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k -anti-power uniform morphisms

Francis Wlazinski

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Abstract

Words whose every $k(\geq 3)$ successive factors of the same length are all different, i.e., k -anti-power words are natural extensions of square-free words (every two successive factors of the same length are different). We give a way to verify whether a uniform morphism preserves k -anti-power words, i.e., the image by this morphism of all k -anti-power words are k -anti-power words.

A consequence of the existence of such morphisms is the possibility of generating an infinite k -anti-power word.

1 Preliminaries

Let us recall some basic notions of Combinatorics of words.

1.1 Words

An *alphabet* A is a finite set of symbols called *letters*. A *word* over A is a finite sequence of letters from A . The *empty word* ε is the empty sequence of letters. Equipped with the concatenation operation, the set A^* of words over A is a free monoid with ε as neutral element and A as set of generators. Since an alphabet with one element is limited interest to us, we always assume that the cardinality of considered alphabets is at least two. Given a non-empty word $u = a_1 \dots a_n$ with $a_i \in A$ for any integer i from 1 to n , the *length* of u denoted by $|u|$ is the integer n that is the number of letters of u . By convention, we have $|\varepsilon| = 0$. We denote by A^+ the set of words of positive length over A , i.e., $A^+ = A^* \setminus \{\varepsilon\}$.

Given two words w and u , we denote by $|w|_u$ the number of different words p such that pu is a prefix of w . For instance, if $w = abaababa$, we have $|w|_a = 5$, $|w|_{aba} = 3$.

An infinite word over A is a map from \mathbb{N} to A that is an infinite sequence of letters $a_1 \dots a_n \dots$ with $a_i \in A$. And $A^{\mathbb{N}}$ is the set of all infinite words over A .

The *mirror image* of u , denoted by \tilde{u} , is the word $a_n \dots a_2 a_1$. In the particular case of the empty word, $\tilde{\varepsilon} = \varepsilon$.

A word u is a *factor* of a word v if there exist two (possibly empty) words p and s such that $v = pus$. We denote $\text{Fcts}(v)$ the set of all factors of v . If $u \in \text{Fcts}(v)$, we also say that v

contains the word u (as a factor). If $p = \varepsilon$, u is a *prefix* of v . If $s = \varepsilon$, u is a *suffix* of v . If $u \neq v$, u is a *proper* factor of v . If u , p and s are non-empty, u is an *internal* factor of v . Furthermore, $\text{alph}(v) = \{u \in \text{Fcts}(v) \mid |u| = 1\}$ is the set of all the letters in v .

Let w be a non-empty word and let i, j be two integers such that $0 \leq i - 1 \leq j \leq |w|$. We denote by $w[i..j]$ the factor of w such that $|w[i..j]| = j - i + 1$ and $w = pw[i..j]s$ for two words s and p verifying $|p| = i - 1$. When $j > i$, $w[i..j]$ is simply the factor of w that starts at the i^{th} letter and ends at the j^{th} . Note that, when $j = i - 1$, we have $w[i..j] = \varepsilon$. When $i = j$, we also denote by $w[i]$ the factor $w[i..i]$ which is the i^{th} letter of w . In particular, $w[1]$ and $w[|w|]$ are respectively the first and the last letter of w .

Powers of a word are defined inductively by $u^0 = \varepsilon$, and for any integer $n \geq 1$, $u^n = uu^{n-1}$. Given an integer $k \geq 2$, since the case ε^k is of little interest, we call a k -*power* any word u^k with $u \neq \varepsilon$. And a word is k -*power-free* if it does not contain any k -power as factor. A *primitive* word is a word which is not a ℓ -power of another word whatever the integer $\ell \geq 2$.

Given two integers $p > q \geq 1$ and two words x and y with $xy \neq \varepsilon$, a word of the form $(xy)^\alpha x$ with $\frac{|(xy)^\alpha x|}{|xy|} = \alpha + \frac{|x|}{|xy|} = \frac{p}{q}$ is called a $\frac{p}{q}$ -*power*. For instance, the word *anchorman* is a $(1 + \frac{2}{7} =) \frac{9}{7}$ -power and the word *abaabaa* is a $(2 + \frac{1}{3} =) \frac{7}{3}$ -power. In particular, a $\frac{3}{2}$ -power is a word of the form xyx with $|x| = |y| \neq \varepsilon$. For instance, the word *antman* is a $\frac{3}{2}$ -power. A word is $\frac{p}{q}$ -*power-free* if it does not contain any ℓ -power as factor with $\ell \geq \frac{p}{q}$. The word *abcaba* is not $\frac{8}{5}$ -power-free. Indeed, it contains the word *abcab* which is a $\frac{5}{3}$ -power.

A *border* of a word w is a factor $v \notin \{\varepsilon, w\}$ of w that is both a prefix and a suffix of w . When $|w| > 2|v|$, we say that the *bordered* word w is a *sesquipower* or a *Zimin word*.

The two following propositions are well known. The first one is about bordered words.

Proposition 1.1 [8] *Let A be an alphabet and u, v, w three non-empty words over A .*

If $vt = uv$ then there exist two words r and s over A and an integer n such that $v = (rs)^n r$, $u = rs$ and $t = sr$.

Lemma 1.2 [6, 7] *If a non-empty word v is an internal factor of vv , i.e., if there exist two non-empty words x and y such that $vv = xvy$, then there exist a non-empty word t and two integers $i, j \geq 1$ such that $x = t^i$, $y = t^j$, and $v = t^{i+j}$.*

Given an integer $k \geq 2$ and an integer $j \geq 1$, a (k, j) -*anti-power sequence* or simply a k -*anti-power* [5] is a concatenation of k consecutive pairwise different words of the same length j .

