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LOWER SPACE BOUNDS FOR ACCEPTING SHUFFLE LANGUAGES

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Abstract. In [6] it was shown that shuffle languages are contained in **one-way-NSPACE**(log n) and in **P**. In this paper we show that nondeterministic one-way logarithmic space is in some sense the lower bound for accepting shuffle languages. Namely, we show that there exists a shuffle language which is not accepted by any deterministic one-way Turing machine with space bounded by a sublinear function, and that there exists a shuffle language which is not accepted with less than logarithmic space even if we allow two-way nondeterministic Turing machines.

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1. INTRODUCTION

The operations shuffle and shuffle closure have been introduced to describe sequentialized execution histories of concurrent processes [7, 8]. Together with other operations they describe various classes of languages which have been extensively studied (see [1, 3–5, 10]). Here, we consider the class of shuffle languages which emerges from the class of finite languages through regular operations (union, concatenation, Kleene star) and shuffle operations (shuffle and shuffle closure). In [6] it was shown that shuffle languages are contained in the class **one-way-NSPACE**(log n) and thus in the class **P** (*i.e.* they are accepted in polynomial time by deterministic Turing machines). For every shuffle expression E, a shuffle automaton was constructed which accepts the language generated by E and it was shown that the computations of the automaton can be simulated by a one-way nondeterministic Turing machine in logarithmic space.

In this paper we show that nondeterministic one-way logarithmic space is in some sense the lower bound for accepting shuffle languages. Namely, we show that there exists a shuffle language which is not accepted by any deterministic one-way

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Turing machine with space bounded by a sublinear function, and that there exists a shuffle language which is not accepted with less than logarithmic space even if we allow two-way nondeterministic Turing machines.

2. Shuffle languages

Let Σ be any fixed alphabet and λ the empty word. The shuffle operation $\odot$ is defined inductively as follows:

- $u \odot \lambda = \lambda \odot u = \{u\}$, for $u, \in \Sigma^*$ and
- $au \odot bv = a(u \odot bv) \cup b(au \odot v)$, for $u, v \in \Sigma^*$ and $a, b \in \Sigma$.

For any languages $L_1, L_2 \subset \Sigma^*$ the shuffle $L_1 \odot L_2$ is defined as

$$L_1 \odot L_2 = \bigcup_{u \in L_1, v \in L_2} u \odot v.$$

For any language L, the shuffle closure operator is defined by:

$$L^{\otimes} = \bigcup_{i=0}^{\infty} L^{\odot i}, \qquad \text{where} \quad L^{\odot 0} = \{\lambda\} \quad \text{and} \quad L^{\odot i} = L^{\odot i-1} \odot L.$$

Definition 1. *Each $a \in \Sigma$, λ and $\emptyset$ are shuffle expressions. Besides, if S_1, S_2 are shuffle expressions, then $(S_1 \cdot S_2)$, ${S_1}^*$, $(S_1 + S_2)$, $(S_1 \odot S_2)$ and ${S_1}^{\otimes}$ are shuffle expressions, and nothing else is a shuffle expression.*

The language $L(S)$ generated by a shuffle expression S is defined as follows. $L(a) = \{a\}$, $L(\lambda) = \{\lambda\}$, $L(\emptyset) = \emptyset$. If $L(S_1) = L_1$ and $L(S_2) = L_2$, then $L((S_1 \cdot S_2)) = L_1 \cdot L_2$, $L((S_1 + S_2)) = L_1 \cup L_2$, $L({S_1}^*) = L_1^*$, $L((S_1 \odot S_2)) = L_1 \odot L_2$, and $L({S_1}^{\otimes}) = L_1^{\otimes}$.

A language L is a shuffle language if there exists a shuffle expression E such that $L = L(E)$. We shall also use the following notation, for arbitrary string z: $|z|$ denotes the length of z, $|z|_e$ the number of occurrences of a symbol e in z, z_i the i-th symbol of z, and z^R the reverse of z (z written backwards).

3. Turing machines

We consider the Turing machine model with a read-only input tape and a separate two-way, read-write work tape. The number of tape cells used on the work tape, called space, is our measure of computational complexity. A Turing machine is called one-way if its input head cannot move to the left.

We use so called weak mode of space complexity. Let $L(n)$ be a function on natural numbers. A Turing machine is said to be weakly $L(n)$ space-bounded if for every accepted input of length n, at least one accepting computation uses no more than $L(n)$ space. But our results are also valid for strong mode of space complexity, which requires that for every input of length n, all computations are $L(n)$ space bounded. We shall use the following notation: $DSPACE[L(n)]$

or $NSPACE[L(n)]$ denotes the class of languages accepted by deterministic or nondeterministic $L(n)$ space-bounded Turing machines, respectively. We add the prefix *one-way* if we consider classes of languages accepted by one-way Turing machines.

