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HAL Id: hal-00143937
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Submitted on 28 Apr 2007

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On two combinatorial problems arising from automata theory

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Abstract

We present some partial results on the following conjectures arising from automata theory. The first conjecture is the triangle conjecture due to Perrin and Schützenberger. Let \( A = \{a, b\} \) be a two-letter alphabet, \( d \) a positive integer and let \( B_d = \{a^i b a^j \mid 0 \leq i + j \leq d\} \). If \( X \subset B_d \) is a code, then \( |X| \leq d + 1 \). The second conjecture is due to Černý and the author. Let \( A \) be an automaton with \( n \) states. If there exists a word of rank \( \leq n - k \) in \( A \), there exists such a word of length \( \leq k^2 \).

1 Introduction

The theory of automata and formal languages provides many beautiful combinatorial results and problems which, I feel, ought to be known. The book recently published: *Combinatorics on words*, by Lothaire [8], gives many examples of this.

In this paper, I present two elegant combinatorial conjectures which are of some importance in automata theory. The first one, recently proposed by Perrin and Schützenberger [9], was originally stated in terms of coding theory. Let \( A = \{a, b\} \) be a two-letter alphabet and let \( A^* \) be the free monoid generated by \( A \). Recall that a subset \( C \) of \( A^* \) is a code whenever the submonoid of \( A^* \) generated by \( C \) is free with base \( C \); i.e., if the relation \( c_1 \cdots c_p = c'_1 \cdots c'_q \), where \( c_1, \ldots, c_p, c'_1, \ldots, c'_q \) are elements of \( C \) implies \( p = q \) and \( c_i = c'_i \) for \( 1 \leq i \leq p \). Set, for any \( d > 0 \), \( B_d = \{a^i b a^j \mid 0 \leq i + j \leq d\} \). One can now state the following conjecture:

**The triangle conjecture.** Let \( d > 0 \) and \( X \subset B_d \). If \( X \) is a code, then \( |X| \leq d + 1 \).

The term “The triangle conjecture” originates from the following construction: if one represents every word of the form \( a^i b a^j \) by a point \( (i, j) \in \mathbb{N}^2 \), the set \( B_d \) is represented by the triangle \( \{(i, j) \in \mathbb{N}^2 \mid 0 \leq i + j \leq d\} \). The second conjecture was originally stated by Černý (for \( k = n - 1 \)) [3] and extended by the author. Recall that a finite automaton \( A \) is a triple (\( Q, A, \delta \)), where \( Q \) is a finite set (called the set of states), \( A \) is a finite set (called the alphabet) and \( \delta : Q \times A \rightarrow Q \) is a map. Thus \( \delta \) defines an action of each letter of \( A \) on \( Q \). For simplicity, the action of the letter \( a \) on the state \( q \) is usually denoted by \( qa \). This action can be extended to \( A^* \) (the free monoid on \( A \)) by the associativity rule

\[(qw)a = q(wa) \text{ for all } q \in Q, w \in A^*, a \in A\]

Thus each word \( w \in A^* \) defines a map from \( Q \) to \( Q \) and the rank of \( w \) in \( A \) is the integer \( \text{Card}\{qw \mid q \in Q\} \).

One can now state the following

**Conjecture (C).** Let \( A \) be an automaton with \( n \) states and let \( 0 \leq k \leq n - 1 \). If there exists a word of rank \( \leq n - k \) in \( A \), there exists such a word of length \( \leq k^2 \).
The triangle conjecture

I shall refer to the representation of $X$ as a subset of the triangle \( \{(i, j) \in \mathbb{N}^2 \mid 0 \leq i + j \leq d\} \) to describe some properties of $X$. For example, “$X$ has at most two columns occupied” means that there exist two integers $0 \leq i_1 < i_2$ such that $X$ is contained in $a^{i_1}ba^* \cup a^{i_2}ba^*$.

Only a few partial results are known on the triangle conjecture. First of all the conjecture is true for $d \leq 9$; this result has been obtained by a computer, somewhere in Italy.

In [5], Hansel computed the number $t_n$ of words obtained by concatenation of $n$ words of $B_d$. He deduced from this the following upper bound for $|X|$.

**Theorem 2.1** Let $X \subset B_d$. If $X$ is a code, then $|X| \leq (1 + (1/\sqrt{2}))(d + 1)$.

Perrin and Schützenberger proved the following theorem in [9].

**Theorem 2.2** Assume that the projections of $X$ on the two components are both equal to the set \( \{0, 1, \ldots, r\} \) for some $r \leq d$. If $X$ is a code, then $|X| \leq r + 1$.

Two further results have been proved by Simon and the author [15].

