Recurrence along directions in multidimensional words

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Abstract

In this paper we study a modification of the notion of uniform recurrence in multidimensional words. A $d$-dimensional word is called a uniformly recurrent if for all sizes $(s_1, \ldots, s_d) \in \mathbb{N}^d$ there exists $n \in \mathbb{N}$ such that each block of size $(n, \ldots, n)$ contains the prefix of size $(s_1, \ldots, s_d)$. We are interested in a modification of this property. Namely, we ask that for each rational direction $(q_1, \ldots, q_d)$, each rectangular prefix occurs along this direction in positions $i(q_1, \ldots, q_d)$ with bounded gaps. Such words are called uniformly recurrent along all directions. We provide several constructions of multidimensional words satisfying this condition, and more generally, a series of four increasingly stronger conditions. We also study the uniform recurrence along directions of fixed points of square morphisms.

1 Introduction

Combinatorics on words in one dimension is a well-studied field of theoretical computer science with its origins in the early 20th century. The study of bidimensional words is less developed, even though many concepts and results are naturally extendable from the unidimensional case (see e.g. [2, 5, 6, 10, 14, 15, 22, 26]). However, some words problems become much more difficult in dimensions higher than one. One of such questions is the connection between local complexity and periodicity. In dimension one, the classical theorem of Morse and Hedlund states that if for some $n$ the number of distinct length-$n$ blocks of an infinite word is less than or equal to $n$, then the word is periodic. In the bidimensional case a similar assertion is known as Nivat’s conjecture, and many efforts are made by scientists for checking this hypothesis [7, 13, 16]. In this paper, we introduce and study new notions of multidimensional uniform recurrence.

A first and natural attempt to generalize the notion of (simple) recurrence to the multidimensional setting quickly turns out to be rather unsatisfying. Recall that an infinite word $w: \mathbb{N} \to A$ (where $A$ is a finite alphabet) is said to be recurrent if each prefix occurs at least twice (and hence every factor occurs infinitely often). A straightforward extension of this definition is to say that a bidimensional infinite word is recurrent whenever each rectangular prefix occurs at least twice (and hence every rectangular factor occurs infinitely often). However, with such a definition of bidimensional recurrence, the following bidimensional infinite word is considered as
uniformly. In the present work, we investigate several notions of recurrence of multidimensional infinite words $w : \mathbb{N}^d \to A$, generalizing the usual notion of uniform recurrence of infinite words.

This paper is organized as follows. In Section 2, we define two new notions of uniform recurrence of multidimensional infinite words: the URD words and the SURD words. We also make some first observations in the bidimensional setting. In Section 3, we show that these two new notions of recurrence along directions do not depend on the choice of the origin. This leads us to the definition of the even stronger notion of SSURDO words. In Section 4, we prove that all multidimensional rotation words are URD but not SURD. In particular, we provide some infinite families of SURD multidimensional infinite words obtained by placing some uniformly recurrent word along every rational direction are URD. In Section 5, we show that bidimensional Sturmian words are UR and URD but not SURD. In particular, this shows that the notion of SURD words is indeed stronger than that of URD words, justifying the introduced terminology. Further, we are able to prove that all multidimensional rotation words are URD but not SURD. In Section 6, we study fixed points of multidimensional square morphisms. In particular, we provide some infinite families of SURD such words. We provide a complete characterization of SURD multidimensional infinite words that are fixed points of square morphisms of size 2. In Section 7, we show how to build uncountably many SURD multidimensional infinite words. In particular, the family of bidimensional infinite words so-obtained contains uncountably many non-morphic SURD elements. We end our study by discussing four open problems in Section 8.

2 Definitions and first observations

Here and throughout the text, $A$ designates an arbitrary finite alphabet and $d$ is a positive integer. For $m, n \in \mathbb{N}$, the notation $[m, n]$ designates the interval of integers $\{m, \ldots, n\}$ (which is considered empty for $n < m$). We write $(s_1, \ldots, s_d) = (t_1, \ldots, t_d)$ if $s_i = t_i$ for each $i \in [1, d]$.

A $d$-dimensional infinite word over $A$ is a map $w : \mathbb{N}^d \to A$. A $d$-dimensional finite word over $A$ is a map $w : [0, s_1 - 1] \times \cdots \times [0, s_d - 1] \to A$, for some $(s_1, \ldots, s_d) \in \mathbb{N}^d$, which is called the size of $w$. A finite word $f$ of size $(s_1, \ldots, s_d)$ is a factor of a $d$-dimensional infinite word $w$ if there exists $p \in \mathbb{N}^d$ such that for each $i \in [0, s_1 - 1] \times \cdots \times [0, s_d - 1]$, we have $f(i) = w(p + i)$. In this case, we say that the factor $f$ occurs at position $p$ in $w$. Similarly, a factor of a $d$-dimensional finite word $w$ of size $(t_1, \ldots, t_d)$ is a finite word $f$ of some size $(s_1, \ldots, s_d) \leq (t_1, \ldots, t_d)$ for which there exists $p \in [0, t_1 - s_1] \times \cdots \times [0, t_d - s_d]$ such that for each $i \in [0, s_1 - 1] \times \cdots \times [0, s_d - 1]$, we have $f(i) = w(p + i)$. In both cases (infinite and finite), if $p = 0$ then the factor $f$ is said to be a prefix of $w$. In some places, for the sake of clarity, we will allow ourselves to write $w_1$ instead of $w(i)$.

**Remark 1.** In general, a factor need not be of the form $[0, s_1 - 1] \times \cdots \times [0, s_d - 1]$ but could be any polytope. Indeed, any occurrence of any given polytope is contained in a larger rectangular factor. If we are interested in bounding the gaps between occurrences of the polytope, then a
bound on the gaps of the larger rectangular factor is sufficient. So, without loss of generality we can restrict our attention to rectangular factors only.

Sometimes, multidimensional words are considered over $\mathbb{Z}^d$, i.e. $w : \mathbb{Z}^d \to A$. Although in our considerations it is more natural to consider one-way infinite words, since for example we will make use of fixed points of morphisms, most of our results and notions can be straightforwardly extended to words over $\mathbb{Z}^d$.

The following notion of uniform recurrence of multidimensional infinite words was studied by many authors, see for example [2, 10].

**Definition 2 (UR).** A $d$-dimensional infinite word $w$ is **uniformly recurrent** if for every prefix $p$ of $w$, there exists a positive integer $b$ such that every factor of $w$ of size $(b, \ldots, b)$ contains $p$ as a factor.

Whenever $d = 1$, the previous definition corresponds to the usual notion of uniform recurrence of infinite words. In the bidimensional setting, the uniform recurrence of the word is not linked to the uniform recurrence of all rows and columns. On the one hand, the fact that rows and columns of a bidimensional word $w : \mathbb{N}^2 \to A$ are uniformly recurrent (in the unidimensional sense) does not imply that $w$ is UR.

**Remark 3.** We choose the convention of representing a bidimensional word $w : \mathbb{N}^2 \to A$ by placing the rows from bottom to top, and the columns from left to right (as for Cartesian coordinates). See Figure 1.

![Figure 1: Convention for the representation bidimensional words.](image)

**Proposition 4.** Let $w : \mathbb{N}^2 \to \{0, 1\}$ be the bidimensional word obtained by alternating two kinds of rows: $01F$ and $10F$ where $F = 01001010\cdots$ is the Fibonacci word, i.e. $F$ is the fixed point of the morphism $0 \mapsto 01, 1 \mapsto 0$ (see Figure 2). The rows and the columns of $w$ are all uniformly recurrent but $w$ is not UR.

![Figure 2: A non UR bidimensional word having uniformly recurrent rows and columns.](image)
Proof. The word \( w \) is not UR since the square prefix \([1 \ldots 0]\) only occurs within the first two columns. The columns of \( w \) are uniformly recurrent since they are periodic. It is well known that the words \( 01F \) and \( 10F \) are uniformly recurrent, hence the rows of \( w \) are uniformly recurrent. \( \square \)

On the other hand, the fact that a bidimensional infinite word is UR does not imply that each of its row/column is uniformly recurrent either.

**Proposition 5.** Let \( w : \mathbb{N}^2 \to \{0, 1\} \) be the bidimensional word constructed as follows. The \( n \)-th row (with \( n \in \mathbb{N} \)) is indexed by \( k \) if \( n = 2^k \) (mod \( 2^{k+1} \)) and is indexed by \(-1\) if \( n = 0 \). Let \( u_k = (10^{2^k-1})^\omega \) for \( k \geq 0 \) and \( u_{-1} = 10^\omega \). Now fill the rows indexed by \( k \) with the words \( u_k \) (see Figure 3). The bidimensional word \( w \) is UR, but its first row is not recurrent.

\[
\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
n & k & u_k \\
\hline
0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots \\
5 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \ldots \\
4 & 2 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \ldots \\
3 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \ldots \\
2 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \ldots \\
1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \ldots \\
6 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \ldots \\
7 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \ldots \\
8 & 3 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \ldots \\
9 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \ldots \\
10 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \ldots \\
11 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \ldots \\
12 & 2 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \ldots \\
13 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \ldots \\
\hline
\end{array}
\]

Figure 3: A UR bidimensional infinite word with a non-recurrent row.

Proof. Consider first the bidimensional infinite word \( w' \) composed of the rows \( u_k \) with \( k \geq 0 \), that is, the word \( w \) without its first row. We show that each prefixes of \( w' \) appears according to a square network. Note that this network argument is also used in the proof of Proposition 50. In \( w' \), let \( p \) be a prefix of some size \((s_1, s_2) \in \mathbb{N}^2 \) and \( N = \max(\log_2(s_1), \log_2(s_2)) \). The prefix \( p' \) of size \((2^N, 2^N)\) appears periodically according to the periods \((2^{N+1}, 0)\) and \((0, 2^{N+1})\). Therefore each factor of \( w' \) of size \((2^{N+1} + 2^N - 1, 2^{N+1} + 2^N - 1)\) contains \( p' \). So it contains \( p \) as well. Hence \( w' \) is UR.

