DENSITY OF CRITICAL FACTORIZATIONS

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Abstract. We investigate the density of critical factorizations of infinte sequences of words. The density of critical factorizations of a word is the ratio between the number of positions that permit a critical factorization, and the number of all positions of a word.

We give a short proof of the Critical Factorization Theorem and show that the maximal number of noncritical positions of a word between two critical ones is less than the period of that word. Therefore, we consider only words of index one, that is words where the shortest period is larger than one half of their total length, in this paper.

On one hand, we consider words with the lowest possible number of critical points and show, as an example, that every Fibonacci word longer than five has exactly one critical factorization and every palindrome has at least two critical factorizations.

On the other hand, sequences of words with a high density of critical points are considered. We show how to construct an infinite sequence of words in four letters where every point in every word is critical. We construct an infinite sequence of words in three letters with densities of critical points approaching one, using square-free words, and an infinite sequence of words in two letters with densities of critical points approaching one half, using Thue–Morse words. It is shown that these bounds are optimal.

Introduction

The Critical Factorization Theorem (CFT) [3, 7] relates local periods with the global period of finite words. Let $w = uv$ with $|u| = p$ and z be the shortest suffix of w_1u and prefix of vw_2 for suitable w_1 and w_2, then z is the shortest repetition word of w at position p. The CFT states that in every finite word w there is a position p where the shortest repetition word z is as long as the global period d of w, moreover, $p < d$. The position p is called critical. Actually, we have at least one critical position in every $d - 1$ consecutive positions in w. Consider the following example:

$$w = ab.aa.b$$

that has two critical positions 2 and 4 which are marked by dots. The period d of w equals 3 and w is of index 1, since $2d > |w|$. The shortest repetition word in both critical positions is aab and baa, respectively. Note, that the shortest repetition words in the positions 1 and 3 are ba and a, respectively. The ratio of the number of critical positions and the number of all positions is called the density of critical positions. The density of w in our example is one half.

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The CFT is often claimed to be one of the most important results about words. However, it does not seem to be well understood due to its little number of applications and known implications. We investigate the frequenzy of occurences of critical factorizations in words in this paper to get a better understanding of critical points in general. We are concerned with words of a very low density, that is one or two critical factorizations in the whole word, and of an as high as possible density of critical factorizations. Prominent classes of words are used in our studies, namely, Fibonacci words, palindromes, and Thue–Morse words.

After we have fixed the basic notations in Section 1, we give a technically improved version of a proof [5] of the Critical Factorization Theorem [3, 7] and give a statement about the maximal distance between two critical points in a word. In Section 2 we show that Fibonacci words, which can be defined by palindromes [6], of length greater than five have exactly one critical position in contrast to the fact that palindromes themselves have at least two critical positions. This result also implies immediately the two well-known facts that the period of a Fibonacci word is a Fibonacci number and that the Fibonacci word is not ultimately periodic, both proven differently in the literature. Section 3 contains the constructions of infinite sequences of words in four letters with density one for every word, infinite sequences of ternary words which has a limit of their densities at one, using square-free words [12, 1, 2], and infinite sequences of binary words which has a limit of their densities at one half, using Thue–Morse words [11, 10, 1, 2]. We also show that these limits are optimal.

1. Preliminaries

In this section we fix the notations for this paper. We refer to [8, 4] for more basic and general definitions.

Let A be a finite nonempty alphabet and A^* be the monoid of all finite words in A; the empty word is denoted by ε. Let A^ω denote the set of all infinite words in A that have a beginning. An infinite word $w \in A^\omega$ is called *ultimately periodic* if there exist two words $u, v \in A^*$ such that $w = uv^\omega$. Let $w \in A^*$ in the following. The length of w is denoted by $|w|$ and its ith letter is denoted by $w_{(i)}$. By definition $|\varepsilon| = 0$. If $w = w_1 u w_2$ then u is called a *factor* of w. If $w = uv$ then u and v are called *prefix* of w, denoted by $u \leq w$, and *suffix* of w, denoted by $v \preccurlyeq w$, respectively, and let $u = wv^{-1}$ and $v = u^{-1}w$. Note, that ε and w are both prefixes and suffixes of w. A word w is called *bordered* if there exists a word $v \neq \varepsilon$ such that $w = vuv$. A prefix u of a word w such that $0 < |u| < |w|$ which is also a suffix of w is called a *border* of w. A word w is called *primitive* if $w = v^k$ implies that $k \leq 1$.