**Theorem 2.3** Let $X \subset B_d$ be a set having at most two rows occupied. If $X$ is a code, then $|X| \leq d + 1$.

**Theorem 2.4** Assume there is exactly one column of $X \subset B_d$ with two points or more. If $X$ is a code, then $|X| \leq d + 1$.

**Corollary 2.5** Assume that all columns of $X$ are occupied. If $X$ is a code, then $|X| \leq d + 1$.

**Proof.** Indeed assume that $|X| > d + 1$. Then one of the columns of $X$ has two points or more. Thus one can find a set $Y \subset X$ such that: (1) all columns but one of $Y$ contain exactly one point; (2) the exceptional column contains two points. Since $|Y| > d + 1$, $Y$ is a non-code by Theorem 2.4. Thus $X$ is a non-code. 

Of course statements 2.3, 2.4, 2.5 are also true if one switches “row” and “column”.

A conjecture on finite automata

We first review some results obtained for Conjecture (C) in the particular case $k = n - 1$: “Let $A$ be an automaton with $n$ states containing a word of rank 1. Then there exists such a word of length $\leq (n - 1)^2$."

First of all the bound $(n - 1)^2$ is sharp. In fact, let $A_n = (Q, \{a, b\}, \delta)$, where $Q = \{0, 1, \ldots, n - 1\}$, $ia = i$ and $ib = i + 1$ for $i \neq n - 1$, and $(n - 1)a = (n - 1)b = 0$.

Then the word $(ab^{n-1})^n a$ has rank 1 and length $(n - 1)^2$ and this is the shortest word of rank 1 (see [3] or [10] for a proof).
Moreover, the conjecture has been proved for \( n = 1, 2, 3, 4 \) and the following upper bounds have been obtained:

- \( 2^n - n - 1 \) (Černý [2], 1964)
- \( \frac{1}{2}n^3 - \frac{3}{2}n^2 + n + 1 \) (Starke [16, 17], 1966)
- \( \frac{1}{2}n^3 - n^2 + \frac{n}{2} \) (Kohavi [6], 1970)
- \( \frac{1}{3}n^3 - \frac{3}{2}n^2 + \frac{25}{6}n - 4 \) (Černý, Pirická et Rosenauerová [4], 1971)
- \( \frac{7}{27}n^3 - \frac{17}{18}n^2 + \frac{17}{6}n - 3 \) (Pin [11], 1978)

For the general case, the bound \( k^2 \) is also the best possible (see [10]) and the conjecture has been proved for \( k = 0, 1, 2, 3 \) [10]. The best known upper bound was:

\[
\frac{1}{3}k^3 - \frac{1}{3}k^2 + \frac{13}{6}k - 1\]  

We prove here some improvements of these results. We first sketch the idea of the proof. Let \( A = (Q, A, \delta) \) be an automaton with \( n \) states. For \( K \subseteq Q \) and \( w \in A^* \), we shall denote by \( Kw \) the set \( \{qw \mid q \in K\} \). Assume there exists a word of rank \( \leq n - k \) in \( A \). Since the conjecture is true for \( k \leq 3 \), one can assume that \( k \geq 4 \). Certainly there exists a letter \( a \) of rank \( \neq n \). (If not, all words define a permutation on \( Q \) and therefore have rank \( n \)). Set \( K_1 = Qa \). Next look for a word \( m_1 \) (of minimal length) such that \( K_2 = K_1m_1 \) satisfies \( |K_2| < |K_1| \). Then apply the same procedure to \( K_2 \), etc. until one of the \( |K_i| \)’s satisfies \( |K_i| \leq n-k \):

\[
Q \xrightarrow{a} K_1 \xrightarrow{m_1} K_2 \xrightarrow{m_2} \cdots K_{r-1} \xrightarrow{m_{r-1}} K_r \quad |K_r| \leq n-k
\]

Then \( am_1 \cdots m_{r-1} \) has rank \( \leq n-k \).

The crucial step of the procedure consists in solving the following problem:

**Problem P.** Let \( A = (Q, A, \delta) \) be an automaton with \( n \) states, let \( 2 \leq m \leq n \) and let \( K \) be an \( m \)-subset of \( Q \). Give an upper bound of the length of the shortest word \( w \) (if it exists) such that \( |Kw| < |K| \).

There exist some connections between Problem P and a purely combinatorial Problem P’.

**Problem P’.** Let \( Q \) be an \( n \)-set and let \( s \) and \( t \) be two integers such that \( s + t \leq n \). Let \( (S_i)_{1 \leq i \leq p} \) and \( (T_i)_{1 \leq i \leq p} \) be subsets of \( Q \) such that:

1. For \( 1 \leq i \leq p \), \( |S_i| = s \) and \( |T_i| = t \).
2. For \( 1 \leq i \leq p \), \( S_i \cap T_i = \emptyset \).
3. For \( 1 \leq j < i \leq p \), \( S_j \cap T_i = \emptyset \).