Now let \( p \) denote a prefix of \( w \) of some size \((s_1, s_2) \in \mathbb{N}^2 \). Let \( N = \max(\log_2(s_1), \log_2(s_2)) \). Using the previous paragraph, we know that the prefix of \( w' \) of size \((2^N, 2^N)\) occurs with periods \((2^{N+1}, 0)\) and \((0, 2^{N+1})\). Since the \( 2^{N+1} \)-th row of \( w \) is filled with the infinite word \( u_{N+1} = (102^{N+1-1})^\omega \) and that \( 2^{N+1} > s_1 \), the prefix \( p \) also appears in position \((0, 2^{N+1})\) in \( w \), i.e. in position \((0, 2^{N+1} - 1)\) in \( w' \). As \( w' \) is UR, \( p \) occurs within every factor of \( w' \) of size \((n, n)\) for some \( n \in \mathbb{N} \). As \( w \) is composed of \( w' \) with an additional row \( u_{-1} \), the prefix \( p \) of \( w \) occurs also within every factor of \( w \) of size \((n + 1, n + 1)\). \( \square \)

In order to obtain the uniform recurrence of all rows and columns in a bidimensional infinite word, we introduce a different version of uniform recurrence of multidimensional infinite words,
which involves directions. Throughout this text, when we talk about a *direction* $\mathbf{q} = (q_1, \ldots, q_d)$, we implicitly assume that $q_1, \ldots, q_d$ are coprime nonnegative integers. For the sake of conciseness, if $\mathbf{s} = (s_1, \ldots, s_d)$, we write $[0, \mathbf{s} - 1]$ in order to designate the $d$-dimensional interval $[0, s_1 - 1] \times \cdots \times [0, s_d - 1]$. In particular, we set $\mathbf{0} = (0, \ldots, 0)$ and $\mathbf{1} = (1, \ldots, 1)$.

In what follows, we will use the following notation. Let $w: \mathbb{N}^d \to A$ be a $d$-dimensional infinite word, $\mathbf{s} \in \mathbb{N}^d$ and $\mathbf{q} \in \mathbb{N}^d$ be a direction. The *word along the direction* $\mathbf{q}$ *with respect to the size* $\mathbf{s}$ *in* $w$ is the unidimensional infinite word $w_{\mathbf{q}, \mathbf{s}}: \mathbb{N} \to A^{[0, \mathbf{s} - 1]}$, where elements of $A^{[0, \mathbf{s} - 1]}$ are considered as letters, defined by

$$\forall \ell \in \mathbb{N}, \forall i \in [0, \mathbf{s} - 1], \ (w_{\mathbf{q}, \mathbf{s}}(\ell))(i) = w(i + \ell \mathbf{q}).$$

See Figure 4 for an illustration in the bidimensional case.

![Figure 4](image)

Figure 4: The word $w_{\mathbf{q}, \mathbf{s}}$ is built from the blocks of size $\mathbf{s}$ occurring at positions $\ell \mathbf{q}$ in $w$. Those blocks in $A^{[0, \mathbf{s} - 1]}$ may or may not overlap.

Note that, for any choice of direction $\mathbf{q}$, the first letter $w_{\mathbf{q}, \mathbf{s}}(0)$ of the unidimensional infinite word $w_{\mathbf{q}, \mathbf{s}}$ is the prefix of size $\mathbf{s}$ of the $d$-dimensional infinite word $w$.

**Definition 6 (URD).** A $d$-dimensional infinite word $w: \mathbb{N}^d \to A$ is uniformly recurrent along all directions (URD for short) if for all $\mathbf{s} \in \mathbb{N}^d$ and all directions $\mathbf{q} \in \mathbb{N}^d$, there exists $b \in \mathbb{N}$ such that, in $w_{\mathbf{q}, \mathbf{s}}$, consecutive occurrences of the first letter $w_{\mathbf{q}, \mathbf{s}}(0)$ are situated at distance at most $b$.

We will see that the uniform recurrence along all directions implies that each row and each column are uniformly recurrent (see Proposition 12). However, a URD word is not necessarily UR as shown by the following proposition. In the next section, we will show that UR does not imply URD either (see Corollary 13).

**Proposition 7.** There exists a URD word that is not UR.

*Proof.* We give a sketch of a construction to avoid cumbersome details. Let $A$ be a finite alphabet containing at least two letters, say $0$ and $1$, and let $d \geq 2$. Consider the following recursive procedure to construct uncountably many such $d$-dimensional infinite words. See Figure 5 for an illustration of a 2-dimensional binary such word. On the first step, fill the position $0$ with the letter $1$. On each step $n \geq 2$, consider the prefix $p_n$ of size $\mathbf{n} = (n, \ldots, n)$ which is partially filled. Choose arbitrary letters of $A$ to complete it (in Figure 5, we chose to complete with $0$’s at each step). For each direction $\mathbf{q} < \mathbf{n}$, choose a constant $b_{\mathbf{q}}$ and copy $p_n$ in all positions $\ell b_{\mathbf{q}} \mathbf{q}$ with $\ell \in \mathbb{N}$. Note that the word $w_{\mathbf{q}, \mathbf{n}}$ may be already partially filled, but there always exists a constant $b_{\mathbf{q}}$ (potentially big) that allows us to perform this procedure. In one of the remaining factors of size $\mathbf{n}$ that do not contain any letters yet, write $n^d$ times the letter $0$ (at each step of
FIGURE 5: The first 5 steps of the construction of a URD word that is not UR, according to the procedure described in Proposition 7. The letters filled at steps 1, ..., 5 are respectively drawn on cells colored in blue, gray, pink, yellow and red.

Figure 5, we chose such a square below the diagonal and the closest possible of the origin). All so-constructed words are URD but are not UR since they contain arbitrarily large hypercubes of 0's.

A natural strengthening of the definition of URD words is to ask that the bound between consecutive occurrences of the prefix only depends on the size of the prefix and not on the chosen direction.

**Definition 8** (SURD). A d-dimensional infinite word $w: \mathbb{N}^d \to A$ is strongly uniformly recurrent along all directions (SURD for short) if for each $s \in \mathbb{N}^d$, there exists $b \in \mathbb{N}$ such that, for each direction $q \in \mathbb{N}^d$, in $w_{q,s}$, consecutive occurrences of the first letter $w_{q,s}(0)$ are situated at distance at most $b$.

In Figure 6, we summarize the relations between the different notions of recurrence we consider.

### 3 Uniform recurrence along all directions from any origin

As a natural generalization of d-dimensional URD and SURD infinite words, we could ask that the recurrence property should not just be taken into account on the lines $\{\ell q: \ell \in \mathbb{N}\}$ for all directions $q$ but on all lines $\{\ell q + p: \ell \in \mathbb{N}\}$ for all origins $p$ and directions $q$. In fact, this would not be a real generalization; the proof of this claim is the purpose of the present section.
Definition 9 (URDO). A \( d \)-dimensional infinite word \( w : \mathbb{N}^d \rightarrow A \) is \textit{uniformly recurrent along all directions from any origin} (URDO for short) if for each \( p \in \mathbb{N}^d \), the translated \( d \)-dimensional infinite word \( w(p) : \mathbb{N}^d \rightarrow A \), \( i \mapsto w(i + p) \) is URD.

Definition 10 (SURDO). A \( d \)-dimensional infinite word \( w : \mathbb{N}^d \rightarrow A \) is \textit{strongly uniformly recurrent along all directions from any origin} (SURDO for short) if for each \( p \in \mathbb{N}^d \), the translated \( d \)-dimensional infinite word \( w(p) : \mathbb{N}^d \rightarrow A \), \( i \mapsto w(i + p) \) is SURD.

Proposition 11.

- A \( d \)-dimensional infinite word is URD if and only if it is URDO.
- A \( d \)-dimensional infinite word is SURD if and only if it is SURDO.

Proof. Both conditions are clearly sufficient. Now we prove that they are necessary. Let \( w : \mathbb{N}^d \rightarrow A \) be URD (SURD, respectively), let \( p, s \in \mathbb{N}^d \) and let \( f : \llbracket 0, s - 1 \rrbracket \rightarrow A \) be the factor of \( w \) of size \( s \) at position \( p \): for all \( i \in \llbracket 0, s - 1 \rrbracket \), \( f(i) = w(i + p) \). We need to prove that for each direction \( q \), there exists \( b \in \mathbb{N} \) such that (that there exists \( b \in \mathbb{N} \) such that for all directions \( q \), respectively) consecutive occurrences of \( f \) at positions of the form \( \ell q + p \) are situated at distance at most \( b \). The situation is illustrated in Figure 7. Consider the prefix \( p \) of size \( p + s \) of \( w \). Since the word is URD (SURD, respectively), for all directions \( q \), there exists \( b' \) such that (there exists \( b' \) such that for all directions \( q \), respectively) consecutive occurrences of \( p \) in positions \( \ell q \) are situated at distance at most \( b' \). Since \( f \) occurs at position \( p \) in \( p \), this implies the condition we need with \( b = b' \).

Figure 7: Illustration of the proof of Proposition 11 in the bidimensional case.

Proposition 12. If a bidimensional infinite word is URD, then all its rows and columns are uniformly recurrent, but the converse does not hold.
Proof. Let \( w \) be a URD bidimensional infinite word. From Proposition 11, \( w \) is also URDO. So, any translated word \( w^{(p)} \) with \( p = (0, m) \) is also URD. Hence, in \( w^{(p)} \), any factor of size of the form \((s, 1)\) occurs along the direction \((1, 0)\) with bounded gaps. In other words, any row is uniformly recurrent. The argument is similar for the columns.

In order to see that the converse is not true, we can for example consider again the bidimensional word of Proposition 4.

\[ \square \]

**Corollary 13.** A bidimensional infinite UR word is not necessarily URD.

**Proof.** This follows from Propositions 5 and 12. \[ \square \]

We can also ask the constant \( b \) to be uniform for all the origins. As previously, the notation \((w^{(p)})_{q,s}\) designates the unidimensional infinite word along the direction \( q \) with respect to the size \( s \) in the translated \( d \)-dimensional infinite word \( w^{(p)}: \mathbb{N}^d \to A, i \mapsto w(i + p) \).

**Definition 14 (SSURDO).** A \( d \)-dimensional infinite word \( w: \mathbb{N}^d \to A \) is super strongly uniformly recurrent along all directions from any origin (SSURDO for short) if for all \( s \in \mathbb{N}^d \), there exists \( b \in \mathbb{N} \) such that, for each direction \( q \in \mathbb{N}^d \) and each origin \( p \in \mathbb{N}^d \), in \((w^{(p)})_{q,s}\), any two consecutive occurrences of the first letter \((w^{(p)})_{q,s}(0)\) are situated at distance at most \( b \).

Clearly, doubly periodic words satisfy the latter definition but there also exist SSURDO aperiodic words. One of them is given as the fixed point of a bidimensional morphism introduced in Section 6 (see Proposition 48). Note that this notion of SSURDO words is distinct from that of SURD words (see Example 49).

**Proposition 15.** A \( d \)-dimensional SSURDO word is necessarily UR.

**Proof.** Let \( w \) be a \( d \)-dimensional SSURDO word and let \( p \) be a prefix of \( w \) of some size \( s \). Let \( b \) be the bound on the distance from Definition 14 and \( b = (b, \ldots, b) \). It is enough to prove that any factor of \( w \) of size \( b + s \) contains \( p \) as a factor.

