Vol. 40 No. SIG 2 (TOM 1) 情報処理学会論文誌 Feb. 1999

Regular Paper

Information Physics Based on the Emergence Hypothesis and a Proof of Computational Universality of Single-NOT Networks

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Based on the emergence hypothesis, this paper proposes information physics. Computational universality called elemental universality is a necessary condition for the emergence at the edge of chaos. As the relation between the edge of chaos and biological life is widely hypothesized, we might think of elemental universality as a kind of natural law which cannot be explained by conventional materialistic physics. This view may bring forth a new paradigm that nature should be investigated by not only physics but also informatics. The study on the fact that computational universality is not a sufficient condition for the emergence at the edge of chaos includes a problem of the minimum number of NOT elements and the investigation of cellular automata. This paper presents a result that so-called 'chaotic' networks are intrinsically more powerful than stable networks.

1. Introduction

Various aspects of complex adaptive systems (CASs) are now actively investigated. Current research covers self-organization and evolution of living organisms, mechanisms of human intelligence, and social activity such as economy. S. A. Kauffman1),2) gave various insights into the edge of chaos. S. Wolfram3) discovered the class 4 using cellular automata.

The edge of chaos, named by N. H. Packard4), can be characterized by its emergent property. Phenomena that structure or order is spontaneously generated from randomness with a high probability are generally called emergence.

In CASs and artificial life5), it is usually hypothesized that the edge of chaos is the region where life was born. Wolfram conjectured computational universality at the edge of chaos.

The author6),7) proposed the emergence hypothesis, and proved that the computational universality called elemental universality8) is a necessary condition for the edge of chaos using Kauffman networks which are based on the operon model9) in molecular biology. This proof indicates a possibility that elemental universality is a law of living organisms, i.e., a kind of natural law.

We may well think that nature is governed by both material and information laws, and that informatics can be another tool to investigate nature. In this context, this paper proposes information physics10),11), in which we investigate nature by informatics. We may have yet another natural science.

This paper also studies the problems of (1) the minimum number of NOT elements and (2) cellular automata. The former is a problem of the computational universality of oscillatory networks with a single NOT element, and the latter is an extension of the theory about the edge of chaos.

2. Emergence Hypothesis and Elemental Universality

If life were based on computational universality, it could almost necessarily acquire some kind of intelligence in the course of evolution. In this respect, the emergence hypothesis tries to unify the evolution of life and intelligence.

Hypothesis(Emergence Hypothesis)

(1) Life and intelligence develop and evolve following the same laws of emergence.
(2) The evolution of life and intelligence is hierarchical and based on the superexponential law.
(3) Life and intelligence utilize elemental universality.

The superexponential law is a piece of hypothetical evidence that life and intelligence have some hierarchical relation. This law was proposed in 1984 by the author12), and is discussed in 6) and 7).

The superexponential law is expressed by

$$a_{n+1} = a_n{}^c, \qquad (1)$$

where the constant c is typically 2. If this formula is transformed into

$$a_n = \sqrt{a_{n+1}}, \qquad (2)$$

it coincides with Kauffman's square-root law found in his random Boolean network model.

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If $c = 2$ and $a_0 = 2$, then the solution is

$$a_n = 2^{2^n}. \tag{3}$$

So this relation is called superexponential.

Elemental universality is a kind of computational universality. It is a concept in switching theory. A logic circuit is constructed from basic logic primitives. A logic primitive realizes a logic function $y = f(x_1, x_2, \cdots, x_n)$.

A set of logic primitives is referred to as universal or complete if arbitrary logic mechanisms can be realized by a logic circuit which is constructed from a finite number of logic primitives in the given set. {AND, OR, NOT} is an example of a universal set, because repeated use of these basic primitives gives arbitrary logic mechanisms. The author proved the following theorem$^{8)}$:

Theorem 1 *A set of logic primitives is universal in the sense of elemental universality if and only if it is not contained in M_4 and M_5.*

M_4 is the set of all linear functions, which are written in the form $y = \alpha_0 \oplus \alpha_1 x_1 \oplus \cdots \oplus \alpha_n x_n$ for some choice of binary constants α's. Here $\oplus$ represents exclusive OR.