Find the maximum value \( p(s, t) \) of \( p \).

We conjecture that \( p(s, t) = \binom{s+t}{s} \). Note that if (3) is replaced by:

(3’) For \( 1 \leq i \neq j \leq p \), \( S_i \cap T_j = \emptyset \),

then the conjecture is true (see Berge [1, p. 406]).

We now state the promised connection between Problems P and P’.

**Proposition 3.1** Let \( A = (Q, A, \delta) \) be an automaton with \( n \) states, let \( 0 \leq s \leq n-2 \) and let \( K \) be an \((n-s)\)-subset of \( Q \). If there exists a word \( w \) such that \( |Kw| < |K| \), one can choose \( w \) with length \( \leq p(s, t) \).
Proof. Let \( w = a_1 \cdots a_p \) be a shortest word such that \(|Kw| < |K| = n - s\) and define \( K_1 = K, K_2 = K_1a_1, \ldots, K_p = K_{p-1}a_p \). Clearly, an equality of the form \(|K_i| = |Ka_1 \cdots a_i| < |K|\) for some \( i < p \) is inconsistent with the definition of \( w \). Therefore \(|K_1| = |K_2| = \cdots = |K_p| = (n-s)\). Moreover, since \(|K_p a_p| < |K_p|\), \( K_p \) contains two elements \( x_p \) and \( y_p \) such that \( x_p a_p = y_p a_p \).

Define 2-sets \( T_i = \{x_i, y_i\} \subseteq K_i \) such that \( x_i a_i = x_{i+1} \) and \( y_i a_i = y_{i+1} \) for \( 1 \leq i \leq p-1 \) (the \( T_i \) are defined from \( T_p = \{x_p, y_p\}\)). Finally, set \( S_i = Q \cap K_i \). Thus we have

1. For \( 1 \leq i \leq p, |S_i| = s \) and \(|T_i| = 2\).
2. For \( 1 \leq i \leq p, S_i \cap T_i = \emptyset \).

Finally assume that for some \( 1 \leq j < i \leq p, S_j \cap T_i = \emptyset\), i.e., \( \{x_i, y_i\} \subseteq K_i \). Since

\[ x_i a_i \cdots a_p = y_i a_i \cdots a_p, \]

it follows that

\[ |K a_1 \cdots a_{j-1} a_i \cdots a_p| = |K_j a_i \cdots a_p| < n - s \]

But the word \( a_1 \cdots a_{j-1} a_i \cdots a_p \) is shorter than \( w \), a contradiction.

Thus the condition (3), for \( 1 \leq j < i \leq p, S_j \cap T_i = \emptyset\), is satisfied, and this concludes the proof. \( \square \)

I shall give two different upper bounds for \( p(s) = p(2, s) \).

**Proposition 3.2**

(1) \( p(0) = 1 \),
(2) \( p(1) = 3 \),
(3) \( p(s) \leq s^2 - s + 4 \) for \( s \geq 2 \).

**Proof.** First note that the \( S_i \)'s (\( T_i \)'s) are all distinct, because if \( S_i = S_j \) for some \( j < i \), then \( S_i \cap T_i = \emptyset \) and \( S_i \cap T_j \neq \emptyset \), a contradiction.

Assertion (1) is clear.

To prove (2) assume that \( p(1) > 3 \). Then, since \( T_4 \cap S_1 \neq \emptyset, T_4 \cap S_2 \neq \emptyset, T_4 \cap S_3 \neq \emptyset \), two of the three 1-sets \( S_1, S_2, S_3 \) are equal, a contradiction.

On the other hand, the sequence \( S_1 = \{x_1\}, S_2 = \{x_2\}, S_3 = \{x_3\}, T_1 = \{x_2, x_3\}, T_2 = \{x_1, x_3\}, T_3 = \{x_1, x_2\} \) satisfies the conditions of Problem \( P^\prime \). Thus \( p(1) = 3 \).

To prove (3) assume at first that \( S_1 \cap S_2 = \emptyset \) and consider a 2-set \( T_i \) with \( i \geq 4 \). Such a set meets \( S_1, S_2 \) and \( S_3 \). Since \( S_1 \) and \( S_2 \) are disjoint sets, \( T_i \) is composed as follows:

- either an element of \( S_1 \cap S_3 \) with an element of \( S_2 \cap S_3 \),
- or an element of \( S_1 \cap S_3 \) with an element of \( S_2 \setminus S_3 \),
- or an element of \( S_1 \setminus S_3 \) with an element of \( S_2 \cap S_3 \).