For instance, if $A = \{a, b\}$, the words $u = aababab$ and $v = ababababaaa$ are respectively $(4, 2)$ -anti-power and $(4, 3)$ -anti-power sequences. But the prefix *abababab* of v is not a 4-anti-power sequence: it is even a 4-power.

Given an integer $k \geq 1$, if $\text{Card}(A) = \alpha \geq 2$ then there exist α^n different words in A^* of length $n \geq 1$. Among the words of length $k \times n$, there are α^n different k -powers (of length $k \times n$) and $A_{\alpha^n}^k = \frac{(\alpha^n)!}{(\alpha^n - k)!}$ different (k, n) -anti-power sequences if $\alpha^n \geq k$ and 0 otherwise.

It particularly means that there exists an integer k_0 such that there are no (k', n) -anti-power sequences over A for any $k' \geq k_0$.

For any alphabet A with $\text{Card}(A) = \alpha \geq 2$ and for any integer $k \geq 2$, there exists a smallest integer p_0 such that $\alpha^{p_0} \geq k$. And, if $p \geq p_0$, the set of (k, p) -anti-power sequences is greater than the set of k -powers of length $p \times k$.

A *2-anti-power word* is simply a square-free word. Given an integer $k \geq 3$, a word w is a *k-anti-power word* if it is a $(k-1)$ -anti-power word and, when $|w| \geq k$, if any factor of w of length $k \times j$ for every integer $1 \leq j \leq \lfloor \frac{|w|}{k} \rfloor$ is a (k, j) -anti-power sequence. As precised, w can contain a factor of length k only if $|w| \geq k$. But, by the choosen definition, a word of length n with $2 \leq n < k$ is a *k-anti-power word* if and only if it is a *n-anti-power word*. Of course, such a word exists only if $\text{Card}(A) = \alpha \geq n$.

In other words, for any integer $2 \leq \ell \leq k$, if we choose ℓ successive factors of the same length of a *k-anti-power word*, they are all different.

A word w is not a *k-anti-power word* ($k \geq 2$) if and only if it contains a factor of the form $U = u_1 u_2 \dots u_\ell$ for an integer $2 \leq \ell \leq k$ and for some non-empty words u_1, u_2, \dots, u_ℓ of the same length and such that $u_1 = u_\ell$. The word U is a $\frac{\ell}{\ell-1}$ -power. So, a word w that is not a *k-anti-power word* contains at least a $\frac{k}{k-1}$ -power (when $\ell = k$). The converse is false. For instance, the word $abcdeabc$ is a $\frac{8}{5} (> \frac{4}{3})$ power. But it is a 4-anti-power word over a five-letter alphabet.

Let $\mathcal{A}_{A,k}$, or \mathcal{A}_k if no doubt exists for the alphabet A , be the set of all *k-anti-power words* over A . By definition, we have $\mathcal{A}_k \subset \mathcal{A}_{k-1} \dots \subset \mathcal{A}_2$. So let $\mathcal{B}_{A,k}$, or \mathcal{B}_k , be the set $\mathcal{A}_{k-1} \setminus \mathcal{A}_k$.

Remark 1.3 *We have $w \in \mathcal{A}_k$ if and only if $\tilde{u} \in \mathcal{A}_k$.*

Lemma 1.4 [5]

Let v be a border of a word w and let u be the word such that $w = uv$.

If $|w| > \ell|u|$ for an integer ℓ then u^ℓ is a prefix of w .

More precisely, by Proposition 1.1, if v is a border of a word $w = uv (\neq \varepsilon)$, there exist two words r and s over A and an integer $n \geq 0$ such that $u = rs$ and $w = (rs)^{n+1}r$. When $|w| \geq 2|u|$, we get that w is a $\frac{p}{q}$ -power with $\frac{p}{q} \geq 2$. So, Proposition 1.1 and Lemma 1.4 mean that a bordered word w that contains a border of length at least $\frac{|w|}{2}$ is not a *k-anti-power word* for all integers $k \geq 2$. So, we will only be interested in Zimin words, i.e., $\frac{p}{q}$ -powers with $1 < \frac{p}{q} < 2$.

Lemma 1.5 *Let A be an alphabet, let $d \geq 1$ be an integer and let $X, Y \in A^*$ such that $XY \neq \varepsilon$. If $d|XY|$ and $|Y| \leq (d-1)|X|$ then $XYX \notin \mathcal{A}_k$ for all integers $k > d$.*

Proof.

In fact, we will show that $XYX \notin \mathcal{A}_{d+1}$.

If $d = 1$ then $Y = \varepsilon$, $X \neq \varepsilon$ and $XYX = X^2 \notin \mathcal{A}_2$.

If $d \geq 2$, we have $|XY| > \frac{d-1}{d}|XY| \geq |Y|$. Let X_2 be the suffix of X such that $|X_2Y| = \frac{d-1}{d}|XY|$ and let X_1 be the non-empty word such that $X = X_1X_2$. Since $|X_1| = |XY| - |X_2Y| = \frac{1}{d}|XY|$, the word $[X_1]X_2Y[X_1] \notin \mathcal{A}_{d+1}$. \square

Taking $d = \gcd(|XY|; k)$, we get:

Corollary 1.6 *Let A be an alphabet and let $X, Y \in A^*$ such that $XY \neq \varepsilon$.*

For any integer $k \geq 2$, if $\gcd(|XY|; k) \neq k$ and if $|Y| \leq (\gcd(|XY|; k) - 1)|X|$, then $XYX \notin \mathcal{A}_k$.

