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A Model of Learning and Recognizing Machine

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1. *Memory structure and self-organization*

Every man has his memory structure that has been constructed through his life and self-organized by his experience. It depends on his memory structure whether a piece of information having been accepted by his sensory organ turns out to be only a noise for him or recalls some concept or other. The S model treated in this paper has also its memory structure changable in its recognition process. A state of the memory structure is called a concept in the S model.

In most papers on pattern recognition, a machine learns a pattern even if it has not recognized any patterns nor organized any concepts in advance. Namely, the machine can recognize a pattern only from input signals. We call the concept which corresponds to this pattern primitive concept. In human cases, on the other hand, there are many abstruct concepts that can not be recognized without prerequisite of other concepts organized in advance. For instance, the concept "symbol" can not exist without a learning stage of remembering individual figures such as +, −, *, ⋯. In the similar way, such a concept of the S model that is recognized by using some previously organized concepts is called compound concept, and the previously organized concepts are called constituents of the new concept. Of course, any concept can be a constituent of a compound concept. The process generating a compound concept from costituents is classified into two groups, that are respectively called concept generation by learning a known pattern and concept generation by discovering an unknown pattern, which will be treated in Section 3.

2. *Language and its semantics*

The reality of a human concept is the mutual relation between substances cognized by a man and is not a connection between words. A word as well as a language is a symbol corresponding to a part of substances understood by human reason when a man cognizes the substances. Even if there might exist a machine which can learn new concepts considered in the previous section, any concept in the machine, as far as it results only from learning a language (that is nothing but a symbol), may be completely different from what a man

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recalls from the same language. The machine could be said to understand a natural language, only if this machine cognizes substances accompanied by the language to the almost same extent as a man does. (Let us call such substances semantics in this paper.)

It seems to be apparent that the semantics which takes an essential role in the learning machine is as well restricted as in human recognition by the following two conditions. i) A restriction from a limited range of input information which the machine can accept from its environment, or a restriction coming from its sphere of action and the quality of its sensory organ. ii) A restriction resulted from structure and entities of the inner system of the machine, which are main factors to provide the ability of the machine.

The first restriction to the quality and quantity of the information is not treated in this paper, while the second restriction to information processing faculty of a machine is the main subject discussed in this paper.

3. *A model of learning and recognizing machine*

——Proposition of the S *model*——

A machine satisfying the following eight assumptions is called the S model.

Assumption 1: The S model is composed of sensory unit I, memory unit M, control unit C and output unit O.

Assumption 2: The sensory unit I can receive input information discretely in time with a constant interval τ. Let Ξ be a set of all acceptable input signals to I, and Ξ^* be a set of all finite sequences of elements in Ξ. Ξ^* implies subsets Φ and Σ which are not null and satisfy the following equation:

$$(\exists m)(\forall \varphi \in \Phi)(\exists \sigma \in \Sigma)(m: \varphi \rightarrow \sigma), \qquad (1)$$

Whenever I accepts an element $\xi \in \Xi$, I transmits a finite number of signals $\{\theta\}_\xi$ to M. By Ξ_t^*, Σ_t and Φ_t we denote the subsets from the sets of input information Ξ^*, Σ and Φ that I has received by the time t respectively.

Assumption 3: The memory unit M is composed of four kinds of entities α, β, γ and δ, that are respectively infinite (or self-reproducible):

$$M = \{\alpha, \beta, \gamma, \delta\}. \qquad (2)$$

Each entity has two states, excited state (1) and unexcited state (0). If necessary, the state at the time t of each entity is denoted as $\alpha_t(0)$, $\beta_t(1)$ and so on. Entities that have never been excited are denoted by $\alpha_t(*)$, $\beta_t(*)$ and so on.

