Evolutionary Regeneration Model of Thought Process

Noboru HOKKYO

Hitachi Energy Research Laboratory, Hitachi 316

(Received September 1, 1981)

A preliminary attempt is made to understand the thought process and the evolution of the nervous system on the same footing as regeneration processes obeying certain recursive algebraic rules which possibly economize the information content of the increasingly complex structural-functional correlate of the evolving and thinking nervous system.

§ 1. Introduction

A mathematical model of the thought process can be given a biological flavour by the inclusion of the evolutionary brain history, and acquires a physical character when each process in the model is understood as an ordered series of developments of a specific structural-functional unit. Previoulsy we proposed a regeneration model of thought process in which the brain was regarded as an autonomous system which not only maps an external object as a pattern of neural firing, but generates automatically a series of patterns out of the original pattern according to certain generation rules. The original firing pattern, the immediate image of the external object, has then a self-reproducing property, and the establishment of the long-term memory, for example, is compared to the fixation of stable biological species according to Darwin’s principle of natural selection in which nature selects species producing the highest number of descendants in a given (fixed or changing) environment. In the case of the brain, past experiences acquired genetically (hereditary skills) as well as individually (memory) through the interaction with the external world constitute the “internal model” of the external world which plays the role of the environment for the “natural selection” of the external information.

In the present paper a preliminary attempt is made to understand the thought process (§ 2) and the evolution of the nervous system (§ 3) on the same footing as regenerative process obeying certain recursive algebraic rules which possibly economize the information content of the increasingly complex structural-functional correlate of the evolving and thinking nervous system.

§ 2. Regeneration model of long-term memory and unstable brain wave oscillations

According to Vygotsky, human thinking is an “inner speech” or a dialogue
with one’s “inner world”. According to Marko,\(^4\) pure thinking is an “inner process” of information flow between the association unit, an integration center for various sensory information, and the memory storage which stores organized past experiences. The information stored in the memory storage is an unconscious information which, however, can be made conscious by being transferred to the association unit by the “stochastic matching”\(^4\) with the sensory information momentarily stored in the association unit.

Previously,\(^1\) we proposed a regeneration model of the long-term memory and unstable brain wave oscillations. There the activity state of the brain was defined by specifying the firing frequency for every cortical neuron of the brain or equivalently by specifying a polynomial

\[ s(x) = \sum_k a_k x^k, \quad s(1) = \sum_k a_k = 1. \quad (1) \]

Here \(a_k\) is the normalized firing frequency of \(k\)th neuron. The firing pattern \(s(x)\) is regarded as an instantaneous reflection within the brain of the immediate sensory information from the external world. It is assumed that the pattern \(s(x)\) is unstable against regenerating its own inner reflection of the type \(s(s(x))\), \(s[s(s(x))], \) etc. in the sense of Hebb’s “disintegrating cell assemblies”\(^5\). Such a model is equivalent to assuming that the function \(s(x)\) not only determines the original pattern of neuron firing in the zeroth generation, but at the same time plays the role of the generating function for new patterns in the next and successive generations (\(a_k\) being reinterpreted as the probability of an active neuron exciting other \(k\) neurons so that \(s'(1) = \sum k a_k = \) regeneration coefficient where \(s' = ds/dx\).)

The regeneration picture is easily generalized to be applicable to composite systems and, in particular, to Marko’s inner process. Let \(s(x)\) be the generating function for the sensory information in the association unit and \(f(x)\) be the generating function for a memory (a set of words or prelinguistic images, feelings or ideas, etc.) in the memory storage. Then the coupled information, \(v(x)\), in the zeroth, first, second, etc. generations are shown to be \(s(x), s(x)s[f(x)], s(x)s[f(x)]s[f^2(x)], \) etc.\(^2\) In general, the generating function for the \(g\)th generation \(v_g(x)\) is

\[ v_g(x) = s(x)v_{g-1}[f(x)], \quad (2) \]

so that the limiting pattern will be a solution of the functional equation

\[ v(x) = s(x)v[f(x)] \quad (3) \]

from which follows

\[ v'(1) = s'(1)/(1-f'(1)). \quad (4) \]

According to Zeeman’s mathematical brain model,\(^6\) the thought process is a
Evolutionary Regeneration Model of Thought Process

Time-dependent transition of the activity pattern $s(x)$ into the fixed point of a continuous map $h: v(x) = h[v(x)]$. In our regeneration model the stable pattern $v(x)$ is reached by the combined action of the external information $s(x)$ and the stored information $f(x)$ so that $v(x) = s(x)v[f(x)]$. This model allows the classification of the memory of the information $s(x)$ into short-term or long-term according as $v'(1) < 1$ or $v'(1) = 1$ (note that $v'(1)$ gives the expected number of secondary neurons activated by a single neuron in the first generation). In particular, the case when $s' = 0$ and $f' = 1$ in Eq. (4) is interpreted as the case of

