

線形分離オートマトンの最小化に関する理論

沼井 裕二^{†1} 宇田川 祥彰^{†2} 小林 聡^{†1}

本論文では、有限オートマトンを拡張した計算モデルである線形分離オートマトン (LSA) の理論的な考察を行う。LSA は実ベクトル系列を受理する能力を持ち、各状態には線形関数と閾値系列が付随する。この二つによって、各時点でのある状態からの遷移先状態が決定する。LSA の状態遷移は、パーセプトロンの振舞いと対応する。

LSA に関する Myhill-Nerode の定理を用いて最小化に関する理論を構築することが、本論文の主目的である。同定理の証明は、LSA の拡張元である有限オートマトンに関する定理の場合と同じように行うことができる。ここから、LSA への拡張は理論的に自然なものであることがわかる。

Theory of Minimizing Linear Separation Automata

YUJI NUMAI,^{†1} YOSHIAKI UDAGAWA^{†2}
and SATOSHI KOBAYASHI^{†1}

In this paper, we theoretically analyze a certain extension of a finite automaton, called a linear separation automaton (LSA). An LSA receives a sequence of real vectors, and has a linear function and a threshold sequence at every state, which determine the transition from some state to another at each step. Transitions of LSAs are just corresponding to the behavior of perceptrons.

We develop the theory of minimizing LSAs by using Myhill-Nerode theorem for LSAs. Its proof is performed as in the proof of the theorem for finite automata. Therefore we find that the extension to an LSA from the original finite automaton is theoretically natural.

^{†1} 電気通信大学大学院電気通信学研究科情報工学専攻

Department of Computer Science, Graduate School of Electro-Communications, The University of Electro-Communications

^{†2} エヌ・ティ・ティ アイティ株式会社

NTT-IT Corporation

1. Introduction

The computational model, finite automata, is an inevitably important concept in computer science. Recent advances in information technology and its related fields reveal the importance of computational models which can deal with time series of real valued data. Many researchers utilize computational tools based on these models to solve various problems including weather forecasting¹⁾, motion recognition^{2),3)}, and time-sequential image analysis⁴⁾.

There are several works proposing an extension of an automaton which can deal with real values in some sense. Models in these works include hybrid automata^{5),6)} and timed automata⁷⁾. Hybrid automata is a mathematical model for describing systems in which computational processes interact with physical processes. More formally speaking, hybrid automata is a finite state machine augmented with differential equations at each state. It is used for modelling various control systems and for verifying various theoretical properties of them. Timed automata is a labeled transition system for modelling real-time systems. It has time-passage action in addition to ordinary inputs, outputs, and internal actions. It was developed as providing a formal framework for simulation proof techniques of such real-time systems.

In this paper, we will theoretically analyze a certain extension of a finite automaton, which has a linear function and a threshold sequence at every state, and receives a sequence of real vectors. We call this automaton a **linear separation automaton (LSA)**.

Let us consider how an LSA works. Transitions of LSAs are just corresponding to the behavior of perceptrons^{8),9)}. Figure 1 shows an example M_1 of an LSA. An LSA has a weight vector $w(q_i)$ of a linear function and a threshold sequence $h(q_i)$ at each state q_i . If a vector $x \in \mathbf{R}^2$ is input to the current state q_i , then the next state is determined by comparing the inner product $x \otimes w(q_i)$ with each element of $h(q_i)$. If a threshold sequence $h(q_i)$ has n elements, then there can be $n + 1$ transitions from a state q_i . In an LSA M_1 , the transition $\delta(q_1, x)$ from q_1 with x is the following:

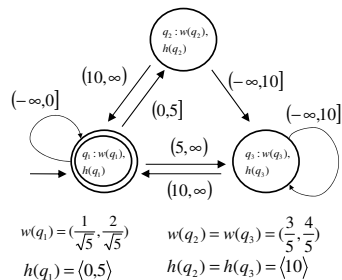


Fig. 1 LSA M_1

$$\delta(q_1, x) = \begin{cases} q_1 & \text{if } x \otimes w(q_1) \leq 0 \\ q_2 & \text{if } 0 < x \otimes w(q_1) \leq 5 \\ q_3 & \text{if } 5 < x \otimes w(q_1) . \end{cases}$$

We will develop the theory of minimizing LSAs by using **Myhill-Nerode theorem** for LSAs. Its proof is performed as in the proof of the theorem for the original finite automaton^{10),11)}. Therefore we find that the extension to an LSA from the original finite automaton is theoretically natural.