Assumption 4: Let M_0 be the initial state of M. Then we have

$$M_0 = \{\alpha_0(*), \beta_0(*), \gamma_0(*), \delta_0(*)\}. \qquad (3)$$

Assumption 5: (Self-organization of associative function)

5.1: Whenever any two entities x and y in M are excited sequentially at the discrete time point $t-1$ and t respectively, x is combined with y by the strength $N_t(x, y)$ in the direction $x \rightarrow y$, where $N_t(x, y)$ is in proportion to the number of times which y was sequentially excited by x by the time t and is in inverse proportion to the number of unexcited times. Then we have

$$\begin{cases} N_t(x, y) = N_{t-1}(x, y) + na - n', \\ N_0(x, y) = 0, \end{cases} \tag{4}$$

with $t = 1, 2, \cdots$,

$$a = \begin{cases} 1, \text{ if } x_{t-1}(1) \wedge y_{t-1}(0) \wedge y_t(1), \\ 0, \text{ otherwise,} \end{cases}$$

and n and n' are the proportional constants.

5.2: Whenever any two entities x and y in M are excited simultaneously, x is combined with y by the strength $K_t(x, y)$, where $K_t(x, y)$ is in proportion to the number of times which x and y were simultaneously excited by the time t and is in inverse proportion to the number of unexcited times. Then we have

$$\begin{cases} K_t(x, y) = K_{t-1}(x, y) + kb - k' \\ K_0(x, y) = 0, \end{cases} \tag{5}$$

with k and k' are the proportional constants and $t = 1, 2 \cdots$,

$$b = \begin{cases} 1, \text{ if } x_t(1) \wedge y_t(1), \\ 0, \text{ otherwise.} \end{cases}$$

5.3: Under the conditions given below, four kinds of entities $\alpha(*)$, $\beta(*)$, $\gamma(*)$, $\delta(*)$ are excited for a certain interval $\varepsilon \ll \tau$. If once excited by a signal, they are excited only by the same signal for the interval ε. In this way, an associative function to the signal is generated.

Condition 1: If an unexperienced signal is applied to M at the time t, an $\alpha(*)$ is excited by the signal.

Condition 2: If a sequence of any entities, that are not necessarily different from one another, has satisfied the following relations for the first time, the sequential excitation of $x_1, x_2, \cdots\cdots, x_n$ causes an excitation of a $\beta(*)$ at the time t:

$$N_{t-n}(x_1, x_2) \geqq T_1 \wedge N_{t-n+1}(x_2, x_3) \geqq T_1 \wedge \cdots \wedge N_{t-1}(x_{n-1}, x_n)$$
$$\geqq T_1 \wedge (\forall x \in M)(N_t(x_n, x) < T_1 \vee N_{t-1}(x_n, x) \geqq T_1).$$

Condition 3: If a set of any entities, that differ from one another, has satisfied the following relation at the time t for the first time, the set $x_1, x_2, \cdots, x_n$ causes an excitation of a $\gamma(*)$ at the time $t+\omega$, where $\omega \ll \tau \wedge \omega > \varepsilon$:

$$K_t(x_i, x_j) \geqq T_2, \; i, j = 1 \sim n, \; i \neq j.$$

Condition 4: If any two of the input signals, φ and σ, satisfy the mapping relation (1), a $\delta(*)$ is excited to combine the entities associated with φ and the entities associated with σ in the learning mode (See Assumption 6.).

Definition 1: $N_t(x, y)$ is called self-organizing state of sequential excitation of x, y at the time t, $\{N_t(x, y) \mid x, y \in M_t\}$ is called self-organizing state of sequential excitation of M at the time t, $K_t(x, y)$ is called self-organizing state of simultaneous excitation of x, y at the time t and $\{K_t(x, y) \mid x, y \in M_t\}$ is called self-organizing state of simultaneous excitation of M at the time t, where M_t is a set of entities that have excited by the time t.

Definition 2: T_1 is called β-threshold and T_2 is called γ-threshold.

Definition 3: The sets $P_t(x)$, $R_t(x)$ and $L_t(x)$ defined by the following equations (6)~(8) are called congener, right series and left series respcctively:

$$P_t(x)=\{y\,|\,K_t(x, y)\geqq T_2\}, \tag{6}$$

$$R_t(x)=\{y\,|\,N_t(x, y)\geqq T_1\}, \tag{7}$$

$$L_t(x)=\{y\,|\,N_t(y, x)\geqq T_1\}. \tag{8}$$

Definition 4: β, γ, $P(x)$, $R(x)$ and $L(x)$ are called concepts.