Remark 1.7 *When $d = 2$ in Lemma 1.5, we get that if $|XY|$ is even and if $|Y| \leq |X|$ then $XYX \notin \mathcal{A}_k$ for all integers $k \geq 3$.*

Lemma 1.8 *Let A be the alphabet $\{a_1, a_2, \dots, a_k, \dots\}$ and let $k \geq 3$ be an integer. The word $[a_1a_2 \dots a_{k-1}]a_k[a_1a_2 \dots a_{k-1}]$ is a k -anti-power word if and only if k is prime.*

Proof.

Let $w_{sp,k}$ be the word $[a_1a_2 \dots a_{k-1}]a_k[a_1a_2 \dots a_{k-1}]$.

Since $w_{sp,k}$ is a ℓ -anti-power word for an integer $2 \leq \ell < k$ only if $\gcd(k; \ell) = 1$, and, since $\mathcal{A}_k \subset \mathcal{A}_\ell$, the word $w_{sp,k}$ is a k -anti-power word only if k is prime.

Let us now assume that k is prime and, by contradiction, let us assume that $w_{sp,k} \notin \mathcal{A}_k$. It means that $w_{sp,k}$ contains a factor of the form $U = u_1u_2 \dots u_\ell$ for an integer $2 \leq \ell \leq k$ and for some words u_1, u_2, \dots, u_ℓ of the same length $\Lambda \geq 1$ with $u_1 = u_\ell$. Let i_0 be the integer such that a_{i_0} is the first letter of u_1 and let u'_1 be the word $u_1 = a_{i_0}u'_1$. So $a_{i_0}u'_1u_2 \dots u_{\ell-1}a_{i_0}u'_1$ is a factor of $w_{sp,k}$. Since a_{i_0} appears only twice in $w_{sp,k}$, we get that $k = |a_{i_0}u'_1u_2 \dots u_{\ell-1}| = (\ell - 1) \times \Lambda$. Since k is a prime number, we get that $\ell = 2$ and $\Lambda = k$. It follows that $|u_1u_\ell| = 2k > |w_{sp,k}|$: this is impossible. \square

Lemma 1.9 *Let A be an alphabet and let $X, Y \in A^*$ such that $|X|_a \times |Y|_a = 0$ for all letters $a \in A$. If $X \in \mathcal{A}_k$ and $Y \in \mathcal{A}_k$ and $|Y| > (k - 2)|X|$ then $XYX \in \mathcal{A}_k$ for any integer $k \geq 2$.*

Proof.

By contradiction, let us assume that $XYX \notin \mathcal{A}_k$ with $X \neq \varepsilon$. It means that XYX contains a factor of the form $U = u_1u_2 \dots u_\ell$ for an integer $2 \leq \ell \leq k$ and for some words u_1, u_2, \dots, u_ℓ of the same length $\Lambda \geq 1$ with $u_1 = u_\ell$.

Let a be the first letter of u_1 and let u'_1 be the word such that $u_1 = au'_1$.

If $|X|_a = 0$ then $au'_1u_2 \dots a \in \text{Fcts}(Y)$. We get that $U \in \text{Fcts}(Y)$: a contradiction with the hypotheses. Thus, $|Y|_a = 0$ and it implies that $au'_1 = u_\ell \in \text{Fcts}(X)$. Since $U \notin \text{Fcts}(X)$, it follows that $|Y| \leq |u_2 \dots u_{\ell-1}| = (\ell - 2) \times \Lambda \leq (k - 2) \times |X|$: a contradiction with the hypotheses. \square

An *infinite k -anti-power word* is an infinite word whose all finite factors are k -anti-power words. Obviously, the first question is whether such a word exists.

If $A = \{a, b\}$, the only 2-anti-power words are aba , bab and their factors. But, for any $k \geq 3$, the only k -anti-power words are a , b , ab and ba .

If $\text{Card}(A) \geq 3$, there exist infinite 2-anti-power (square-free) words [1, 10, 11].

If $k = 3$ and $A = \{a, b, c\}$, the only 3-anti-power words are $abcab$, the exchange of letters of this word and their factors. Let us note that the word $abcab$ is not $\frac{3}{2}$ -power-free.

A $\frac{3}{2}$ -power-free word contain neither a factor of the form xyx with $|x| = |y|$, nor a factor of the form xx . Thus a $\frac{3}{2}$ -power-free word is a 3-anti-power word (but the converse does not hold). Thus a Dejean's word [4, 3, 9] over a four-letter alphabet, which does not contain any ℓ -power with $\ell > \frac{7}{5}$ -power-free, is a 3-anti-power word.

More generally, if $k \geq 3$ is a prime number and if A is a k -letter alphabet $\{a_1, a_2, \dots, a_k\}$, the word $a_1 a_2 \dots a_{k-1} a_k a_1 a_2 \dots a_{k-1}$ is a k -anti-power word. But it contains a $\frac{2k-1}{k}$ ($> \frac{k}{k-1}$) power. Furthermore, a Dejean's word over a $(k+1)$ -letter alphabet that avoids any power greater than $\frac{k+1}{k}$ ($\leq \frac{k}{k-1}$) is a k -anti-power word.

