mathrm{S}_a := \mathrm{S}(a)$, $\mathrm{S}_b := \mathrm{S}(b)$.

Theorem 2.1 *Let* $\mathrm{S} : \mathcal{L}_{\mathrm{GM}} \to \mathbb{N}$ *be a homomorphism. Suppose* $\gcd(\mathrm{S}_a, \mathrm{S}_b) = 1$*, and both* $\mathrm{S}_a > 1$ *and* $\mathrm{S}_b > 1$*. Then the Frobenius number of* $\mathrm{S}(\mathcal{L}_{\mathrm{GM}})$ *is equal to*

$$\max \mathbb{N} \setminus \mathrm{S}(\mathcal{L}_{\mathrm{GM}}) = \mathrm{S}_a(\mathrm{S}_a - 3) + \mathrm{S}_b(\mathrm{S}_a - 1).$$

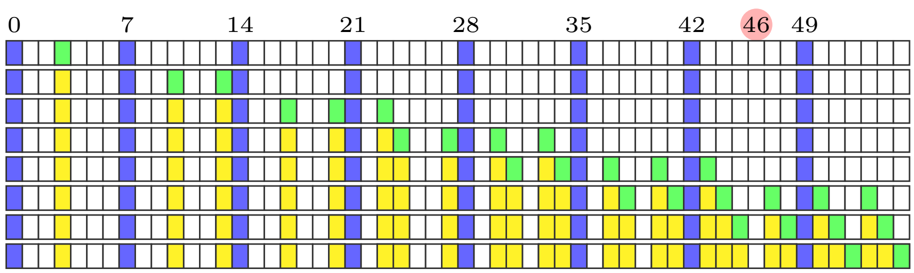
Proof: Let an S_a-*point* be defined as a multiple $n\mathrm{S}_a$, $n = 0, 1, \ldots$, and an S_a-*interval* as the set of numbers between two consecutive S_a-points. We also consider S_b-*chains*, defined for $n \geq 0$ by

$$C(n) = \{n\mathrm{S}_a + \mathrm{S}_b,\, n\mathrm{S}_a + 2\mathrm{S}_b, \ldots, n\mathrm{S}_a + (n+1)\mathrm{S}_b\}.$$

The union of the S_a-points and the S_b-chains will give $\mathcal{L}_{\mathrm{GM}}$: the S_a-points are the images of the words a^n, and the S_b-chains are the images of the words in which n letters a occur, and k letters b for $k = 1, 2, \ldots, n+1$. Here $n+1$ is the maximal number of letters b that can occur because of the "no bb" constraint.
The key observation is that the S_b-chain $C(\mathrm{S}_a - 2)$ has $\mathrm{S}_a - 1$ elements, which are all distinct modulo S_a. This is a consequence of $\gcd(\mathrm{S}_a, \mathrm{S}_b) = 1$. It follows that the S_b-chains fill in more and more points of the S_a-intervals. The last point to be filled in is equal to $\mathrm{S}_a - \mathrm{S}_b$ modulo S_a, produced by the last element of the chain $C(\mathrm{S}_a - 2)$. This is the number

$$P := (\mathrm{S}_a - 2)\mathrm{S}_a + (\mathrm{S}_a - 1)\mathrm{S}_b.$$

But then the largest number in the complement of $\mathcal{L}_{\mathrm{GM}}$ is $P - \mathrm{S}_a$, which is the number as claimed in the theorem. In this argument we used that if a point in an S_a-interval is filled in, then the corresponding points modulo S_a in all later intervals will also be filled in, simply because the later chains will be extensions of the earlier ones. $\square$



$S(a) = 7$, $S(b) = 3$: row n shows $C(n-1)$ in green, $n = 1, \ldots, 8$ (truncated at 56).

Figure 1: Example with $\mathrm{S}(a) = 7, \mathrm{S}(b) = 3$: row n shows the S_a-points in blue, and the S_b-chain $C(n-1)$ in yellow and green, for $n = 1, \ldots, 8$ (truncated at 56).