Therefore

\[
p(s) - 3 \leq |S_1 \cap S_3||S_2 \cap S_3| + |S_1 \cap S_3||S_2 \setminus S_3| + |S_1 \setminus S_3||S_2 \cap S_3|
\]

\[
= |S_1 \cap S_3||S_2| + |S_1||S_2 \cap S_3| - |S_1 \cap S_3||S_2 \cap S_3|
\]

\[
= s(|S_1 \cap S_3| + |S_2 \cap S_3|) - |S_1 \cap S_3||S_2 \cap S_3|
\]

Since \( S_1, S_2, S_3 \) are all distinct, \( |S_1 \cap S_3| \leq s - 1 \). Thus if \( |S_1 \cap S_3| = 0 \) or \( |S_2 \cap S_3| = 0 \) it follows that

\[
p(s) \leq s(s - 1) + 3 = s^2 - s + 3
\]

If \( |S_1 \cap S_3| \neq 0 \) and \( S_2 \cap S_3 \neq 0 \), one has

\[
|S_1 \cap S_3||S_2 \cap S_3| \geq |S_1 \cap S_3||S_2 \cap S_3| - 1
\]
Proposition 3.5 Let \( \leq 3 + (s - 1)(|S_1 \cap S_2| + |S_2 \cap S_3|) + 1 \leq s^2 - s + 4, \)

since \(|S_1 \cap S_2| + |S_2 \cap S_3| \leq |S_3| = s.\)

We now assume that \( a = |S_1 \cap S_2| > 0, \) and we need some lemmata.

**Lemma 3.3** Let \( x \) be an element of \( Q. \) Then \( x \) is contained in at most \( (s + 1)T_i \)’s.

**Proof.** If not there exist \( (s + 2) \) indices \( i_1 < \ldots < i_{s+2} \) such that \( T_i = \{x, x_i\} \) for \( 1 \leq j \leq s \). Since \( S_1 \cap T_i \neq \emptyset, \) \( x \notin S_1. \) On the other hand, \( S_1 \) meets all \( T_i \) for \( 2 \leq j \leq s + 2 \) and thus the \( s \)-set \( S_1 \) has to contain the \( s + 1 \) elements \( x_{i_2}, \ldots, x_{i_{s+2}}, \) a contradiction.

**Lemma 3.4** Let \( R \) be an \( r \)-subset of \( Q. \) Then \( R \) meets at most \( (rs + 1)T_i \)’s.

**Proof.** The case \( r = 1 \) follows from Lemma 3.3. Assume \( r \geq 2 \) and let \( x \) be an element of \( R \) contained in a maximal number \( N_x \) of \( T_i \)’s. Note that \( N_x \leq s + 1 \) by Lemma 3.3. If \( N_x \leq s \) for all \( x \in R, \) then \( R \) meets at most \( rs T_i \)’s. Assume there exists an \( x \in R \) such that \( N_x = s + 1. \) Then \( x \) meets \( (s + 1)T_i \)’s, say \( T_i_1 = \{x, x_i_1\}, \ldots, T_i_{s+1} = \{x, x_{i_{s+1}}\} \) with \( i_1 < \ldots < i_{s+1}. \)

We claim that every \( y \neq x \) meets at most \( s T_i \)’s such that \( i \neq i_1, \ldots, i_{s+1}. \) If not, there exist \( s + 1 \) sets \( S_{i_1} = y, y_{j_1}, \ldots, T_{j_{s+1}} = y, y_{j_{s+1}} \) with \( j_1 < \ldots < j_{s+1} \) containing \( y. \) Assume \( i_1 < j_1 \) (a dual argument works if \( j_1 < i_1 \)). Since \( S_{i_1} \cap T_{i_1} = \emptyset, \) \( x \notin T_{i_1} \) and since \( S_{i_1} \) meets all other \( T_{i_n} \), \( S_{i_1} = \{x_{i_2}, \ldots, x_{i_{s+1}}\}. \) If \( y \in T_{i_1}, \) \( y \) belongs to \( (s + 2) T_i \)’s in contradiction to Lemma 3.3. Thus \( |S_{i_1}| > s, \) a contradiction. This proves the claim and the lemma follows easily.