By a configuration of a Turing machine M we shall mean a tuple (q, γ, j), where q is the current state of M, γ are the contents of the non-blank sector of the work tape, and j is the position of the work head, $1 \leq j \leq |\gamma| + 1$ (we assume that M cannot write the blank symbol on its work tape). The space used by the configuration (q, γ, j) is equal to $|\gamma|$ –the number of non-blank cells on the work tape. It is easy to see that the number of all configurations with space bounded by k is less than r^k, for some constant $r > 1$ (for more details see [9] or [2]).

4. Lower bound for one-way Turing machines

In this section we show that there exists a shuffle language which is not accepted by any deterministic one-way Turing machine in space bounded by a sublinear function.

Theorem 2. *There exists a shuffle language L such that $L \notin$ one-way-$DSPACE[S(n)]$, for any $S(n) = o(n)$.*

Proof. Consider the shuffle language

$$L = (a+b)^*a(ac+bd)^{\otimes}d(c+d)^* + (a+b)^*b(ac+bd)^{\otimes}c(c+d)^*$$

and let $h : \{a,b\}^* \to \{c,d\}^*$ be the isomorphism described by $h(a) = c$ and $h(b) = d$. First we shall prove the following.

Lemma 3. *Let k be a positive number. For every u, v : $u \in (a+b)^k$ and $v \in (c+d)^k$, the concatenation uv belongs to L if and only if $h(u) \neq v^R$ (v^R denotes the reverse of v).*

Proof. If $uv \in L$ then uv can be decomposed into

$$uv = u'au''v''dv' \qquad \text{or} \qquad uv = u'bu''v''cv'$$

with u', $u'' \in (a+b)^*$, v', $v'' \in (c+d)^*$, and $u''v'' \in (ac+bd)^{\otimes}$. We shall only deal with the first case. Note that in this case $u = u'au''$ and $v = v''dv'$.

Since $u''v'' \in (ac+bd)^{\otimes}$, we have

$$|u''v''|_a = |u''v''|_c \qquad \text{and} \qquad |u''v''|_b = |u''v''|_d$$

(where $|z|_e$ denotes the number of occurrences of a symbol e in a string z).

And because

$$|u''v''|_a + |u''v''|_b = |u''| \qquad \text{and} \qquad |u''v''|_c + |u''v''|_d = |v''|$$

we have

$$|u''| = |v''|$$

and hence

$$|u'| = |v'|.$$

Let $i = |u'|+1 = |v'|+1$. Then the words $h(u)$ and v^R disagree on the i-th symbol, $(h(u))_i = h(u_i) = h(a) = c$ and $(v^R)_i = d$ (where z_i denotes the i-th symbol of a word z). Thus $h(u) \neq v^R$.

Suppose now that $h(u) \neq v^R$ and that i is the last index, where $h(u)$ and v^R disagree. We can assume that $u_i = a$ and $(v^R)_i = d$. Then u and v can be decomposed in the following way: $u = u'au''$, $v = v''dv'$, and $h(u'') = (v'')^R$. (It is possible that $u'' = v'' = \lambda$.) In this situation $u''v'' \in (ac+bd)^{\otimes}$ and thus $uv \in L$. This ends the proof of the lemma. □

Suppose now, for a contradiction, that L is accepted by a one-way deterministic Turing machine M with space weakly bounded by $S(n)$.

Let k be a positive number. For every $u \in (a+b)^k$, let $conf(u)$ be the configuration reached by M after reading u. Because there exists $v \in \{c,d\}^k$ such that the word $uv \in L$, then $conf(u)$ uses at most $S(2k)$ cells on the work tape. There are 2^k different words in $(a+b)^k$, and at most $r^{S(2k)}$ configurations with space bounded by $S(2k)$, for some constant $r > 1$. Since $\lim \frac{S(n)}{n} = 0$, there exists k such that $r^{S(2k)} < 2^k$, and there exist two different words x, $y \in (a+b)^k$, such that $conf(x) = conf(y) = \alpha$.

Consider now the accepting computation of M on the word $x(h(y))^R$. By Lemma 3, $x(h(y))^R \in L$, because $h(x) \neq (h(y)^R)^R = h(y)$. In this computation M reaches the configuration α just after reading x. This means that M also accepts the word $y(h(y))^R$ because M reaches α after reading y and afterwards it proceeds exactly like for $x(h(y))^R$ and accepts at the end. But, by Lemma 3, $y(h(y))^R$ does not belong to L, a contradiction. □

5. Lower bound for two-way Turing machines

In this section we show that there exists a shuffle language which is not accepted by any nondeterministic two-way Turing machine in space bounded by a sublogarithmic function.

Theorem 4. *There exists a shuffle language L_1 such that $L_1 \notin NSPACE[S(n)]$ for any $S(n) = o(\log n)$.*

Proof. Consider the shuffle language

$$L_1 = (ab)^{\otimes}.$$

The theorem follows from the fact that the class $NSPACE[S(n)]$ is closed under intersections with regular languages, and that the language

$$L_1 \cap a^*b^* = \{a^n b^n \mid n \geq 0\}$$

is not accepted by any nondeterministic Turing machine with space bounded by $S(n) = o(\log n)$ (see [9]). □

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