Definition 5: If a concept y is excited by set of concepts $\{x\}$, such relation is expressed as $[y\,|\,\{x\}]$. Members x inside the right half of the square blacket $[\ ]$ are called constituents of the concept y inside the left half. Then we have the following relations:

$$[P_t(x)\,|\,\{y\,|\,K_t(x, y)\geqq T_2\}], \tag{9}$$

$$[R_t(x)\,|\,\{y\,|\,N_t(x, y)\geqq T_1\}], \tag{10}$$

$$[L_t(x)\,|\,\{y\,|\,N_t(y, x)\geqq T_1\}], \tag{11}$$

$$[\beta_t\,|\,\{x_1, x_2, \cdots, x_n \text{ that satisfy Condition 2}\}], \tag{12}$$

$$[\gamma_t\,|\,\{x_1, x_2, \cdots, x_n \text{ that satisfy Condition 3}\}]. \tag{13}$$

Definition 6: A concept x which satisfies the following relation is called primitive concept:

$$[x\,|\,\{\alpha\}]. \tag{14}$$

Definition 7: Let ξ^+ be a set of concepts excited corresponding to the input signal $\xi\in\Xi$, and let $\delta(\varphi^+, \sigma^+)$ express the relation between two concepts φ^+ and σ^+ that are excited corresponding respectively to two inputs φ and σ according to Condition 4 in Assumption 5. φ^+ is called semantics of σ, and the set $\{\sigma^+\}$ is called language of the S model.

Assumption 6: The control unit C has two modes, learning mode and normal mode. In the learning mode, inputs provided by eqs. (15)~(17) below immediately cause the self-organizing state of simultaneous and/or sequential excitation over the β- and/or γ-threshold, and make $\delta(*)$ turns into $\delta(1)$ to form the relation $\delta(\varphi^+, \sigma^+)$:

$$\sigma\cap\varphi, \tag{15}$$

$$\sigma\cap\{\varphi'\,|\,[\varphi^+\,|\,\{\varphi'^+\}]\}, \tag{16}$$

$$\sigma\cap\{\sigma'\,|\,[\varphi^+\,|\,\{\varphi'^+\}]\wedge\delta(\varphi'^+, \sigma'^+)\}, \tag{17}$$

where $m: \varphi\rightarrow\sigma$. $\sigma\cap\varphi$ in eq. (15) means that the language σ and its substance φ are applied to the input unit I at the same time, eq. (16) means that the language σ and the constituents of its substance are applied to I, and eq. (17) means that the language σ and the languages $\{\sigma'\}$ of the constituents of its substance are applied to I if $\{\sigma'^+\}$ have already organized.

In the normal mode, on the other hand, σ and φ are independently applied to I and a number of repeated input signals are necessary for $N_t(x, y)$ or $K_t(x, y)$

to exceed its threshold and to produce a new concept φ^+ or σ^+. That is to say, the coefficients in eqs. (4) and (5) have the following properties:

$$n_L > n_N,\ k_L > k_N, \tag{18}$$

$$n_{N'} > n_{L'},\ k_{N'} > k_{L'}, \tag{19}$$

where the suffices N and L denote the normal and learning mode respectively.

Assumption 7: After a relation $\delta(\varphi, \sigma)$ is formed in the memory unit M, φ(or σ) operates to excite σ(or φ) if the system is in the normal mode. In this case the excitation occurs in the probabilistic way, i.e., the probability of the excitation is proportional to the self-organizing state of the constituents if φ^+ is $P(x)$, $R(x)$ or $L(x)$ defined in Definition 3. In contrast, the excitation occurs in the deterministic way if φ^+ is composed of the entity β or γ.

Definition 8: The self-organization of a new concept in the learning mode in Assumption 6 is called "concept generation by learning a known pattern", while the self-organization of a new concept in the normal mode is called "concept generation by discovering an unknown pattern". In either case, the constituents of a concept are called "characteristics" of the concept and the language σ^+ that corresponds to the concept φ^+ through the relation $\delta(\varphi^+, \sigma^+)$ is called "definition" of the concept. This relation——which language corresponds to what semantics——is called "law of the definition". Differences between numbers of definitions are determined by the relation $\delta(\varphi^+, \sigma^+)$.

