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3-anti-power uniform morphisms

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Abstract

Words whose three successive factors of the same length are all different i.e. 3-anti-power words are more natural extensions of square-free words (two successive factors of the same length are different) than cube-free words. We give a way to verify whether a uniform morphism preserves 3-anti-power words (the image of a 3-anti-power word is a 3-anti-power word).

A consequence of the existence of such morphisms is the possibility of generating an infinite 3-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 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., $A^+ = A^* \setminus \{\varepsilon\}$.

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 .

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 u

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 .

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 $u \neq \varepsilon$.

Given an integer $k \geq 2$, 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 k -power of another word whatever the integer $k \geq 2$.

Given two integers $p > q > 1$ and two words x and y with $xy \neq \varepsilon$, a word of the form $(xy)^\alpha x$ with $\alpha + \frac{|x|}{|xy|} = \frac{p}{q}$ 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 $\frac{3}{2}$ -power-free. Indeed, it contains the word *abcab* which is a $\frac{5}{3}$ -power.

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

For instance, if $A = \{a, b\}$, the words $u = aa\,ba\,bb\,ab$ and $v = aba\,bab\,abb\,aaa$ 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 , 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 sequence over A for any $k' \geq k_0$.

For any alphabet A with $\text{Card}(A) = \alpha \geq 2$ and for any integer k , 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 if any factor of w of length $k \times \ell$ for every $1 \leq \ell \leq \left\lfloor \frac{|w|}{k} \right\rfloor$ is a (k, ℓ) -anti-power. By this 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.

An *infinite k -anti-power word* is an infinite word whose finite factors are all 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, 9, 10].

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, 8] 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, a non- k -anti-power word (among k consecutive factors of the same length of this word, at least two of them are equal) contains at least one fractionnal ℓ -power with $\ell \geq \frac{k}{k-1}$. Therefore, a Dejean's word over a $(k+1)$ -letter alphabet is a k -anti-power word.

Remark 1.1 *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 whose length is a multiple of k . Obviously, if these k factors are different, the same olds for $k-1$ ones.

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 $v = t^{i+j}$.*

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 $L \geq 1$.

A morphism f on A is k -anti-power ($k \geq 2$) if and only if $f(w)$ is a k -anti-power word for every k -anti-power word w over A . For instance, the *identity endomorphism* Id ($\forall a \in A, Id(a) = a$) is a k -anti-power morphism.

By definition of k -anti-power words, a k -anti-power morphism is a $(k-1)$ -anti-power morphism when $k \geq 3$. In particular, all k -anti-power morphisms are 2-anti-power morphisms, i.e., square-free morphisms. These last morphisms have been characterized in [2].

We say that a morphism is *non-erasing* if, for all letters $a \in A$, $f(a) \neq \varepsilon$. A k -anti-power morphism, as every square-free morphism, is necessarily non-erasing.

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 1.3 *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 1.4 *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 1.5 *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 $s_1f(u) = s_2f(v)$ implies $u = v$ and $s_1 = s_2$.*

Taking $p_1 = p_2 = \varepsilon$ (resp. $s_1 = s_2 = \varepsilon$) in Lemma 1.4 (resp Lemma 1.5), we get that a prefix (resp. suffix) morphism is injective.

Definition 1.6 *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 1.7 [6, 7] *If f is not a ps-morphism then f is not a k -power-free morphism for every integer $k \geq 2$.*

Since a k -anti-power morphism is a square-free morphism, we get the following Corollary.

Corollary 1.8 *For every integer $k \geq 2$, a k -anti-power morphism is a ps-morphism.*

Proposition 1.9 *Let A and B be two alphabets with $\text{Card}(A) \geq 2$ and let f be a morphism from A^* to B^* . 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 non-empty suffix of $f(c)$, π is a non-empty prefix of $f(d)$, and $sp = \sigma f(x)\pi$ then f is not a square-free morphism.*

Proof.

Since $|sp| > |\sigma f(x)|$ and $|sp| > |f(x)\pi|$, 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 square-free 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 $p'p'$ i.e. f is not a square-free morphism. \square

Proposition 1.10 *Let A and B be two alphabets with $\text{Card}(A) \geq 3$ and let f be a L -uniform morphism from A^* to B^* . If L is an even number then f is not a 3-anti-power morphism.*

Proof.