LSA-like computational models have been already utilized in some application problems. For instance, Matsunaga and Oshita proposed to use a state transition system for recognizing a specified motion. Their system receives at each state feature vector values acquired from a camera or a motion capture, and determines its transition from the current state by using Support Vector Machines.

In order to develop a theory of learning such computational models, we need computational analysis on the proposed models themselves. For instance, the uniqueness of the minimum state finite automaton for a given one is crucially important in the theory of learning finite automata, because almost all of the learning algorithms try to identify the minimum state automaton of a target language^{12),13)}. Therefore we will develop the theory of minimizing LSAs in this paper.

In section 2, we will give necessary definitions and notation needed in the sequel of this paper. Section 3 introduces a linear separation automaton (LSA). We show that Myhill-Nerode theorem for LSAs is established as in the original finite automata in section 4. The uniqueness of the minimum state LSA is shown in section 5. In section 6, we will characterize the minimum state LSA for a given one by using Myhill-Nerode theorem for LSAs. Section 7 includes concluding remarks and future works.

2. Preliminaries

We introduce basic definitions and notation needed later in this paper.

By \mathbf{R} , we denote the set of real numbers. For a positive integer d , by \mathbf{R}^d we denote d -dimensional vector space over \mathbf{R} . For $x, y \in \mathbf{R}^d$, $x \otimes y$ denotes the inner product of x and y . We define $(\mathbf{R}^d)^*$ as the set of all finite sequences of vectors in \mathbf{R}^d . For a sequence $\alpha = \langle x_1, \dots, x_n \rangle \in (\mathbf{R}^d)^*$, we denote the length of α by $|\alpha|$, that is, $|\alpha| = n$. An element in $(\mathbf{R}^d)^*$ of length 0 is called an empty sequence, and is denoted by λ . For sequences $\alpha, \beta \in (\mathbf{R}^d)^*$, we denote the concatenation of α and β by $\alpha\beta$. For $\alpha = \langle x_1, \dots, x_n \rangle \in (\mathbf{R}^d)^*$, the sequence α is said to be increasing if the inequality $x_i < x_{i+1}$ holds for every i .

A partition $\pi = \{S_1, \dots, S_k\}$ of \mathbf{R}^d (i.e., S_1, \dots, S_k are mutually disjoint non-empty subsets of \mathbf{R}^d such that $\cup_{i=1, \dots, k} S_i = \mathbf{R}^d$) is said to be **linearly separable** iff there exists $w \in \mathbf{R}^d$ and an increasing $h = \langle h_1, \dots, h_{k-1} \rangle \in (\mathbf{R}^1)^*$ such that

$$h_{i-1} < w \otimes x \leq h_i \Leftrightarrow x \in S_i \quad (i = 1, \dots, k) ,$$

where $h_0 = -\infty$ and $h_k = \infty$.

Consider equivalence relations \equiv, \equiv_1 , and \equiv_2 over $(\mathbf{R}^d)^*$. An equivalence relation \equiv_1 is finer than an equivalence relation \equiv_2 (or \equiv_2 is coarser than \equiv_1) iff $x \equiv_1 y$ implies $x \equiv_2 y$ for any x and y . An equivalence relation \equiv is **right invariant** iff $\alpha \equiv \beta$ implies $\alpha\gamma \equiv \beta\gamma$ for any α, β and γ . Consider partitions π_1 and π_2 of \mathbf{R}^d . A partition π_1 is finer than a partition π_2 (or π_2 is coarser than π_1) iff for any block $B \in \pi_1$, there exists a block $B' \in \pi_2$ such that $B \subseteq B'$.

3. Linear Separation Automata

This section introduces an extension of a finite automaton, called a **linear separation automaton (LSA)**. This automaton has a linear function and a threshold sequence at every state, and receives a sequence of real vectors. The transition from the current state to another is determined by the linear function and the threshold sequence associated with the current state.

An LSA M is defined as a 7-tuple

$$M = (d, Q, q_0, F, w, h, s) ,$$

where

d is a positive integer specifying the dimension of input vectors to M ,

Q is a finite set of states,

q_0 is an initial state ($q_0 \in Q$),

F is a finite set of final states ($F \subseteq Q$),

w is a weight function from Q to \mathbf{R}^d such that $w(q)$ is a unit vector for any $q \in Q$,

h is a threshold function from Q to $(\mathbf{R}^1)^*$ such that $h(q)$ is increasing for every $q \in Q$,

and s is a sub-transition function from Q to Q^* .