We can now conclude the proof of (3) in the case \(|S_1 \cap S_2| = a > 0. \) Consider a \( 2 \)-set \( T_i \) with \( i \geq 3. \) Since \( T_i \) meets \( S_1 \) and \( S_2, \) either \( T_i \) meets \( S_1 \cap S_2, \) or \( T_i \) meets \( S_1 \setminus S_2 \) and \( S_2 \setminus S_1. \) By Lemma 3.4, there are at most \((a + 1) T_i \)’s of the first type and at most \((s - a)^2 T_i \)’s of the second type. It follows that

\[
p(s) - 2 \leq (s - a)^2 + as + 1
\]

and hence \( p(s) \leq s^2 + a^2 - as + 3 \leq s^2 - s + 4, \) since \( 1 \leq a \leq s - 1. \)

Two different upper bounds were promised for \( p(s). \) Here is the second one, which seems to be rather unsatisfying, since it depends on \( n = |Q|. \) In fact, as will be shown later, this new bound is better than the first one for \( s > [n/2]. \)

**Proposition 3.5** Let \( a = \lfloor n/(n - s) \rfloor. \) Then

\[
p(s) \leq \frac{1}{2}ns + a = \left(\frac{a + 1}{2}\right)s^2 + (1 - a^2)ns + \left(\frac{a}{2}\right)n^2 + a
\]

if \( n - s \) divides \( n, \) and

\[
p(s) \leq \left(\frac{a + 1}{2}\right)s^2 + (1 - a^2)ns + \left(\frac{a}{2}\right)n^2 + a + 1
\]

if \( n - s \) does not divide \( n. \)
Proof. Denote by $N_i$ the number of 2-sets meeting $S_j$ for $j < i$ but not meeting $S_i$. Note that the conditions of Problem $P'$ just say that $N_i > 0$ for all $i \leq p(s)$. The idea of the proof is contained in the following formula

$$\sum_{1 \leq i \leq p(s)} N_i \leq \binom{n}{2}$$

This is clear since the number of 2-subsets of $Q$ is $\binom{n}{2}$. The next lemma provides a lower bound for $N_i$.

**Lemma 3.6** Let $Z_i = \bigcap_{j < i} S_j \setminus S_i$ and $|Z_i| = z_i$. Then $N_i \geq \binom{z_i}{2} + z_i(n - s - z_i)$.

**Proof.** Indeed, any 2-set contained in $Z_i$ and any 2-set consisting of an element of $Z_i$ and of an element of $Q \setminus (S_i \cup Z_i)$ meets all $S_j$ for $j < i$ but does not meet $S_i$.

We now prove the proposition. First of all we claim that

$$\bigcup_{1 \leq i \leq p(s)} Z_i = Q$$

If not,

$$Q \setminus (\cup Z_i) = \bigcap_{1 \leq i \leq p(s)} S_i$$

is nonempty, and one can select an element $x$ in this set. Let $T$ be a 2-set containing $x$ and $S$ be an $s$-set such that $S \cap T = \emptyset$. Then the two sequences $S_1, \ldots, S_{p(s)}, S$ and $T_1, \ldots, T_{p(s)}, T$ satisfy the conditions of Problem $P'$ in contradiction to the definition of $p(s)$. Thus the claim holds and since all $Z_i$'s are pairwise disjoint:

$$\sum z_i = n$$

It now follows from (1) that

$$p(s) \leq \binom{n}{2} - \sum_{1 \leq i \leq p(s)} (N_i - 1)$$

Since $N_i > 0$ for all $i$, Lemma 3.6 provides the following inequality:

$$p(s) \leq \binom{n}{2} - \sum_{z_i > 0} f(z_i)$$

where $f(z) = \binom{z}{2} + z(n - s - z) - 1$.

Thus, it remains to find the minimum of the expression $\sum f(z_i)$ when the $z_i$'s are submitted to the two conditions

(a) $\sum z_i = n$ (see (2)) and

(b) $0 < z_i \leq n - s$ (because $Z_i \subset Q \setminus S_i$).

Consider a family $(z_i)$ reaching this minimum and which furthermore contains a minimal number $\alpha$ of $z_i$'s different from $(n - s)$.

We claim that $\alpha \leq 1$. Assume to the contrary that there exist two elements different from $n - s$, say $z_1$ and $z_2$. Then an easy calculation shows that

$$f(z_1 + z_2) \leq f(z_1) + f(z_2) \quad \text{if } z_1 + z_2 \leq n - s,$$

$$f(n - s) + f(z_1 + z_2 - (n - s)) \leq f(z_1) + f(z_2) \quad \text{if } z_1 + z_2 > n - s.$$

Thus replacing $z_1$ and $z_2$ by $z_1 + z_2$ — in the case $z_1 + z_2 \leq n - s$ — or by $(n - s)$ and $z_1 + z_2 - (n - s)$ — in the case $z_1 + z_2 > n - s$ — leads to a family $(z_i')$ such that $\sum f(z_i') \leq \sum f(z_i)$ and containing at most $(\alpha - 1)$ elements $z_i'$ different from $n - s$, in
contradiction to the definition of the family \((z_i)\). Therefore \(\alpha = 1\) and the minimum of \(f(z_i)\) is obtained for
\[
z_1 = \cdots = z_\alpha = n-s \quad \text{if } n = a(n-s),
\]
and for
\[
z_1 = \cdots = z_\alpha = n-s, \quad z_{\alpha+1} = r \quad \text{if } n = a(n-s) + r \text{ with } 0 < r < n-s.
\]
It follows from inequality (4) that
\[
p(s) \leq \binom{n}{2} - a f(n-s) \quad \text{if } n = a(n-s),
\]
\[
p(s) \leq \binom{n}{2} - a f(n-s) - f(r) \quad \text{if } n = a(n-s) + r \text{ with } 0 < r < n-s.
\]
where \(f(z) = \binom{n}{2} + z(n-z) - 1\).
Proposition 3.5 follows by a routine calculation.