An integer d, with $1 \leq d \leq |w|$, is called *a period* of w if $w_{(i)} = w_{(i+d)}$, for all $1 \leq i \leq |w| - d$. The smallest period of w is denoted by $\partial(w)$ and it is also called the *minimal period* or the *global period* of w. We define the *index* $\operatorname{ind}(w)$ of a word w by

$$\operatorname{ind}(w) = \left\lfloor \frac{|w|}{\partial(w)} \right\rfloor \ .$$

Note, that the index is often defined by $\operatorname{ind}(w) = |w|/\partial(w)$ in the literature, however, we use the integer part here, only. Let an integer p with $1 \leq p < |w|$ be called *position* or *point* in w. Intuitively, a position p denotes the place between $w_{(p)}$ and $w_{(p+1)}$ in w. A word $u \neq \varepsilon$ is called a *repetition word* at position p if $w = xy$

with $|x| = p$ and there exist x' and y' such that $u \preccurlyeq x'x$ and $u \leq yy'$. For a point p in w, let

$$\partial(w, p) = \min\{|u| \mid u \text{ is a repetition word at } p\}$$

denote *the local period* at point p in w. Note, the repetition word of length $\partial(w, p)$ at point p is unbordered and $\partial(w, p) \leq \partial(w)$. A factorization $w = uv$, with $u, v \neq \varepsilon$ and $|u| = p$, is called *critical* if $\partial(w, p) = \partial(w)$, and, if this holds, then p is called *critical point*, otherwise it is called *noncritical point.* Let $\eta(w)$ denote the number of critical points in a word w. We shall represent critical points of words by dots. For instance, the critical points of $w = abaaba$ are 2 and 4, and we show this by writing $w = ab.aa.ba$. In this example, $\partial(w) = 3$.

Let $\widetilde{w} = w_{(n)} \cdots w_{(2)}w_{(1)}$ denote the *reverse* of $w = w_{(1)}w_{(2)} \cdots w_{(n)}$. We call a word w a *palindrome* if $w = \widetilde{w}$.

Let $\lhd$ be an ordering of $A = \{a_1, a_2, \ldots, a_n\}$, say $a_1 \lhd a_2 \lhd \cdots \lhd a_n$. Then $\lhd$ induces a *lexicographic order* on A^* such that

$$u \lhd v \iff u \leq v \quad \text{or} \quad u = xau' \text{ and } v = xbu' \text{ with } a \lhd b$$

where $a, b \in A$. A suffix v (prefix u) of w is called *maximal* w.r.t. $\lhd$ if $v' \lhd v$ (and $\widetilde{u}' \lhd \widetilde{u}$) for any suffix v' (prefix u') of w. We will identify orders on alphabets and their respective induced lexicographic orders throughout this article. Let $\lhd^{-1}$ denote the *inverse order*, say $a_n \lhd^{-1} \cdots \lhd^{-1} a_2 \lhd^{-1} a_1$, of $\lhd$. Let $\mu_\lhd(w)$ and $\mu_\rhd(w)$ denote the maximal suffixes of w w.r.t. $\lhd$ and $\lhd^{-1}$, respectively, and let $\nu_\lhd(w)$ and $\nu_\rhd(w)$ denote the maximum prefixes of w w.r.t. $\lhd$ and $\lhd^{-1}$, respectively. If the context is clear, we may write $\mu_\lhd$, $\mu_\rhd$, $\nu_\lhd$, and $\nu_\rhd$ for $\mu_\lhd(w)$, $\mu_\rhd(w)$, $\nu_\lhd(w)$, and $\nu_\rhd(w)$, respectively. We only consider alphabets of size larger than one in the following.

The critical factorization theorem (CFT) was discovered by Césari and Vincent [3] and developed into its current form by Duval [7].

Theorem 1 (Critical Factorization Theorem)**.** *Every word w, with $|w| \geq 2$, has at least one critical factorization $w = uv$, with $u, v \neq \varepsilon$ and $|u| < \partial(w)$, i.e., $\partial(w, |u|) = \partial(w)$.*

This theorem is a direct consquence from the following proposition which describes one critical point in any word and will be technically more useful in the following. The proof of Proposition 2 is a technically improved version of the proof of the CFT by Crochemore and Perrin in [5]. Note, that $\mu_\lhd(w) \neq \mu_\rhd(w)$ for any word w since they start with a different letter.