M_5 is the set of all positive functions. Binary vector $(x_1, \cdots, x_n) \leq (y_1, \cdots, y_n)$ if and only if $x_i \leq y_i$ for all i. Logic function f is called positive if $f(x_1, \cdots, x_n) \leq f(y_1, \cdots, y_n)$ when $(x_1, \cdots, x_n) \leq (y_1, \cdots, y_n)$.

This theorem was applied to Kauffman networks. Since M_4 and M_5 are closed under functional composition, respectively, either of them does not exhibit typical characteristics at the edge of chaos. The next theorem holds$^{6),7)}$. An example of insufficiency is {NAND}.

Theorem 2 *Elemental universality is a necessary condition of the edge of chaos for Kauffman networks, but is not a sufficient condition.*

Elemental universality plays an essential role in Kauffman networks which are abstract models of biological metabolism in living organisms. The author hypothesized that computational universality called elemental universality may be a kind of natural law$^{7),8),10)}$.

We find that this law cannot be derived from conventional physical laws. This law does not belong to materialistic physics. Our former dogma was that all natural laws could be explained by materialistic physics. Then, if we are to have a natural law which cannot be explained by conventional physics, we may be faced with a paradigm shift in natural science, that is, a scientific revolution$^{13)}$.

3. Information Physics

3.1 Reconsidering Natural Laws

Physics has been rigidly based on materialism. However, from the viewpoint of the emergence hypothesis, the author surmises that a science which investigates laws of information in nature is now emerging in the field of complex systems.

Since this view may bring forth a paradigm shift or a scientific revolution, we must be as cautious as possible. The supposition that elemental universality is a natural law may not necessarily accord with our common sense. Computational universality has been regarded as an artificial law for computers.

However, the author would like to ask what we imagine from the word 'nature.' We will imagine such scenes as mountains full of trees, waters where fishes are swimming, and the sky where birds are flying. Nature is full of life.

On the other hand, conventional physics covers mainly the lifeless world; e.g., the laws of particles, forces, and motions, the relation between material and energy, and spatiotemporal laws of space. Such materialistic laws have not yet solved the mystery of life.

Conventional physics may not be an almighty tool to investigate nature. Natural laws should explain living organisms. Now we may well think that informatics can contribute to the investigation of nature, in particular, the essential mechanisms of life. If so, nature will be explained by not only physics but also informatics.

Some researchers have surmised the relation between life and universal computation. E. Schrödinger$^{14)}$ called a chromosome fiber an aperiodic crystal. Aperiodicity is a well-known characteristic of Turing computation. J. von Neumann$^{15)}$ studied self-reproduction using universal cellular automata. The author indicated$^{11)}$ that the operon control discovered by F. Jacob and J. Monod$^{9)}$ is universal in the sense of elemental universality. An activator (x) and a repressor (y) in a *lac* operon of *Escherichia coli* form a logic $x\overline{y}$, which has elemental universality.

3.2 Definition of Information Physics

The author would like to call this new science information physics, where physics means science of nature in its general sense.. He proposes this science on the basis of the emergence hypothesis and, in particular, elemental universality. While information physics has, of course, open-ended fields, here a tentative definition of this science is presented:

Information physics deals with nature by principally discrete methods in informatics. It covers information aspects of nature, and sciences of interactions, relations, networks, functions, and shapes of things, including the studies on probabilistic and combinatorial aspects of natural phenomena.

The most interesting subject at present is the origin of life. Other interesting subjects will be found in the sciences of complexity and theoretical physics.

Up to now various researchers have investigated information aspects of nature, and proposed information physics or related sciences. As far as the author knows, information physics was proposed by T. Umesao16) in 1967. He said that it might merge with biology. T. Stonier17) used this term in 1990. The Santa Fe Institute held a workshop18) on the physics of information in 1989. K. Fukui19) also presented an interesting insight. However, results that can establish this new paradigm of science would not have been obtained as yet.