We now compare the two upper bound for \(p(s)\) obtained in Propositions 3.2 and 3.5 for \(2 \leq s \leq n-2\).

**Case 1.** \(2 \leq s \leq (n/2) - 1\).
Then \(a = 1\) and Proposition 3.5 gives \(p(s) \leq s^2 + 2\). Clearly \(s^2 - s + 4\) is a better upper bound.

**Case 2.** \(s = n/2\).
Then \(a = 2\) and Proposition 3.5 gives \(p(s) \leq s^2 + 2\). Again \(s^2 - s + 4\) is better.

**Case 3.** \((n+1)/2 \leq s \leq (2n-1)/3\).
Then \(a = 2\) and Proposition 3.5 gives
\[
p(s) \leq 3s^2 - 3ns + n^2 + 3 = s^2 - s + 4 + (n-s-1)(n-2s+1)
\leq s^2 - s + 4
\]

**Case 4.** \(2n/3 \leq s\).
Then \(a \geq 3\) and Proposition 3.5 gives
\[
p(s) \leq \frac{a+1}{2} s^2 + (1-a^2)ns + \left(\frac{a}{2}\right)^2 n^2 + a + 1
\leq s^2 - s + \frac{1}{2a}(a-1)(n-s)^2 - ((a-1)(n-s) - 1)s + a + 1
\]
Since \(s \leq (1-a)(n-s)\), a short calculation shows that
\[
p(s) \leq s^2 - s + 4 - \frac{1}{2}(a-1)(a-2)(n-s)^2 + (a-1)(n-s) + (a-3)
\]
Since \(a \geq 3, -\frac{1}{2}(a-1) \leq -1\) and thus
\[
p(s) \leq s^2 - s + 4 - (a-2)(n-s)^2 + (a-1)(n-s) + (a-3),
\]
and it is not difficult to see that for \(n-s \geq 2\),
\[
-(a-2)(n-s)^2 + (a-1)(n-s) + (a-3) \leq 0
\]
Therefore Proposition 3.5 gives a better bound in this case.

The next theorem summarizes the previous results.
Theorem 3.7 Let $\mathcal{A} = (Q, A, \delta)$ be an automaton with $n$ states, let $0 \leq s \leq n - 2$ and let $K$ be an $(n-s)$-subset of $Q$. If there exists a word $w$ such that $|Kw| < |K|$, one can choose $w$ with length $\leq \varphi(n,s)$ where $a = \lfloor n/(n-s) \rfloor$ and

$$
\varphi(n,s) = \begin{cases} 
1 & \text{if } s = 0, \\
3 & \text{if } s = 3, \\
s^2 - s + 4 & \text{if } 3 \leq s \leq n/2, \\
\left(\frac{a + 1}{2}\right)s^2 + (1 - a^2)ns + \left(\frac{a}{2}\right)n^2 + a = \frac{1}{2}ns + a & \text{if } n = a(n-s) \text{ and } s > n/2, \\
\left(\frac{a + 1}{2}\right)s^2 + (1 - a^2)ns + \left(\frac{a}{2}\right)n^2 + a + 1 & \text{if } n-s \text{ does not divide } n \text{ and } s > n/2. 
\end{cases}
$$

We can now prove the main results of this paper.

Theorem 3.8 Let $\mathcal{A}$ be an automaton with $n$ states and let $0 \leq k \leq n - 1$. If there exists a word of rank $\leq n - k$ in $\mathcal{A}$, there exists such a word of length $\leq G(n,k)$ where

$$
G(n,k) = \begin{cases} 
k^2 & \text{for } k = 0, 1, 2, 3, \\
\frac{1}{3}k^3 - k^2 + \frac{14}{3}k - 5 & \text{for } 4 \leq k \leq (n-2) + 1, \\
9 + \sum_{3 \leq s \leq k-1} \varphi(n,s) & \text{for } k \geq (n+3)/2. 
\end{cases}
$$

Observe that in any case

$$
G(n,k) \leq \frac{1}{3}k^3 - k^2 + \frac{14}{3}k - 5
$$

Table 1 gives values of $G(n,k)$ for $0 \leq k \leq n \leq 12$.