Remark 1.10 *If we had chosen not to add that a k -anti-power word must be a $(k-1)$ -anti-power word, we would have, for instance, that, for $A = \{a; b; c\}$, the word $abcabcab$ would have been a 3-anti-power word but not a 2-anti-power word.*

More precisely, without the condition that a k -anti-power word w must be a $(k-1)$ -anti-power word, we only could say that all prefixes and all suffixes of w of length between $k-1$ and $\left\lfloor \frac{(k-1)|w|}{k} \right\rfloor$ are $(k-1)$ -anti-power words.

For an infinite word, it does not change anything to add the condition that a k -anti-power word w must be a $(k-1)$ -anti-power word. Indeed, every factor of w whose length is a multiple of $k-1$ can be extended to a factor of w whose length is a multiple of k . Obviously, if these k factors are different, the same holds for $k-1$ ones.

Corollary 1.11 *Let $k \geq 2$ be an integer, let A be the alphabet $\{a_0, a_1, \dots, a_{k+3}, \dots\}$, and let w be a Dejean's word over $\{a_0, a_1, \dots, a_k\}$. The word $a_{k+1} a_{k+2} w a_{k+1} a_{k+2}$ is a k -anti-power word if at least one of these conditions holds :*

- i. $|w| \geq 2k - 3$.*
- ii. $|w| \geq k - 2$ and $|w|$ is not a multiple of 2*

The word $a_{k+1} a_{k+2} a_{k+3} w a_{k+1} a_{k+2} a_{k+3}$ is a k -anti-power word if at least one of these conditions holds :

- i. $|w| \geq 3k - 5$.*
- ii. $|w| \geq 2k - 4$ and $|w|$ is not a multiple of 3*
- iii. $|w| \geq k - 3$, $|a_{k+3} w|$ is not a multiple of 2 and $|w|$ is not a multiple of 3*

More generally, for any integer $p \geq 2$, let w_p be the word $a_{k+1} \dots a_{k+p} w a_{k+1} \dots a_{k+p}$. If $|w| + i$ is not a multiple of $p - i$ for every integer $0 \leq i \leq p - 2$ and if $|w| \geq k - p$ then w_p is a k -anti-power word.

Proof. It directly comes from Lemma 1.9 and the fact that the word Sw is a k -anti-power word for any suffix S of $a_{k+1} \dots a_{k+p}$. \square

1.2 Morphisms

Let A and B be two alphabets. A *morphism* f from A^* to B^* is a mapping from A^* to B^* such that $f(uv) = f(u)f(v)$ for all words u, v over A . When B has no importance, we say that f is a morphism on A or that f is defined on A .

Given an integer $L \geq 1$, f is L -uniform if $|f(a)| = L$ for every letter a in A . A morphism f is *uniform* if it is L -uniform for some integer $L \geq 1$.

Let $k \geq 2$ be an integer and let A and B be two alphabets. A morphism f from A^* to B^* is a k -anti-power morphism if and only if $f(w)$ is a k -anti-power word over B for every k -anti-power word w over A , i.e., $f(\mathcal{A}_{A,k}) \subset \mathcal{A}_{B,k}$. For instance, the *identity endomorphism* Id ($\forall a \in A, Id(a) = a$) is a k -anti-power morphism.

In particular, a 2-anti-power morphism is a square-free morphism. These last morphisms have been characterized in [2].

Given a morphism f on A , the *mirror morphism* \tilde{f} of f is defined for all words w over A , by $\tilde{f}(w) = f(\tilde{w})$. In particular, $\tilde{f}(a) = \tilde{f(a)}$ for every letter a in A .

Remark 1.12 *By remark 1.3, we get that f is a k -anti-power morphism if and only if \tilde{f} is a k -anti-power morphism.*

A morphism on A is called *prefix* (resp. *suffix*) if, for all different letters a and b in A , the word $f(a)$ is not a prefix (resp. not a suffix) of $f(b)$. A prefix (resp. suffix) morphism is non-erasing. A morphism is *bifix* if it is prefix and suffix.

Proofs of the following lemmas are left to the reader.

Lemma 1.13 *Let f be a bifix morphism on an alphabet A and let u, v, w , and t be words over A .*

The equality $f(u) = f(v)p$ with p be a prefix of $f(w)$ implies $u = vw'$ for a prefix w' of w such that $f(w') = p$.

And the equality $f(u) = sf(v)$ with s a suffix of $f(t)$ implies $u = t'v$ for a suffix t' of t such that $f(t') = s$.

Lemma 1.14 *Let f be a prefix morphism on an alphabet A , let u and v be words over A , and let a and b be letters in A . Furthermore, let p_1 (resp. p_2) be a prefix of $f(a)$ (resp. of $f(b)$). If $(p_1; p_2) \neq (\varepsilon; f(b))$ and if $(p_1; p_2) \neq (f(a); \varepsilon)$ then the equality $f(u)p_1 = f(v)p_2$ implies $u = v$ and $p_1 = p_2$.*

Lemma 1.15 *Let f be a suffix morphism on an alphabet A , let u and v be words over A , and let a and b be letters in A . Furthermore, let s_1 (resp. s_2) be a suffix of $f(a)$ (resp. of $f(b)$). If $(s_1; s_2) \neq (\varepsilon; f(b))$ and if $(s_1; s_2) \neq (f(a); \varepsilon)$ then the equality $s_1 f(u) = s_2 f(v)$ implies $u = v$ and $s_1 = s_2$.*

Taking $p_1 = p_2 = \varepsilon$ (resp. $s_1 = s_2 = \varepsilon$) in Lemma 1.14 (resp Lemma 1.15), we get that a prefix (resp. suffix) morphism is injective.