Let \( p = (p_1, \ldots, p_d) \) and let \( f \) be the factor of size \( b + s \) occurring in \( w \) at position \( p \). For each \( i \in [1, d] \), let \( e_i \) denote the direction \((0, \ldots, 0, 1, 0, \ldots, 0)\) with 1 in the \( i \)-th coordinate. By definition, in the word \((w^{(0)})_{e_1}s\), consecutive occurrences of \( p \) (considered as a letter) are within distance \( b \). Therefore, there exists a position \( k_1e_1 \) with \( p_1 \leq k_1 \leq p_1 + b \) where \( p \) occurs in \( w \). By definition again, in the word \((w^{(k_1e_1)})_{e_2,s}\), consecutive occurrences of \( p \) are also within distance \( b \). So there exists a position \( k_1e_1 + k_2e_2 \) with \( p_2 \leq k_2 \leq p_2 + b \) where \( p \) occurs in \( w \). Applying the same argument \( d - 2 \) more times, we find a position \( k_1e_1 + \cdots + k_de_d \) with \( k_i \in \[p_i, p_i + b\] \) where \( p \) occurs in \( w \). Thus, \( p \) occurs as a factor of \( f \) as desired. \[ \square \]

4 Construction of URD multidimensional words using the gcd

In this section, we consider a specific construction of \( d \)-dimensional infinite words starting from a single unidimensional infinite word. More precisely, for any \( u: \mathbb{N} \to A \), we define a \( d \)-dimensional infinite word \( w: \mathbb{N}^d \to A \) by setting

\[ \forall i \in \mathbb{N}^d, \ w(i) = u(\gcd(i)), \tag{1} \]

where \( \gcd(i) = \gcd(i_1, \ldots, i_d) \) if \( i = (i_1, \ldots, i_d) \). Otherwise stated, one places the infinite word \( u \) in every rational direction: for all directions \( q \in \mathbb{N}^d \) and all \( \ell \in \mathbb{N} \), we have \( w(\ell q) = u(\ell) \).
Lemma 16. Let \( \mathbf{q} = (q_1, \ldots, q_d) \in \mathbb{Z}^d \) such that \( q_1, \ldots, q_d \) are coprime, let \( \alpha_1, \ldots, \alpha_d \in \mathbb{Z} \) such that \( \alpha_1 q_1 + \cdots + \alpha_d q_d = 1 \), and let \( \mathbf{i} = (i_1, \ldots, i_d) \in \mathbb{Z}^d \setminus \mathbb{N} \mathbf{q} \). Then, for all \( \ell \in \mathbb{Z} \), we have

\[
\gcd(\ell \mathbf{q} + \mathbf{i}) = \gcd(\ell + \alpha_1 i_1 + \cdots + \alpha_d i_d, \ \gcd(i_j q_k - i_k q_j : j, k \in \llbracket 1, d \rrbracket))
\]

In particular, the sequence \( (\gcd(\ell \mathbf{q} + \mathbf{i}))_{\ell \in \mathbb{Z}} \) is periodic of period \( \gcd(i_j q_k - i_k q_j : j, k \in \llbracket 1, d \rrbracket) \).

Proof. Let \( d = \gcd(\ell \mathbf{q} + \mathbf{i}) \) and \( D = \gcd(\ell + \alpha_1 i_1 + \cdots + \alpha_d i_d, \ \gcd(i_j q_k - i_k q_j : j, k \in \llbracket 1, d \rrbracket)) \). Then \( d \) divides

\[
\sum_{j=1}^{d} \alpha_j (\ell q_j + i_j) = \ell \sum_{j=1}^{d} \alpha_j q_j + \sum_{j=1}^{d} \alpha_j i_j = \ell + \sum_{j=1}^{d} \alpha_j i_j.
\]

Moreover, for all \( j, k \in \llbracket 1, d \rrbracket \), \( d \) also divides \( (\ell q_j + i_j) q_k - (\ell q_k + i_k) q_j = i_j q_k - i_k q_j \). This shows that \( d \leq D \). Conversely, for all \( k \in \llbracket 1, d \rrbracket \), \( D \) divides

\[
\left( \ell + \sum_{j=1}^{d} \alpha_j i_j \right) q_k + \sum_{j \in \llbracket 1, d \rrbracket} (i_j q_j - i_j q_k) \alpha_j = \ell q_k + i_k.
\]

We obtain that \( D \leq d \), hence \( d = D \). The particular case follows from the fact that \( \gcd(a, b) = \gcd(a + b, b) \).

An arithmetical subsequence of a word \( w: \mathbb{N} \to A \) is a word \( v: \mathbb{N} \to A \) such that there exist \( p, q \in \mathbb{N} \) with \( q \neq 0 \) such that, for all \( \ell \in \mathbb{N} \), \( v(\ell) = w(\ell q + p) \). A proof of the following result can be found in [1].

Lemma 17. An arithmetical subsequence of a uniformly recurrent infinite word is uniformly recurrent.

Example 18. Consider the occurrence of the prefix 01 of the Thue-Morse word occurring at positions multiple of 3:

\[
011010011001011010011010011010011010011010110 \cdots
\]

From Lemma 17 we know that there is a uniform bound \( b \) such that the distance between any two consecutive such occurrences is at most \( b \).

Theorem 19. For any uniformly recurrent word \( u: \mathbb{N} \to A \), the \( d \)-dimensional word \( w: \mathbb{N}^d \to A \) built from \( u \) as in (1) is URD.

Proof. Let \( u: \mathbb{N} \to A \) be a uniformly recurrent word and let \( w: \mathbb{N}^d \to A \) be the \( d \)-dimensional word built from \( u \) as in (1). Let \( \mathbf{q} \) be a direction, let \( p \) be a prefix of \( w \) of some size \( s \) and let \( y: \mathbb{N} \to A^{[0, s-1]} \) be the word defined by

\[
\forall \ell \in \mathbb{N}, \ \forall \mathbf{i} \in \llbracket 0, s - 1 \rrbracket, \ (y(\ell))(\mathbf{i}) = w(\mathbf{i} + \ell \mathbf{q}).
\]

We claim that \( y \) contains the letter \( y(0) = p \) with bounded gaps. By construction of \( w \), we have

\[
\forall \ell \in \mathbb{N}, \ \forall \mathbf{i} \in \llbracket 0, s - 1 \rrbracket, \ (y(\ell))(\mathbf{i}) = u(\gcd(\mathbf{i} + \ell \mathbf{q})).
\]

Now the conclusion follows from Lemma 16 and the uniform recurrence of \( u \). More precisely, let

\[
B = \prod_{0 \leq (i_1, \ldots, i_d) < s \atop (i_1, \ldots, i_d) \notin \mathbb{N}^d \mathbf{q}} \gcd(i_j q_k - i_k q_j : j, k \in \llbracket 1, d \rrbracket)
\]

and \( r = \min \{\frac{\alpha_1}{q_1}, \ldots, \frac{\alpha_d}{q_d} \} \). By Lemma 17, the distance between consecutive occurrences in \( u \) of its prefix of length \( r \) at positions multiples of \( B \) is bounded by some constant \( C \). Then, by Lemma 16, the distance between consecutive occurrences of \( p \) in \( y \) is at most \( BC \).
5 Recurrence properties of multidimensional rotation words

We illustrate that URD and SURD notions are distinct using a generalization of rotation words to the multidimensional setting. This generalization includes the multidimensional Sturmian words, which were proved to be UR [3].

**Definition 20.** Let \( \alpha = (\alpha_1, \ldots, \alpha_d) \in [0,1)^d \) and \( \rho \in [0,1) \) be such that \( 1, \alpha_1, \ldots, \alpha_d \) are rationally independent and let \( \{I_1, \ldots, I_k\} \) be a partition of \([0,1)\) into half-open intervals on the right. The \( d \)-dimensional (lower) rotation word \( w : \mathbb{N}^d \to [1,k] \) (with parameters \( \alpha, I_1, \ldots, I_k, \rho \)) is defined as
\[
\forall i \in \mathbb{N}^d, \ \forall j \in [1,k], \quad w(i) = j \iff (\rho + i \cdot \alpha) \mod 1 \in I_j
\]
(where \( i \cdot \alpha \) is the scalar product \( i_1\alpha_1 + \cdots + i_d\alpha_d \)). Similarly, we can also consider half-open intervals on the left. In this case, we talk about \( d \)-dimensional upper rotation words.

Note that for \( d = 2 \), \( I_1 = [0,\alpha_1) \) and \( I_2 = [\alpha_1,1) \), we recover the definition of bidimensional Sturmian words from [3].

With the previous notation, for \( s \in \mathbb{N}^d \) and for \( f \) a \( d \)-dimensional finite word of size \( s \) over the alphabet \( \{1, \ldots, k\} \), we let
\[
I_f = \bigcap_{i \in [0,s-1]} R_{i \cdot \alpha}^{-1}(I_{f(i)})
\]
where \( R_\alpha : [0,1) \to [0,1), \ x \mapsto (x+a) \mod 1 \). Note that an intersection of intervals on the circle is a union of intervals (it does not have to be connected). Observe that since \( I_f \) is an intersection of finitely many intervals, it is also a finite union of nonempty disjoint intervals. We let \( l(f) \) denote the number of such intervals and \( I_{f,1} \ldots I_{f,l(f)} \) the intervals, so that:
\[
I_f = \bigcup_{j=1}^{l(f)} I_{f,j}.
\]
In the case where \( I_f \) is empty, then the union is empty, meaning that there is no interval \( I_{f,j} \) at all, or equivalently that \( l(f) = 0 \).

**Lemma 21.** Let \( w \) be a \( d \)-dimensional rotation word with parameters \( \alpha, I_1, \ldots, I_k, \rho \).

- A \( d \)-dimensional finite word \( f \) occurs as a factor of \( w \) at some position \( p \) if and only if \( (\rho + p \cdot \alpha) \mod 1 \in I_f \).
- A \( d \)-dimensional finite word \( f \) is a factor of \( w \) if and only if \( I_f \) is nonempty.

**Proof.** The proof is an adaptation of that of [3, Lemma 1]. Let \( f \) be a \( d \)-dimensional finite word. Then \( f \) occurs as a factor in \( w \) at position \( p \) if and only if for all \( i \in [0,s-1] \) we have that \( (\rho + (p+i) \cdot \alpha) \mod 1 \in I_{f(i)} \), which is equivalent to saying that \( (\rho + p \cdot \alpha) \mod 1 \in I_f \).

