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A note on the languages recognized by commutative asynchronous automata*

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Abstract

The languages recognized by commutative asynchronous automata are studied and described here. It turns out that over a finite nonvoid alphabet X with $|X| = k$, the languages recognized by commutative asynchronous automata constitute such a Boolean algebra which is isomorphic to the Boolean algebra consisting of all subsets of the set $\{0,1\}^k$.

1 Introduction

The decomposition of commutative asynchronous automata is studied in [1] and it is proved that every commutative asynchronous automaton can be embedded isomorphically into a suitable quasi-direct power of a two-state commutative asynchronous automaton. Moreover, the directable commutative asynchronous automata are also investigated in [1], and it is shown that the exact bound for the maximal length of minimum-length directing words

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of commutative asynchronous automata of n states is equal to $n-1$, *i.e.*, the exact bound is the same as in the commutative case (see *eg.* [3] or [4]). Surprisingly, the exact bound decreases drastically to $[\log_2(n)]$ if we consider only such elements of this class which are generated by one element. Paper [2] deals with the decomposition of commutative asynchronous nondeterministic automata. Here, we study now the languages recognized by commutative asynchronous automata. It turns out that there are a few of them, and they constitute a Boolean algebra under a fixed alphabet.

2 Preliminaries

We recall here a few notions and notation necessary in the sequal. Let X be a nonempty alphabet with $|X| = k$. Without loss of generality, we may assume that $X = \{x_1, \ldots, x_k\}$. Throughout this paper we shall work uder this fixed alphabet X. The set of all finite words over X is denoted by X^*. For the length of a word $p \in X^*$, we use the notation $|p|$. For any $p \in X^*$, let us denote by alph(p) the set of the all letters occuring in the word p. One can extend the function alph to languages in a natural way. The *shuffle product* of two words $u, v \in X^*$ is the set

$$u \diamond v = \{w : w = u_1v_1 \ldots u_nv_n,\ u = u_1 \ldots u_n,\ v = v_1 \ldots v_n,\ u_i.v_j \in X^*\}.$$

The shuffle product can be extended to languages as well. We use the *Parikh mapping* denoted by Ψ. For its definitions, let $N = \{0, 1, 2, \ldots\}$, and let us define the mapping $\Psi : X^* \to N^k$, by

$$\Psi(u) = (\mu_{x_1}(u), \ldots, \mu_{x_k}(u)),$$

where $\mu_{x_j}(u)$ denotes the number of the occurrences of x_j in u, for every j, $j = 1, \ldots, k$.

By *automaton* or *X-automaton* we mean a system $\mathbf{A} = (A, X)$, where A is the finite nonvoid set of *states*, X is the finite nonempty set of *input signs*, and every input sign $x \in X$ is realized as a unary operation $x^{\mathbf{A}} : A \to A$. The automaton $\mathbf{A} = (A, X)$ is *commutative* if $a(xy)^{\mathbf{A}} = a(yx)^{\mathbf{A}}$ is valid, for all $a \in A$ and $x, y \in X$. Another particular automata are the asynchronous ones. $\mathbf{A}$ is called *asynchronous* if $ax^{\mathbf{A}} = a(xx)^{\mathbf{A}}$, for all $a \in A$ and $x \in X$.

Some particular commutative asynchronous automata introduced in [1] will be used in the following section.

For every $n \geq 1$, let us define the automaton $\mathbf{H}_n = (\{0,1\}^n, \{x_1, \ldots, x_n\})$ in the following way. For all $(i_1, \ldots, i_n) \in \{0,1\}^n$ and $x_j \in \{x_1, \ldots, x_n\}$, let

$$(i_1, \ldots, i_n)x_j^{\mathbf{H}_n} = \begin{cases} (i'_1, \ldots, i'_n) & \text{if } i_j = 0, \text{ where } i'_t = i_t,\ t = 1, \ldots, n,\ t \neq j, \\ & \text{and } i'_j = 1, \\ (i_1, \ldots, i_n) & \text{otherwise.} \end{cases}$$

The automaton $\mathbf{H}_n$ can be visualized as follows. Its states are the vertices of the n-dimensional hyper-cube and any input sign takes the automaton from a vertex into its neighbour or fixes the state given. Moreover, x_j changes only the jth component. By the definition of $\mathbf{H}_n$, it is easy to see that $\mathbf{H}_n$ is commutative and asynchronous.

A *recognizer* or *X-recognizer* is a system $\mathcal{A} = (\mathbf{A}, a_0, F)$ which consists of an X-automaton $\mathbf{A}$, an *initial state* $a_0 \in A$, and a set $F(\subseteq A)$ of *final states.* The language *recognized* by $\mathcal{A}$ is

$$L(\mathcal{A}) = \{w : w \in X^* \text{ and } a_0 w^{\mathbf{A}} \in F\}.$$

It is also said that $L(\mathcal{A})$ is *recognizable* by the automaton $\mathbf{A}$.