Here the author attaches much importance to elemental universality. A reason is that it is based on finite sets of logic primitives. It does not conflict with the finiteness of the material universe, while well-known formalization of universal computation based on Turing machines conflicts with finiteness, because Turing machines require unbounded recording tapes.

The other reason is found in its reductionistic approach. Reductionism is the most fundamental methodology of physics. Theorem 1 can be interpreted as follows8): The condition that a universal set is not contained in M_4 means that some primitive is nonlinear, although this nonlinearity is a property of finite Galois fields. The condition that it is not in M_5 means the existence of negation. If feedback loops are permitted, it means the use of negative feedback.

Intuitively, nonlinearity and the existence of negative feedback can be regarded as the necessary and sufficient condition of computational universality. These two happen to be the main concepts in the sciences of complexity.

Such reductionistic view will make it possible to merge information physics with conventional materialistic physics. At the deepest level of information physics, we will be able to ask: What laws in particle physics are the origin of nonlinear logic and the logic of negation? Those laws might have at last developed intellectual organisms in this universe.

3.3 Some Concrete Problems in Information Physics

Can we bridge between particle physics and the evolution of life? Now we cannot, but the author would like to present several illustrative and concrete problems to show some possible way to information physics.

Notice that the emergence hypothesis is a kind of network theory, in which networks composed of logic primitives exhibit computational universality. When we investigate living organisms, we will be able to apply such a network theory to atomic or molecular levels.

For example, if we assume the covalent bond model, hydrogen (H) has only one 'arm.' Such atoms cannot construct complex networks. Oxygen (O) has two arms, which can construct only a simple chain or a ring. We know that carbon (C), the group IV atom, can construct complex networks and create living organisms. Then the first problem the author can propose is whether an atom with three covalent bond arms, such as nitrogen (N), has elemental universality.

If we can prove that the set {H, O, N} is endowed with elemental universality, we will obtain a method to synthesize new artificial life from this set of atoms. On the contrary, if we can prove that this set is not universal, we may be able to know that all living organisms in this universe utilize the group IV atoms. It is sufficient to prove the elemental universality, because any characteristics of life will be simulated by computers in principle.

The author surmises that such proof must be based on both quantum mechanics and informatics. Quantum mechanics alone will not be able to give a solution to the mechanisms of networks composed of elements with logical abilities.

The second important, but rather abstract, problem is as follows: What types of universes can develop life, among all the possible universes that are defined by a set of physical laws? We can also ask whether our universe must be constructed from discrete quanta or waves, because biological life should be based on digital mechanisms. The author proved that the edge of chaos is essentially a kind of discrete phenomenon20),21). A purely continuous universe would not develop any living organisms.

Information physics will be also applicable to various problems in the field of complex systems. The third problem proposed here is $1/f$ fluctuations. The $1/f$ noise was discovered in 1925[22), but its physical mechanism has not been completely known as yet. Similar relations appear in a wide range of fields including physical, biological, and even sociological phenomena.

The author discovered a strict $1/f$ relation in graph theory[20),21), and he supposes that $1/f$ fluctuations may be some kind of relaxation processes[12). T. Musha and R. Kobayashi[23) also pointed out the same hypothesis.

Since $1/f$ fluctuations are found even in sociological phenomena, it will be difficult to explain such phenomena by pure physics, while methods based on informatics may be applicable to such probabilistic problems.

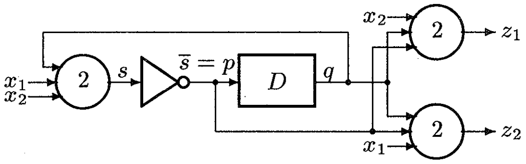
Notice that the problems stated above are not purely materialistic ones. We may be able to find various physical problems which are not purely materialistic. For example, whether space and time is continuous or discrete is not necessarily a materialistic one. This problem may have some relation to chaos theory, or may be dealt with by information physics.

Here, as a small step to information physics, the author studies the elemental universality from the standpoint of the number of NOT elements, and the edge of chaos exhibited by cellular automata.