Proposition 2. *Let w be a word of length $n \geq 2$, and let β be the shorter of the two suffixes $\mu_\lhd(w)$ and $\mu_\rhd(w)$. Then $|w\beta^{-1}|$ is a critical point.*

Proof. Assume $\beta = \mu_\rhd(w)$ by symmetry. Let $\alpha = \mu_\lhd(w)$, so, $\alpha = u'\beta$. Let z be an unbordered repetition word at $|w\beta^{-1}|$. We show that $|z|$ is a period of w, which will prove the claim.

If w is a factor of z^2, then obviously $|z|$ is a period of w. If $w = w_1\beta w_2$ for some $w_2 \neq \varepsilon$, then $\beta \lhd^{-1} \beta w_2$ contradicts the choice of β. If $w\beta^{-1} = yz$, then, by the above, $z \leq \beta$, say $\beta = z\beta'$; but then $z^2\beta' = z\beta \lhd^{-1} \beta = z\beta'$ implies that $\beta = z\beta' \lhd^{-1} \beta'$; a contradiction. Consequently, $\beta = zw'$ and $w = z_1zw'$ for a suffix z_1 of the unbordered word z. Therefore u' is a suffix of z, and hence, $u'w'$ is a suffix of α. Consequently, $u'w' \lhd \alpha = u'\beta$, and so $w' \lhd \beta$, which together with $w' \lhd^{-1} \beta$

implies that $w' \leq \beta$. Therefore $\beta = zw' = w'z'$, and thus $\beta = z^k z_2$ for some $z_2 \leq z$, which shows that $|z|$ is a period of w. □

The CFT follows since $|w\beta^{-1}| < \partial(w)$. For a different proof of the CFT by Duval, Mignosi, and Restivo, see Chapter 8 in [9]. The next theorem justifies why we are only interested in words of index one in our investigation of the density of critical points.

Theorem 3. *Each set of $\partial(w) - 1$ consecutive points in w, where $|w| \geq 2$, has a critical point.*

Proof. If $w = u^i u_1$, where $u_1 \leq u$ and $\partial(w) = |u|$, then the maximal suffixes w.r.t. any orders of A are longer than $|u^{i-1}u_1|$. Hence w has a critical point at point p, where $p < \partial(w)$.

Let p be any critical point of $w = uv$, where $|u| = p$, and let z be the smallest repetition word at position p. So, $|z| = \partial(w)$.

We need to show that if $|v| \geq \partial(w)$, then there is critical point at $p + k$ for $1 \leq k < \partial(w)$. We have $z \leq v$ and $\partial(v) = \partial(w)$. For, if $\partial(v) < \partial(w)$, then z is bordered; a contradiction. Now, v has a critical point k such that we have $k < \partial(v) = \partial(w)$. Clearly, this point $p + k$ is critical also for w since the smallest repetition word at point $p+k$ is a conjugate of z. Now, $(p + k) - p = k < \partial(w)$. □

Maybe an even stronger motivation for considering only words of index one, is that in w^k, with $k \geq 3$, the critical points of the first factor w are inherited by the next $k - 2$ factors w. That is, if $w^k = w_1.w_2w^{k-1}$, where $|w_1|$ is a critical point, then also $|ww_1|$ is a critical point of w^k.

2. Words with Exactly One Critical Factorization

Every word longer than one letter has at least one critical factorization. We investigate words with only one critical factorization in this section. Trivially, words of length two have no more than one critical point. We do not consider such cases but arbitrary long words. However, the following lemma limits our investigation to words in two letters.

Lemma 4. *A word w with only one critical factorization is binary, that is, it is over a two-letter alphabet.*

Proof. Assume a word w contains the letters a, b, and c and has exactly one critical factorization. Let $a \lhd b \lhd c$. By symmetry, we can assume that $|\mu_{\rhd}| < |\mu_{\lhd}|$. Then $p = |w\mu_{\rhd}^{-1}|$ is a critical point of w by Proposition 2. Let $a \blacktriangleleft c \blacktriangleleft b$. Now, either $|w\mu_{\blacktriangleleft}^{-1}|$ or $|w\mu_{\blacktriangleright}^{-1}|$ is a critical point p' of w, again by Propposition 2. But, $p \neq p'$ since $\mu_{\rhd}$ begins with c and $\mu_{\blacktriangleleft}$ and $\mu_{\blacktriangleright}$ begin with a and b, respectively. So, w has at least two critical points; a contradiction. □