![Figure 1](https://academic.oup.com/ptp/article-abstract/67/4/1029/1842394)

Fig. 1. Block diagram indicating the flow of information through nervous system (blocks are functional rather than anatomical). The cortex originates as an offshoot of the olfactory sensory organ as an improved organizer of information from thalamic sensory integration center (Th) and as a memory reservoir (Mem). The limbic cortex is found in the brains of all mammals and seems to be responsible for the mood change or other slowly developing change in the internal attitude caused presumably by hormonal mechanisms related to the visceral control. The human consciousness is supposed to be possessed somewhere (Ass) in liaison with linguistic and ideation zone (Mem II) developed late in the neocortical hemisphere of the neomammalian brain. The sensory information $s(x)$ from the external world can acquire an adequate conscious meaning only as far as it requires the modification of the past experience $f(x)$ of the interaction with the external world stored in the memory storage I or requires the improvement of our inner picture $g(x)$ of the external world (our world models) stored in the memory reservoir II. The information $f(x)$, $g(x)$ retrieved from the memory storage I, II is then incorporated into the current information $s(x)$ to yield improved response or improved world models. Thus the main function of the consciousness is thought to be the critical evaluation of our world models (see the Appendix). Hereditary or instinctive bias exemplified by the basal ganglia (Gan) in the reptilian core is found in all animals and serves as a memory storage of the unconscious inherited knowledge for survival.
the instantaneous establishment of the long-term memory (in the Skinner type reinforcement model of learning the instantaneous establishment of the long-term memory is impossible). In the case of an "inner iteration" of a stored information \( f(x) \), we have \( v(x) = f(x)v[f(x)] \). This also explains the occurrence of unstable brain wave oscillations (spontaneous eruption of past experiences \( f(x) \)) when all input sensory information \( s(x) \) are removed.\(^7\)

The block diagram of Fig. 1 shows the regeneration of sensory input information flowing through the model nervous system. In Fig. 1 Marko's original diagram is generalized to take account of the evolutionary aspect of the multilevel brain of higher animals.

§ 3. Evolutionary multilayer model of nervous system

It has been said that Darwin's principle of survival of the fittest is nothing but the tautology of survival of the survivoirs unless we can relate the concept of the fittest to a physically objective "value" characterizing the level of the evolution such as the degree of self-organization.\(^8\) At the molecular level Eigen\(^8\) defined the "selective value" of biopolymers (nucleic acids and proteins) in terms of their ability to reproduce themselves. Then the selective value is regarded as a driving force or a "gradient" for prebiotic evolution of these polymers. At higher organizational levels, the evolution towards higher organisms through selection is thought to proceed concomitantly with the "economization" of the structural information content, that is, the lowering of the number of instructions or specifications required to create, from a molecular chaos, organisms possessing increasingly complex and subtle structural-functional architecture.

It is known that brains of lower animals, say lizards, contain main division and levels of the human brain.\(^9\) In fact, recent anatomophysiochemical observations seem to provide evidence that the human brain has expanded along the lines of three basic patterns which may be characterized as the ancient reptilian core, the old mammalian or visceral brain (limbic system), and the neocortex corresponding to three levels of the brain activity: instinctive, emotional, and intellectual (Fig. 1).\(^9\)

Imagine a simplest sensory information flow structure through the thalamo-cortical system of "lizard" in which the thalamus, the integration center of sensory information, is connected by a feedback loop to the cortex originated as a modifier or a facilitator of olfactory sensory system. Let the regeneration function for the sensory information arriving at the thalamus and the cortex be denoted by \( s(x) \) and \( f_c(x) \), respectively. Then the regeneration function \( v(x) \) for the combined thalamo-cortical system of our hypothetical lizard will have the property (c.f., Eq. (4))

\[
v'(1) = R(s'(1), f_c'(1)) = \frac{s'(1)}{1 - f_c'(1)},
\]

(5)
where the function $R$ is defined by

$$R(x, y) = x/(1 - y).$$

The next step in the development of lizard's brain towards, say reptilian brains, will be the transfer of individually acquired memories and skills for the survival to the hereditary memory storage. Then "reptilian brains" equipped with improved hereditary (instinctive) skills and the memory storage of current and temporal experience (sensory and motory) will have the regenerative property

$$v'(1) = R(s'(1), s''(1)) + R(f_h'(1), f_s'(1), f_m'(1))$$

$$= \frac{s'(1)}{1 - \frac{f_h'(1) + f_s'(1)}{1 - f_m'(1)}}.$$

Here the indices $h$, $s$ and $m$ refer, respectively, to hereditary, sensory and motory memory.