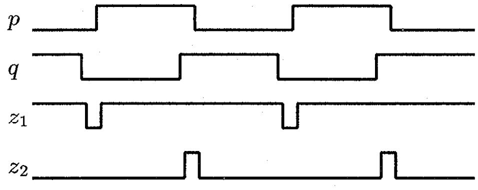
4. Minimum Number of NOT Elements and Oscillatory Networks

The author asserts that computational universality is not a sufficient condition for emergence. Emergence generally depends on stochastic parameters. An example is the λ-parameter[5).

However, if we adopt a fully artificial procedure, we can overcome the problem of probability. We might be able to create even *life-as-it-couldn't-be* against the probabilistic evolution in nature. A purely theoretical example is {NAND} with a unit delay[8). This set does not exhibit emergent properties in Kauffman networks, but is used for the design of universal computers.



(a) Huffman's basic circuit



(b) Hazards at output terminals

Fig. 1 Huffman's single-NOT circuit for two-variable inversion.

Here another example is investigated by using a set containing positive threshold elements and a single NOT element. The minimum number of NOT elements for a logic circuit was first studied by A. A. Markov[24). He devised a circuit in which k NOT elements negate $2^k - 1$ variables. D. A. Huffman[25) tried to construct a circuit in which only one NOT element can negate any number of variables. He employed a tricky feedback scheme.

Huffman's scheme, however, does not work correctly because of a serious problem of hazards. Here a new scheme which resolves this problem is presented. A universal Turing machine can be contructed by using only a single NOT element.

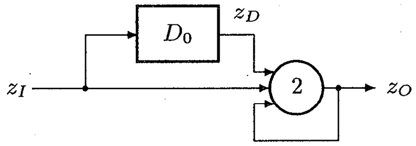
Fig. 1(a) shows Huffman's single-NOT circuit for two variables, i.e., $z_1 = \overline{x}_1$ and $z_2 = \overline{x}_2$. This circuit uses a NOT and three positive threshold elements. It is assumed that the delay D associated with a delay element is sufficiently larger than any other delays in the circuit.

A positive threshold element of variables x_1, $\cdots$, x_n takes on 1 if and only if $\sum_{i=1}^{n} w_i x_i \geq \theta$, where all weights $w_i \geq 0$ and θ is a threshold constant. A positive threshold element can be constructed from only AND and OR elements. Here θ is written in a circle and all $w_i = 1$.

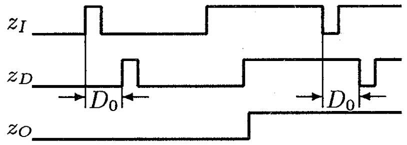
If $x_1 = x_2 = 0$, then $s = 0$ and $p = 1$. After delay time D, q becomes 1. Then $z_1 = z_2 = 1$. The case where $x_1 = x_2 = 1$ is similarly analized, and $z_1 = z_2 = 0$.

The case where $x_1 = 0$ and $x_2 = 1$ is interesting. If $q = 1$, then $s = 1$ and $p = 0$. After delay D, q becomes 0. Then s changes to 0 and p changes to 1. The values of p and q oscillate.

However, $x_2 + p + q = 2$ and $x_1 + p + q = 1$ except the transient timing of p and q. Then $z_1 = 1$ and $z_2 = 0$, thus two variables being



(a) A circuit



(b) Time chart of hazard elimination

Fig. 2 A hazard eliminator.

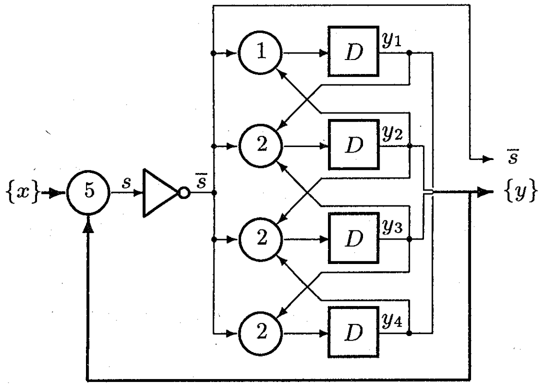


Fig. 3 A single-NOT circuit for five-variable inversion.

inverted. The case where $x_1 = 1$ and $x_2 = 0$ is similar.