Definition 1.16 *A morphism f from A^* to B^* is a ps-morphism (Keränen [6] called f a ps-code) if and only if the equalities*

$$f(a) = ps, f(b) = ps' \text{ and } f(c) = p's$$

with $a, b, c \in A$ (possibly $c = b$) and $p, s, p', s' \in B^$ imply $b = a$ or $c = a$.*

Obviously, taking $c = b$, and $s = \varepsilon$ in a first time and $p = \varepsilon$ in a second time, we obtain that a ps-morphism is a bifix morphism.

Lemma 1.17 [6, 7] *If f is not a ps-morphism then f is not a k -power-free morphism for every integer $k \geq 2$.*

Proposition 1.18 *Let $k \geq 2$ be an integer, let A and B be two alphabets with $\text{Card}(A) = p \geq k$ and let f be a L -uniform morphism from A^* to B^* (with $L \geq 1$). If there exist five letters a, b, c, d and x (possibly equal) and four words p, s, π and σ such that s is a suffix of $f(a)$, p is a prefix of $f(b)$, σ is a suffix of $f(c)$, π is a prefix of $f(d)$, $(\pi; p) \neq (\varepsilon; f(b))$, $(\sigma; s) \neq (\varepsilon; f(a))$ and $sp = \sigma f(x)\pi$ then f is not a k -anti-power morphism.*

Proof.

In fact, we will show that there exists a square-free word of length at most two whose image by f contains a square. Therefore, this word will be a k -anti-power-word for any $k \geq 2$ but its image will not be. This will mean that f is not a k -anti-power morphism.

Since $(\pi; p) \neq (\varepsilon; f(b))$, $(\sigma; s) \neq (\varepsilon; f(a))$ and $|sp| = L + |\sigma\pi|$, we get $|s| > |\sigma|$ and $|p| > |\pi|$.

Let s' be the non empty prefix of $f(x)$ such that $s = \sigma s'$ and let p' be the non empty suffix of $f(x)$ such that $p = p'\pi$.

If $x = a$ and $x = b$, then $f(x)$ is an internal factor of $f(xx)$. By Lemma 1.2, $f(x)$ is not primitive, i.e., f is not a k -anti-power morphism.

Therefore, at least one of the word ax or bx is not a square. But $f(ax)$ contains the square $s's'$ and $f(xb)$ contains the square $p'p'$. \square

Proposition 1.19 *Let $k \geq 2$ be an integer. Let A and B be two alphabets. Let f be a L -uniform morphism from A^* to B^* (with $L \geq 2$). Let us assume that there exists a prime number p such that $\text{Card}(A) \geq p \geq k$.*

If there exists an integer $2 \leq d < k$ such that $d|L$ then f is not a k -anti-power morphism.

Proof.

Let us assume that $A = \{a_1, a_2 \dots a_p, \dots\}$.

The word $w_{(A,p)} = a_1 a_2 \dots a_{p-1} a_p a_1 a_2 \dots a_{p-1} \in \mathcal{A}_p \subset \mathcal{A}_k \subset \mathcal{A}_{d+1}$. But, by Lemma 1.5, the word $[f(a_1)(a_2) \dots f(a_{p-1})] f(a_p) [f(a_1)(a_2) \dots f(a_{p-1})] \notin \mathcal{A}_{d+1}$, i.e., $f(w_{(A,p)}) \notin \mathcal{A}_k$. \square

Proposition 1.20 *Let $k \geq 3$ and $L \geq 2$ be two integers. Let A and B be two alphabets with $\text{Card}(A) \geq k$ and let f be L -uniform morphism from A^* to B^* . Let us assume that there exist three letters a, b and c such that $a \notin \{b, c\}$ and $f(bac)$ contains a square $T^2 (\neq \varepsilon)$.*

If there exists an integer $2 \leq d < k$ such that $d \mid |T|$ then f is not a k -anti-power morphism.

Proof.

If $b \neq c$ then abc is a k -anti-power word and f is not a k -anti-power morphism.

From now, let us assume that $f(bab) = \pi T^2 \sigma$ (with $|T| \geq 1$).

If $|\pi| > |f(b)|$ (resp. $|\sigma| > |f(b)|$) then T^2 is factor of $f(ab)$ (resp. $f(ba)$) with ab (resp. ba) a k -anti-power word: f is not a k -anti-power morphism.

Thus there exist two words p and s such that $f(a) = ps$, $\pi T = f(b)p$ and $T\sigma = sf(b)$. Without loss of generality (using mirror image for instance), we may assume that $|p| \geq |s|$.

If $|T| = |L|$ then $T = sp$, $f(b) = ps$ and $f(ba)$ contains the square $(ps)^2$: f is not a k -anti-power morphism.

If $|T| > |L|$, let Y be non-empty word such that $T = sYp$. It follows that $f(b) = \pi sY = Yp\sigma$. By Lemma 1.1, there exist two words u and v and an integer n such that $Y = u(vu)^n$, $p\sigma = vu$ and $\pi s = uv$. Moreover, since $Y \neq \varepsilon$, we get that $uv \neq \varepsilon$. If $n \geq 1$ then $f(b)$ contains $(uv)^2$ that is f is not a k -anti-power morphism. From now, $u = Y$ and $f(b) = YvY$. If $|p| \geq |v|$ (resp. $|s| \geq |v|$) then p starts with v (resp. s ends with v) and $f(ba)$ (resp. fab) contains the square $(Yv)^2$ (resp. $(vY)^2$): f is not a k -anti-power morphism. When $|p| < |v|$ and $|s| < |v|$, the word v starts with p and ends with s . But $|v| < |f(b)| = |f(a)| = |ps|$. Thus there exist three words p' , s' and $Z \neq \varepsilon$ such that $v = p'Zs'$, $p = p'Z$ and $s = Zs'$. It means that $f(a)$ contains Z^2 : f is not a k -anti-power morphism.