3 Sturmian languages

Sturmian words are infinite words over a two letter alphabet that have exactly $n+1$ subwords for each $n = 1, 2, \ldots$. We call the collection of these subwords a

Sturmian language. There is a surprising characterization of Sturmian words: s is Sturmian if and only if s is irrational *mechanical*, which means that there exist an irrational number $\alpha \in (0,1)$ and a number ρ such that $s = s_{\alpha,\rho}$, or $s = s'_{\alpha,\rho}$, where

$$s_{\alpha,\rho} = \big([(n+1)\,\alpha+\rho] - [n\,\alpha+\rho]\big)_{n\geq 0},\ s'_{\alpha,\rho} = \big(\lceil(n+1)\,\alpha+\rho\rceil - \lceil n\,\alpha+\rho\rceil\big)_{n\geq 0}.$$

See, e.g., [10, Prop. 2.1.13]. Because of this representation, we will use the alphabet $\{0,1\}$ instead of $\{a,b\}$ in this section.
Of special interest are the Sturmian words $s_\alpha := s_{\alpha,0}$ and $s'_\alpha := s'_{\alpha,0}$ of intercept 0. These have the property that they only differ in the first element:

$$s_\alpha = 0\,c_\alpha, \qquad s'_\alpha = 1\,c_\alpha.$$

Here $c_\alpha := s_{\alpha,\alpha}$ is called the *characteristic word* of α. For $n \geq 0$ we have

$$c_\alpha(n) = s_{\alpha,\alpha}(n) = [(n+1)\,\alpha+\alpha] - [n\,\alpha+\alpha] = [(n+2)\,\alpha] - [(n+1)\,\alpha].$$

The words s_α, s'_α and c_α generate the same language ([10, Prop. 2.1.18]), which we denote $\mathcal{L}_\alpha$. Recall that $\mathcal{L}^n_\alpha$ is the set of words of length n in $\mathcal{L}_\alpha$.

Lemma 3.1 *Let $\mathcal{L}_\alpha$ be a Sturmian language, and let* S *be a homomorphism with* $\mathrm{S}(0) \neq \mathrm{S}(1)$. *Then* $\mathrm{Card}\,\mathrm{S}(\mathcal{L}^n_\alpha) = 2$ *for all* $n \geq 1$.

Proof: This follows directly from the fact ([10, Th. 2.1.5]) that Sturmian words are *balanced*, i.e., any two words of the same length can differ by at most 1 in their number of ones. □

A sequence $([n\alpha])$, where $[.]$ denotes integer part, is called a *Beatty sequence* if $\alpha > 1$, and a *slow Beatty sequence* if $0 < \alpha < 1$ (terminology from [9]).

Theorem 3.1 *Let α be an irrational number from $(0,1)$. Let $\mathcal{L}_\alpha$ be the Sturmian language generated by α, and let $(q_n)_{n\geq 0}$ be the slow Beatty sequence defined by*

$$q_n = [(n+1)\alpha].$$

Let $\mathrm{S} : \mathcal{L}_\alpha \to \mathbb{N}$ *be a homomorphism. Define* $\mathrm{S}_0 = \mathrm{S}(0), \mathrm{S}_1 = \mathrm{S}(1)$. *Then*

$$\mathrm{S}(\mathcal{L}_\alpha) = \{(\mathrm{S}_1-\mathrm{S}_0)q_n + n\mathrm{S}_0 + \mathrm{S}_0 :\ n = 0,\dots\} \cup \{(\mathrm{S}_1-\mathrm{S}_0)q_n + n\mathrm{S}_0 + \mathrm{S}_1 :\ n = 0,\dots\}.$$