By Lemma 4, we will only consider words in a and b in the rest of this section. Let $a \lhd b$. Note, that $\mu_{\lhd} \neq \mu_{\rhd}$ and $\nu_{\lhd} \neq \nu_{\rhd}$ for any word since $\mu_{\lhd}$ and $\mu_{\rhd}$ start and $\nu_{\lhd}$ and $\nu_{\rhd}$ end with different letters. Proposition 2 straightforwardly leads to the following two facts.

Lemma 5. *If a word w has exactly one critical point, then either*

$$w = \nu_{\lhd}\mu_{\rhd} \quad \textit{and} \quad \nu_{\lhd} \leq \nu_{\rhd} \quad \textit{and} \quad \mu_{\rhd} \preccurlyeq \mu_{\lhd}$$

or

$$w = \nu_\triangleright \mu_\triangleleft \quad \textit{and} \quad \nu_\triangleright \leq \nu_\triangleleft \quad \textit{and} \quad \mu_\triangleleft \preccurlyeq \mu_\triangleright \ .$$

The inverse of Lemma 5 does not hold in general. Consider $w = aa.bb.abab$ which has two critical points, but we do have

$$\nu_\triangleleft = aa \leq aabb = \nu_\triangleright \qquad \text{and} \qquad \mu_\triangleright = bbabab \preccurlyeq aabbabab = \mu_\triangleleft$$

and $w = \nu_\triangleleft \mu_\triangleright$.

Proposition 6. *Every palindrome has at least two critical factorizations.*

Proof. Let w be a palindrome. Assume w has exactly one critical point. By symmetry, we can also assume that $\mu_\triangleright \preccurlyeq \mu_\triangleleft$. By the definition of maximal prefix and suffix and since w is a palindrome we have

$$\mu_\triangleleft(w) = \widetilde{\nu}_\triangleleft(\widetilde{w}) = \widetilde{\nu}_\triangleleft(w) \qquad \text{and} \qquad \mu_\triangleright(w) = \widetilde{\nu}_\triangleright(\widetilde{w}) = \widetilde{\nu}_\triangleright(w)$$

where $\widetilde{\nu}_\triangleright(w)$ and $\widetilde{\nu}_\triangleleft(w)$ denote the reversal of $\nu_\triangleright(w)$ and $\nu_\triangleleft(w)$, respectively. Now, $\widetilde{\nu}_\triangleright \preccurlyeq \widetilde{\nu}_\triangleleft$, and hence, $\nu_\triangleright \leq \nu_\triangleleft$, which contradicts Lemma 5 since $\nu_\triangleright \neq \nu_\triangleleft$ in any case. □

Let us now consider the critical points of Fibonacci words. Fibonacci numbers are defined by

$$f_0 = 1 \ , \qquad f_1 = 1 \ , \qquad f_{k+2} = f_{k+1} + f_k \ .$$

Fibonacci words are defined by

$$F_1 = a \ , \qquad F_2 = ab \ , \qquad F_{k+2} = F_{k+1} F_k \ .$$

Obviously, $|F_i| = f_i$. Let $F = \lim_{n \to \infty} F_n$ be *the* Fibonacci word. Observe that $F_i \leq F_n$, if $1 \leq i \leq n$. It is also clear that all Fibonacci words are primitive. The following lemma will be used to estimate the number of critical points in Fibonacci words.

Lemma 7. *We have that* $f_{n-2} < \partial(F_n) \leq f_{n-1}$ *for all* $n > 2$.

Proof. The cases for F_3 and F_4 are easily checked. Assume $n > 4$. Clearly, $\partial(F_n) \leq f_{n-1}$ in any case. If $\partial(F_n) < f_{n-2}$, then F_{n-2} is not primitive since

$$F_{n-2} F_{n-2} \leq F_{n-2} F_{n-3} F_{n-2} = F_n \ ,$$

a contradiction. If $\partial(F_n) = f_{n-2}$, then $F_n \leq F_{n-2}^3$, and $F_{n-2} \preccurlyeq F_n$ implies that F_{n-1} or F_{n-2} is not primitive; a contradiction. □

Remark 8. Fibonacci words have a close connection to palindromes as the following properties show. Firstly, $F_n = \alpha_n d_n$ where $n \geq 3$ and α_n is a palindrome and $d_n = ab$ if n is even and $d_n = ba$ if n is odd. This result has been credited to Berstel in [6]. Secondly, $F_n = \beta_n \gamma_n$, where $n \geq 5$ and β_n and γ_n are palindromes of length $f_{n-1} - 2$ and $f_{n-2} + 2$, respectively, by de Luca [6]. Moreover, de Luca shows that these two properties define the set of Fibonacci words.