If $0 < |T| < |L| (= |sp|)$, since T starts with s and ends with p , let p' , s' and $Y \neq \varepsilon$ be the words such that $p = Yp'$, $s = s'Y$ and $T = s'Yp'$. It follows that $f(a) = Yp's'Y$. Moreover, from the equality $f(bab) = \pi T^2 \sigma$, we get that $f(b)$ starts with p' and ends with s' . Thus, there exist a word B such that $|B| = 2|Y|$ and $f(b) = p'Bs'$.

We have $f(ab) = Y[p'][s'Y][p']Bs'$ and $f(ba) = p'B[s'Y][p'][s'Y]$. If there exist an integer $2 \leq d < k$ such that $d \mid |T|$, i.e., $d \mid |p's'Y|$, since either $|s'Y| \leq |p'| \leq (d-1)|p'|$ or $|p'| \leq |s'Y| \leq (d-1)|s'Y|$, by Lemma 1.5, $f(ab) \notin \mathcal{A}_{B,k}$ or $f(ba) \notin \mathcal{A}_{B,k}$: f is not a k -anti-power morphism.

\square

Remark 1.21 *Let B_0 be the alphabet $\{a, b, c, d, e, f, g, h, i, j, k, l, m\}^*$.*

Let f be a uniform morphism from $\{a, b\}^$ to B_0^* such that $f(a) = abcdefghiab$, $f(b) = cdefjklmghi$.*

Then $f(bab)$ contains the square $(ghiabcdef)^2$. Therefore, f is not a 2-anti-power morphism (is not a square-free morphism).

For any integer $k \geq 3$, the only k -anti power words over $\{a, b\}$ are a , b , ab , and ba .

Moreover, $f(ab)$ and $f(ba)$ are 3-anti-power words: f is a 3-anti-power morphism.

But $f(ba)$ contains $ghiabcdefghi$. Thus f is not a k -anti-power morphism for any integer $k \geq 4$.

Let $A = \{a_1, a_2, \dots, a_\alpha\}$ be an alphabet. A *trivial* morphism from A^* to B^* is an injective 1-uniform morphism. That is, $f(a_i) = b_i$ for some letter $b_i \in B$ and $b_i \neq b_j$ when $i \neq j$.

Proposition 1.22 *Let $k \geq 2$ be an integer and let A be an alphabet. Let f be a non-trivial L -uniform morphism defined on A . If $(\text{alph}(f(a)))_{a \in A}$ are not pairwise disjoint sets and if $L < k$ then f is not a k -anti-power morphism.*

Proof.

Let assume that $\text{Card}(A) = \alpha$ and $A = \{a_1, a_2, \dots, a_\alpha\}$.

Since $(\text{alph}(f(a)))_{a \in A}$ are not pairwise disjoint sets, let x be a letter and let $\ell \neq m$ two integers such that $x \in \text{alph}(f(a_\ell)) \cap \text{alph}(f(a_m))$.

We have $f(a_\ell) = A'_\ell x A''_\ell$ and $f(a_m) = A'_m x A''_m$ for four words A'_ℓ , A''_ℓ , A'_m and A''_m such that $A'_\ell + A''_\ell = A'_m + A''_m = L - 1$.

So $f(a_\ell a_m) = A'_\ell x A''_\ell A'_m x A''_m$ and $f(a_m a_\ell) = A'_m x A''_m A'_\ell x A''_\ell$ with either $|xA''_\ell A'_m| \leq L \leq k - 1$ or $|xA''_m A'_\ell| \leq L \leq k - 1$. Since $a_\ell a_m$ and $a_m a_\ell$ are k -anti-power words, it means that f is not a k -anti-power morphism. \square

A morphism f on A is k -anti-power up to ℓ ($k, \ell \geq 2$) if and only if $f(w)$ is a k -anti-power word for every k -anti-power word w over A of length at most ℓ .

Remark 1.23 *Let A and B be two alphabets with $\text{Card}(A) \geq k \geq 3$ and let f be a 1-uniform morphism. Then f is a k -anti-power morphism if and only if f is trivial. So f is a k -anti-power morphism if and only if it is a k -anti-power morphism up to 2.*

Proposition 1.24 *Let $k \geq 3$ be an integer and let A and B be two alphabets. Let us assume that there exists a prime number p such that $\text{Card}(A) \geq p \geq k$. Let f be a square-free L -uniform morphism from A^* to B^* .*

Then f is a k -anti-power morphism if and only if it is a k -anti-power morphism up to $2p - 1$.

Proof.

By definition of k -anti-power morphisms, we only have to prove the "if" part of Proposition 1.24.

By Lemma 1.17, f (square-free) is a ps-morphism and so injective.

We may assume that, if there exists an integer $d \geq 2$ such that $d|L$ then $d \geq k$. Indeed (see the Proof of Proposition 1.19), if $d|L$ and $d < k$ then there exists a word $w_{A,p} \in \mathcal{A}_{A,k}$ such that $|w_{A,p}| = 2p - 1$ and $f(w_{A,p}) \notin \mathcal{A}_{B,k}$: f is not a k -anti-power morphism. It particularly means that if $2 \leq \ell \leq k$, then $\gcd(L, \ell - 1) = 1$.