If $|s(q)| \geq 1$, then the equality $|h(q)| = |s(q)| - 1$ holds for every $q \in Q$.

Let us define the transition function δ_M of M from $Q \times \Sigma$ to Q . First, in case of $|s(q)| = 0$, the transition function δ_M is undefined. Secondly, suppose that $|s(q)| \geq 1$. Consider any state $q \in Q$. In order to improve the readability, we define $i_q = |h(q)|$ for any $q \in Q$. Let $s(q) = \langle p_1, \dots, p_{i_q+1} \rangle$ and $h(q) = \langle h_1, \dots, h_{i_q} \rangle$. The value $\delta_M(q, x)$ for a given $x \in \mathbf{R}^d$ is defined as follows:

$$\delta_M(q, x) = \begin{cases} p_1 & \text{if } x \otimes w(q) \leq h_1 \\ p_2 & \text{if } h_1 < x \otimes w(q) \leq h_2 \\ \vdots & \vdots \\ p_{i_q} & \text{if } h_{i_q-1} < x \otimes w(q) \leq h_{i_q} \\ p_{i_q+1} & \text{if } h_{i_q} < x \otimes w(q) . \end{cases}$$

We sometimes write δ for δ_M .

In the state transition diagrams of LSAs as in Figure 1, we illustrate the condition of the transition from a state p to a state q by using an interval $I \subseteq \mathbf{R}$. Suppose that $\delta(p, x) = q$ holds if $h_i < x \otimes w(p) \leq h_j$. In the diagram, the transition from p to q is associated with an interval $(h_i, h_j]$.

For $\alpha = \langle x_1, \dots, x_l \rangle \in (\mathbf{R}^d)^*$, we write $\delta(p, \alpha) = q$ if there exists a sequence $p_1 (= p), p_2, \dots, p_{l+1} (= q)$ of states such that $\delta(p_i, x_i) = p_{i+1}$ holds for $i = 1, \dots, l$. We define the set of sequences accepted by an LSA M , denoted by $L(M)$, as

$$L(M) = \{ \alpha \in (\mathbf{R}^d)^* \mid \delta(q_0, \alpha) \in F \} .$$

A subset L of $(\mathbf{R}^d)^*$ is said to be **regular** if there exists an LSA M such that $L = L(M)$. We define the size of M as $\text{size}(M) = |Q|$.

A state $q \in Q$ is said to be **reachable** if there exists $\alpha \in (\mathbf{R}^d)^*$ such that $\delta(q_0, \alpha) = q$. A state is said to be **unreachable** if it is not reachable.

Let $M = (d, Q, q_0, F, w, h, s)$ be an LSA. We define an equivalence relation \equiv_M over $(\mathbf{R}^d)^*$ as follows:

$$\alpha \equiv_M \beta \stackrel{\text{def}}{\iff} \delta(q_0, \alpha) = \delta(q_0, \beta) .$$

Example 1. Consider an LSA $M_1 = (d = 2, Q = \{q_1, q_2, q_3\}, q_1, F = \{q_1\}, w, h, s)$ in Figure 1. Let δ be the transition function of M_1 , and let $\alpha = \langle x_1, x_2, x_3 \rangle$ be a sequence of vectors in \mathbf{R}^2 with $x_1 = (1, 1)$, $x_2 = (2, 2)$, and $x_3 = (10, 10)$. The inner product $x_1 \otimes w(q_1) = 3/\sqrt{5}$ is in the interval $(0, 5]$, which implies that $\delta(q_1, x_1) = q_2$. We see in the same way that $\delta(q_2, x_2) = q_3$ and $\delta(q_3, x_3) = q_1 \in F$. Hence the sequence α is accepted by M_1 . □

4. Myhill-Nerode Theorem for LSAs

In the sequel of this paper, we will develop the theory of minimizing LSAs by using Myhill-Nerode theorem for LSAs. Its proof is performed as in the proof of the theorem for the original finite automaton.

In this section, we will show that Myhill-Nerode theorem for LSAs is established as in the original finite automata.

Myhill-Nerode theorem is originally proved by Myhill¹⁰⁾ and Nerode¹¹⁾. This theorem characterizes the class of languages accepted by a finite automaton. We modify this theorem in order to develop the theory of minimizing linear separation automata.