Given Remark 8 and Proposition 6, every palindrome has at least two critical factorizations, Theorem 10 is rather surprising.

Example 9 (Fibonacci words)**.** *We have*

$$F_2 = a.b\ , \qquad\qquad F_3 = a.b.a\ , \qquad\qquad F_4 = ab.aa.b\ .$$

By the following Theorem, however, every Fibonacci word F_n, with $n > 4$ has exactly one critical point, and that critical point is at position $f_{n-1} - 1$.

Theorem 10. *A Fibonacci word F_n, with $n > 4$, has exactly one critical point p. Moreover, p is at position $f_{n-1} - 1$.*

Proof. Let $n \geq 7$, and let p be a critical point of F_n. Then $p > f_{n-2}$, because otherwise

$$F_{n-2}F_{n-2} \leq F_{n-2}F_{n-3}F_{n-2} = F_n$$

implies that $\partial(w,p) \leq f_{n-2}$ contradicting Lemma 7. Consider the factorization

$$F_n = F_{n-2}F_{n-3}F_{n-2} = F_{n-2}F_{n-4}F_{n-5}F_{n-2}\ .$$

Then $p > f_{n-2} + f_{n-4}$, since otherwise

$$F_{n-3}F_{n-4}F_{n-4}F_{n-4} = F_{n-2}F_{n-4}F_{n-4} < F_{n-2}F_{n-4}F_{n-5}F_{n-2} = F_n\ ,$$

implies $|F_{n-3}F_{n-4}| < p \leq |F_{n-3}F_{n-4}F_{n-4}|$ which gives $\partial(w,p) \leq f_{n-4}$, a contradiction.

By induction we obtain

$$\begin{aligned} & F_{n-2}\ F_{n-4} \cdots F_{n-2i+1}\ F_{n-2i}\ F_{n-2i}\ F_{n-2i} \\ = {} & F_{n-2}\ F_{n-4} \cdots \qquad F_{n-2i+2} \quad F_{n-2i}\ F_{n-2i} \\ < {} & F_{n-2}\ F_{n-4} \cdots \qquad F_{n-2i+2} \quad F_{n-2i}\ F_{n-2i-1}F_{n-2} \\ = {} & F_n \end{aligned}$$

where $1 \leq i \leq \lceil \frac{n}{2} \rceil - 2$, and

$$p > \sum_{i=1}^{\lceil \frac{n}{2} \rceil - 2} f_{n-2i}\ .$$

So, we have

$$F_n = F_{n-2}F_{n-4} \cdots F_3F_2F_{n-2} \qquad \text{or} \qquad F_n = F_{n-2}F_{n-4} \cdots F_4F_3F_{n-2}$$

where $p > f_{n-1} - 2$ and $p > f_{n-1} - 3$, respectively, and $f_{n-1} > p$ by Lemma 7 and Theorem 3. So, $p = f_{n-1} - 1$ or $p = f_{n-1} - 2$, that is, a critical point has to exist in the suffix

$$F_2F_{n-2} \preccurlyeq F_n \qquad \text{or} \qquad F_3F_{n-2} \preccurlyeq F_n$$

where the former case gives the result. The latter case leaves the possibilities $a.b.aF_{n-2} \preccurlyeq F_n$. But since $b \preccurlyeq F_4$, we have $bab.aF_{n-2} \preccurlyeq F_n$ and only the marked position is critical which proves the claim. □

The following well known facts follow immediately from Theorem 10.

Corollary 11. *A Fibonacci word F_n has the period f_{n-1}, and the Fibonacci word F is not ultimately periodic.*

The Fibonacci words are certainly not the only words with exactly one critical factorization.