Moreover, by Kronecker’s theorem (see for example [12]) and since \( \alpha_d \) is irrational, we know that the orbit \( \{ (\rho + pd\alpha_d) \mod 1 : pd \in \mathbb{N} \} \) of \( \rho \) under the rotation \( R_{\alpha_d} \) is dense in \([0,1)\). Therefore, if \( I_f \) is nonempty then it has nonempty interior and hence, for any \( p_1, \ldots, p_{d-1} \in \mathbb{N} \), there exists some \( p_d \in \mathbb{N} \) such that \( \rho + p_1\alpha_1 + \cdots + p_{d-1}\alpha_{d-1} + p_d\alpha_d \) belongs to \( I_f \). Thus \( f \) occurs as a factor of \( w \) at position \( p = (p_1, \ldots, p_d) \). \( \square \)

**Proposition 22.** All \( d \)-dimensional rotation words are URD, but not SURD.
Proof. Consider a $d$-dimensional rotation word $w$ with parameters $\alpha, I_1, \ldots, I_k, \rho$. First, we show that $w$ is URD. Let $q \in \mathbb{N}^d$ be a direction and $s = (s_1, \ldots, s_d) \in \mathbb{N}^d$. We claim that the unidimensional word $w_{q,s}$ is the image of a unidimensional rotation word under a letter-to-letter projection. Indeed, by definition, for each $j$, the letter $w_{q,s}(j)$ corresponds to the factor of size $s$ occurring at position $jq$ in $w$. By Lemma 21, we get that the word $w_{q,s}$ is the coding of the rotation on the unit circle of the point $\rho$ under the irrational angle $q \cdot \alpha$ with respect to the interval partition $\{I_{f_1,1}, \ldots, I_{f_1,l(f_1)}, \ldots, I_{f_r,1}, \ldots, I_{f_r,l(f_r)}\}$ where $f_1, \ldots, f_r$ are the factors of $w$ of size $s$ and the intervals $I_{f_r,j}$ are defined as in (2). I do not understand: who are those $i$ and $j$? Note that since all intervals of the form $I_{f_r,j}$ is coded by the same "letter" $f_i$ in $w_{q,s}$, we do not necessarily obtain a rotation word but a letter-to-letter projection of a rotation word. Now, we obtain that $w$ is URD as a direct consequence of the three-gap theorem [24, 23] stating the following: if $\delta$ is an irrational number and $I$ is an interval of the unit circle then the gaps between the successive integers $j$ such that $\delta j \in I$ take at most three values. So, in $w_{q,s}$, the distance between consecutive occurrences of the first letter $w_{q,s}(0)$ is bounded by the largest gap corresponding to $\delta = q \cdot \alpha$ and the interval $I = I_{w_{q,s}(0),j}$ where $j \in \mathbb{N}[1,k(w_{q,s}(0))]$ corresponds to the index of the interval $I_{w_{q,s}(0),j}$ containing $\rho$.

However, $w$ is not SURD since the uniform recurrence constant of $w_{q,1}$ can be arbitrarily large depending on the direction $q$. Indeed, by Kronecker’s theorem, for each integer $N$, one can choose $q_N = (q_1, N, \ldots, N)$ so that $\ell(q_N \cdot \alpha \mod 1) < \min(|I_1|, \ldots, |I_k|)$ for any $\ell \in [0, N]$. Therefore, the word $w_{q_N,1}$ contains all the factors $j^N$ for $j \in \mathbb{N}[1,k]$. $\square$

To end this section, we present an alternative proof of Proposition 22 using the notion of Cartesian product of words. As it happens, this second proof reveals a property of $d$-dimensional rotation words which is stronger than the URD property (see Remark 24). Further, we hope that this technique could be useful in order to prove that some other families of $d$-dimensional infinite words are URD.

Recall that the direct product of two unidimensional words $v: \mathbb{N} \to A$ and $w: \mathbb{N} \to B$ (possibly over different alphabets $A$ and $B$) is defined as the word $v \times w: \mathbb{N} \to A \times B$ where the $i$-th letter is $(v(i), w(i))$; for example see [20]. The direct product of $k \geq 2$ unidimensional words can be defined inductively.

First, we need a lemma based on Furstenberg’s results [11] and their consequences on the direct product of unidimensional rotation words.

Lemma 23. Any direct product of unidimensional lower (resp. upper) rotation words is uniformly recurrent.

Proof. Let $k \geq 2$ and consider $k$ unidimensional lower (resp. upper) rotation words $R_{i_1}, \ldots, R_{i_k}$. For each $i$, suppose that $R_i$ has slope $\alpha_i$ and intercept $\rho_i$. Let $T_i$ be the transformation associated with $R_i$, i.e. $T_i: [0, 1) \to [0, 1)$, $x \mapsto (x + \alpha_i) \mod 1$. By definition, $R_i$ is the coding of the orbit of the intercept $\rho_i$ in the dynamical system $([0,1), T_i)$ with respect to some interval partition $(I_{i,1}, \ldots, I_{i,k})$ of $[0,1)$ where each interval $I_{i,j}$ is half open on the right. Moreover, the direct product of $k$ codings can be seen as the coding of the dynamical system product $([0,1)^k, T_1 \times \cdots \times T_k)$ where $T_1 \times \cdots \times T_k: (x_1, \ldots, x_k) \mapsto (T_1(x_1), \ldots, T_k(x_k))$.

The maps $T_i$ correspond to the transformation $T$ defined in [11, Prop. 5.4] with $d = 1$. Thus, from a dynamical point of view, every point of $([0,1), T_i)$ is recurrent [11, Prop. 5.4] and their product with any recurrent point of $([0,1), T_j)$ is also recurrent [11, Prop. 5.5] for the product system. Such points are called strongly recurrent by Furstenberg. Since the direct product of strongly recurrent points is also strongly recurrent [11, Lem. 5.10] and since strong recurrence implies uniform recurrence [11, Thm. 5.9], we obtain that the product of any $k$
points of \( ([0, 1), T_1), \ldots, ([0, 1), T_k) \) respectively is uniformly recurrent with respect to the product system \( ([0, 1)^k, T_1 \times \cdots \times T_k) \).

Finally, since \( R_1, \ldots, R_k \) are all rotation words of the same orientation, there is no ambiguity in the coding and the dynamical systems results can be translated in terms of words. Therefore, their direct product is uniformly recurrent.

**Alternative proof of the URD part of Proposition 22.** Consider a \( d \)-dimensional rotation word \( w \) with parameters \( \alpha, I_1, \ldots, I_k, \rho \). First, we show that \( w \) is URD. Let \( q \in \mathbb{N}^d \) be a direction and \( s = (s_1, \ldots, s_d) \in \mathbb{N}^d \). For any \( p \in \llbracket 0, s-1 \rrbracket \), the unidimensional word \( (w(p + \ell q))_{\ell \in \mathbb{N}} \) is a rotation word. Indeed, it is the coding of the rotation of the point \( \rho + p \cdot \alpha \) of the unit circle under the irrational angle \( q \cdot \alpha \), with respect to the partition into the intervals \( I_1, \ldots, I_k \). Therefore, the word \( w_{q,s} \) is a direct product of \( s_1 \cdots s_d \) unidimensional rotation words (of the same orientation):

\[
w_{q,s} = \bigotimes_{i \in [0,s-1]} \ w(i + \ell q)_{\ell \in \mathbb{N}}
\]

By Lemma 23, we obtain that \( w_{q,s} \) is uniformly recurrent. This proves that \( w \) is URD.

**Remark 24.** In fact, the second proof of Proposition 22 shows that \( d \)-dimensional rotation words satisfy a stronger property than URD which is not the SURD property. Indeed, we have proved that for any \( q \), the unidimensional word \( w_{q,s} \) along the direction \( q \) with respect to the size \( s \) is uniformly recurrent, whereas for the URD property, it is only needed that the first letter of this word occurs in it with bounded gaps.

**Remark 25.** In the particular case of rotation words of the same slope \( \alpha \), one can directly prove (without using Furstenberg’s results) that their direct product is uniformly recurrent, except in some exceptional cases described below. See [8] for similar concerns on rotation words.

The proof goes as follows. Let \( R_1, \ldots, R_k \) be unidimensional lower (resp. upper) rotation word of intercepts \( \rho_1, \ldots, \rho_k \) respectively. As in the proof of Proposition 22, for each \( i \), the factor of length \( s \) at position \( m \) in \( R_i \) corresponds to the interval of the point \( \rho_i + m \alpha \).

For each \( i \), let us shift all the intervals of the \( i \)-th circle by \( \rho_1 - \rho_i \). Now the factor at the position \( m \) of each \( R_i \) corresponds to the (shifted) interval of the point \( \rho_i + (p_1 - \rho_i) + m \alpha = \rho_1 + m \alpha \). Consider the intervals created as the intersections of all shifted intervals (we have at most \( \ell_1 + \cdots + \ell_k \) of them where each \( \ell_i \) is the number of intervals in the interval partition corresponding to \( R_i \)). These new intervals correspond to the factors of the product \( R_1 \times \cdots \times R_k \). Namely, the factor at position \( m \) of \( R_1 \times \cdots \times R_k \) corresponds to the interval containing the point \( \rho_1 + m \alpha \).

This shows that \( R_1 \times \cdots \times R_k \) is a rotation word. So, it is uniformly recurrent by the three-gap theorem. The only exception is when some intersection of the intervals is a single point, which can only happen in the case when in one of the words the intervals are half-open on the right, and in the other one they are half-open on the left, and the orbit of each point contains this point. If one of the words never touches the intervals endings (which corresponds to an orbit not containing zero), it means that orientation does not play any role for this word and we can assume it is the same as for the other word.

### 6 Fixed point of multidimensional square morphisms

Similarly to unidimensional words, one can define morphisms and their fixed points in any dimension; for example, see [6, 19, 21]. For simplicity, we only consider constant length morphisms.
Definition 26. A d-dimensional morphism of constant size $s = (s_1, \ldots, s_d) \in \mathbb{N}^d$ is a map $\varphi : A \to A^{[0,s-1]}$. For each $a \in A$ and for each integer $n \geq 2$, $\varphi^n(a)$ is recursively defined as

$$ \varphi^n(a) : [0, s^n - 1] \to A, \ i \mapsto \left( \varphi((\varphi^{n-1}(a))(q)) \right)(r), $$

where $q$ and $r$ are defined by the componentwise Euclidean division of $i$ by $s$: $i = qs + r$. With these notation, the preimage of the letter $(\varphi^n(a))(i)$ is the letter $(\varphi^{n-1}(a))(q)$. In the case $s = (s, \ldots, s)$, we say that $\varphi$ is a d-dimensional square morphism of size $s$.

Note that $\varphi^n(a)$ is obtained by concatenating $\prod_{i=1}^d s_i$ copies of the images $\varphi^{n-1}(b)$ for the letters $b$ occurring in $\varphi(a)$. For instance, if $d = 2$ and $s = (s_1, s_2)$, the $n$-th image $\varphi^n(a)$ has size $s^n = (s_1^n, s_2^n)$ and, with the convention of Remark 3, we have

$$ \varphi^n(a) = \left[ \varphi^{n-1}(\varphi(a)_{0,s_2-1}) \cdots \varphi^{n-1}(\varphi(a)_{s_1-1,s_2-1}) \right] $$

where we have used the lighter notation $\varphi(a)_{i,j}$ instead of $(\varphi(a))(i,j)$.