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Figure 1: Values of $G(n,k)$ for $0 \leq k \leq n \leq 12$.

Proof. Assume that there exists a word $w$ of rank $\leq n - k$ in $\mathcal{A}$. Since Conjecture (C) has been proved for $k \leq 3$, we may assume $k \geq 4$ and there exists a word $w_1$ of length $\leq 9$ such that $Qw_1 = K_1$ satisfies $|K_1| \leq n - 3$. It suffices now to apply the method described at the beginning of this section which consists of using Theorem 3.7 repetitively. This method shows that one can find a word of rank $\leq n - k$ in $\mathcal{A}$ of length
\[ \leq 9 + \sum_{3 \leq s \leq k-1} \varphi(n, s) = G(n, k). \] In particular, \( \varphi(n, s) = s^2 - s + 4 \) for \( s \leq n/2 \) and thus
\[ G(n, k) = \frac{1}{3} k^3 - k^2 + \frac{14}{3} k - 5 \quad \text{for} \quad 4 \leq k \leq (n - 2) + 1 \]
It is interesting to have an estimate of \( G(n, k) \) for \( k = n - 1 \).

**Theorem 3.9** Let \( A \) be an automaton with \( n \) states. If there exists a word of rank 1 in \( A \), there exists such a word of length \( \leq F(n) \) where
\[ F(n) = \left( \frac{1}{2} - \frac{\pi^2}{36} \right) n^3 + o(n^3). \]
Note that this bound is better than the bound in \( \frac{7}{27} n^3 \), since \( \frac{7}{27} \approx 0.2593 \) and \( \left( \frac{1}{2} - \frac{\pi^2}{36} \right) \approx 0.2258 \).

**Proof.** Let \( h(n, s) = \binom{n+1}{2} s^2 + (1 - a^2) ns + \binom{n}{2} n^2 + a + \varepsilon(s) \), where
\[ \varepsilon(s) = \begin{cases} 0 & \text{if } n = a(n - s) \\ 1 & \text{if } n - s \text{ does not divide } n. \end{cases} \]
The above calculations have shown that for \( 3 \leq s \leq n/2 \),
\[ s^2 - s + 4 \leq h(n, s) \leq s^2 + 2. \]
Therefore
\[ \sum_{0 \leq s \leq n/2} \varphi(n, s) \sim 9 + \sum_{3 \leq s \leq n-2} s^2 \sim \frac{1}{24} n^3 \sim \sum_{0 \leq s \leq n/2} h(n, s) \]
It follows that
\[ F(n) = G(n, n - 1) = \sum_{0 \leq s \leq n-2} h(n, s) + o(n^3) \\
= \sum_{0 \leq s \leq n-1} h(n, s) + o(n^3) \]
A new calculation shows that
\[ h(n, n - s) = n^2 + (\lfloor n/s \rfloor + 1) \left( \frac{1}{2} \lfloor n/s \rfloor s^2 - sn + 1 \right) - \varepsilon(n - s) \]
Therefore
\[ F(n) = \sum_{1 \leq l \leq 6} T_l(n) + o(n^3) \]
where
\[ T_1 = \sum_{s=1}^{n} n^2 = n^3, \quad T_4 = -n \sum_{s=1}^{n} \lfloor n/s \rfloor s, \]
\[ T_1 = \frac{1}{2} \sum_{s=1}^{n} \lfloor n/s \rfloor s^2, \quad T_5 = -n \sum_{s=1}^{n} s, \]
\[ T_3 = \frac{1}{2} \sum_{s=1}^{n} \lfloor n/s \rfloor s, \quad T_6 = \sum_{s=1}^{n} \lfloor n/s \rfloor s + 1 - \varepsilon(n - s). \]
Clearly \( T_5 = -\frac{1}{2} n^3 + o(n^3) \) and \( T_6 = o(n^3) \). The terms \( T_2, T_3 \) and \( T_4 \) need a separate study.
Lemma 3.10 We have \( T_3 = \frac{1}{6} \zeta(3) n^3 + o(n^3) \) and \( T_4 = -\frac{1}{2} \zeta(2) n^3 + o(n^3) \), where \( \zeta(s) = \sum_{n=1}^{\infty} n^{-s} \) is the usual zeta-function.

These two results are easy consequences of classical results of number theory (see [7, p. 117, Theorem 6.29 and p. 121, Theorem 6.34])

\[
(a) \quad \sum_{s=1}^{n} \frac{n}{s} s = \sum_{s=1}^{n} \frac{[n/s]^2 + [n/s]}{2} = \frac{1}{2} n^2 \sum_{k=1}^{n} \frac{1}{k^2} + o(n^2) = \frac{1}{2} \zeta(2) n^2 + o(n^2)
\]

Therefore \( T_4 = -\frac{1}{2} \zeta(2) n^3 + o(n^3) \).

\[
(b) \quad \sum_{s=1}^{n} \frac{n}{s} s^2 = \sum_{s=1}^{n} \frac{2[n/s]^3 + 3[n/s]^2 + [n/s]}{2} = \frac{1}{3} n^3 \left( \sum_{k=1}^{n} \frac{1}{k^3} \right) + o(n^3) = \frac{1}{3} \zeta(3) n^3 + o(n^3)
\]

Therefore \( T_3 = \frac{1}{6} \zeta(3) n^3 + o(n^3) \).