Example 12. *Let $w = a^iba^j$, with $i \neq j$ and $i + j > 0$, then $\eta(w) = 1$. If $i > j$, then $\partial(w) = |a^ib|$ and i is the only critical point of w. Similarly for $i < j$, where $i+1$ is the only critical point of w. See Lemma 14 for the case when $i = j$.*

3. Words with a High Density of Critical Factorizations

We investigate the densities of the critical points in words. The *density* $\delta(w)$ of a word w is defined by

$$\delta(w) = \frac{\eta(w)}{|w| - 1} \ .$$

Notice that in the above $|w| - 1$ is the number of all positions in w, and recall that $\eta(w)$ denotes the number of critical positions in w.

Throughout this section we require all words to be of index one, otherwise, for any given alphabet $\{a_1, a_2, \dots, a_k\}$ and $n > 0$, we have

$$\delta\big((a_1a_2 \cdots a_k)^n\big) = 1$$

that is, every position is critical. Moreover, there exists a sequence of words of index one in the alphabet $A = \{a, b, c\}$ such that the limit of their densities is one.

Example 13 (Square-free words)**.** *Consider the endomorphism $\psi \colon A^* \to A^*$ with*

$$a \mapsto abc \qquad\qquad b \mapsto ac \qquad\qquad c \mapsto b$$

by Thue [12], *cf*[1, 2], *and let*

$$T_{2k+1} = a\ \psi^{2k+1}(a)\ c \qquad \textit{and} \qquad T_{2k} = a\ \psi^{2k}(a)\ b,$$

for all $k > 0$, then

$$\lim_{n \to \infty} \delta(T_n) = 1$$

because every word T_n has a square prefix and suffix and $\psi^n(a)$ is square-free, so, $\eta(T_n) = |T_n| - 3$ and $\delta(T_n) = 1 - 2/(|T_n| - 1)$.

Of course, any square-free word with suitable borders can be used in Example 13. It is also clear that with an alphabet with at least four letters, say a, b, c, and d, the sequence $\{T'_n\}$, with $n \geq 1$ and $T'_n = d\ \psi^n(a)\ d$, consists of words with density one, only. Words in two letters, however, cannot be square-free, if they are longer than three. So, the question arises: What is the highest density for words in $A = \{a, b\}$? The following lemma implies that ab, ba, aba, and bab are the only words in A which have density one.

Lemma 14. *If w is of index one and has two consecutive critical points, then either $w = a^iba^i$ or $w = b^iab^i$, with $i \geq 1$.*

Proof. Assume, two consecutive critical points in w that are around b. Let i and j be maximal integers such that $w = w_1a^i.b.a^jw_2$. Clearly, $i, j \geq 1$. If $w_1 = \varepsilon = w_2$, then necessarily $i = j$, see Example 12. Assume, $i \neq j$. By symmetry, we can assume that $w_1 \neq \varepsilon$, that is, $w = vba^iba^jw_2$. If $j \geq i$, then w has the repetition ba^i at the first critical point: $w = v[ba^i][ba^i]a^{j-i}w_2$, where $\partial(w) = |ba^i|$. But then w has index greater than one; a contradiction. Therefore, $j < i$, and in this case, $w_2 = \varepsilon$ in order to avoid repetition inside w at the second critical point. Also, $\partial(w) = |a^jb|$, which implies that $i = j$; again a contradiction. □

By Lemma 14 we have $\limsup_{n\to\infty} \delta(w_n) \leq 1/2$, for any infinite sequence w_1, w_2, w_3, ... of words in a binary alphabet A, and this bound is tight by the following example.

Example 15 (Thue–Morse words)**.** *Let us consider the Thue–Morse endomorphism* $\varphi\colon A^* \to A^*$ *with*

$$a \mapsto ab \qquad\qquad \textit{and} \qquad\qquad b \mapsto ba$$

see [11, 10, 1, 2]. *For the sake of brevity, let* φ_n *denote* $\varphi^n(a)$ *and* $\bar{\varphi}_n$ *denote* $\varphi^n(b)$. *Let*

$$M_{2k+1} = a^2\varphi_{2k+1}b^2 \qquad\qquad \textit{and} \qquad\qquad M_{2k} = a^2\varphi_{2k}a^2,$$

for all $k \geq 0$. *We show in Theorem 16 that* $\eta(M_n) = 2^{n-1} + 1$ *and*

$$\delta(M_n) = \frac{1}{2} - \frac{1}{2^{n+1}+6}$$

and hence,

$$\lim_{n\to\infty} \delta(M_n) = \frac{1}{2}\ .$$

Note, that φ_n equals $\bar{\varphi}_n$ up to exchanging of a and b. Moreover, φ_n does not contain overlapping factors, that is, factors of the form $cucuc$ where $c \in A$. Note, also that $|\varphi_n| = 2^n$.