Let \equiv be a right invariant equivalence relation over $(\mathbf{R}^d)^*$ and consider an equivalence class $[\alpha]_{\equiv}$ containing $\alpha \in (\mathbf{R}^d)^*$. An equivalence relation $R([\alpha]_{\equiv})$ over \mathbf{R}^d induced by $[\alpha]_{\equiv}$ is defined as follows:

$$x R([\alpha]_{\equiv}) y \stackrel{\text{def}}{\iff} \alpha x \equiv \alpha y .$$

For any α and β with $\alpha \equiv \beta$, the equality $R([\alpha]_{\equiv}) = R([\beta]_{\equiv})$ holds, because \equiv is right invariant.

We say that a right invariant equivalence relation \equiv over $(\mathbf{R}^d)^*$ is **right linearly separable** iff for any equivalence class $[\alpha]_{\equiv}$, there exists a finite linearly separable partition of \mathbf{R}^d that is finer than the equivalence classes of $R([\alpha]_{\equiv})$.

Lemma 1. Consider two right invariant equivalence relations \equiv_1 and \equiv_2 over $(\mathbf{R}^d)^*$ such that \equiv_1 is finer than \equiv_2 . If \equiv_1 is right linearly separable, then \equiv_2 is right linearly separable.

Proof. Let $\alpha \in (\mathbf{R}^d)^*$. We have

$$\begin{aligned} x R([\alpha]_{\equiv_1}) y &\stackrel{\text{def}}{\iff} \alpha x \equiv_1 \alpha y , \text{ and} \\ x R([\alpha]_{\equiv_2}) y &\stackrel{\text{def}}{\iff} \alpha x \equiv_2 \alpha y . \end{aligned}$$

Since \equiv_1 is finer than \equiv_2 , we have $\alpha x \equiv_1 \alpha y$ implies $\alpha x \equiv_2 \alpha y$. Hence we obtain

$$x R([\alpha]_{\equiv_1}) y \Rightarrow x R([\alpha]_{\equiv_2}) y .$$

Thus, $R([\alpha]_{\equiv_1})$ is finer than $R([\alpha]_{\equiv_2})$. Since \equiv_1 is right linearly separable, there exists a finite linearly separable partition \mathcal{P} of \mathbf{R}^d that is finer than the equivalence classes of $R([\alpha]_{\equiv_1})$. Then, \mathcal{P} is finer than the equivalence classes of $R([\alpha]_{\equiv_2})$, because $R([\alpha]_{\equiv_1})$ is finer than $R([\alpha]_{\equiv_2})$. We have finally proven the claim. \square

We modify a Myhill-Nerode relation for finite automata as follows.

Definition 1 (Modified Myhill-Nerode Relation for LSAs). Let $S \subseteq (\mathbf{R}^d)^*$ be a set of sequences. The equivalence relation \equiv over $(\mathbf{R}^d)^*$ satisfying the following conditions is called a **modified Myhill-Nerode relation** with respect to S .

- (1) The equivalence relation \equiv is right invariant.
- (2) The equivalence relation \equiv is of finite index.
- (3) The equivalence relation \equiv is right linearly separable.
- (4) The set S is a union of some equivalence classes of \equiv .

\square

For any subset S of $(\mathbf{R}^d)^*$, we define an equivalence relation \approx_S over $(\mathbf{R}^d)^*$ as follows:

$$\alpha \approx_S \beta \stackrel{\text{def}}{\iff} \forall \gamma \in (\mathbf{R}^d)^* (\alpha\gamma \in S \text{ iff } \beta\gamma \in S) .$$

We can demonstrate the following, which is the most important theorem in this paper.

Theorem 1 (Myhill Nerode Theorem for LSAs). Let $S \subseteq (\mathbf{R}^d)^*$ be a set of sequences. The following three statements are equivalent.

- (1) The set S is regular.
- (2) there exists a modified Myhill-Nerode relation with respect to S .
- (3) The equivalent relation \approx_S is of finite index and right linearly separable.