Detailed timing analysis in Fig. 1(b) shows the existence of hazards at z_1 and z_2. Hazards are transient spike signals and caused by small delays or timing skews in a circuit.

Such hazards can be eliminated by connecting a hazard eliminator as in **Fig. 2**(a) to each output. Fig. 2(b) shows the time chart. This circuit eliminates static hazards, i.e., spikes appearing in a quiescent input. The duration of a hazard must be less than D_0, and the quiescent interval between two successive hazards must be greater than D_0. This hazard eliminator is used in this paper wherever it is necessary.

We use the following notations: $\{x\}$ represents $x_1, \cdots, x_n$; $|x|$ means the number of x_i's which take on value 1. **Fig. 3** shows Huffman's circuit for five-variables. The relation $\overline{s} + |y| = n - |x|$ holds.

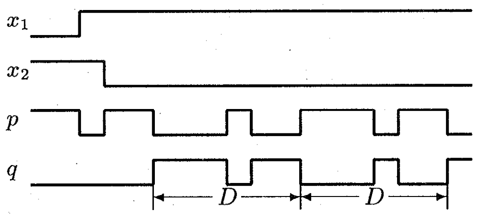


Fig. 4 A problem incidental to Huffman's scheme.

Output elements for z_i's are not shown in the figure. They are realized by threshold n and inputs $\overline{s}$, $\{y\}$, and $n - 1$ variables other than x_i. Since the weighted input for z_i is always $n - x_i$, z_i realizes x_i after hazard elimination. Unless inputs are all 0's or 1's, the internal circuit oscillates.

Such circuits look amazing, but Huffman did not comletely verified his circuits. In Fig. 1(a), if (x_1, x_2) change from (0, 1) to (1, 0) at slightly different timing, the oscillatory signal in the circuit cannot hold its shape. The time chart is shown in **Fig. 4**. A spike caused by this time skew does not disappear forever.

If such inputs are applied repeatedly, the oscillatory signals will be broken at last. Any hazard elimination method cannot recover such disorder. Huffman's scheme is not correct.

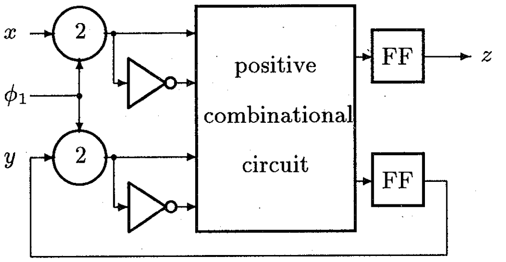
NOT elements are used in various portions of a sequential circuit. Their signal transitions are not necessarily simultaneous. Huffman failed to prove that any sequential machines are realizable by means of a single NOT and positive elements.

Here this problem is resolved by two ideas: a multiphase clocking circuit and a flip-flop constructed from positive elements. **Fig. 5**(a) is a simple schematic diagram. Input x and state variable y determines output z. NOT elements are virtual ones realized by Huffman's scheme. Fig. 5(b) depicts a flip-flop used in this circuit.

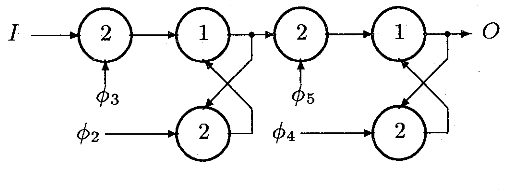
Five-phase clock signals $\phi_1, \cdots, \phi_5$ are applied to this circuit. The time chart is shown in **Fig. 6**(a).

At the leading edge of ϕ_1, the positive combinational circuit in Fig. 5(a) starts its calculation. After its outputs have become stable, the first stage of a flip-flop controlled by ϕ_2 and ϕ_3 captures the value. It is copied to the second-stage flip-flop controlled by ϕ_4 and ϕ_5 after the trailing edge of ϕ_1.