Example 27. In Figure 8, the third iteration of a bidimensional morphism $\varphi$ of size $s = (3, 2)$ is given. The gray zone corresponds to $\varphi^2(1)$. The preimages of different letters is highlighted in colors. For instance, the preimage of $\varphi^3(1)_{4,7}$ (in red) is the letter $\varphi^2(1)_{1,3}$ as $(4, 7) = (1, 3)s + (1, 1)$ (where the product and sum are understood componentwise). Note that it is also the preimage of $\varphi^3(1)_{3,6}, \varphi^3(1)_{3,7}$ and $\varphi^3(1)_{5,7}$ for example.

Definition 28. Let $\varphi$ be a d-dimensional morphism such that there exists $a \in A$ with $\varphi(a)_{0,0} = a$. We say that $\varphi$ is prolongable on $a$ and the limit $\lim_{n \to \infty} \varphi^n(a)$ is well defined. The limit d-dimensional infinite word so obtained is called the fixed point of $\varphi$ beginning with $a$ and it is denoted by $\varphi^\infty(a)$. A d-dimensional infinite word is said to be pure morphic if it is the fixed point of a d-dimensional morphism.

Example 29. Figure 9 depicts the first five iterations of a bidimensional square morphism with the convention that a black (resp. white) cell represents the letter 1 (resp. 0). The limit object of this process is the famous Sierpinski gasket.

A first interesting observation is that in order to study the uniform recurrence along all directions (URD) of d-dimensional infinite words of the form $\varphi^n(a)$ for a square morphism $\varphi$, we only have to consider the distances between consecutive occurrences of the letter $a$. 

Figure 8: Third iteration of the morphism $0 \mapsto \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, 1 \mapsto \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$ starting from 1.
Along any direction is at most and by using Proposition 30, we obtain that the distance between consecutive occurrences of the letter in is at most , then, for all the distance between consecutive occurrences of the prefix of size of along is at most .

**Proof.** Let be a direction. If there exists such that then, for all the distance between consecutive occurrences of along is at most . This implies that is at most . Let be a direction. Let be a given direction. Then, we let such that and consider the prefix of size of along . Therefore and because we consider a square morphism, if the distance between consecutive occurrences of along is at most then the distance between consecutive occurrences of along is at most .

In order to provide a family of SURD -dimensional infinite words, we introduce the following definition.

**Definition 31.** For an integer and a vector , we define to be the additive subgroup of such that are coprime, we define to be the additive subgroup of such that is generated by : 

\[ \langle i \rangle = \{ ki : k \in \mathbb{Z}/s\mathbb{Z} \}. \]

Then, we let be the family of all cyclic subgroups of : 

\[ C(s) = \{ \langle i \rangle : i \in (\mathbb{Z}/s\mathbb{Z})^d, \gcd(i) = 1 \}. \]

**Proposition 32.** If is a -dimensional square morphism of size prolongable on , then its fixed point is SURD. More precisely, for each , the distance between consecutive occurrences of the prefix of size of along any direction is at most .

**Proof.** Let be a direction. Let be a given direction. Let be (componentwise) and . By hypothesis, there exists such that (componentwise) for each . Let such that . Then . Observe that divides and , hence also divides . This implies that divides and . Let . Then . We obtain that for all , hence . This proves that the distance between consecutive occurrences of the letter in along the direction is at most .

Now let and consider the prefix of size of . From the first part of the proof and by using Proposition 30, we obtain that the distance between consecutive occurrences of along any direction is at most .

Figure 9: The first five iterations of the 2D morphism

\[
\begin{bmatrix}
0 & 0 \\
0 & 0
\end{bmatrix}, \begin{bmatrix}
1 & 0 \\
1 & 1
\end{bmatrix}
\]

starting from 1.
Since each subgroup of $(\mathbb{Z}/s\mathbb{Z})^d$ contains $0$, the following result is immediate.

**Corollary 33.** Let $\varphi$ be a $d$-dimensional square morphism of size $s$ such that $(\varphi(b))_0 = a$ for each $b \in A$. Then the fixed point $\varphi^a(a)$ is SURD. More precisely, for each $m \in \mathbb{N}^d$, the distance between consecutive occurrences of the prefix of size $m$ of $\varphi^a(a)$ along any direction is at most $s^{\log_s(max(m))} + 1$.

When the alphabet $A$ is binary (in which case we assume without loss of generality that $A = \{0, 1\}$), then we talk about binary morphism and we always consider that it has a fixed point beginning with 1.

**Example 34.** By Corollary 33, the fixed point $\varphi^a(1)$ of

$$\varphi: 0 \mapsto \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}, \ 1 \mapsto \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

is SURD: for all $(m, n) \in \mathbb{N}^2$, the distance between consecutive occurrences of the prefix of size $(m, n)$ of $\varphi^a(1)$ along any direction is at most $2^{\log_s(max(m,n))} + 1$.

**Remark 35.** When the size $s$ is prime, orbits of any two elements either coincide, or have only the element $0$ in common. Therefore we have exactly $s^d$ distinct orbits. In particular, for $d = 2$, this gives $s + 1$ distinct orbits. Hence we can consider a partition of $(\mathbb{Z}/s\mathbb{Z})^d$ into $s + 1$ sets: $s + 1$ orbits without $0$ and $0$ itself. When $s$ is not prime, the structure is a bit more complicated and we do not have such a nice partition. Below we consider examples to illustrate the two situations.

**Example 36.** Partition for $s = 5$ and $d = 2$ can be illustrated by the following picture where each letter in $\{\alpha, \ldots, \zeta\}$ represents an orbit:

Due to Proposition 32, in order to obtain a SURD fixed point of a bidimensional square morphism, it is enough to have the letter $a$ in the image of each letter $b \in A$ in one of the coordinates marked by each Greek letter. And by Corollary 33, having the letter $a$ in the coordinate $(0,0)$ in the image of each letter is enough.

**Example 37.** For $s = 6$ and $d = 2$, one has 12 orbits (which can be checked by considering the 36 possible cases of pairs of remainders of the Euclidean division by 6, out of which there are only 21 coprime pairs to consider):
Here are the correspondence between the 12 orbits and letters (where we do not write (0, 0), which belongs to every orbit):

\[
\begin{array}{c|c}
\alpha & (1, 0) \\
\beta & (0, 1) \\
\gamma & (1, 1) \\
\delta & (2, 1), (4, 5) \\
\epsilon & (1, 2), (5, 4) \\
\zeta & (3, 1), (3, 5) \\
\eta & (1, 3), (5, 3) \\
\theta & (4, 1), (2, 5) \\
\iota & (1, 4), (5, 2) \\
\kappa & (5, 1), (1, 5) \\
\lambda & (3, 4), (3, 2) \\
\mu & (4, 3), (2, 3)
\end{array}
\]

\[
\{(1, 0), (2, 0), (3, 0), (4, 0), (5, 0)\}
\]

\[
\{(0, 1), (0, 2), (0, 3), (0, 4), (0, 5)\}
\]

\[
\{(1, 1), (2, 2), (3, 3), (4, 4), (5, 5)\}
\]

\[
\{(2, 1), (4, 2), (0, 3), (2, 4), (4, 5)\}
\]

\[
\{(1, 2), (2, 4), (3, 0), (4, 2), (5, 4)\}
\]

\[
\{(3, 1), (0, 2), (3, 3), (0, 4), (3, 5)\}
\]

\[
\{(1, 3), (2, 0), (3, 3), (4, 0), (5, 3)\}
\]

\[
\{(4, 1), (2, 2), (0, 3), (4, 4), (2, 5)\}
\]

\[
\{(1, 4), (2, 2), (3, 0), (4, 4), (5, 2)\}
\]

\[
\{(5, 1), (4, 2), (3, 3), (2, 4), (1, 5)\}
\]

\[
\{(3, 4), (0, 2), (3, 0), (0, 4), (3, 2)\}
\]

\[
\{(4, 3), (2, 0), (3, 0), (4, 0), (2, 3)\}
\]

We remark that here the orbits intersect, for example, first and third orbits have the element (3, 3) in common. Due to Proposition 32, in order to obtain a SURD word, it suffices to have the letter \(a\) in the image of each letter in at least one of the elements of each orbit. For example, it is the case of the fixed point of any morphism with \(a\)’s in the marked positions in the images of each letter:

\[
\begin{bmatrix}
* & * & * & * & * \\
a & a & * & * & * \\
* & * & a & * & * \\
* & * & * & * & * \\
* & * & * & * & a
\end{bmatrix}
\]

**Corollary 38.** If \(\psi\) is a \(d\)-dimensional square morphism of size \(s\) such that for some integer \(i\), its power \(\varphi = \psi^i\) satisfies the conditions of Proposition 32, then the fixed point \(\psi^i(a)\) is SURD. More precisely, for all \(m \in \mathbb{N}^d\), the distance between consecutive occurrences of each prefix \(p\) of size \(m\) of \(\psi^i(a)\) is at most \(s^{\left\lceil \log(\max(m)) \right\rceil + i}\).

**Proof.** Clearly, the fixed points of \(\psi\) and \(\varphi\) are the same. Now apply Proposition 32 to \(\varphi\). \(\square\)

**Example 39.** The morphism

\[
\psi: 0 \mapsto \begin{bmatrix} 0 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}
\]

satisfies the hypotheses of Corollary 38 for \(s = 3\), \(i = 2\). Indeed, it can be checked that for each \(C \in \mathcal{C}_9\), we can find a 1 in both images \(\psi^2(0)\) and \(\psi^2(1)\).

**Remark 40.** The hypotheses of Proposition 32 should be compared to the primitivity property of a morphism. In the unidimensional case, a morphism is said to be primitive if its incidence matrix is primitive; see for example [9]. In higher dimensions, it is not clear how this notion generalizes since we have too take into account infinitely many directions. Thus, we should not only consider the number of times a letter occur in the image of another letter but also the positions where the letters occur in each image. See Section 8 for some perspectives in this direction.

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Now we give a family of examples of SURD $d$-dimensional words which do not satisfy the hypotheses of Corollary 38, showing that it does not give a necessary condition. We first need the following observation on unidimensional fixed points of morphisms.

**Lemma 41.** Let $\varphi$ be a unidimensional morphism of constant prime size $s$ and prolongable on $a \in A$ for which there exists $i \in \{0, s - 1\}$ such that $\varphi(b)_i = a$ for each $b \in A$. For all positive integers $m$, the maximal distance between consecutive occurrences of $a$ in the arithmetic subsequence $(\varphi^m(a))_{m \in \mathbb{N}}$ of $\varphi^a(a)$ is at most $s$.

