Weakly Self-Avoiding Words and a Construction of Friedman

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Abstract

H. Friedman obtained remarkable results about the longest finite sequence x over a finite alphabet such that for all $i \neq j$ the word $x[i..2i]$ is not a subsequence of $x[j..2j]$. In this note we consider what happens when "subsequence" is replaced by "subword"; we call such a sequence a "weakly self-avoiding word". We prove that over an alphabet of size 1 or 2, there is an upper bound on the length of weakly self-avoiding words, while if the alphabet is of size 3 or more, there exists an infinite weakly self-avoiding word.

1 Introduction

We say a word y is a *subsequence* of a word z if y can be obtained by striking out 0 or more symbols from z. For example, "iron" is a subsequence of "introduction". We say a word y is a *subword* of a word z if there exist words w, x such that $z = wyx$. For example, "duct" is a subword of "introduction".[1]

We use the notation $x[k]$ to denote the k'th letter chosen from the string x. We write $x[a..b]$ to denote the subword of x of length $b - a + 1$ starting at position a and ending at position b.

Recently H. Friedman has found a remarkable construction that generates extremely large numbers [1, 2]. Namely, consider words over a finite alphabet Σ of cardinality k. If

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[1] Europeans usually use the term "factor" for what we have called "subword", and they sometimes use the term "subword" for what we have called "subsequence".

an infinite word $\mathbf{x}$ has the property that for all i, j with $0 < i < j$ the subword $\mathbf{x}[i..2i]$ is not a subsequence of $\mathbf{x}[j..2j]$, we call it *self-avoiding*. We apply the same definition for a finite word x of length n, imposing the additional restriction that $j \leq n/2$.

Friedman shows there are no infinite self-avoiding words over a finite alphabet. Furthermore, he shows that for each k there exists a longest finite self-avoiding word x over an alphabet of size k. Call $n(k)$ the length of such a word. Then clearly $n(1) = 3$ and a simple argument shows that $n(2) = 11$. Friedman shows that $n(3)$ is greater than the incomprehensibly large number $A_{7198}(158386)$, where A is the Ackermann function.

Jean-Paul Allouche asked what happens when "subsequence" is replaced by "subword". A priori we do not expect results as strange as Friedman's, since there are no infinite anti-chains for the partial order defined by "x is a subsequence of y", while there *are* infinite anti-chains for the partial order defined by "x is a subword of y".

2 Main Results

If an infinite word $\mathbf{x}$ has the property that for all i, j with $0 \leq i < j$ the subword $\mathbf{x}[i..2i]$ is not a subword of $\mathbf{x}[j..2j]$, we call it *weakly self-avoiding*. If x is a finite word of length n, we apply the same definition with the additional restriction that $j \leq n/2$.

Theorem 1 *Let* $\Sigma = \{0, 1, \ldots, k-1\}$*.*

(a) If $k = 1$*, the longest weakly self-avoiding word is of length* 3*, namely* 000*.*

(b) If $k = 2$*, there are no weakly self-avoiding words of length* > 13*. There are* 8 *longest weakly self-avoiding words, namely* 0010111111010*,* 0010111111011*,* 0011110101010*,* 0011110101011 *and the four words obtained by changing* 0 *to* 1 *and* 1 *to* 0*.*

(c) If $k \geq 3$*, there exists an infinite weakly self-avoiding word.*

Proof.

(a) If a word x over $\Sigma = \{0\}$ is of length ≥ 4, then it must contain 0000 as a prefix. Then $x[1..2] = 00$ is a subword of $x[2..4] = 000$.

(b) To prove this result, we create a tree whose root is labeled with ϵ, the empty word. If a node's label x is weakly self-avoiding, then it has two children labeled $x0$ and $x1$. This tree is finite if and only if there is a longest weakly self-avoiding word. In this case, the leaves of the tree represent non-weakly-self-avoiding words that are minimal in the sense that any proper prefix is weakly self-avoiding.

Now we use a classical breadth-first tree traversal technique, as follows: We maintain a queue, Q, and initialize it with the empty word ϵ. If the queue is empty, we are done. Otherwise, we pop the first element q from the queue and check to see if it is weakly self-avoiding. If not, the node is a leaf, and we print it out. If q is weakly self-avoiding then we append $q0$ and $q1$ to the end of the queue.

If this algorithm terminates, we have proved that there is a longest weakly self-avoiding word. The proof may be concisely represented by listing the leaves in breadth-first order. We may shorten the tree by assuming, without loss of generality, that the root is labeled 0.