Multiphase clock signals can be realized by a circuit as shown in Fig. 6(b). This circuit is a loop connection of many delays. If the initial

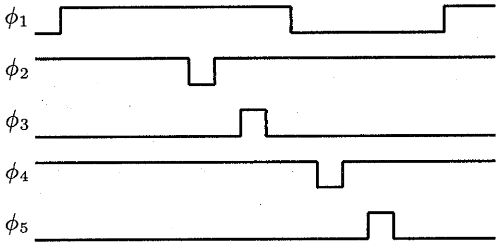


(a) A scheme of a multiphase sequential circuit

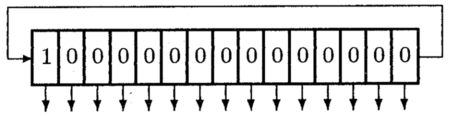


(b) A flip-flop (FF) circuit

Fig. 5 A multiphase sequential circuit with a single NOT.



(a) Time chart



(b) Multiphase clock signals

Fig. 6 Generation of multiphase clock signals.

values of these delays are set as in the figure, each clock signal can be generated by an OR element which is selectively connected to the outputs of this circuit.

If the assignment of initial values is not allowed, we can devise a clock circuit containing a NOT. It can be initialized by a start signal. The details are omitted in this paper.

The other notice is concerning the proof of elemental universality. Although the proof in 8) is done by using self-triggering circuit, the use of a synchronous clocking scheme will drastically simplify the proof of elemental universality for sequential circuits.

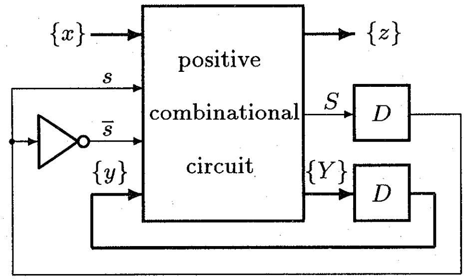


Fig. 7 A general scheme of single-NOT inversion.

Now we know that artificial procedures can create any logical mechanisms by means of a single NOT and plural positive elements. However, such an aggregate of logic primitives does not exhibit emergent phenomena in Kauffman networks. Therefore computational universality is not a sufficient condition for emergence.

The next theorem is also interesting. It is an important result of this paper.

Theorem 3 *Oscillatory networks are more powerful than stable networks (in the sense of computational universality).*

Our definition means that oscillatory networks may or may not oscillate, and stable ones never oscillate. The set of all oscillatory networks properly contains the set of stable ones. Now we shall prove that stable networks constructed from a single NOT and plural positive elements are not computationally universal.

A general scheme of inversion by means of a single NOT is shown in **Fig. 7**. Although this figure is drawn as if s and $\overline{s}$ were fed back, it is mere appearance. Feedforward circuits are also represented by this general scheme.

We assume that, after inputs $\{x\}$ had changed from X_0 (all 0's) to X_1 (some are 0's and others are 1's), the circuit at last reached a stable state. Then $S = 1$ or $S = 0$.

If $S = 1$, we shall change a variable x_i which is 0 in X_1 to 1 and call such inputs X_2. Then we shall analyze a transition from X_0 to X_2.

Consider the output f of an arbitrary element in the positive combinational circuit shown in the figure. If S remains 1, $f(X_1) \leq f(X_2)$ because the circuit is positive. However, z_i must decrease from 1 to 0. Then at least one input of the positive circuit must be decreased. Although only $\overline{s}$ can be decreased by the change from X_1 to X_2, $\overline{s}$ is already 0 for X_1. Therefore z_i cannot be 0.

The case where $S = 0$ can be analyzed similarly. Choose a variable x_j which is 1 in X_1 and change it to 0. Then z_j cannot be changed from 0 to 1.

The theorem has been proved by contradiction. This proof does not exclude the existence of stable states where all inputs are either 0's or 1's. Huffman also proved that stable circuits with two NOT elements can invert arbitrary number of variables.