Proof: If $\mathrm{S}_0 = \mathrm{S}_1$ then this is certainly true, so suppose $\mathrm{S}_0 \neq \mathrm{S}_1$ in the sequel. We denote $c_\alpha[i,j] := c_\alpha(i)\dots c_\alpha(j)$ for integers i,j with $0 \leq i < j$. Let $N_\ell(w)$ denote the number of occurrences of the letter ℓ in a word w for $\ell = 0,1$. Then

$$N_1(c_\alpha[0,n-1]) = \sum_{k=0}^{n-1} c_\alpha(k) = [(n+1)\alpha] - [\alpha] = q_n, \quad N_0(c_\alpha[0,n-1]) = n - q_n.$$

Of course all words $c_\alpha[0,n-1]$ are in the Sturmian language $\mathcal{L}_\alpha$, but $\mathcal{L}_\alpha$ also contains the words $0c_\alpha[0,n-1]$ and $1c_\alpha[0,n-1]$. It thus follows from Lemma 3.1 that $\mathrm{S}(\mathcal{L}_\alpha)$ is given by the union of all images $\mathrm{S}(0c_\alpha[0,n-1])$ and $\mathrm{S}(1c_\alpha[0,n-1])$. Since

$$\mathrm{S}(0c_\alpha[0,n-1]) = \mathrm{S}_0 + (n-q_n)\mathrm{S}_0 + q_n\mathrm{S}_1 = (\mathrm{S}_1-\mathrm{S}_0)q_n + n\mathrm{S}_0 + \mathrm{S}_0,$$

the result follows. □

3.1 The Fibonacci language

Let $\Phi = (\sqrt{5}+1)/2 = 1.61803\ldots$ be the golden mean, and let $\alpha := 2 - \Phi = \Phi^{-2}$. We have (see, e.g., [10, Example 2.1.24])

$$c_\alpha = ([(n+1)\alpha] - [n\alpha])_{n\geq 1} = 0,1,0,0,1,0,1,0,0,1,0,0,1,0,1,0,0,\ldots,$$

the infinite Fibonacci word. We write $\mathcal{L}_{\rm F} := \mathcal{L}_\alpha$.

Theorem 3.2 *Let* $\mathrm{S} : \mathcal{L}_{\rm F} \to \mathbb{N}$ *be a homomorphism. Then*

$$\mathrm{S}(\mathcal{L}_{\rm F}) = \big((\mathrm{S}_0-\mathrm{S}_1)[n\Phi]+(2\mathrm{S}_1-\mathrm{S}_0)n+\mathrm{S}_0-\mathrm{S}_1\big)_{n\geq 1} \cup \big((\mathrm{S}_0-\mathrm{S}_1)[n\Phi]+(2\mathrm{S}_1-\mathrm{S}_0)n\big)_{n\geq 1}.$$

Proof: This is a corollary to Theorem 3.1, using $[-x] = -[x]-1$ for non-integer x:

$$\begin{aligned}(\mathrm{S}_1-\mathrm{S}_0)q_{n-1}+n\mathrm{S}_0 &= (\mathrm{S}_1-\mathrm{S}_0)[n\alpha]+n\mathrm{S}_0 = (\mathrm{S}_1-\mathrm{S}_0)[n(2-\Phi)]+n\mathrm{S}_0\\ &= 2(\mathrm{S}_1-\mathrm{S}_0)n+(\mathrm{S}_1-\mathrm{S}_0)[-n\Phi]+n\mathrm{S}_0\\ &= (2\mathrm{S}_1-\mathrm{S}_0)n+(\mathrm{S}_1-\mathrm{S}_0)(-[n\Phi]-1)\\ &= (\mathrm{S}_0-\mathrm{S}_1)[n\Phi]+(2\mathrm{S}_1-\mathrm{S}_0)n+\mathrm{S}_0-\mathrm{S}_1.\end{aligned}$$

□

Lemma 3.2 *For* $\mathrm{S}(0)=1$, $\mathrm{S}(1)\leq 3$ *or* $\mathrm{S}(0)=2$, $\mathrm{S}(1)=1$ *one has* $\mathrm{S}(\mathcal{L}_{\rm F})=\mathbb{N}$.