**Proof.** Let $w = \varphi^a(a)$ and let $m$ be a positive integer. Let $d_m$ denote the maximal distance between consecutive occurrences of $a$ in $(w_{mk})_{k \in \mathbb{N}}$. We have to show that $d_m \leq s$. The integer $m$ can be decomposed in a unique way as $m = s^e \ell$ with $e, \ell \in \mathbb{N}$ and $\ell \neq 0 \mod s$. We prove the result by induction on $e \in \mathbb{N}$. If $e = 0$ then $m \neq 0 \mod s$. Since the letter $a$ appears in the $i$-th place of the images of all letters and since $i \neq 0$, we obtain that $d_m \leq s$ in this case. Now suppose that $e > 0$ and that the result is correct for $e - 1$. Observe that, for every $k \in \mathbb{N}$, the preimage of the letter $w_{mk} = w_{s^e \ell k}$ is the letter $w^{\varphi^m}_k = w_{s^e \ell k}$. By definition of the morphism and since $m \equiv 0 \mod s$, for each $k \in \mathbb{N}$, the letter $w_{mk}$ is equal to $a$ if its preimage is $a$. But by induction hypothesis, for all $k \in \mathbb{N}$, at least one of the $s$ preimages $w^{\varphi^m}_k$, $w^{\varphi^m}_{m(k+1)}$, ..., $w^{\varphi^m}_{m(k+\ell - 1)}$ is equal to $a$. Therefore, we obtain that for all $k \in \mathbb{N}$, at least one of the $s$ letters $w_{mk}$, $w_{m(k+1)}$, ..., $w_{m(k+\ell - 1)}$ is equal to $a$ as well, which shows that $d_m \leq s$. \hfill \Box

**Proposition 42.** If $\varphi$ is a $d$-dimensional square morphism of some prime size $s$ such that

1. $\forall i_2, \ldots, i_d \in \{0, s - 1\}$, $\varphi(a)_{0, i_2, \ldots, i_d} = a$

2. $\exists i_1 \in \{0, s - 1\}, \forall i_2, \ldots, i_d \in \{0, s - 1\}$, $\varphi(b)_{i_1, i_2, \ldots, i_d} = a$ for each $b \in A$

then $\varphi^a(a)$ is SURD.

**Proof.** By Proposition 30, we only have to show that there exists a uniform bound $t$ such that the distance between consecutive occurrences of $a$ along any direction of $\varphi^a(a)$ is at most $t$. It is sufficient to prove the result for the fixed point beginning with 1 of the binary morphism $\psi$ satisfying the hypotheses (1) and (2) and having 0 at any other coordinates in the images of both 0 and 1. Indeed, any fixed point $\varphi^{\omega}(a)$ of a morphism $\varphi$ satisfying (1) and (2) differs from this one only by replacing occurrences of 1 by $a$ and occurrences of 0 by any letter of the alphabet. For example, for $d = 2$, the morphism $\psi$ is

$$
\psi: 0 \mapsto \begin{bmatrix} 0 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\
\vdots & \vdots & & \vdots & \vdots & \vdots & & \vdots \\
0 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\
\end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 1 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\
1 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\
\vdots & \vdots & & \vdots & \vdots & \vdots & & \vdots \\
1 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\
\end{bmatrix}
$$

(where the common columns of 1’s are placed at position $i_1$ in both images). Each of the hyperplanes

$$
H_k = \{\psi^{\omega}(1)_{k, i_2, \ldots, i_d} : i_2, \ldots, i_d \in \mathbb{N}\}, \quad k \in \mathbb{N}
$$

of $\psi^{\omega}(1)$ contains either only 0’s or only 1’s. Therefore, for any direction $q = (q_1, \ldots, q_d)$, we have $\psi^{\omega}(1)_{i q} = \psi^{\omega}(1)_{q_1, 0, \ldots, 0}$, hence the unidimensional word $\mathbb{N} \to A$, $\ell \mapsto \psi^{\omega}(1)_{i q}$ is the fixed point of the unidimensional morphism

$$
\sigma: 0 \mapsto \begin{bmatrix} 0 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\
\end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 1 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\
\end{bmatrix}
$$

(where, again, the common 1’s are placed at position $i_1$ in both images). By Lemma 41, we obtain that $\psi^{\omega}(1)$ is SURD with the uniform bound $t = s$. \hfill \Box

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Note that the role of the first coordinate $i_1$ could be played by any of the other coordinates $i_2, \ldots, i_d$ with the ad hoc modifications in the statement of Proposition 42.

Now we give a sufficient condition for a $d$-dimensional word to be non URD.

**Proposition 43.** Let $\varphi$ be a $d$-dimensional square morphism of a prime size $s$ prolongable on $a \in A$. Let $q$ be a direction and let $C = (q \mod s)$. If $\varphi(b) \neq a$ for each $b \in A$ and $1 \in C$ except for $\varphi(a)q = a$, then $(\varphi^\omega(a)_{tq})_{t \in \mathbb{N}} \in a(A\setminus\{a\})^\omega$. In particular, $\varphi^\omega(a)$ is not recurrent along the direction $q$.

**Proof.** Suppose that the first occurrence of $a$ after that in position $0$ along the direction $q$ occurs in position $kq$. Since, for each $b \in A$, $\varphi(b)$ has non-$a$ elements on all places defined by $C\setminus\{0\}$, the letter $\varphi^\omega(1)_{tq}$ must be placed at the coordinate $0$ of the image of $a$. In particular, the preimage of $\varphi^\omega(a)_{tq}$ must be $a$. Because $s$ is prime, $\ell$ must be divisible by $s$ and the preimage of $\varphi^\omega(a)_{tq}$ is $\varphi^\omega(a)_{\ell q}$. But by the choice of $\ell$ and since $0 < \ell s < \ell$, we must also have $\varphi^\omega(a)_{\ell q} \neq a$, a contradiction.  

The next results shows that the condition of Proposition 43 is not necessary.

**Proposition 44.** The fixed point $\varphi^\omega(1)$ of the morphism

$$
\varphi : 0 \mapsto \begin{bmatrix}
1 & 1 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix}
\quad 1 \mapsto \begin{bmatrix}
1 & 1 & 1 \\
0 & 1 & 0 \\
1 & 1 & 0
\end{bmatrix}
$$

is not recurrent along the direction $(1, 3)$.

**Proof.** We let $w = \varphi^\omega(1)$. We show that the sequence we get along the direction $(1, 3)$ is $10^\omega$. It can be seen directly that the first symbols are 100, then we proceed by induction. Suppose the converse, and that $i$ is the smallest positive integer such that $w_{i,3i} = 1$. We consider three cases: $i = 3i'$, $i = 3i' + 1$, or $i = 3i' + 2$. In each case, our aim is to prove that $w_{i',3i'} = 1$, contradicting the minimality of $i$.

Case 1: $i = 3i'$. In this case $\varphi(w_{i',3i'})_{0,0} = w_{i,3i}$. Since $\varphi(0)_{0,0} = 0$ and $w_{i,3i} = 1$ by the assumption, we must have $w_{i',3i'} = 1$.

Case 2: $i = 3i' + 1$. In this case $\varphi(w_{i',3i'+1})_{1,0} = w_{i,3i}$. Since $\varphi(0)_{1,0} = 0$ and $w_{i,3i} = 1$, we have $w_{i',3i'+1} = 1$. The coordinate $(i',3i'+1)$ being a position $(i' \mod 3, 1)$ in some image $\varphi(a)$, this is possible only in the case when $a = 1$ and $i' \equiv 1 \pmod{3}$. Indeed, this is the only non-0 position with second coordinate 1 in $\varphi(0)$ and $\varphi(1)$. Therefore, we obtain $w_{i',3i'} = 1$.

Case 3: $i = 3i' + 2$. In this case $\varphi(w_{i',3i'+2})_{2,0} = w_{i,3i}$. Since $\varphi(1)_{2,0} = 0$ and $w_{i,3i} = 1$, we have $w_{i',3i'+2} = 0$. The coordinate $(i',3i'+2)$ being a position $(i' \mod 3, 2)$ in some image $\varphi(a)$, we must have $a = 0$ and $i' \equiv 2 \pmod{3}$. Indeed, this is the only non-1 position with second coordinate 2 in $\varphi(0)$ and $\varphi(1)$. We obtain once again that $w_{i',3i'} = 1$.

The next theorem gives a characterization of SURD fixed points of square binary morphisms of size 2.

**Theorem 45.** Let $\varphi$ be a bidimensional binary square morphism of size 2 prolongable on 1. The fixed point $\varphi^\omega(1)$ is SURD if and only if either $\varphi(0)_{0,0} = 1$ or $\varphi(1) = [\frac{1}{1} \frac{1}{1}]$.

The “if” part follows from Corollary 33. The “only if” part is proved with a rather technical argument involving a case study analysis and using certain properties of arithmetic progressions in the Thue-Morse word $t = 0110100110010110 \cdots$. 

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We first provide two useful lemmas about the Thue-Morse word. Recall that this word is the fixed point of the unidimensional morphism $0 \mapsto 01$, $1 \mapsto 10$. It can also be defined thanks to the function $s_2 : \mathbb{N} \to \mathbb{N}$ that returns the sum $s_2(n)$ of the digits in the binary expansion of $n$: the $(n+1)$-th letter $t_n$ of the Thue-Morse word $t$ is equal to $0$ if $s_2(n) \equiv 0 \mod 2$ and to $1$ otherwise.

**Lemma 46.** For any odd integer $\ell \geq 3$, the Thue–Morse word $t = (t_n)_{n \in \mathbb{N}}$ satisfies $t_0 = 0$, $t_d = t_{2d} = t_{3d} = \ldots = t_{2\ell d} = 1$ with $d = 2^\ell - 1$.

**Proof.** Let $m \in \lfloor 1, 2^\ell \rfloor$. There exist $r$ odd and $i \geq 0$ such that $m = r 2^i$. Denote by $r_j r_{j-1} \cdots r_1 r_0$ the binary expansion $(r)_2$ of $r$. In particular, $r_0 = 1$ since $r$ is odd. Also $r \leq m \leq 2^\ell$ and $r$ odd imply that $r < 2^\ell$ and $|(r)_2| \leq \ell$. We have $(r 2^\ell)_2 = r_j r_{j-1} \cdots r_1 r_0 0^\ell$ and $(r 2^\ell - 1)_2 = r_j r_{j-1} \cdots r_1 01^\ell$. Therefore,

$$s_2(r(2^\ell - 1)) = s_2(r 2^\ell - 1 - (r - 1))$$

$$= s_2(r) - 1 + \ell - s_2(r - 1) \quad \text{(as } |(r)_2| \leq \ell)$$

$$= s_2(r) - 1 + \ell - s_2(r) + 1 \quad \text{(as } r \text{ odd)}$$

$$= \ell.$$

Since $s_2(m(2^\ell - 1)) = s_2(r(2^\ell - 1)) = \ell$ is odd, we get that $t_{m(2^\ell - 1)} = 1$. \hfill \Box

Note that the proof of the previous lemma is a modification of Lemma 3.2 in [4].