Assumption 8: The output unit O puts out the elements $\{\sigma\}$ in the set Σ, which correspond to the language of the S model $\{\sigma^+\}$ in the following way:

$$\{\sigma^+ \mid \delta(\varphi^+, \sigma^+) \wedge ((\varphi^+(1) \vee [\varphi^+ \mid \{\varphi'^+(1), \cdots\}]) \vee \sigma^+(1))\} \tag{20}$$

where $\{\varphi'^+(1), \cdots\}$ means that there exists at least one element of the set $\{\varphi'^+, \cdots\}$ in the excitation state.

4. *Behaviour of the S model*

Let $\{x\}_\alpha$ denote the set of all concepts that include some specified α-entity in the inverse tracing of the constituents of the concepts x. If the concepts which are included in any two elements $\{x\}_{\alpha_i}$ and $\{x\}_{\alpha_j}$ of a family of set $\{\{x\}_\alpha$: for all $\alpha \in M\}$ are completely coincide, we denote the relation between the two elements by

$$\{x\}_{\alpha_i} \equiv \{x\}_{\alpha_j}.$$

Because this relation expresses the equivalence relation, the family of sets is partitioned into equivalence classes of the family, which are the smallest units of recognizing function in the S model at a time t.

Definition 9: A set of index in an equivalence class formed by the relation $\equiv$ on a family of sets $\{\{x\}_\alpha$, for all $\alpha \in M_t\}$ is called elementary concept e_i. A set of the elementary concept at a discrete time t is denoted E_t.

Let an input $\xi^* = \xi_1 \xi_2 \cdots \xi_n$ be applied to the S model at a discrete time t.

The following notations are introduced:

$$\{\alpha\}_{\xi_i}=\{\alpha \mid \alpha \text{ excited by } \xi_i\} \text{ for } i=1, 2, \cdots, n, \tag{21}$$

$$\{e\}_{\xi^*}=\{e \mid \{\alpha\}_{\xi_i} \cap e \neq \phi, \text{ for } e \in E_t,\ i=1, 2, \cdots, n\}, \tag{22}$$

$$e^c=\{\alpha \mid \alpha \in \{\alpha\}_{\xi_i} \wedge (\forall e \in \{e\}_{\xi^*})(\alpha \notin e), \text{ for } i=1, 2, \cdots, n\}. \tag{23}$$

With these notations every $\{\alpha\}_{\xi_i}$, $i=1, 2, \cdots, n$ falls into one of the following five cases:

Case 1: $(\exists \alpha_i, \alpha_j)(K_{t+l}(\alpha_i, \alpha_j) < T_2)$, $l=1, 2, \cdots, n$. (24)

No elementary concepts can be formed.

Case 2: $(\exists \alpha_i, \alpha_j)(\alpha_i, \alpha_j \in e^c \wedge K_{t+l}(\alpha_i, \alpha_j) \geq T_2)$, $l=1, 2, \cdots, n$. (25)

A new elementary concept e_1 is formed:

$$e_1=\{\alpha_i, \alpha_j\}. \tag{26}$$

Case 3: $(\exists \alpha_i, \alpha_j)(\alpha_i \in e^c \wedge \alpha_j \in e_k \wedge e_k \in \{e\}_{\xi^*} \wedge K_{t+l}(\alpha_i, \alpha_j) \geq T_2)$,
$l=1, 2, \cdots, n$. (27)

Let $\{\alpha_i\}$ (or $\{\alpha_j\}$) be the set of all α_i(or α_j) satisfying eq. (27), then the following three new elementary concepts are formed:

$$e_{2.1}=\{\alpha_i\},\ e_{2.2}=\{\alpha_j\},\ e_{2.3}=e_k-e_{2.2}. \tag{28}$$

Case 4: $(\exists \alpha_i, \alpha_j)(\alpha_i \in e \wedge \alpha_j \in e' \wedge e \in \{e\}_{\xi^*} \wedge e' \in \{e\}_{\xi^*} \wedge e \neq e' \wedge$
$K_{t+l}(\alpha_i, \alpha_j) \geq T_2)$, $l=1, 2, \cdots, n$. (29)