3 Results

For every k dimensional binary vector $\mathbf{i} = (i_1, \ldots, i_k)$, a language $L_{\mathbf{i}}$ over X can be defined as follows. Let

$$L_{\mathbf{i}} = \Psi^{-1}(\mathbf{i}) \diamond (\mathrm{alph}(\Psi^{-1}(\mathbf{i}))^*.$$

Moreover, if $B \subseteq \{0,1\}^k$, then we can define the language L_B by

$$L_B = \cup_{\mathbf{i} \in B} L_{\mathbf{i}}.$$

The languages L_B, $B \subseteq \{0,1\}^k$ are strongly related to the languages recognizable by commutative asynchronous X-automata. This strong relationship is presented by the following statement.

Proposition 1. *A language $L \subseteq X^*$ is recognized by a commutative asynchronous X-automaton if and only if $L = L_B$ for some $B \subseteq \{0,1\}^k$.*

Proof. Let $L \subseteq X^*$ be an arbitrary language and let us suppose that L can be recognized by a recognizer $\mathcal{A} = (\mathbf{A}, a_0, F)$, where $\mathbf{A} = (A, X)$ is a commutative asynchronous X-automaton. Let us observe that $ap^{\mathbf{A}} = a(x_{i_1} \ldots x_{i_s})^{\mathbf{A}}$, $1 \leq s \leq k$ is valid for every $p \in X^*$ with $\text{alph}(p) = \{x_{i_1}, \ldots, x_{i_s}\}$ since $\mathbf{A} = (A, X)$ is commutative and asynchronous. By the commutativity, we may suppose that $i_1 < i_2 < \ldots < i_s$. Therefore, for every $p \in L$, there exists a uniquely determined word $x_{i_1} \ldots x_{i_s}$ such that $a_0 p^{\mathbf{A}} = a_0(x_{i_1} \ldots x_{i_s})^{\mathbf{A}}$. Now, let us denote by K the subset of L which consists of all words q in L for which $|q| = |\text{alph}(q)|$ and if $q = x_{i_1} \ldots x_{i_s}$, then $i_1 < i_2 < \ldots < i_s$. Then it is easy to see that

$$L = \bigcup_{q \in K} (\Psi^{-1}(\Psi(q))) \diamond (\text{alph}(q))^*.$$

On the other hand, by the definition of K, the mapping μ which is defined by $\mu : q \to \Psi(q)$, $q \in K$, is a one-to-one mapping of the language K into $\{0,1\}^k$. Consequently, if the image of K under μ is denoted by B, then $B \subseteq \{0,1\}^k$, moreover,

$$L = \bigcup_{q \in K} (\Psi^{-1}(\Psi(q))) \diamond (\text{alph}(q))^* = \bigcup_{\mathrm{i} \in B} \Psi^{-1}(\mathrm{i}) \diamond (\text{alph}(\Psi^{-1}(\mathrm{i}))^* = \cup_{\mathrm{i} \in B} L_{\mathrm{i}} = L_B.$$

and consequently, $L = L_B$. In particular, if $L = \emptyset$, then $B = \emptyset$.

Conversely, let $L = L_B = \cup_{\mathrm{i} \in B} L_{\mathrm{i}}$ for some $B \subseteq \{0,1\}^k$. Then it is easy to prove that the commutative asynchronous automaton $\mathbf{H}_k$ based on the k dimensional hyper-cube recognizes L by $(\mathbf{H}_k, (0,0,\ldots,0), B)$, and thus, L can be recognized by a commutative asynchronous X-automaton.

From the description of the languages over X, recognized by commutative asynchronous X-automata, it follows that these languages are closed under the union and intersection. What is more that is presented by the following assertion.

Proposition 2. *The number of the languages over $X = \{x_1, \ldots, x_k\}$, which can be recognized by commutative asynchronous X-automata, is equal to 2^{2^k}, moreover, these languages constitute a Boolean algebra which is isomorphic to the Boolean algebra consisting of all the subsets of the set $\{0,1\}^k$.*

Proof. Let us denote by $\mathcal{L}_X$ the set of languages, recognized by commutative asynchronous X-automata. Let $L \in \mathcal{L}_X$ be an arbitrary language. By the proof of Proposition 1, there exists a $B \subseteq \{0,1\}^k$ such that $L = L_B$. Therefore, to every language $L \in \mathcal{L}_X$, we can assign a subset B of $\{0,1\}^k$. Let us denote this mapping by φ. Then φ is a mapping of $\mathcal{L}_X$ into $\{0,1\}^k$. On the other hand, in the proof of Proposition 1 it is shown that for every $B \subseteq \{0,1\}^k$, there exists a language $L \in \mathcal{L}_X$ such that $L \doteq L_B$, and therefore, φ is surjective. Finally, it is easy to see that if $L_1 \neq L_2 \in \mathcal{L}_X$, then $L_1\varphi \neq L_2\varphi$.

Consequently, φ is a one-to-one mapping of $\mathcal{L}_X$ onto $\{0,1\}^k$. Moreover, it is evident that $(L_1 \cup L_2)\varphi = L_1\varphi \cup L_2\varphi$, $(L_1 \cap L_2)\varphi = L_1\varphi \cap L_2\varphi$, and $\bar{L}_1\varphi = \overline{L_1\varphi}$, for all $L_1, L_2 \in \mathcal{L}_X$, where $\bar{L}$ and $\bar{L}\varphi$, denotes the corresponding complements, respectively. Consequently, φ is an isomorphism. This isomorphism provides that $|\mathcal{L}_X| = 2^{2^k}$. This ends the proof of Proposition 2.

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