When we perform this procedure, we obtain a tree with 92 leaves, whose longest label is of length 14. The following list describes this tree:

0000	00111100	0011010101	001011111011
0001	00111110	0011010110	001011111100
0101	00111111	0011010111	001011111110
001000	01000000	0011101000	001011111111
001001	01000001	0011101001	001110101000
001010	01000010	0011101011	001110101001
001100	01000011	0011110100	001110101010
010001	01100001	0011110110	001110101011
010010	01100010	0011110111	001111010100
010011	01100011	0110000000	001111010110
011001	01110001	0110000001	001111010111
011010	01110010	0110000010	011100000000
011011	01110011	0110000011	011100000001
011101	0010110100	0111000001	011100000010
011110	0010110101	0111000010	011100000011
011111	0010110110	0111000011	00101111110100
00101100	0010110111	001011110100	00101111110101
00110100	0010111000	001011110101	00101111110110
00110110	0010111001	001011110110	00101111110111
00110111	0010111010	001011110111	00111101010100
00111000	0010111011	001011111000	00111101010101
00111001	0010111100	001011111001	00111101010110
00111011	0011010100	001011111010	00111101010111

Figure 1: Leaves of the tree giving a proof of Theorem 1 (b)

(c) Consider the word

$$\begin{aligned}\mathbf{x} &= 22010110111011111011111110111111111110\cdots \\ &= 2\,2\,0\,1\,0\,1^2\,0\,1^3\,0\,1^5\,0\,1^7\,0\,1^{11}\,0\,1^{15}\,0\,1^{23}\,0\,1^{31}\,0\,1^{47}\,0\,\cdots\end{aligned}$$

where there are 0's in positions $3, 5, 8, 12, 18, 26, 38, 54, 78, 110, 158, \ldots$. More precisely, define $f_{2n+1} = 5 \cdot 2^n - 2$ for $n \geq 0$, and $f_{2n} = 7 \cdot 2^{n-1} - 2$ for $n \geq 1$. Then $\mathbf{x}$ has 0's only in the positions given by f_i for $i \geq 1$.

First we claim that if $i \geq 3$, then any subword of the form $\mathbf{x}[i..2i]$ contains exactly two 0's. This is easily verified for $i = 3$. If $5 \cdot 2^n - 1 \leq i < 7 \cdot 2^n - 1$ and $n \geq 0$, then there are

0's at positions $7 \cdot 2^n - 2$ and $5 \cdot 2^{n+1} - 2$. (The next 0 is at position $7 \cdot 2^{n+1} - 2$, which is $> 2(7 \cdot 2^n - 2)$.) On the other hand, if $7 \cdot 2^{n-1} - 1 \leq i < 5 \cdot 2^n - 1$ for $n \geq 1$, then there are 0's at positions $5 \cdot 2^n - 2$ and $7 \cdot 2^n - 2$. (The next 0 is at position $5 \cdot 2^{n+1} - 2$, which is $> 2 \cdot (5 \cdot 2^n - 2)$.)

Now we prove that $\mathbf{x}$ is weakly self-avoiding. Clearly $\mathbf{x}[1..2] = 22$ is not a subword of any subword of the form $\mathbf{x}[j..2j]$ for any $j \geq 2$. Similarly, $\mathbf{x}[2..4] = 201$ is not a subword of any subword of the form $\mathbf{x}[j..2j]$ for any $j \geq 3$. Now consider subwords of the form $t := \mathbf{x}[i..2i]$ and $t' := \mathbf{x}[j..2j]$ for $i, j \geq 3$ and $i < j$. From above we know $t = 1^u 0 1^v 0 1^w$, and $t' = 1^{u'} 0 1^{v'} 0 1^{w'}$. For t to be a subword of t' we must have $u \leq u'$, $v = v'$, and $w \leq w'$. But since the blocks of 1's in $\mathbf{x}$ are distinct in size, this means that the middle block of 1's in t and t' must occur in the same positions of $\mathbf{x}$. Then $u \leq u'$ implies $i \geq j$, a contradiction. ■

3 Another construction

Friedman has also considered variations on his construction, such as the following: let $M_2(n)$ denote the length of the longest finite word $\mathbf{x}$ over $\{0, 1\}$ such that $\mathbf{x}[i..2i]$ is not a subsequence of $\mathbf{x}[j..2j]$ for $n \leq i < j$. We can again consider this where "subsequence" is replaced by "subword".

Theorem 2 *There exists an infinite word $\mathbf{x}$ over $\{0, 1\}$ such that $\mathbf{x}[i..2i]$ is not a subword of $\mathbf{x}[j..2j]$ for all i, j with $2 \leq i < j$.*

Proof. Let

$$\begin{aligned} \mathbf{x} &= 0\,0\,1\,0\,0\,1^3\,0\,1^2\,0\,1^7\,0\,1^5\,0\,1^{15}\,0\,1^{11}\,0\,1^{31}\,0\,1^{23} \cdots \\ &= 0\,0\,1\,0\,0\,1^{g_1}\,0\,1^{g_2}\,0\,1^{g_3}\,0 \cdots \end{aligned}$$

where $g_1 = 3$, $g_2 = 2$, and $g_n = 2g_{n-2} + 1$ for $n \geq 3$. Then a proof similar to that above shows that every subword of the form $\mathbf{x}[i..2i]$ contains exactly two 0's, and hence, since the g_i are all distinct, we have $\mathbf{x}[i..2i]$ is not a subword of $\mathbf{x}[j..2j]$ for $j > i > 1$. ■

References

[1] H. Friedman. Long finite sequences. To appear, *J. Combinat. Theory A*. Also available at `<http://www.math.ohio-state.edu/foundations/manuscripts.html>`.

[2] H. Friedman. Enormous integers in real life. Manuscript, dated June 1 2000, available at `<http://www.math.ohio-state.edu/foundations/manuscripts.html>`.