Let $\{\alpha_i\}$(or $\{\alpha_j\}$) be the set of all α_i(or α_j) satisfying eq. (29) simultaneously, then the following four new elementary concepts are formed:

$$e_{3.1}=\{\alpha_i\},\ e_{3.2}=e-e_{3.1}, \tag{30}$$

$$e_{3.3}=\{\alpha_j\},\ e_{3.4}=e'-e_{3.3}. \tag{31}$$

Case 5: $(\exists \alpha_i, \alpha_j)(\alpha_i, \alpha_j \in e \wedge e \in \{e\}_{\xi^*})$. (32)

Let $\{\alpha_i\}$ be the set of all α_i and α_j satisfying eq. (32), then the two new elementary concepts $e_{3.1}$ and $e_{3.2}$ in eq. (30) are formed.

Using eqs. (26), (28), (30) and (31), the congeners that are generated by the new elementary concepts in the above cases are gained:

$$P(e_1)=\phi, \tag{33}$$

$$P(e_{2.1})=\{e_{2.2}\}, \tag{34}$$

$$P(e_{2.2})=\{e_{2.1}, e_{2.3}\} \cup P(e_k), \tag{35}$$

$$P(e_{2.3})=P(e_k) \cup \{e_{2.2}\}, \tag{36}$$

$$P(e_{3.1})=\{e_{3.3}, e_{3.2}\} \cup P(e), \tag{37}$$

$$P(e_{3.2})=P(e) \cup \{e_{3.1}\}, \tag{38}$$

$$P(e_{3.3})=\{e_{3.1}, e_{3.4}\} \cup P(e'), \tag{39}$$

$$P(e_{3.4})=P(e') \cup \{e_{3.3}\}. \tag{40}$$

By repeating the above mentioned procedure for all pairs of $\alpha \in \bigcup_{i=1}^{n} \{\alpha\}_{\xi_i}$, whose self-organizing state of simultaneous excitation exceeds the γ-threshold, the $\gamma(*)$-entity obtained by $\{\alpha\}_{\xi_l}$ in eq. (21) is given as follows:

$$[\gamma_l \mid \{x \mid x \subseteqq e_1 \cup e_{2.1} \cup e_{2.2} \cup e_{3.1} \cup e_{3.3}\}], \text{ for } l=1, 2, \cdots, n. \tag{41}$$

Using eq. (41), the $\beta(*)$-entity obtained by the input ξ^* is given as follows:

$$[\beta | \{x_i x_j \cdots x_k x_l\}], \tag{42}$$

where i, j, $\cdots$, k, l are consecutive numbers ($i \geqq 1$ and $l \leqq n$) and the self-organizing state of the simultaneous excitation of $x_i \sim x_l$ satisfies Condition 2.

The above consideration directly leads to the following theorems.

Theorem 1: When the S model which is in a self-organizing state receives an input $\xi^* \in \Xi^*$, the behavior of the S model is uniquely determined by eqs. (26), (28), (30), (31) and (33)~(42).

Theorem 2: At any discrete time point, the self-organization of the system S is uniquely determined by all input sequences and their order that have been ever experienced by the S model.

In the original paper in Japanese we discussed on behavior of the S model at a discrete time point t using 7-tuple Fuzzy automaton and on recognition by S model.

5. *Conclusion*

Keeping step with the development of the so called electronic computer, many efforts have been made to afford it with more and more intellectual (non-calculational) works. The efforts are indeed fruitful, so that the objects within capability of the computer are constantly extending. However, in the field of information processing on which the latent meaning of the natural language would have considerable influence, it will take almost unimaginable time and labour to treat ploblems by the present-day electronic computer. In addition to the study of the natural language making use of the present-day computer, it may be worthwhile to examine problems possibly beyond the limit of applicability of the present-day computer.

The language on the one hand and the recognition and control of the primitive concept on the other have been independently dealt with by the learning machine. The research to recognition and control of the primitive concept has been developed as a problem of pattern recognition and as a problem of classification to control adjustable characteristics of patterns by keeping them in the best available state to be separated by various discrimination functions, such as the recognition of the voice, the letter and the figure. On the other hand, the research to the language has been developed as the theory of class provided by its grammar or the theory of automaton to accept the class. It seems to the author to be necessary to unify the results of the both researches, namely, to develope the processing of the natural language standing, in some form or other, on the basis of the problem of pattern recognition.