Proof. (1) \Rightarrow (2):

Let $M = (d, Q, q_0, F, w, h, s)$ be an LSA accepting S . The relation \equiv_M is right invariant because

$$\begin{aligned} \alpha \equiv_M \beta &\Rightarrow \delta(q_0, \alpha) = \delta(q_0, \beta) \\ &\Rightarrow \forall \gamma \in (\mathbf{R}^d)^* \delta(q_0, \alpha\gamma) = \delta(q_0, \beta\gamma) \\ &\Rightarrow \forall \gamma \in (\mathbf{R}^d)^* \alpha\gamma \equiv_M \beta\gamma . \end{aligned}$$

The relation \equiv_M is of finite index because the number of equivalence classes of \equiv_M is bounded by $|Q|$.

Let $[\alpha]_{\equiv_M}$ be any equivalence class of \equiv_M . Consider the relation $R([\alpha]_{\equiv_M})$ induced by $[\alpha]_{\equiv_M}$. Let $p = \delta(q_0, \alpha)$ and let $h(p) = \langle h_1, \dots, h_{i_p} \rangle$. We define a partition

$\pi = \{S_1, \dots, S_{i_p+1}\}$ of \mathbf{R}^d such that, for $k = 1, \dots, i_p + 1$, it holds that

$$S_k \stackrel{\text{def}}{=} \{x \in \mathbf{R} \mid h_{k-1} < x \otimes w(p) \leq h_k\} ,$$

where $h_0 = -\infty$ and $h_{i_p+1} = \infty$. It is clear that the partition π of \mathbf{R}^d is linearly separable. Furthermore, it is straightforward to see that $x, y \in S_k$ implies $\delta(p, x) = \delta(p, y)$ implies $\alpha x \equiv_M \alpha y$ implies $x R([\alpha]_{\equiv_M}) y$. Thus, π is finer than the equivalence classes of $R([\alpha]_{\equiv_M})$, which implies that \equiv_M is right linearly separable.

Finally, we have

$$\begin{aligned} S &= L(M) = \{\alpha \in (\mathbf{R}^d)^* \mid \delta(q_0, \alpha) \in F\} \\ &= \cup_{f \in F} \{\alpha \in (\mathbf{R}^d)^* \mid \delta(q_0, \alpha) = f\} \\ &= \cup_{f \in F} [\alpha_f]_{\equiv_M} , \end{aligned}$$

where α_f is any representative element α such that $\delta(q_0, \alpha) = f$. Thus, S is a union of some equivalence classes of \equiv_M .

Therefore, \equiv_M is a Myhill-Nerode relation with respect to S .

(2)⇒(3):

Let \equiv be a Myhill-Nerode relation with respect to S . The relation \equiv is finer than \approx_S because

$$\begin{aligned} \alpha \equiv \beta &\Rightarrow \forall \gamma \in (\mathbf{R}^d)^*, \alpha\gamma \equiv \beta\gamma \\ &\Rightarrow \forall \gamma \in (\mathbf{R}^d)^*, \alpha\gamma \in S \text{ iff } \beta\gamma \in S \\ &\Rightarrow \alpha \approx_S \beta . \end{aligned}$$

Thus, the relation \approx_S is of finite index.

It is clear from definition of \approx_S that \approx_S is right invariant. Therefore we deduce from Lemma 1 that \approx_S is right linearly separable.

(3)⇒(1):

Let α be any element in $(\mathbf{R}^d)^*$. Since \approx_S is right linearly separable, there exists a finite linearly separable partition $\pi = \{S_1, \dots, S_k\}$ which is finer than the equivalence classes of $R([\alpha]_{\approx_S})$. Thus, there exist $w \in \mathbf{R}^d$ and $h = \langle h_1, \dots, h_{k-1} \rangle \in (\mathbf{R}^1)^*$ such

that

$$h_{i-1} < w \otimes x \leq h_i \Leftrightarrow x \in S_i \quad (i = 1, \dots, k) ,$$

where $h_0 = -\infty$ and $h_k = \infty$. Such w and h are denoted by w_α and h_α , respectively. Note that $h_{\alpha, i-1} < x \otimes w_\alpha \leq h_{\alpha, i}$ iff $x \in S_i$. Then, we define an LSA $M' = (d, Q', q'_0, F', w', h', s')$, where

$$\begin{aligned} Q' &= (\mathbf{R}^d)^* / \approx_S , & q'_0 &= [\lambda]_{\approx_S} , & F' &= \{[\alpha]_{\approx_S} \mid \alpha \in S\} , \\ \delta'([\alpha]_{\approx_S}, x) &= [\alpha x]_{\approx_S} , & w'([\alpha]_{\approx_S}) &= w_\alpha , & h'([\alpha]_{\approx_S}) &= h_\alpha . \end{aligned}$$