**Lemma 47.** For any positive integer $\ell$, the Thue–Morse word $t = (t_n)_{n \in \mathbb{N}}$ satisfies $t_0 = 0$, $t_d = t_{2d} = t_{3d} = \ldots = t_{2\ell d} = 0$ with $d = 2^\ell + 1$.

**Proof.** Let $m \in \lfloor 0, 2^\ell - 1 \rfloor$. Since $m < 2^\ell$, $|(m)_2| \leq \ell$. So $s_2(m(2^\ell + 1)) = s_2(m) + s_2(m)$ is even. It follows that $t_{m(2^\ell + 1)} = 0$. For $m = 2^\ell$, we have $s_2(m(2^\ell + 1)) = s_2(2 2^\ell + 2^\ell) = 2$ and $t_{m(2^\ell + 1)} = 0$. \hfill \Box

**Proof of Theorem 45.** The condition is sufficient by Corollary 33. To prove that it is necessary, we show by a case study that the fixed points beginning with $1$ of all the other possible morphisms are not SURD. For the sake of clarity, we set $w = \varphi^1$.

First, note that $\varphi(1)_{i,j} = \varphi(0)_{i,j} = 0$ for some $(i, j) \neq (0, 0)$ implies that $w$ contains $10^\ell$ along the direction $(i, j)$. Hence for a given position $(i, j)$, it is sufficient to consider $(\varphi(1)_{i,j}, \varphi(0)_{i,j}) \in \{(0, 1), (1, 0), (1, 1)\}$. The graph of our case study is depicted in Figure 10, where the missing transitions lead to a morphism of the form

$$\varphi : 0 \mapsto \begin{bmatrix} 0 & * \\ * & * \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

giving rise to a periodic all-1 fixed point.

**Case 1**

$$\varphi : 0 \mapsto \begin{bmatrix} 1 & * \\ 0 & 1 \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 0 & * \\ 1 & 0 \end{bmatrix}$$

We show that the factor $10^{2\ell - 1}$ occurs along the direction $(p, q) = (2^\ell(2^\ell - 1), 2^\ell + 1)$ with $\ell$ odd (see Figure 11). First note that the first row of $\varphi^1(1)$ is equal to $1$, hence, the first $2^\ell$ rows contain $\varphi(2^\ell)$. Let $d = 2^\ell - 1$. By Lemma 46, the arithmetical subsequence $(\ell_{md})_{m \in \mathbb{N}}$ begins with $10^\ell$. Thus, $w_{mp,0} = w_{md2^\ell,0} = 0$ for $m \in \{1, \ldots, 2^\ell\}$. To conclude, observe that the first
Figure 10: Square morphisms of size 2. A black (resp. white) cell corresponds to a position filled with letter 1 (resp. 0). A gray cell corresponds to a position which can contain any letter. The possible pairs \((\varphi(1)_{i,j}, \varphi(0)_{i,j})\) with \(i, j \in \{0, 1\}\) are successively considered. A blue line corresponds to the pair \((\varphi(1)_{i,j}, \varphi(0)_{i,j})\), a red one to \((1, 0)\) and a green one to \((1, 1)\).

Figure 11: Structure of Case 1 morphisms with \((p, q) = (2^\ell(2^\ell - 1), 2^\ell + 1)\) where \(\ell\) is odd.

column of \(\varphi^{2\ell}(0)\) is a prefix of \(t\). By Lemma 47, the arithmetical subsequence \((t_{mq})_{m \in \mathbb{N}}\) begins with \(0^{2\ell}\). Let \(m \in [1, 2^\ell - 1]\). As \((2^\ell - 1)q = 2^\ell - 1 < 2^\ell\), the letter \(w_{mp,mq}\) is inside a square \(\varphi^{2\ell}(0)\) with the bottom left corner at position \((mp, 0)\), hence \(w_{mp,mq} = 0\).

**Case 2**

\[\varphi: 0 \mapsto \begin{bmatrix} 1 & * \\ 0 & 0 \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 0 & * \\ 1 & 0 \end{bmatrix}\]

In this case we will prove that for all odd \(n \in \mathbb{N}\), the factor \(0^{2^n-1}\) occurs along the direction \((1, (2^n - 1)2^n)\). More precisely, we claim that for all odd \(n \in \mathbb{N}\) and all \(i \in [1, 2^n - 1]\), we have \(w_{i,(2^n-1)2^n} = 0\). First, notice that there are only 0’s on the bottom line of the images \(\varphi^n(0)\) for all \(m \in \mathbb{N}\), namely, \(\varphi^n(0)_{i,0} = 0\) for all \(m \in \mathbb{N}\) and all \(i \in [0, 2^n - 1]\). Second, we use Lemma 46 which gives \(w_{0,i(2^n-1)} = 0\) for all odd \(n \in \mathbb{N}\) and all \(i \in [1, 2^n]\). By applying the power morphism \(\varphi^{2^n}\), we get \(w_{0,i(2^n-1)2^n} = 0\) for all odd \(n \in \mathbb{N}\) and all \(i \in [1, 2^n]\). Since the latter points belong
to left bottom corner of $\varphi^n(0)$, we obtain that $w_{i,i(2^n-1)2^n} = 0$ for every $i \in [1, 2^n - 1]$ as desired.

**Case 3.1**

$\varphi: 0 \mapsto \begin{bmatrix} 1 & 1 \\ 0 & * \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 0 & 0 \\ 1 & * \end{bmatrix}$

Similarly to Case 1, we can show that the factor $10^{2^{\ell-1}}$ occurs along the direction $(p, q) = (2^\ell + 1, 2^{2\ell}(2^\ell - 1) + 2^\ell + 1)$ with $\ell$ odd. Indeed, in this case, the Thue-Morse word or its complement appears in the first column and in the diagonal; see Figure 12.

![Figure 12: Structure of Case 3.1 morphisms with \((p, q) = (2^\ell + 1, 2^{2\ell}(2^\ell - 1) + 2^\ell + 1)\) where \(\ell\) is odd.](image)

**Case 3.2**

$\varphi: 0 \mapsto \begin{bmatrix} 1 & * \\ 0 & 1 \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 0 & 1 \\ 1 & 1 \end{bmatrix}$
In this case we will prove that the word is not recurrent in direction (2, 1). More precisely, we show that \((w_{2i,i})_{i \in \mathbb{N}} = 10^\omega\). Clearly \(w_{0,0} = 1\). We prove \(w_{2i,i} = 0\) for all \(i \geq 1\) by induction on \(i\). The base case \(w_{2,1} = 0\) is easily verified. Now let \(i > 1\) and suppose that \(w_{2i',i'} = 0\) for all \(1 \leq i' < i\). If \(i\) is even, then \(w_{2i,i} = \varphi(w_{i,i/2})_{0,0} = 0\), where the last equality comes from the induction hypothesis with \(i' = i/2\) and the fact that \(\varphi(0)_{0,0} = 0\). If \(i\) is odd, then \(w_{2i,i} = \varphi(w_{i,i/2})_{0,1}\). Remark that \(w_{i,i/2}\) is an element in a right column of a \(2 \times 2\) block which is an image of \(0\) or \(1\). An element \(w_{i-1,i/2}\) (which is equal to \(0\) by induction hypothesis with \(i' = (i-1)/2\)) is an element in the same block which is situated to the left of \(w_{i,i-1}\). Due to the forms of \(\varphi(0)\) and \(\varphi(1)\), if a left element is \(0\), then the right element in the same line is \(1\). So, \(w_{i,i/2} = 1\), hence \(w_{2i,i} = \varphi(1)_{0,1} = 0\).

**Case 4**

\[
\varphi: 0 \mapsto \begin{bmatrix} * & * \\ 0 & * \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}
\]

In this case we will prove that for all \(n \in \mathbb{N}\), the factor \(0^{2^n-1}\) occurs along the direction \((2^n - 1, 1)\). More precisely, for all \(n \in \mathbb{N}\), we have \(w_{j,(2^n-1),j} = 0\) for every \(j \in \llbracket 1, 2^n - 1 \rrbracket\). First, an easy induction on \(n\) shows that there are \(0\) just above the diagonal in the images \(\varphi^n(1)\) for all \(n \geq 1\), namely \(\varphi^n(1)_{2^n-j,j} = 0\) for all \(n \geq 1\) and all \(j \in \llbracket 1, 2^n - 1 \rrbracket\). For example, for \(n = 3\), we have

\[
\varphi^3(1) = \varphi^2 \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} = \begin{bmatrix}
1 & 0 & * & * & * & * & * & * \\
1 & 0 & * & * & * & * & * & * \\
1 & 0 & 1 & 0 & * & * & * & * \\
1 & 0 & 1 & 0 & * & * & * & * \\
1 & 0 & 1 & 0 & * & * & * & * \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{bmatrix}.
\]

Second, since \(w_{i,0} = 1\) for all \(i \in \mathbb{N}\), we obtain that, for all \(n, k \in \mathbb{N}\), the square factor of size \(2^n\) occurring at position \((2^n k, 0)\) is equal to \(\varphi^n(1)\). Therefore, we have \(w_{2^n k + 2^n-j,j} = 0\) for all \(n, k \in \mathbb{N}\) and \(j \in \{1, \ldots, 2^n - 1\}\). The claim follows by considering the latter equality with \(k = j - 1\).

The previous theorem gives a characterization of strong uniform recurrence along all directions for fixed points of bidimensional square binary morphisms of size 2. For larger sizes of morphism, we gave several conditions that are either necessary (Proposition 43) or sufficient (Propositions 32 and 42). An open problem is to find a necessary and sufficient condition in general (see Section 8).

We end this section by a small discussion on the SSURDO notion. First we provide an example of SSURDO aperiodic words. Then, we give an example of a SURD word that is not SSURDO.

**Proposition 48.** Let \(\varphi\) be the square binary morphism defined by

\[
\varphi: 0 \mapsto \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}.
\]

The fixed point \(\varphi^\omega(1)\) is SSURDO.
Proof. Let \( w = \varphi^\omega(1) \) and \( q \) be any direction. By definition of \( \varphi \), for every position \( p \neq (2, 2) \mod 3 \), we have \( w(p) = w(p + 3q) \). If follows that \( w(p) = w(p + 3q) \) for all such \( p \).

Consider now a position \( p = (2, 2) \mod 3 \). Since \( \gcd(q) = 1 \), we have \( p + q \neq (2, 2) \mod 3 \) and \( p + 2q \neq (2, 2) \mod 3 \). So \( w(p + q) = w(p + q \mod 3) \) and \( w(p + 2q) = w(p + 2q \mod 3) \). By checking all the possible values modulo 3 of \( p + q \) and \( p + 2q \), we can verify that \( w(p + q) \neq w(p + 2q) \). So the letter \( w(p) \) along the direction \( q \) is firstly repeated within a distance two, then it is repeated every three letters.