Theorem 16. *Every odd position in* M_n, *with* $n \geq 1$, *except position* 1 *and* $2^n + 3$, *is critical.*

We consider the following lemma before proving Theorem 16.

Lemma 17. *The repetition words at every noncritical position in* M_n, *for all* $n \geq 1$, *are of length one or two.*

Proof. In M_n, for any $n > 2$, the positions 1, 2, $2^n + 2$, and $2^n + 3$ are noncritical, with repetition words of length one, and the positions 3 and $2^n + 1$ are critical.

Clearly, the repetition word at every noncritical position in $M_1 = aaabbb$ and $M_2 = aaabbaaa$ is of length one.

Assume, the repetition word at every noncritical position in M_k, with $k > 2$, is of length one or two. By induction, the repetition word at every noncritical position in M_{k+1} is at most of length two because we have $M_{k+1} = a^2\varphi_k\bar{\varphi}_k a^2$ and $M_{k+1} = a^2\varphi_k\bar{\varphi}_k b^2$ for odd end even k, respectively. Note, that, by induction hypothesis, the repetition word at every noncritical position in M_k is at most of length two. Clearly, the repetition words of length less or equal than two at positions 2 to $2^k - 2$ in φ_k are not changed by preceding and succeeding words (a^2 or b^2). The repetition word at position $|M_{k+1}|/2 = 2^k + 2$ in M_{k+1} is either b or ba since $ab \preccurlyeq \varphi_k$ or $ba \preccurlyeq \varphi_k$ and $ba \leq \bar{\varphi}_k$.

It remains to show that the positions $2^k + 1$ and $2^k + 3$ are critical in M_{k+1}. Assume position $2^k + 1$ or $2^k + 3$ is not critical.

If k is even, then the repetition word u at position $2^k + 1$ is of the form $abavb$ and $|u| < 2^k + 2$, otherwise position $2^k + 1$ is critical. The factor uu is followed by b in M_{k+1}, otherwise $abavbabavba$ is an overlapping factor of φ_{k+1}; a contradiction. But, now we have $a \preccurlyeq v$, otherwise b^3 is a factor of φ_{k+1}, a contradiction, and $ababa$ is a factor of φ_{k+1}; again a contradiction.

If k is odd, then the repetition word u at position 2^k+1 is of the form $bbava$ and $|u| < 2^k - 1$, otherwise position 2^k+1 is critical. Certainly, the factor uu must be preceded by a in M_{k+1}, otherwise b^3 is a factor of φ_{k+1}; a contradiction. But, now $abbavabbava$ is an overlapping factor of φ_{k+1}; again a contradiction.

Position 2^k+3 is shown to be critical by similar arguments. □

Proof of Theorem 16. We show that there are no two consecutive noncritical positions in M_n except 1 and 2, and 2^n+2 and 2^n+3.

By Lemma 17, the words a, b, ab, and ba are the only repetition words at noncritical positions in M_n. We need to consider only positions from 4 to 2^n, since positions 3 and 2^n+1 are certainly critical.

Assume a is the repetition word at some position p and position $p-1$ is noncritical. Now, a must be the repetition word at position $p-1$ and a^3 is a factor of φ_n; a contradiction. The same argument holds if b is the repetition word at position p.

Assume ab is the repetition word at some position p and position $p-1$ is noncritical. Now, ba must be the repetition word at position $p-1$ and $babab$ is a factor of φ_n; a contradiction. The same argument holds if ba is the repetition word at position p.

The claim follows now from Lemma 14. □

Remark 18. Is there a sequence with a higher density of critical points than $\{M_n\}$, with $n > 0$? Certainly, there is no sequence with a limit larger than 1/2 by Lemma 14. Actually, there is no binary word larger than 5 with a density equal to 1/2 by the following Lemma 19. A word M_n is basically an overlap-free word with cubic prefix and suffix. In any case, Lemma 21 will show that any infinite sequence with a limit 1/2 of densities must include infinitely many words where the first and the last two positions are noncritical. However, could we use other words than Thue–Morse words to construct $\{M_n\}$, with $n > 0$? If we choose a word with an overlapping factor, say $w = w_1 a u_\circ a_\circ u a w_2$, then w has two consecutive positions, marked by $\circ$, that are not critical. Lemma 14 implies that w would not be a good choice. So, what about other overlap-free words? Any infinite set of finite overlap-free binary words would certainly do for $\{M_n\}$, with $n > 0$. However, φ is the smallest morphism that takes an overlap-free word to a longer overlap-free word. So, $\{M_n\}$, with $n > 0$, is optimal from that point of view.