Since \approx_S is of finite index, the set Q' is finite. The function δ' is well-defined since \approx_S is right invariant and right linearly separable. The selection of α in the definition of w' and h' could be arbitrary. Note that for any $\alpha, \beta \in (\mathbf{R}^d)^*$, the equality $\delta_{M'}([\alpha]_{\approx_S}, \beta) = [\alpha\beta]_{\approx_S}$ holds. Finally, we have

$$\begin{aligned} \alpha \in L(M') &\Leftrightarrow \delta_{M'}(q'_0, \alpha) \in F' \\ &\Leftrightarrow \delta_{M'}([\lambda]_{\approx_S}, \alpha) \in F' \\ &\Leftrightarrow [\alpha]_{\approx_S} \in F' \\ &\Leftrightarrow \alpha \in S . \end{aligned}$$

Therefore, $L(M') = S$, which implies that S is regular. \square

5. Uniqueness of Minimum State LSA

In this section, we demonstrate the uniqueness of the minimum state LSA for a given one.

Let S be any regular subset of $(\mathbf{R}^d)^*$. In the sequel, by

$$M_{\min} = (d, Q_{\min}, q_{0\min}, F_{\min}, w_{\min}, h_{\min}, s_{\min})$$

we denote the LSA M' constructed in the proof **(3)→(1)** of Theorem 1. We will prove that the minimum state LSA accepting S is determined uniquely in the sense that M_{\min} is **isomorphic** to every minimum state LSA. The definition of isomorphism is described below.

Let $M = (d, Q, q_0, F, w, h, s)$ and $M' = (d, Q', q'_0, F', w', h', s')$ be LSAs. We say that

M is isomorphic to M' iff there exists a bijection f from Q to Q' satisfying the following conditions:

- (1) $f(q_0) = q'_0$.
- (2) $f(\delta(q, x)) = \delta'(f(q), x)$ holds for any $q \in Q$ and $x \in \mathbf{R}^d$.
- (3) $f(F) = F'$.

Theorem 2 (Uniqueness of Minimum State LSA). Let S be a regular subset of $(\mathbf{R}^d)^*$. The LSA M_{\min} is isomorphic to every minimum state LSA accepting S .

Proof. Omitted because of the space constraint. This theorem can be proved in the similar way as in the theorem for finite automata. \square

6. Characterization of Minimum State LSA

In this section, we characterize the minimum state LSA for a given one.

Let $M = (d, Q, q_0, F, w, h, s)$ be an LSA accepting the set of sequences S with no unreachable states. For any $p, q \in Q$, there exists $\alpha, \beta \in (\mathbf{R}^d)^*$ such that $\delta(q_0, \alpha) = p$ and $\delta(q_0, \beta) = q$. We define the equivalence relation \sim over Q as follows:

$$p \sim q \stackrel{\text{def}}{\iff} \alpha \approx_S \beta .$$

The choice of α and β can not be determined uniquely. However, for $\alpha', \alpha'' \in (\mathbf{R}^d)^*$ such that $\delta(q_0, \alpha') = \delta(q_0, \alpha'')$, we have $\delta(q_0, \alpha'\gamma) = \delta(q_0, \alpha''\gamma)$ for any $\gamma \in (\mathbf{R}^d)^*$. Hence, it holds that $\alpha' \approx_S \alpha''$. Therefore, \sim is well-defined.

We say that p and q are **indistinguishable** iff $p \sim q$. The states p and q are said to be **distinguishable** iff $p \not\sim q$.

Example 2. Consider an LSA in Figure 1. The equality $w(q_2) = w(q_3)$ holds, which implies that $x \otimes w(q_2) = x \otimes w(q_3)$ for any $x \in \mathbf{R}^d$. If $x \otimes w(q_2) = x \otimes w(q_3) \leq 10$ holds, then $\delta(q_2, x) = \delta(q_3, x) = q_3$; otherwise $\delta(q_2, x) = \delta(q_3, x) = q_1$ holds. Thus we have $\delta(q_2, x) = \delta(q_3, x)$ for any $x \in \mathbf{R}^d$, which implies that $q_2 \sim q_3$, that is, q_2 and q_3 are indistinguishable.