Let a, b and c be three different letters in A . Let A_1 and A_2 be the words such that $f(a) = A_1A_2$ with $|A_1| = |A_2|$.

Then $f(abcab)$ contains the non-3-anti-power sequence $A_2f(b)f(c)A_1A_2f(b)$ with $abcab$ a 3-anti-power word.

\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 .

Proposition 1.11 *Let A and B be two alphabets with $\text{Card}(A) \geq 3$ and let f be a square-free L -uniform morphism from A^* to B^* (with L odd).*

Then f is a 3-anti-power morphism if and only if it is a 3-anti-power morphism up to 5.

Proof.

By definition of 3-anti-power morphisms, we only have to prove the "if" part of Proposition 1.11.

By Lemma 1.7, f (square-free) is a ps-morphism and so injective.

By contradiction, we assume that a shortest 3-anti-power word w (not necessarily unique) such that $f(w)$ contains a non-3-anti-power satisfy $|w| \geq 6$. We will show that this assumption leads to contradictions.

Since the length of w is minimal, we may assume that there exist five words p, s, U_1, U_2 and U_3 such that $f(w) = pU_1U_2U_3s$ 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_1, U_2, U_3 have the same length (≥ 1) and two of them are equal.

If $U_1 = U_2$ or if $U_2 = U_3$, it means that $f(w)$ contains a square with w a 3-anti-power word so a square-free word. That is f is not a square-free morphisms: a contradiction with the definition of f . The only remaining case is $U_1 = U_3$. To simplify notations, we denote by U the words U_1 and U_3 and by V the word U_2 .

Let i_2 be the shortest integer such that $f(w) = pU$ is the prefix of $f(w[1..i_2])$ and let i_3 be the shortest integer such that $f(w) = pUV$ is the prefix of $f(w[1..i_3])$.

If $i_2 = 1$ then $|V| = |U| \leq |pU| \leq |f(w[1])| = L$ and $|pUVUs| < 4L$. This is impossible since $|f(w)| \geq 6L$.

On the same way, by a length criterion, the cases $i_2 = i_3$ and $i_3 = |w|$ are impossible.

If we denote $x = w[2..i_2 - 1]$, $y = w[i_2 + 1..i_3 - 1]$, $z = w[i_3 + 1..|w| - 1]$, $a_1 = w[1]$, $a_2 = w[i_2]$, $a_3 = w[i_3]$ and $a_4 = w[|w|]$ then $w = a_1xa_2ya_3za_4$ with $|w| = 4 + |x| + |y| + |z|$. It implies that $|x| + |y| + |z| \geq 2$.

Moreover, there exists some words p_i and s_i ($1 \leq i \leq 4$) such that $f(a_i) = p_is_i$ with $p_1 = p$, $s_4 = s$. By definition, the words s_1, p_2, p_3 and p_4 are non empty.

In other words, we have $U = s_1f(x)p_2 = s_3f(z)p_4$ and $V = s_2f(y)p_3$.

Since $\max\{1 + L|x|; L|y|\} < |U| = |V| \leq \min\{L(|x| + 2); L(|y| + 2) - 1\}$, we get that $||x| - |y|| < 2$. It means that, if $|x| + |y|$ is even then $|x| = |y|$ and, if $|x| + |y|$ is odd then $|x| = |y| \pm 1$. In the same way, if $|z| + |y|$ is even then $|z| = |y|$ and, if $|z| + |y|$ is odd then $|z| = |y| \pm 1$.

• *Case 1* : $|s_1| = |s_3|$

Since $2 \times |U| = |U| + |V| = |s_1f(x)p_2| + |s_2f(y)p_3| = (|x| + |y| + 2) \times L$, we get that $|x| + |y|$ is even i.e. $|x| = |y|$.

From the equality $s_1f(x)p_2 = s_3f(z)p_4 (= U)$, we get $s_3 = s_1 (\neq \varepsilon)$. By Lemma 1.4, it also implies $z = x$ and $p_2 = p_4 (\neq \varepsilon)$.

In particular, since $|x| = |y|$ and since $w = a_1xa_2ya_3xa_4$ is a 3-anti-power word, we have $a_1 \neq a_3$ and $a_2 \neq a_4$.