By contradiction, we assume that a shortest k -anti-power word w (not necessarily unique) such that $f(w)$ contains a non- k -anti-power satisfies $|w| \geq 2p$. We will show that this assumption leads to contradictions.

Since the length of w is minimal, we may assume that there exist an integer $2 \leq \ell \leq k$ and some words $p, s, u_1, u_2, \dots, u_\ell$ such that $f(w) = pu_1u_2 \dots u_\ell s = p \left(\prod_{q=1}^{\ell} u_q \right) s$ where p is a prefix of $f(w[1])$ different from $f(w[1])$ and s is a suffix of $f(w[|w|])$ different from $f(w[|w|])$. Moreover, the words $(u_j)_{j=1, \dots, \ell}$ have the same length $\Lambda (\geq 1)$ and $u_1 = u_\ell$.

Let $i_0 = 1$ and, for all integers $1 \leq j \leq \ell$, let i_j be the shortest integer such that $p \prod_{q=1}^j u_q$ is the prefix of $f(w[1..i_j])$. By definition, we have $i_\ell = |w|$.

If there exist two different integers j and j' such that $i_j = i_{j'}$ then we get that $\Lambda \leq L$. It implies that $f(w) = |p| + |s| + \ell \times \Lambda \leq (k + 2)L$, i.e., $|w| \leq k + 2 < 2p$: a contradiction.

Thus $1 = i_0 < i_1 < \dots < i_\ell = |w|$. If we denote a_j the letter $w[i_j]$ and x_j the word $w[i_{j-1} + 1..i_j - 1]$, we have $w = a_0 x_1 a_1 x_2 a_2 \dots x_\ell a_\ell$. And there exist some words p_j and s_j ($0 \leq j \leq \ell$) such that $f(a_j) = p_j s_j$ with $p_0 = p$ and $s_\ell = s$. By definition, the words $s_0, p_1, p_2, \dots, p_\ell$ are non empty and $u_j = s_{j-1} f(x_j) p_j$ for all $1 \leq j \leq \ell$.

Let us note that, for all integers $1 \leq j_1, j_2 \leq \ell$, we have $||x_{j_1}| - |x_{j_2}|| \leq 1$. Indeed, in the contrary, for instance if $|x_{j_1}| \geq |x_{j_2}| + 2$ (obviously with $j_1 \neq j_2$), we get that $\Lambda = |u_{j_1}| = |s_{j_1-1} f(x_{j_1}) p_{j_1}| > |f(x_{j_1})| \geq |f(x_{j_2})| + 2L$. Moreover $\Lambda = |u_{j_2}| = |s_{j_2-1} f(x_{j_2}) p_{j_2}| < |f(x_{j_2})| + 2L$: this is impossible. Since $\sum_{q=1}^{\ell} x_q \geq 2p - \ell - 1 \geq \ell - 1$, it also implies that $\text{card}\{q \mid 1 \leq q \leq \ell \text{ and } x_q = \varepsilon\} \leq 1$.

If $j_1 < j_2$ and $u_{j_1} = u_{j_2}$ with $(j_1, j_2) \neq (1, \ell)$ then $w[i_{j_1-1}..i_{j_2}]$ is a proper factor of w and $f(w[i_{j_1-1}..i_{j_2}])$ contains the non- $(j_2 - j_1 + 1)$ -anti-power word $\prod_{q=j_1}^{j_2} u_q$ that is a non- k -anti-power word: a contradiction with the hypothesis of the minimal length of w .

In particular, we have $s_0 f(x_1) p_1 = u_1 = u_\ell = s_{\ell-1} f(x_\ell) p_\ell$.

- *Case 1* : $|s_0| \neq |s_{\ell-1}|$ and $(s_0, s_{\ell-1}) \neq (f(a_0), \varepsilon)$

Since $\text{card}\{q \mid 1 \leq q \leq \ell \text{ and } x_q = \varepsilon\} \leq 1$, we have either $x_1 \neq \varepsilon$ or $x_\ell \neq \varepsilon$.

If $s_{\ell-1} \neq \varepsilon$ and $(0 <) |s_0| < |s_{\ell-1}|$, by a length criterion, we necessarily have $x_1 \neq \varepsilon$. Let χ be the first letter of x_1 and let x'_1 be the word such that $x_1 = \chi x'_1$. If $x_\ell = \varepsilon$, let $P = p_\ell$ and if $x_\ell \neq \varepsilon$, let $P = f(\gamma)$ where γ is the first letter of x_ℓ . In particular, we have P non-empty. Let π be the non empty prefix of $f(x'_1) p_1$ such that $s_0 f(\chi) \pi = s_{\ell-1} P$. By Proposition 1.18, this last equation implies that f is not a square-free morphism: a contradiction with the hypotheses.

The case $s_{\ell-1} \neq \varepsilon$ with $|s_0| > |s_{\ell-1}|$ and the case $s_{\ell-1} = \varepsilon$ with $s_0 \neq f(a_0)$ are solved as previous one using Proposition 1.18.

- *Case 2* : $(s_0, s_{\ell-1}) = (f(a_0), \varepsilon)$

We get that $f(a_0x_1)p_1 = f(x_\ell)p_\ell$. By Lemma 1.14, we get $a_0x_1 = x_\ell$ and $p_1 = p_\ell$. It implies that $|s_1| = |s_\ell|$.