Let $x_1 = (1, 1)$. We obtain $x_1 \otimes w(q_1) = 3/\sqrt{5}$, which implies that $\delta(q_1, x_1) = q_2$. We

also obtain $x_1 \otimes w(q_2) = x_1 \otimes w(q_3) = 7/5$, which implies that $\delta(q_2, x_1) = \delta(q_3, x_1) = q_3$. Thus we have $q_1 \not\sim q_2$ and $q_1 \not\sim q_3$, that is, q_1 and q_2 (or q_1 and q_3) are distinguishable. \square

Lemma 2.

$$p \sim q \iff \forall \gamma \in (\mathbf{R}^d)^*, \delta(p, \gamma) \in F \text{ iff } \delta(q, \gamma) \in F .$$

Proof. We have

$$\begin{aligned} p \sim q &\iff \exists \alpha, \beta \in (\mathbf{R}^d)^*, \delta(q_0, \alpha) = p, \delta(q_0, \beta) = q, \alpha \approx_S \beta \\ &\iff \exists \alpha, \beta \in (\mathbf{R}^d)^*, \delta(q_0, \alpha) = p, \delta(q_0, \beta) = q, \\ &\quad \forall \gamma \in (\mathbf{R}^d)^*, \alpha\gamma \in L(M) \text{ iff } \beta\gamma \in L(M) \\ &\iff \exists \alpha, \beta \in (\mathbf{R}^d)^*, \delta(q_0, \alpha) = p, \delta(q_0, \beta) = q, \\ &\quad \forall \gamma \in (\mathbf{R}^d)^*, \delta(q_0, \alpha\gamma) \in F \text{ iff } \delta(q_0, \beta\gamma) \in F \\ &\iff \forall \gamma \in (\mathbf{R}^d)^*, \delta(p, \gamma) \in F \text{ iff } \delta(q, \gamma) \in F . \end{aligned}$$

\square

Furthermore, Lemma 2 immediately implies Lemma 3.

Lemma 3.

$$p \sim q \iff \forall \alpha \in (\mathbf{R}^d)^*, \delta(p, \alpha) \sim \delta(q, \alpha) .$$

Proof. We have

$$\begin{aligned} p \sim q &\iff \forall \alpha, \beta \in (\mathbf{R}^d)^*, \delta(p, \alpha\beta) \in F \text{ iff } \delta(q, \alpha\beta) \in F \\ &\iff \forall \alpha, \beta \in (\mathbf{R}^d)^*, \delta(\delta(p, \alpha), \beta) \in F \text{ iff } \delta(\delta(q, \alpha), \beta) \in F \\ &\iff \forall \alpha \in (\mathbf{R}^d)^*, \delta(p, \alpha) \sim \delta(q, \alpha) . \end{aligned}$$

\square

For any $p \in Q$, by $r(p)$ we denote a **representative element** of $[p]_{\sim}$.

Lemma 4.

$$\delta(r(p), x) \sim r(\delta(p, x)) .$$

Proof. For any $x \in (\mathbf{R}^d)^*$, we have

$$\begin{aligned} \delta(r(p), x) &\sim \delta(p, x) \quad (\text{By Lemma 3}) \\ &\sim r(\delta(p, x)) . \end{aligned}$$

□

We will prove that the minimum state LSA is obtained by identifying indistinguishable states.

We define an LSA

$$M/\sim = (d, Q', q'_0, F', w', h', s') ,$$

where

$$\begin{aligned} Q' &= Q/\sim , \quad q'_0 = [q_0]_{\sim} , \quad F' = \{[q]_{\sim} \mid q \in F\} , \quad \delta'([q]_{\sim}, x) = [\delta(r(q), x)]_{\sim} , \\ w'([q]_{\sim}) &= w(r(q)) , \quad h'([q]_{\sim}) = h(r(q)) . \end{aligned}$$

Lemma 5. For $\alpha \in (\mathbf{R}^d)^*$,

$$\delta_{M/\sim}([p]_{\sim}, \alpha) = [\delta(p, \alpha)]_{\sim} .$$

Proof. We will prove this lemma by induction on $|\alpha|$.