Proof: Take $(\mathrm{S}_0,\mathrm{S}_1) = (1{,}1)$. Then obviously $\mathrm{S}(\mathcal{L}_{\rm F})=\mathbb{N}$.
Take $(\mathrm{S}_0,\mathrm{S}_1) = (2{,}1)$. Then $\mathrm{S}(\mathcal{L}_{\rm F})=\mathbb{N}$, since by Theorem 3.2 $\mathrm{S}(\mathcal{L}_{\rm F})$ is the union of $([n\Phi])$ and $([n\Phi]+1)$, where the difference of two consecutive terms in $([n\Phi])$ is never more than 2.
Take $(\mathrm{S}_0,\mathrm{S}_1) = (1{,}2)$. Then $\mathrm{S}(\mathcal{L}_{\rm F})=\mathbb{N}$, since $\mathrm{S}(\mathcal{L}_{\rm F})$ is the union of $([n(3-\Phi)])$ and $([n(3-\Phi)])+1)$, where the difference of two consecutive terms in $([n(3-\Phi)])$ is never more than 2.
Take $(\mathrm{S}_0,\mathrm{S}_1) = (1{,}3)$. This case is more complicated. Let $u := (-2[n\Phi]+5n-2)_{n\geq 1}$, and $v := u+2$. Then according to Theorem 3.2, the union of the sets determined by u and v is $\mathrm{S}(\mathcal{L}_{\rm F})$. Let Δu be the difference sequence defined by $\Delta u_n = u_{n+1}-u_n$ for $n\geq 0$. It is easy to see that the difference sequences Δv and Δu are both equal to the Fibonacci sequence $1,3,1,1,3,1,\ldots$ on the alphabet $\{1,3\}$ (cf. [1]). We claim that if two consecutive numbers $m, m+1$ are missing in u, then these two do appear in v, implying that $\mathrm{S}(\mathcal{L}_{\rm F})=\mathbb{N}$. Indeed the two missing numbers are characterized by $u_{n+1}-u_n = 3$ for some n, and the missing numbers are $m = u_n+1$ and u_n+2. The second number appears in v, simply because $v = u+2$. The first number appears because $u_{n+1}-u_n = 3$ implies $u_n - u_{n-1} = 1$ (no 33 in the 1-3-Fibonacci sequence), and so $v_{n-1} = v_n - 1 = u_n + 1$. □

We define $\mathcal{E} := \{(1,1),(1,2),(1,3),(2,1)\}$.

Theorem 3.3 *Let* $\mathrm{S} : \mathcal{L}_{\rm F} \to \mathbb{N}$ *be a homomorphism. Then* $\mathbb{N}\setminus\mathrm{S}(\mathcal{L}_{\rm F})$ *has infinite cardinality,* unless $(\mathrm{S}(0),\mathrm{S}(1))\in\mathcal{E}$, *in which case the complement is empty.*

Proof: According to Lemma 3.2 the complement of $\mathrm{S}(\mathcal{L}_\mathrm{F})$ is empty for $(\mathrm{S}_0, \mathrm{S}_1) \in \mathcal{E}$. The density of the set $\mathrm{S}(\mathcal{L}_\mathrm{F})$ in the natural numbers exists, and equals

$$\delta := \frac{2}{(\mathrm{S}_0 - \mathrm{S}_1)\Phi + 2\mathrm{S}_1 - \mathrm{S}_0}.$$

The theorem will be proved if we show that $\delta < 1$ for $(\mathrm{S}_0, \mathrm{S}_1)$ not in $\mathcal{E}$. First we note that the denominator of δ is positive:

$$(\mathrm{S}_0 - \mathrm{S}_1)(\Phi - 1) + \mathrm{S}_1 > -\mathrm{S}_1(\Phi - 1) + \mathrm{S}_1 = \mathrm{S}_1(2 - \Phi) > 0,$$

where we used that $1 < \Phi < 2$. We now have

$$\delta < 1 \;\Leftrightarrow\; (\mathrm{S}_0 - \mathrm{S}_1)\Phi + 2\mathrm{S}_1 - \mathrm{S}_0 > 2 \;\Leftrightarrow\; (\mathrm{S}_0 - \mathrm{S}_1)\Phi > \mathrm{S}_0 - \mathrm{S}_1 + 2 - \mathrm{S}_1.$$