The transition from (5) to (7) implies that our hypothetical brain evolves from the previous structure by a recursive formation of hierarchical structure

$$f_u(x) \rightarrow f_v(x) + R(f_v(x), f_w(x)),$$

where indices $v$, $w$, $z$ denote functional units of successively higher levels evolved from the unit $u$. The idea underlying this formation is that the "economization" of the structural information content or the increase of the "selective value" of a nervous system will result in the simplification in the way of writing the algebraic expression for $v'(1)$.

It is encouraging that some of main psychological functions characterizing the human brain can reasonably be summarized by a simple regenerative structure

$$v'(1) = R(s'(1), f_h'(1)) + R(f_e'(1), f_s'(1), f_e'(1))$$

*) The structural information content of a nervous system can be given a unique numerical value in terms of, for example, the Gödel number $G_n(v'(1))$ associated with the expression for $v'(1)$:

$$G_n(v'(1)) = \prod_{i=1}^{\text{leng}(\omega)} \text{Pr}(k)^{\text{ord}(\omega)}.$$
which is obtained from the corresponding structure (7) for "reptilian brain" by the substitution

\[ f_s \rightarrow f_e, \quad f_m \rightarrow f_h + R(f_i, f_c). \]

Here the index \( e \) refers to the emotional stimulation arriving at the "association unit" from the hypothalamic region lying deep in the cerebral hemispheres of the brain which seems to be responsible for the mood change or other slowly developing change in the internal attitude caused presumably by hormonal mechanisms related to the visceral control; \( b \) to the nonlinguistic information, retrieved from the memory storage of the minor (right) cerebral hemisphere, of past interactions with the external world which is incorporated into the current information \( s(x) \) at the association unit to yield improved anticipately or planned behaviour; \( l \) to the linguistic information of past experience of verbal interactions with the outer or the inner world stored in the dominant (left) hemisphere associated with the "recently" evolved linguistic zone; \( c \) to the information from the conscious self which is supposed to be possessed somewhere in liaison with linguistic and ideatational zones of the dominant hemisphere.

Equation (9) states that the unconscious (reflective) instinctive response \((f_n'(1) \approx 1, v'(1) \approx 1)\) arises for emotionary neutral \((f_e' = 0)\) external stimulation \( s(x) \) under the condition \( f_s'(1) \approx f_i'(1) \approx 0 \) and \( f_e'(1) = 0 \). It is known experimentally\(^{11}\) that the emotionally neutral stimulation does not retrieve information from the memory storage, while action commanding or descriptive verbal stimulation \((f_e'(1) \approx 1)\) is easy to retrieve memory. In general, the external stimulation can acquire adequate conscious meaning \((f_e'(1) \approx 0)\) only so far as it modifies preceding pattern of past experience and future anticipation, giving rise to the emotional insecurity or instability.\(^{11}\)

\(^{11}\) It is also possible to interpret the criterion \( v'(1) = 1 \) as an informational version of Freudian psychodynamic conservation law according to which the creative thinking, for example, is viewed as an eruption of excess psychoenergy generated by the emotional insecurity brought about by a conflict (or an "informational mismatch" in the sense of Marko)\(^{10}\) between the "pleasure principle" (evolutionary skills \( f_s \) for preservation of self and species) and the "reality principle" (individually acquired anticipatory behaviour pattern \( f_i \) coupled with the criterial information from the cultural (verbal) world). Recent clinical and experimental observations seem to provide evidence that the limbic system of the visceral brain has the capacity to generate "eureka pleasure" associated with the sudden leaps of innovative scientific ideas (MacLean).\(^{9}\) A theoretical model of thought processes in which the creative thinking is regarded as an instability or resonant process of selecting a particular mode of thinking was recently proposed by Josephson.\(^{13}\) In our present model the criterion \( v'(1) = 1 \) is interpreted as the criterion for the resonant transfer of the input information into the long-term memory reservoir (§ 2) and the critical correction of our previous long-term world models.
§ 4. Conclusion

A preliminary attempt was made to understand the evolutionary brain history and the thought process on the same footing as regeneration processes obeying certain recursive algebraic rules which possibly economize the information content of the increasingly complex structural-functional correlate of evolving nervous system. It is encouraging that known psychological functions of the human brain can reasonably be summarized in terms of a simple regenerative structure (9) of the nervous system which is obtainable from the corresponding structure (5) for "lizards" by the substitution rules (8) and (10). However, we are left with the difficult task of finding a suitable numerical index (such as structural or functional "entropy") characterizing the level of evolution (such as the degree of self-organization) of the nervous system.