Lemma 3.11 We have \( T_2 = \frac{1}{6} (2 \zeta(2) - \zeta(3)) n^3 + o(n^3) \).

Proof. It is sufficient to prove that

\[
\lim_{n \to \infty} \frac{1}{n^3} \sum_{s=1}^{n} \frac{n}{s} s^2 = \frac{1}{6} (2 \zeta(2) - \zeta(3))
\]

Fix an integer \( n_0 \). Then

\[
\frac{1}{n^3} \sum_{j=1}^{n_0} j^2 \sum_{s=[n/(j+1)]+1}^{[n/j]} s^2 \leq \frac{1}{n^3} \sum_{s=1}^{n} [n/s]^2 s^2
\]

\[
\leq \frac{1}{n} \left( \frac{n}{n_0 + 1} \right) + \frac{1}{n^3} \sum_{j=1}^{n_0} j^2 \sum_{s=[n/(j+1)]+1}^{[n/j]} s^2
\]

Indeed, \([n/s] s \leq n\) implies the inequality

\[
\frac{1}{n^3} \sum_{s=1}^{[n/(n_0+1)]} [n/s]^2 s^2 \leq \frac{1}{n} \left( \frac{n}{n_0 + 1} \right)
\]

Now

\[
\lim_{n \to \infty} \frac{1}{n^3} \sum_{[n/(j+1)]+1 \leq s \leq [n/j]} s^2 = \frac{1}{3} \left( \frac{1}{j^3} - \frac{1}{(j+1)^3} \right)
\]
It follows that for all \( n_0 \in \mathbb{N} \)
\[
\frac{1}{2} \sum_{j=1}^{n_0} j^2 \left( \frac{1}{j^3} - \frac{1}{(j+1)^3} \right) \leq \lim \inf_{n \to \infty} \frac{1}{n^3} \sum_{k} \left\lfloor \frac{n}{k} \right\rfloor^2 k^2 \\
\leq \lim \sup_{n \to \infty} \frac{1}{n^3} \sum_{k} \left\lfloor \frac{n}{k} \right\rfloor^2 k^2 \\
\leq \lim \sup_{n \to \infty} \frac{1}{n} \left( \frac{n}{n_0+1} \right) + \frac{1}{3} \sum_{j=1}^{n_0} j^2 \left( \frac{1}{j^3} - \frac{1}{(j+1)^3} \right)
\]

Since
\[
\lim \sup_{n \to \infty} \frac{1}{n} \left( \frac{n}{n_0+1} \right) = \frac{1}{n_0+1}
\]
We obtain for \( n_0 \to \infty \),
\[
\lim_{n \to \infty} \frac{1}{n^3} \sum_{s=1}^{n} \left\lfloor \frac{n}{s} \right\rfloor^2 s^2 = \frac{1}{3} \sum_{j=1}^{\infty} j^2 \left( \frac{1}{j^3} - \frac{1}{(j+1)^3} \right) \\
= \frac{1}{3} \sum_{j=1}^{\infty} \left( \frac{2j-1}{j^2} \right) = \frac{1}{3}(2\zeta(2) - \zeta(3))
\]
Finally we have
\[
F(n) = n^3 \left( 1 + \frac{1}{6} (2\zeta(2) - \zeta(3)) + \frac{1}{6} \zeta(3) - \frac{1}{2} \zeta(2) - \frac{1}{2} \right) + o(n^3)
\]
\[
= \left( \frac{1}{2} - \frac{1}{6} \zeta(2) \right) n^3 + o(n^3)
\]
\[
= \left( \frac{1}{2} - \frac{\pi^2}{36} \right) n^3 + o(n^3)
\]
which concludes the proof of Theorem 3.9. □

Note added in proof

(1) P. Shor has recently found a counterexample to the triangle conjecture.
(2) Problem P' has been solved by P. Frankl. The conjectured estimate \( p(s, t) = (s+t)^3 \) is correct. It follows that Theorem 3.8 can be sharpened as follows: if there exists a word of rank \( \leq n-k \) in \( A \) there exists such a word of length \( \leq \frac{1}{6} k(k+1)(k+2) - 1 \) (for \( 3 \leq k \leq n - 1 \)).

References