If $\mathrm{S}_0 > \mathrm{S}_1$, this is satisfied, since under this condition $(2 - \mathrm{S}_1)/(\mathrm{S}_0 - \mathrm{S}_1) \le 0$, unless $(\mathrm{S}_0, \mathrm{S}_1) = (2, 1) \in \mathcal{E}$. If $\mathrm{S}_0 < \mathrm{S}_1$, we have to see that $\Phi < 1 + (2 - \mathrm{S}_1)/(\mathrm{S}_0 - \mathrm{S}_1)$. This holds for $\mathrm{S}_0 \ge 2$, since then $(2 - \mathrm{S}_1)/(\mathrm{S}_0 - \mathrm{S}_1) \ge 1$. If $\mathrm{S}_0 = 1$, then this does not hold for $\mathrm{S}_1 = 1, 2, 3$, i.e., for pairs from $\mathcal{E}$, but it will hold for all $\mathrm{S}_1 \ge 4$. □

For particular values of S(0) and S(1) the complement of the embedding of the language has a nice structure, as it can be expressed in the classical Beatty sequences $A(n) = [n\Phi]$ for $n \ge 1$, and $B(n) = [n\Phi^2]$ for $n \ge 1$. The sequences A and B are called the *lower Wythoff sequence* and *upper Wythoff sequence*; they are extremely well-studied.

Example 1. Let S be given by S(0) = 3 and S(1) = 2. In the following we consider A and B as functions from $\mathbb{N}$ to $\mathbb{N}$, and define functions $pX + qY + r$ by

$(pX + qY + r)(n) = pX(n) + qY(n) + r$

for real numbers p, q, r and functions $X, Y : \mathbb{N} \to \mathbb{N}$. Then

$\mathrm{S}(\mathcal{L}_\mathrm{F}) = B(\mathbb{N}) \cup (B{+}1)(\mathbb{N}), \quad \mathbb{N} \backslash \mathrm{S}(\mathcal{L}_\mathrm{F}) = \{1, 4, 9, 12, \dots\} = (2A{+}\mathrm{Id}{+}1)(\mathbb{N} \cup \{0\})$.

The first statement follows from Theorem 3.2, and the relationship $B = A + \mathrm{Id}$. The second statement follows in a number of steps from the fact that A and B form a Beatty pair: $A(\mathbb{N}) \cap B(\mathbb{N}) = \emptyset$, and $A(\mathbb{N}) \cup B(\mathbb{N}) = \mathbb{N}$. This implies that $A(A(\mathbb{N})) \cup A(B(\mathbb{N})) \cup B(\mathbb{N}) = \mathbb{N}$, where the three sets are disjoint. But $AA = B - 1$ (see, e.g., Formula (3.2) in [4]). Adding 1 to all three sequences it follows that

$B(\mathbb{N}) \,\cup\, (B + 1)(\mathbb{N}) \,\cup\, (AB + 1)(\mathbb{N}) = \mathbb{N} \setminus \{1\}$.

Moreover, according to [4, Formula (3.5)] one has $AB = A + B = 2A + \mathrm{Id}$.
But then the three sequences $([n\Phi] + n)_{n\ge1}$, $([n\Phi] + n + 1)_{n\ge1}$, $(2[n\Phi] + n + 1)_{n\ge0}$, form a complementary triple, i.e., as sets they are disjoint, and their union is $\mathbb{N}$.
A similar result holds for[2] S(0) = 4, S(1) = 3.