CAS researchers often regard oscillatory networks as 'chaotic' networks. W. J. Freeman[26] indicates that brains are chaotic networks in the sense of oscillatory systems. In such a meaning, this theorem gives a piece of knowledge that so-called 'chaotic' networks are intrinsically more powerful than stable ones.

5. Elemental Universality for Cellular Automata

Elemental universality is an essential concept for Wolfram's cellular automata as well as Kauffman networks. Here we assume ordinary definitions of cellular automata. A cellular automaton is a synchronous array of identical finite-state automata called cells, each of which is uniformly connected to a finite number of other cells called neighborhood.

We assume that the number of cells is finite but arbitrary. When we consider the state transition function f of a cell, the discussion of two-state automata is parallel to that of Kauffman networks. M_4 and M_5 are closed under functional composition, respectively.

Assume that f is not a trivial function, i.e., neither a constant nor one-variable function. If f is trivial, the automaton never exhibits complex behavior.

If $f \in M_4$, the behavior of the cellular automaton is chaotic. Because such an automaton is a linear sequential machine which ordinarily emits pseudo-random sequences.

If $f \in M_5$, state transitions are always monotonic. The number of 1's monotonically changes with time, which means that this machine is not emergent.

The next theorem holds. Insufficiency can be shown by a counterexample. We can find many counterexamples, because emergent automata are only a small part.

Theorem 4 *Elemental universality is a necessary condition of the edge of chaos for two-state cellular automata, but is not a sufficient condition.*

Cellular automata are synchronous machines. By virtue of Theorem 5 in 8), this theorem can be immediately extended to the next one. Here M_6 means the set of all negative functions. Logic function f is called negative if $f(x_1, \cdots, x_n) \geq f(y_1, \cdots, y_n)$ when $(x_1, \cdots, x_n) \leq (y_1, \cdots, y_n)$.

Theorem 5 *A neccesary condition for a two-state cellular automaton to exhibit the characteristics typical at the edge of chaos is that its state transition function does not belong to neither M_4, M_5, nor M_6.*

The condition for general multiple-state automata is an open problem. The formalization based on ordinary multiple-valued logic is not applicable to this problem. If a machine can realize binary logic, i.e., a subset of multiple-valued logic, it may exhibit emergence. Such a machine is not universal in the sense of multiple-valued logic. The author's conjecture is that the necessary condition would be similar to Theorem 5.

6. Conclusions

This paper has proposed information physics. The discussion was based on the emergence hypothesis proposed by the author. Informatics will be another tool to investigate nature, and it may find some important connection with theoretical physics. Elemental universality, which is based on nonlinearity and negative feedback, will not be derived by conventional materialistic physics.

This paper is a mere entrance to this new field of science. Whether information physics is a kind of natural science or not should be determined by the consensus of many scientists in various fields. The author supposes that informatics based on discrete mathematics is not restricted to sciences of the artificial.

The proof of the computational universality of single-NOT networks has indicated the usefulness of oscillatory networks. Nature might have utilized this property in the course of evolution of living organisms. We also have found a close relation between the edge of chaos and elemental universality in cellular automata.

A notice should be given concerning a kind of mismatch between physics and mathematics[11]. Theorem 1 is simple and its physical meaning is easily understood. Compare it with Theorem 1 in 8). Conventional formalization based on pure mathematics does not bring us clear physical insight. Some serious problems may be hidden in modern mathematics.

Acknowledgments The author expressses his sincere thanks to Kenichi Fukui of blessed memory, Heisuke Hironaka, Shinjiro Kodama of blessed memory, Osamu Matsumoto, Wataru Mori, Kazuo Nishimura, Masatoshi Shima, Yoshisuke Ueda, and Tadao Umesao for their encouragement, cooperation, discussion, and inspiration. This research was supported in part by the Hayao Nakayama Foundation for Science & Technology and Culture.

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(Received September 7, 1998)
(Revised October 15, 1998)
(Accepted November 5, 1998)

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