It follows that $(\ell - 1) \times \Lambda = \left| \prod_{q=2}^{\ell} u_q \right| = |s_1 f(x_2 a_2 x_3 a_3 \dots x_\ell) p_\ell| = |f(x_2 a_2 x_3 a_3 \dots x_\ell a_\ell)| = L \times |x_2 a_2 x_3 a_3 \dots x_\ell a_\ell| = L \times (\ell - 1) + L \times \sum_{q=2}^{\ell} |x_q|$. Since $\gcd(L, \ell - 1) = 1$, we get that $\sum_{q=2}^{\ell} |x_q|$ (≥ 1) is a multiple of $\ell - 1$. But $||x_{j_1}| - |x_{j_2}|| \leq 1$ for all integers $2 \leq j_1, j_2 \leq \ell$, so it implies that $|x_{j_1}| = |x_{j_2}| = |x_1| + 1$, $\Lambda = L \times (|x_1| + 2)$ and $|s_{j-1}p_j| = L$ for all $1 \leq j \leq \ell$.

For all integers $2 \leq q \leq \ell$, we have $|u_q| = |f(a_0x_1)p_1| = |f(x_\ell)p_\ell| = |s_{q-1}f(x_q)p_q|$ and so $|s_{q-1}p_q| = |p_\ell|$. It means that all the $(|s_q|)_{q=1..l}$ are equal to 0 and that all the $(|p_q|)_{q=1..l}$ are equal to L , i.e., $p_q = f(a_q)$.

In particular, we get that $f(a_1) = p_1 = p_\ell = f(a_\ell)$ and thus $a_1 = a_\ell$. It follows that $w = a_0x_1a_1x_2a_2 \dots x_{\ell-1}a_{\ell-1}x_1a_1$ with $|a_qx_q| = |x_1a_1|$ for all integers $q \in \llbracket 2; \ell - 1 \rrbracket$, i.e., w is not a k -anti-power word: a contradiction.

• *Case 3* : $|s_0| = |s_{\ell-1}|$

As previous case, we obtain, as a first step, that Λ is a multiple of L . Indeed, we have $(\ell - 1) \times \Lambda = \left| \prod_{q=1}^{\ell-1} u_q \right| = |s_0 f(x_1 a_1 x_2 a_2 \dots x_{\ell-1}) p_{\ell-1}| = |f(x_1 a_1 x_2 a_2 \dots x_{\ell-1} a_{\ell-1})| = L \times |x_1 a_1 x_2 a_2 \dots x_{\ell-1} a_{\ell-1}| = L \times (\ell - 1) + L \times \sum_{q=1}^{\ell-1} |x_q|$. Since $\gcd(L, \ell - 1) = 1$, we get that $\sum_{q=1}^{\ell-1} |x_q|$ (≥ 1) is a multiple of $\ell - 1$. So $|x_j| = |x_1|$, $\Lambda = L \times (1 + |x_1|)$ and $|s_{j-1}p_j| = L$ for all $1 \leq j \leq \ell$.

As previous case, it means that all the $(|s_q|)_{q=0..l}$ are equal and, consequently, all the $(|p_q|)_{q=0..l}$ are also equal.

From the equalities $s_0 f(x_1) p_1 = s_{\ell-1} f(x_\ell) p_\ell$ and $|s_0| = |s_{\ell-1}|$, we get $s_{\ell-1} = s_0 (\neq \varepsilon)$. By Lemma 1.14, it also implies $x_\ell = x_1$ and $p_1 = p_\ell (\neq \varepsilon)$.

In particular, since all the $(|x_i|)_{i=1..l}$ are equal and since $w = a_0x_1a_1x_2a_2 \dots x_{\ell-1}a_{\ell-1}x_1a_\ell$ is a k -anti-power word, we have $a_0 \neq a_{\ell-1}$ and $a_1 \neq a_\ell$.

If $a_0 = a_1$ then we get $p_0 = p_1 (= p_\ell)$, $f(a_0) = p_0 s_0$, $f(a_{\ell-1}) = p_{\ell-1} s_{\ell-1} = p_{\ell-1} s_0$ and $f(a_\ell) = p_\ell s_\ell = p_0 s_\ell$. It means that $f(a_{\ell-1} a_0 a_\ell)$ contains $(s_0 p_0)^2$ with $a_{\ell-1} a_0 a_\ell$ square-free since $a_0 \neq a_{\ell-1}$ and $a_0 = a_1 \neq a_\ell$: a contradiction with the hypothesis that f is a square-free morphism.

In the same way, if $a_{\ell-1} = a_\ell$, we get that $f(a_0 a_\ell a_1)$ contains $(s_\ell p_\ell)^2$ with $a_0 a_\ell a_1$ square-free. If $a_0 = a_\ell$, we get that $f(a_{\ell-1} a_\ell a_1)$ contains $(s_\ell p_\ell)^2$ with $a_0 a_\ell a_1$ square-free. And, if $a_1 = a_{\ell-1}$, we get that $f(a_0 a_1 a_\ell)$ contains $(s_1 p_1)^2$ with $a_0 a_1 a_\ell$ square-free. All these cases lead to the same contradiction.

Thus $a_0, a_1, a_{\ell-1}$ and a_ℓ are four different letters. It means that $a_0 a_1 a_{\ell-1} a_\ell$ is a k -anti-power word of length lower than $2p$. But $f(a_0 a_1 a_{\ell-1} a_\ell)$ contains the non-3-anti-power sequence $s_0 p_1 s_1 p_{\ell-1} s_{\ell-1} p_\ell = s_0 p_1 s_1 p_{\ell-1} s_0 p_1$: a (final) contradiction with the minimality of $|w|$. \square

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