Example 2. Let S be given by S(0) = 3 and S(1) = 1, then by Theorem 3.2

$\mathrm{S}(\mathcal{L}_\mathrm{F}) = (2A - \mathrm{Id})(\mathbb{N}) \,\cup\, (2A - \mathrm{Id} + 2)(\mathbb{N})$.

It is proved in [1] that

$\mathbb{N} \setminus \mathrm{S}(\mathcal{L}_\mathrm{F}) = \{2, 9, 20, 27, 38, 49, \dots\} = (4A + 3\mathrm{Id} + 2)(\mathbb{N} \cup \{0\})$,

and that the three sequences $(2[n\Phi] - n)_{n\ge1}$, $(2[n\Phi] - n + 2)_{n\ge1}$, $(4[n\Phi] + 3n + 2)_{n\ge0}$, form a complementary triple.

[2]In these two cases $\mathbb{N} \setminus \mathrm{S}(\mathcal{L}_\mathrm{F})$ is given by sequences A276885, respectively A276886 in OEIS ([11]). It is easily seen that the definitions of these sequences in OEIS are equivalent to the way in which we obtain them.

4 The Thue-Morse language

Let θ given by $\theta(a) = ab$, $\theta(b) = ba$ be the Thue-Morse morphism. Let $\mathcal{L}_{\mathrm{TM}}$ be the language generated by this morphism.
Let $R_{r,s} = \{s, r+s, 2r+s, \dots\}$ be the set determined by the arithmetic sequence with terms $rn+s$ for $n = 0, 1 \dots$.

Theorem 4.1 *Let* $\mathrm{S} : \mathcal{L}_{\mathrm{TM}} \to \mathbb{N}$ *be a homomorphism. Define* $p = \mathrm{S}(a), q = \mathrm{S}(b)$. *Then*

$$\mathrm{S}(\mathcal{L}_{\mathrm{TM}}) = R_{p+q,0} \cup R_{p+q,p} \cup R_{p+q,q} \cup R_{p+q,2p} \cup R_{p+q,2q}.$$

Proof: Let $\mathcal{L}^n_{\mathrm{TM}}$ be the set of words of length n in the Thue-Morse language. Put $r = \mathrm{S}(ab) = p+q$. It is clear (and for $p = 0, q = 1$ also observed in [13]) that since the Thue-Morse word is a non-periodic concatenation of ab and ba that for $n = 1, 2, \dots$

$$\mathrm{S}(\mathcal{L}^{2n}_{\mathrm{TM}}) = \{rn, rn+q-p, rn+p-q\}, \quad \mathrm{S}(\mathcal{L}^{2n-1}_{\mathrm{TM}}) = \{rn+p, rn+q\}.$$

This implies the statement of the theorem. □

Theorem 4.2 *Let* $\mathrm{S} : \mathcal{L}_{\mathrm{TM}} \to \mathbb{N}$ *be a homomorphism. Then* $\mathbb{N} \setminus \mathrm{S}(\mathcal{L}_{\mathrm{F}})$ *has infinite cardinality if and only if* $\mathrm{S}(a) + \mathrm{S}(b) \geq 6$. *For* $\mathrm{S}(a) + \mathrm{S}(b) < 6$, *the complement is either empty or a singleton.*

Proof: This follows directly from Theorem 4.1. If $\mathrm{S}(a) + \mathrm{S}(b) \geq 6$, then the density of $\mathbb{N} \setminus \mathrm{S}(\mathcal{L}_{\mathrm{TM}})$, is at least 1/6, so the set has infinite cardinality.
When $\mathrm{S}(a) + \mathrm{S}(b) < 6$, then, because of symmetry, we only have to consider the four cases $(\mathrm{S}(a), \mathrm{S}(b)) = (1, 2)$, $(\mathrm{S}(a), \mathrm{S}(b)) = (1, 3)$, $(\mathrm{S}(a), \mathrm{S}(b)) = (1, 4)$, and $(\mathrm{S}(a), \mathrm{S}(b)) = (2, 3)$. In these cases one will find with Theorem 4.1 that the complement of $\mathrm{S}(\mathcal{L}_{\mathrm{F}})$ is empty in the first two cases, and equal to $\{3\}$, respectively $\{1\}$ in the last two. □

Remark Let σ given by $\sigma(a) = ab, \sigma(b) = aa$ be the period-doubling or Toeplitz morphism. The difficulty—see [8, Lemma 6]—of determining the abelian complexity of the period-doubling morphism already indicates that solving the Frobenius problem for the period-doubling language will be much more involved than for the Thue-Morse language.