Now consider a position \( p \) and a factor \( f \) of size \( s \) occurring at position \( p \). Let \( i = \lceil \max(\log_3 s) \rceil \). We will show that the distance between two occurrences of \( f \) along \( q \) is bounded by \( 3^{i+1} \). To do so, we will consider a covering of the grid by the square factors \( \varphi^i(0) \) and \( \varphi^i(1) \) and study the position of the factor \( f \) relatively to this covering; see Figure 13.

![Figure 13: The factor \( f \) at position \( p \) occurs “completely” inside a factor of the form \( \varphi^i(0) \) or \( \varphi^i(1) \), while the factor \( f' \) (of the same size) at position \( p' \) does not.](image)

If \( f \) occurs “completely” inside a factor \( \varphi^i(0) \) or \( \varphi^i(1) \), i.e. if

\[
\exists k \in \mathbb{N}^2, \quad 3^i k \leq p \leq p + s < 3^i (k + 1),
\]

then we use the previous observation about the occurrence of any letter every three positions along \( q \) to conclude that consecutive occurrences of \( f \) along \( q \) are within distance \( 3^{i+1} \).

If \( f \) does not “completely” occur inside a factor \( \varphi^i(0) \) or \( \varphi^i(1) \), i.e. if

\[
\exists k \in \mathbb{N}^2, \quad 3^i k \leq p < 3^i (k + 1) \leq p + s,
\]

then we note that \( p + s < 3^i (k + 2) \) by definition of \( i \). Consider the factor \( z: [0, 3^i - 1] \times [0, 3^i - 1] \rightarrow A \) of size \( (3^i, 3^i) \) at position \( 3^i k \): for all \( i \in [0, 3^i - 1] \times [0, 3^i - 1] \), \( z(i) = w(i + 3^i k) \). This factor \( z \) corresponds exactly to a square factor of the grid, that is either \( \varphi^i(0) \) or \( \varphi^i(1) \). Hence it occurs along \( q \) from the position \( 3^i k \) with gaps bounded by \( 3^{i+1} \). Now, an easy recurrence shows that \( \varphi^i(0) \) and \( \varphi^i(1) \) coincide everywhere except in position \( (3^j - 1, 3^j - 1) \) for any \( j \in \mathbb{N} \). It follows that any factor of size \( (3^i, 3^i) \) occurring at a position of the form \( 3^i(x, y) \) extends in a unique way to a factor of size \( (2 \cdot 3^i - 1, 2 \cdot 3^i - 1) \) occurring at the same position. Applying this to the factor \( z \), we deduce that distances between consecutive occurrences of \( f \) along \( q \) from the position \( p \) coincide with the distances between consecutive occurrences of \( z \) along \( q \) from the position \( 3^i k \). Hence the conclusion. \( \square \)

Thanks to Theorem 45, we are able to show that SURD does not imply SSURDO, as illustrated by the following example.
Example 49. SURD and SSURDO properties define two distinct classes of words. Consider the fixed point \( w \) of the square binary morphism \( \varphi \) defined by

\[
\varphi: 0 \mapsto \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix},
\]

which is SURD by Theorem 45. We can show that for the size \( s = (1,1) \), the direction \( q = (1,0) \) and the translations \( p_n = (2^{n+1} - 1, 2^n - 1) \) with \( n \in \mathbb{N} \), the words \( (w(p_n))_{q,s} \) begins with \( \bar{a}a^{3 \cdot 2^n} \bar{a} \) where \( a \in \{0,1\} \), by observing that \( p_n \) begins with \( \bar{a}a^{3 \cdot 2^n} \bar{a} \). This is illustrated in Figure 14. It follows that \( w \) is not SSURDO.

7 Non-morphic bidimensional SURD words

In this section we provide a construction of non-morphic bidimensional SURD words. To construct such a word \( w: \mathbb{N}^2 \rightarrow A \) (where \( A \) is any alphabet of size at least 2), we proceed recursively. The construction is illustrated in Figure 15.

![Figure 14: A prefix of the fixed point of \( \varphi: 0 \mapsto \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \).](image)

**Figure 14:** A prefix of the fixed point of \( \varphi: 0 \mapsto \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}, \quad 1 \mapsto \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \). follows that \( w \) is not SSURDO.

**Step 0.** Pick some \( a \in A \) and for each \((i, j) \in \mathbb{N}^2\), put \( w(2i, 2j) = a \).

**Step 1.** Fill anything you want in positions \((0,1), (1,0)\) and \((1,1)\). For each \((i, j) \in \mathbb{N}^2\), put \( w(4i, 4j + 1) = w(0, 1) \), \( w(4i + 1, 4j) = w(1, 0) \), \( w(4i + 1, 4j + 1) = w(1, 1) \). Note that the filled positions are doubly periodic with period 4.

**Step \( n \geq 2 \).** At step \( n \), we have filled all the positions \((i, j)\) for \( i, j < 2^n \), and the positions with filled values are doubly periodic with period \( 2^{n+1} \). Let \( S \) be the set of pairs \((k, \ell)\) with

![Figure 15: Construction of a non-morphic SURD bidimensional word.](image)
\(k, \ell < 2^{n+1}\) which have not been yet filled in. Fill anything you want in the positions from \(S\). Now for each \((k, \ell)\) and each \((k', \ell') \in S\), define \(w(2^{n+2}k + k', 2^{n+2}\ell + \ell') = w(k', \ell')\). Note that the filled positions are doubly periodic with period \(2^{n+2}\).

**Proposition 50.** The bidimensional infinite word \(w\) defined by the construction above is SURD. More precisely, for all \(s \in \mathbb{N}^2\), the distance between consecutive occurrences of the prefix of size \(s\) of \(w\) along any direction is at most \(2^{\lfloor \log_2(\text{max } s) \rfloor}\).

**Proof.** Let \(p\) be the prefix of \(w\) of size \(s\) and let \(q\) be a direction. We show that the square prefix \(p'\) of size \((2^k, 2^k)\) with \(k = \lfloor \log_2(\text{max } s) \rfloor\) appears within any consecutive \(2^k+1\) positions along \(q\), hence this is also true for \(p\) itself. By construction, at step \(k\) we have filled all the positions \(i\) for \(i < (2^k, 2^k)\), and the positions with filled values are doubly periodic with periods \((2^{k+1}, 0)\) and \((0, 2^{k+1})\). Therefore the factor of size \((2^k, 2^k)\) occurring at position \(2^k+1q\) in \(w\) is equal to \(p'\). The claim follows. \(\square\)

Observe that the morphic words satisfying Corollary 33 for \(s = 2\) can be obtained by this construction. This construction can be generalized for any \(s \in \mathbb{N}\) instead of 2. Moreover, on each step we can choose as a period any multiple of a previous period.

**Proposition 51.** Among the bidimensional infinite words obtained by the construction above, there are uncountably many words which are not morphic.

**Proof.** The construction provides uncountably many bidimensional infinite words. However, there exist only countably many morphic words. \(\square\)

### 8 Perspectives

There remain many open questions related to the new notions of directional recurrence introduced in this paper. For example, we would like to generalize the characterization given by Theorem 45 to any morphism size.

**Question 52.** Find a characterization of strong uniform recurrence along all directions for bidimensional square binary morphisms of size bigger than 2.

Another question is the missing relation between different notions of recurrence indicated in Figure 6.

**Question 53.** Prove or disprove: Strong uniform recurrence along all directions implies uniform recurrence.

The original motivation to introduce new notions of recurrence comes from the study of return words. In the unidimensional case, a return word to \(u\) in an infinite word \(w\) is a factor starting at an occurrence of \(u\) in \(w\) and ending right before the next occurrence of \(u\) in \(w\). For instance, the set of return words to \(u = 011\) in the Thue-Morse word is equal to \(\{011010, 011001, 01101001, 0110\}\). When the infinite word \(w\) is uniformly recurrent, there are finitely many return words. By coding each return word to \(u\) by its order of occurrence in \(w\), one obtain the *derived sequence of \(w\) with respect to the prefix \(u\).* Pursuing our example, the derived sequence of the Thue-Morse word with respect to \(011\) begins with \(1234124312341241234124\). Using these sequences, Durand obtained in 1998 the following characterization of primitive pure morphic words, i.e. fixed points of morphisms having a primitive incidence matrix.
Theorem 54 (Durand [9]). A word is primitive substitutive if and only if the number of its derived sequences is finite.

In dimension higher than one, it not clear how to generalize the notion of primitivity of a morphism (see Remark 40). A generalization of Durand’s result to a bidimensional setting was investigated by Priebe [17]. In that generalization, words are replaced by tilings, the primitive substitutive property by self-similarity and the notion of derived tilings involves Voronoï cells. Recall that a Voronoï tessellation is a partition of the plane into regions, called Voronoï cells, based on the distance to a set of given points, called seeds [25]. The Voronoï cell of a seed consists of all the points in the plane that are closer to it than to any other seed. Priebe aimed towards a characterization of self-similar tilings in terms of derived Voronoï tessellations and proved the following result.

Theorem 55 (Priebe [17]). Let $T$ be a tiling of the plane.

- If $T$ is self-similar, then the number of its different derived Voronoï tilings is finite (up to similarity).
- If the number of its different derived Voronoï tilings is finite (up to similarity), then $T$ is pseudo-self-similar.

The bidimensional words we are considering are a particular case of tilings (see for instance Figure 16, which has been reproduced from [17]) where the letters correspond to colored unit squares (1 for black and 0 for white).

![Figure 16: A tiling (a), the set of positions where the factor $u$ occurs (b) with $u =$ ](image)

The main drawback of this notion of derived tilings is that, starting from a bidimensional word, we do not obtain another bidimensional word in general (as illustrated in Figure 16).

Question 56. Find a differential operator for $d$-dimensional words with respect to its prefixes, that is, an operator

$$D : (A^{\mathbb{N}^d}, \mathbb{N}^d) \to (B^{\mathbb{N}^d}, (w, s) \mapsto D_s(w)$$

where $A$ and $B$ are potentially distinct alphabets and $D_s(w)$ designates the derivative of $w$ with respect to its prefix of size $s$, such that the finiteness of the set

$$\{D_s(w) : s \in \mathbb{N}^d\}$$

would provide us with some nice property of the $d$-dimensional infinite word $w$ (such that being primitive substitutive if one thinks of Durand’s theorem).
Here is a variant of the previous question.

**Question 57.** Find a differential operator for \(d\)-dimensional words with respect to its prefixes, that is, an operator

\[
D : (A^{\mathbb{N}^d}, \mathbb{N}^d) \to (B^{\mathbb{N}^d}, (w,s) \mapsto D_s(w)
\]

where \(A\) and \(B\) are potentially distinct alphabets and \(D_s(w)\) designates the derivative of \(w\) with respect to its prefix of size \(s\), such that for all \(w \in A^{\mathbb{N}^d}\) and all \(s, t \in \mathbb{N}^d\) we have

\[
D_s(D_t(w)) = D_u(w)
\]

for some well-chosen size \(u \in \mathbb{N}^d\).

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References