In case of $|\alpha| = 0$, i.e., $\alpha = \lambda$, we have

$$\begin{aligned} \delta_{M/\sim}([p]_{\sim}, \lambda) &= [p]_{\sim} \\ &= [\delta(p, \lambda)]_{\sim} . \end{aligned}$$

Assume that the claim holds for $|\alpha| \leq k$ and consider the case of $|\alpha| = k + 1$. Let $\alpha = \beta x$ ($\beta \in (\mathbf{R}^d)^*$, $x \in \mathbf{R}^d$). Then, we have

$$\begin{aligned} \delta_{M/\sim}([p]_{\sim}, \alpha) &= \delta_{M/\sim}(\delta_{M/\sim}([p]_{\sim}, \beta), x) \\ &= \delta_{M/\sim}([\delta(p, \beta)]_{\sim}, x) \quad (\text{By induction hypothesis}) \\ &= [\delta(r(\delta(p, \beta)), x)]_{\sim} \\ &= [r(\delta(\delta(p, \beta), x))]_{\sim} \quad (\text{By Lemma 4}) \\ &= [r(\delta(p, \beta x))]_{\sim} \\ &= [\delta(p, \beta x)]_{\sim} \\ &= [\delta(p, \alpha)]_{\sim} . \end{aligned}$$

□

Lemma 6.

$$p \in F \text{ iff } [p]_{\sim} \in F' .$$

Proof. From the definition of F' , it is clear that $p \in F$ implies $[p]_{\sim} \in F'$. Suppose that $[p]_{\sim} \in F'$. Then, there exists $q \in F$ such that $p \sim q$. We deduce from $\delta(q, \lambda) \in F$ and Lemma 2 that $p = \delta(p, \lambda) \in F$ holds. □

Lemma 7.

$$L(M/\sim) = L(M) .$$

Proof. For any $\alpha \in (\mathbf{R}^d)^*$, we have

$$\begin{aligned} \alpha \in L(M/\sim) &\Leftrightarrow \delta_{M/\sim}(q'_0, \alpha) \in F' \\ &\Leftrightarrow \delta_{M/\sim}([q_0]_{\sim}, \alpha) \in F' \\ &\Leftrightarrow [\delta_M(q_0, \alpha)]_{\sim} \in F' \quad (\text{By Lemma 5}) \\ &\Leftrightarrow \delta_M(q_0, \alpha) \in F \quad (\text{By Lemma 6}) \\ &\Leftrightarrow \alpha \in L(M) . \end{aligned}$$

□

Theorem 3 (Characterization of Minimum State LSA). Let M be an LSA. The LSA M/\sim is a minimum state LSA such that $L(M/\sim) = L(M)$.

Proof. Lemma 7 implies that $L(M/\sim) = L(M)$ holds.

It is clear that \sim is an equivalence relation. From the definition of \sim , the index $|Q/\sim|$ of \sim is equal to $|(\mathbf{R}^d)^*/\approx_S|$. Therefore we conclude that $\text{size}(M/\sim) = |Q/\sim| = |(\mathbf{R}^d)^*/\approx_S| = \text{size}(M_{\min})$. □

Example 3. Consider an LSA M_1 in Figure 1. From the example above, the states q_2 and q_3 are indistinguishable; and the states q_1 and q_2 (or q_1 and q_3) are distinguishable. Let q_4 be a state obtained by merging q_2 with q_3 . Thus, we obtain the minimum state LSA for M_1 , illustrated in Figure 2. □

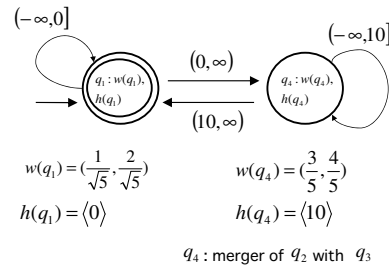


Fig. 2 LSA M_1 / \sim

7. Conclusions

In this paper, we theoretically analyzed a certain extension of a finite automaton, called a linear separation automaton (LSA). We developed the theory of minimizing LSAs by using Myhill-Nerode theorem for LSAs. Myhill-Nerode theorem for LSAs is established as in the original finite automata. The minimum state LSA for a given one is unique, and is characterized by using Myhill-Nerode theorem for LSAs.

In order to develop a theory of learning computational models like LSAs, we need computational analysis on the models themselves. The theory of minimizing LSAs will play a crucial roles in the theory of learning LSAs as in the original finite automata^{12),13)}.

Some of our future works are the following.

In this paper, we do not give algorithms for minimizing LSAs. Therefore in the next paper, we will present some algorithms for minimizing LSAs, which are the naive algorithm directly induced by Myhill-Nerode theorem for LSAs, and a more efficient algorithm.

The development of the theory of learning LSAs is one of the future research topics. Its theory will help us solve some application problems including weather forecasting, motion recognition, and time-sequential image analysis.

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