5 Two dimensional embeddings

Here we consider homomorphisms $\mathrm{S} : \mathcal{L} \to \mathbb{N} \times \mathbb{N}$ and $\mathrm{S} : \mathcal{L} \to \mathbb{Z} \times \mathbb{Z}$. The situation changes drastically for this 'double-coin' problem.

Proposition 5.1 *Let* $\mathcal{L}$ *be a language on the alphabet* $\{a, b\}$, *and let* $\mathrm{S} : \mathcal{L} \to \mathbb{N} \times \mathbb{N}$ *be a homomorphism. Then* $\mathbb{N} \times \mathbb{N} \setminus \mathrm{S}(\mathcal{L})$ *has infinite cardinality for all pairs* $\{\mathrm{S}(a), \mathrm{S}(b)\}$ *which are not equal to the pair* $\{(0, 1), (1, 0)\}$.

Proof: It suffices to prove this for the full language $\mathcal{L}_{\text{full}}$. The image under S is an integer lattice, with a complement of infinite cardinality, unless $\mathrm{S}(a)$ and $\mathrm{S}(b)$ are the unit vectors. □

We learn from this that the alphabet is 'too small', and that we should rather consider embeddings in $\mathbb{Z} \times \mathbb{Z}$ instead of $\mathbb{N} \times \mathbb{N}$. We focus again on low complexity languages, in particular on those generated by a primitive morphism φ on an alphabet A. Such a morphism has a language $\mathcal{L}_\varphi$ associated to it, where each word $w \in \mathcal{L}_\phi$ has a measure $\mu_\varphi(w)$. For a given homomorphism $\mathrm{S} : \mathcal{L}_\varphi \to \mathbb{Z} \times \mathbb{Z}$ we call the average

$$\Delta_\varphi(\mathrm{S}) := \sum_{a \in A} \mu_\varphi(a)\mathrm{S}(a)$$

the *drift* of S.

Proposition 5.2 *Let $\mathcal{L}_\varphi$ be a language generated by a primitive morphism on an alphabet A, and let $\mathrm{S} : \mathcal{L}_\varphi \to \mathbb{Z} \times \mathbb{Z}$ be a homomorphism. Then $\mathbb{Z} \times \mathbb{Z} \setminus \mathrm{S}(\mathcal{L})$ has infinite cardinality if $\Delta_\varphi(\mathrm{S}) \neq (0, 0)$.*

Proof: It is well-known that the measure μ_φ is strictly ergodic (see, e.g., [12]). Because of this, we have for words w from $\mathcal{L}_\varphi$, where $|w|$ denotes the length of w,

$$\frac{1}{|w|}\mathrm{S}(w) = \frac{1}{|w|}\sum_{a \in A} N_a(w)\mathrm{S}(a) \to \sum_{a \in A} \mu_\varphi(a)\mathrm{S}(a) = \Delta_\varphi(\mathrm{S}) \text{ as } |w| \to \infty.$$

Thus for long words w the images $\mathrm{S}(w)$ will be concentrated around the line in the direction of the drift of S, and so the complement of $\mathrm{S}(\mathcal{L}_\varphi)$ will have infinite cardinality if the drift is not $(0, 0)$. □