Lemma 19. *Every binary word w of index one and length greater than five implies $\delta(w) < \frac{1}{2}$.*

Proof. Assume $|w| > 5$ and $\delta(w) = 1/2$. Then there are no two consecutive critical points in w by Lemma 14. Certainly, $\partial(w) > 3$ since $\operatorname{ind}(w) = 1$.

The first and the last position of w is not critical. Otherwise, let $a.b \leq w$ and point 1 is critical, then aba and $abba$ are not prefixes of w since the repetition word in position 1 are then ba and bba, respectively; contradicting $\partial(w) > 3$. Also, $abbbb$ is not a prefix of w since then $\delta(w) < 1/2$ by Lemma 14. Hence, $abbba \leq w$ and $\partial(w) = 4$ since the smallest repetition word in position 1 is now $bbba$. So, w equals $a.bbb.aa$ or $a.bbb.aab$ and has just two critical points; a contradiction. The last position is a symmetric case.

The claim follows now from Lemma 14. □

Remark 20. The largest binary words of index one and density one half are given by Lemma 14:

$$aa.b.aa\ , \qquad\qquad bb.a.bb\ ,$$

and by the Fibonacci word F_4 and its reverse $\widetilde{F}_4$:

$$ab.aa.b\ , \qquad ba.bb.a\ , \qquad b.aa.ba\ , \qquad a.bb.ab\ .$$

Lemma 21. *Let $\{w_n\}$, with $|w_n| > 5$ for all $n > 0$, be an infinite sequence of binary words such that*

$$\limsup_{n\to\infty} \delta(w_n) = \frac{1}{2}\ .$$

Then there is an infinite set I of natural numbers such that the first and the last two positions of w_i, for all $i \in I$, are noncritical.

Proof. Let w_k be such that $\delta(w_k) > 1/2 - \epsilon$ for some positive real number $\epsilon < 1/4$. The first and the last position of w_k is not critical by the proof of Lemma 19. We have $|w_k| > 1/(2\epsilon)$ since

$$\frac{\eta(w_k)}{2\eta(w_k)+1} \geq \delta(w_k) > \frac{1}{2} - \epsilon$$

by the proof of Lemma 19 which implies

$$\eta(w_k) > \frac{1}{4\epsilon} - \frac{1}{2}$$

and hence,

$$|w_k| \geq 2(\eta(w_k)+1) > \frac{1}{2\epsilon}$$

using again the proof of Lemma 19. Assume the second position of w_k is critical.

Let $aa.b \leq au \leq w_k$ where $|u| = \partial(w_k) - 1$. The factor aa does not appear in u. Actually, $u = ab^{k_1}ab^{k_2}\cdots ab^{k_t}$, where $k_j \geq 1$ for all $1 \leq j \leq t$, and since $|w_k| > 1/\epsilon$ and $\operatorname{ind}(w) = 1$, we have $|u| > 1/(4\epsilon)$ and $t > 1/(8\epsilon)$. Since $C = \{ab^i \mid 1 \leq i \leq t\}$ is a code, we can consider u to be encoded in an alphabet X of size $|C|$, let u' be the encoded u. However, by the assumption that $\delta(w_k) > 1/2 - \epsilon$, we must have a factor v in u, with $|v| > 1/(4\epsilon)$, where critical and noncritical positions alternate, so, bbb is not a factor of v. Let v' be the encoding in X of the smallest factor that contains v. Now, v' must be a square-free word in at most two letters, namely the once that encode ab and abb. But the longest square-free word in two letters is xyx, with $x, y \in X$, and hence, $|v| < 9$; a contradiction.

Let $ab.a \leq w = uv$ where $|u| = \partial(w)$. Then $u = aba^{\partial(w)-2}$; a contradiction.

Similar arguments hold for the last but one position when u ends in aa or ba. □

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