Since $|U| = |V|$, we get $|s_1| + |p_2| = |s_2| + |p_3|$. Since $|s_1| = |s_3|$, we get $|p_1| = |p_3|$ and $2|p_1| = L + |p_1| - |s_1| = L + |p_3| - |s_1| = L + |p_2| - |s_2| = 2|p_2|$ i.e. $|p_1| = |p_2|$.

In a same way, since $|p_2| = |p_4|$ we get $|s_2| = |s_4| = |s_3|$.

If $a_1 = a_2$ then $p_1 = p_2 (= p_4)$, $f(a_1) = p_1 s_1$, $f(a_3) = p_3 s_3 = p_3 s_1$ and $f(a_4) = p_4 s_4 = p_1 s_4$. It means that $f(a_3 a_1 a_4)$ contains $(s_1 p_1)^2$ with $a_3 a_1 a_4$ square-free since $a_1 \neq a_3$ and $a_1 = a_2 \neq a_4$: a contradiction with the hypothesis that f is a square-free morphism.

In the same way, if $a_3 = a_4$, we get that $f(a_1 a_4 a_2)$ contains $(s_4 p_4)^2$ with $a_1 a_4 a_2$ square-free. And, if $a_2 = a_3$, we get that $f(a_1 a_2 a_4)$ contains $(s_2 p_2)^2$ with $a_1 a_2 a_4$ square-free. Both cases lead to the same contradiction.

Thus a_1 , a_2 and a_3 are three different letters and a_2 , a_3 and a_4 are also three different letters. It means that $a_1 a_2 a_3 a_4$ is a 3-anti-power word. But $f(a_1 a_2 a_3 a_4)$ contains the non-3-anti-power sequence $s_1 p_2 s_2 p_3 s_3 p_4 = s_1 p_2 s_2 p_3 s_1 p_2$: a contradiction with the minimality of $|w|$.

- *Case 2* : $s_1 = f(a_1)$ and $s_3 = \varepsilon$

We have $|f(a_1)f(x)p_2| = |s_1 f(x)p_2| = |U| = |V| = |s_2 f(y)p_3| = |s_2 f(y)f(a_3)|$ i.e. $|p_2| = |s_2|$: this contradicts the fact that L is odd.

- *Case 3* : $s_1 \neq s_3$

If $x = \varepsilon$ and $z = \varepsilon$ then $i_2 = 2$, $i_3 = |w| - 1$ and $|y| = |w[i_2 + 1..i_3 - 1]| = |w| - 4 \geq 2$: this is impossible.

Thus, in the equality $s_1 f(x)p_2 = s_3 f(z)p_4 (= U)$, we have either $x \neq \varepsilon$ or $z \neq \varepsilon$.

Since the equality is symmetric, without loss of generality, we may assume that $|s_1| < |s_3|$. In this case, we necessarily have $x \neq \varepsilon$. Let χ be the first letter of x and let x' be the word such that $x = \chi x'$. If $z = \varepsilon$, let $P = p_4$ and if $z \neq \varepsilon$ let $P = f(\gamma)$ where γ is the first letter of z . In particular, we have P non-empty. Let π be the (non empty) prefix of $f(x')p_2$ such that $s_1 f(\chi)\pi = s_3 P$. By proposition 1.9, this last equation implies that f is not a square-free morphism: a final contradiction.

□

2 An example

As stated in the first section, Dejean's words are anti-power words. But we can build 3-power-free words without using fractionnal powers.

According to my computer, the following morphism h is a 3-anti-power morphism (but I do not really trust my programming skills).

$$\begin{aligned}
h : \{a; b; c; d; e\}^* &\rightarrow \{a; b; c; d; e\}^* \\
a &\mapsto abceacd \\
b &\mapsto abecaed \\
c &\mapsto acbaecd \\
d &\mapsto acbeabd \\
e &\mapsto acebced
\end{aligned}$$

The word $h^\omega(a) = \lim_{n \rightarrow +\infty} h^n(a) = abceacd abecaed acbaecd acebced abceacd acbaecd acbeabd abceacd abecaed acebced acbaecd abceacd \dots$ generated by h is thus an infinite 3-anti-power word.

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