Acknowledgements

The author is grateful to Professor Paul McLean, director of the Laboratory of Brain Evolution and Behavior, U. S. National Institute of Mental Health, for the critical reading of the manuscript and for pointing out the relation between the present recursive multilayer brain model and his Triune brain model summarized in the Appendix in comparison with the Three World brain model of K. Popper and J. Eccles.\textsuperscript{11,12} The author would also like to thank Professor A. Salam of the International Centre for Theoretical Physics, Trieste, for calling his attention to the book by Popper and Eccles.

Appendix

The brain science offers a unique area of the intersection of many branches of science. The ingredients of the evolutionary brain model of the present paper naturally come from many sources in sister sciences of physics which are not always expressed in physicist's language. In Table I the views of neurophysiologists (J. Eccles and P. MacLean) are compared with those of a philosopher of scientific method (K. Popper) on the central issues of brain-mind problems and the evolutionary aspect of thought processes treated in the present paper. Although it is difficult, at the present stage, to justify any physical model of the brain by means of anatomical and physiological evidences, it would be worth while to try further to see if and to what extent these views are interpretable in physicist's language.
### Table I. Comparison of three world model and triune model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Three World Model</th>
<th>Triune Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Comparison of three world model and triune model.</strong></td>
<td>Everything in existence and in experience is subsumed in one or other of three worlds: the world of physical objects including human brains and all kinds of artefacts that man has made for coding information; the world of self-consciousness (mind) and subjective knowledge; and the world of man-made culture and world models.</td>
<td>The human brain (mind) is three brains (minds) in one: the ancient reptilian core (primal mind); the old mammalian or visceral brain (emotional mind); and the neocortex (rational mind).</td>
</tr>
<tr>
<td><strong>Origin of self consciousness</strong></td>
<td>The origin of self consciousness goes together with the origin of language. The language created the selective pressure under which the cerebral cortex developed, and with it, the human consciousness of self emerged through its active exploration of the external world. It is incredibly improbable that life ever emerged from non-living and language emerged from non-consciousness. But they did emerge (Popper).</td>
<td>External sensory information arriving at the visceral brain retrieves information (memory and hereditary knowledge for survival) from our inner world; a mental blending of information from the dual source, external and internal, generates emotional feelings which are fundamental to our consciousness of our environment and ourselves. These feelings are often reflections of what's already started in even deeper levels of reptilian core.</td>
</tr>
<tr>
<td><strong>Multilevel brain structure</strong></td>
<td>Most of the information received from our senses is unconscious. But our world model must result from a conscious critical correction of existing models. Although what may be called our critical acumen may largely be unconscious, the completed model must be capable of being objectified or formulated in language to make the model accessible to criticism (Popper).</td>
<td>The conscious subjective world has three levels. The first level is the world of ordinary perceptions by all our sense organs. The next level is the world of emotions and other prelinguistic responses of all levels of subtlety. At the innermost core there is the self which is the basis of our integrated unity as conscious experiencing beings (Eccles).</td>
</tr>
<tr>
<td><strong>Self and creative thinking</strong></td>
<td>Physical laws are eternal, but the evolution of the world is unpredictable because of the voluntary nature of man's creative imagination which transcends existing world models encoded in books and all kinds of artefacts. The ideation area exemplified by the Wernicke centre seems to be responsible for a direct and critical grasping of the linguistic meaning of world models (Popper).</td>
<td>Our right and left cerebral hemispheres seem to perform complementary brain functions. Although the left hemisphere derives its dominance from its linguistic and ideational abilities and its liaison to self consciousness, the right hemisphere, which cannot express itself in language, seems to be responsible for coherent, holistic, and aesthetic evaluation of the creative logical inference of the left hemisphere (Eccles).</td>
</tr>
<tr>
<td></td>
<td>With 30,000 or so genes contained in the immense double helix of DNA the incredible improbability (even 1 in 10^{4000}) of achieving the marvelous creative productivity of a Mozart or Mendelssohn or a Keats as well as our unique individual selfhood requires the hypothesis of an independent and supernatural origin of the self or soul (Eccles).</td>
<td>There are three levels of inference, personal, emotional, and intellectual, corresponding to the three levels of brain organization; primal, visceral, and neocortical. The conscious rational thinking in our neocortex generates or controls a state of emotion in the visceral brain. The reciprocal mechanism exists by which the visceral brain creates a vivid affective feeling of what is novel, true, and beautiful.</td>
</tr>
</tbody>
</table>
Evolutionary Regeneration Model of Thought Process

References