Can we say something about the Frobenius problem for homomorphic images of morphic languages of an embedding with drift $(0, 0)$? We shall give an infinite family of morphic languages $\mathcal{L}_\theta$ on an alphabet $A = \{a, b, c, d\}$ of four letters where for the homomorphism $\mathrm{S}^\oplus$ given by

$$\mathrm{S}^\oplus(a) = (1, 0),\ \mathrm{S}^\oplus(b) = (0, 1),\ \mathrm{S}^\oplus(c) = (-1, 0),\ \mathrm{S}^\oplus(d) = (0, -1)$$

the homomorphic embedding is the whole $\mathbb{Z} \times \mathbb{Z}$—and thus the complement is empty. We shall make use of the paperfolding morphisms introduced in [6]. Let σ be the rotation morphism on the alphabet $\{a, b, c, d\}$ given by $\sigma(a) = b,\ \sigma(b) = c,\ \sigma(c) = d,\ \sigma(d) = a$, and let τ be the anti-morphism given by $\tau(w_1 \dots w_n) = w_n \dots w_1$.
A morphism θ on $\{a, b, c, d\}$ is called a *paperfolding* morphism if

1) $\sigma\tau\theta = \theta\sigma\tau$,
2) Letters from $\{a, c\}$ alternate[3] with letters from $\{b, d\}$ in $\theta(a)$.

A paperfolding morphism is called *symmetric* if $\sigma\theta = \theta\sigma$. It is clear that this happens if and only if the word $\theta(a)$ is a palindrome.

Let G be a (semi-) group with operation $+$ and unit e. In general an infinite word $x = (x_n)$ over an alphabet A and a homomorphism $\mathrm{S} : A^* \to G$ generate a *walk* $Z = (Z_n)_{n \geq 0}$ by (cf. [5])

$$Z_0 = e, \qquad Z_{n+1} = Z_n + \mathrm{S}(x_n) = \mathrm{S}(x_0 \dots x_n), \text{ for } n \geq 0.$$

[3] This corrects an omission in [6, Definition 1].

A paperfolding morphism θ with $\theta(a) = a...$ is called *perfect* if the four walks generated by the fixed point $x = \theta^\infty(a)$, and its three rotations over $\pi/2, \pi$ and $3\pi/2$ visit every integer point in the plane exactly twice (except the origin, which is visited 4 times).
In [6] it is—not explicitly—proved that for any odd integer N that is the sum of two squares there exists a perfect symmetric paperfolding morphism of length N. To make the proof explicit, one uses that, according to the paragraph at the end of Section 7 in [6], there exists a symmetric plane-filling and self-avoiding string for each such N, and then one observes that the construction of such a string in the proof of [6, Theorem 4] always satisfies the perfectness criterion given in [6, Theorem 5].

The smallest length is $N = 5$, with morphism θ given by

$$\theta(a) = abcba,\ \theta(b) = bcdcb,\ \theta(c) = cdadc,\ \theta(d) = dabad.$$

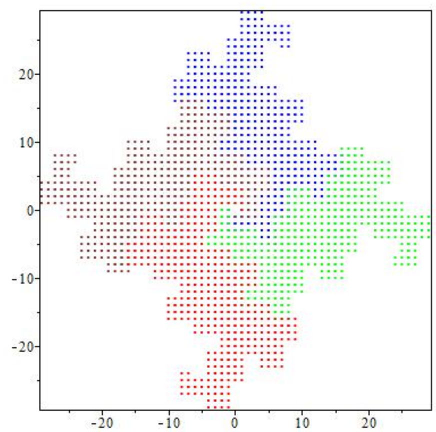


Figure 2: The four images of the words $\theta^4(a), \ldots, \theta^4(d)$ under $\mathrm{S}^\oplus$, where θ is the perfect symmetric 5-folding morphism. The origin is not covered, but it is the image of the word $abcd \in \mathcal{L}_\theta$.

Proposition 5.3 *Let $\mathcal{L}_\theta$ be the language generated by a perfect symmetric paperfolding morphism θ. Then $\mathrm{S}^\oplus(\mathcal{L}_\theta) = \mathbb{Z} \times \mathbb{Z}$.*

Proof: This follows directly from Theorem 5 in [6], using the observation above. $\square$

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