Evolvability of Machines and Tapes*

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Abstract

A self-reproduction process is described and discussed via a network model of machines and description tapes. Emergence of a core network which dynamically sustains the rewriting processes of machines on tapes is reported. Structures of the core networks are quite generic and include Eigen's Hypercycle as a special case.

In the cell assembly model, where each cell contains machines and tapes, we show that the instability of the core network in some cells is sustained by those cells with stable core networks. The instability of the core network is transferred to its offspring when the cells divide. What is inherited here is not the patterns of tapes, but the way machines read tapes in a core network.

[Keywords : Mutation, Self-reproduction, Inheritance]

Introduction

Von Neumann's work

The definition of biological self-reproduction is, in the narrowest sense, synthesizing the DNA by the encoded enzyme. This is considered universal in the sense that it can copy any DNA independent of its information content. Also, the translation of DNA into a protein structure gives another universality in biology. This process is universal in the same sense that the process systematically translates DNA's pattern. We call it a universal construction-capability.

Universality in von Neumann's theory of self-reproduction is used in the same context. His theory is based on replicating patterns of a 2-dimensional cellular automaton (1), where each cell has 29 different states. A particular spatial configuration is found to work almost in the same way that an encoded enzyme does to a DNA sequence. Von Neumann calls this configuration a universal constructor (UC). There is also a chain configuration (we call it tape) which encodes the universal constructor. When a UC is attached to the tape, it reads the tape and reconstructs the tape and the UC itself, at the specified location, by the tape. This behavior is called "universal" in the sense that any machine can be reconstructed whenever it is described by the tape configuration.

It is remarkable that for this universality to exist in both biology and cellular automaton, the separation of program (i.e., machine) and data (i.e., tape) is prerequisite. The separation should be made in order to prohibit the mutual interference of machines and/or tapes. However, a self-interference is required for self-reproduction. In other words, life has to observe itself in order to replicate itself, but what an individual really observes is the individual who observes himself. Hence, self-observation never stops. Therefore, to achieve a stable self-reproduction we have to obtain a stable *self description*. Von Neumann himself was also annoyed with this problem, but he knew that this fragility of separation meant at the same time of life itself (2). And as is mentioned, the separation of the tape from the machine is established by preparing 29 states with a peculiar configuration.

Separation for Evolution

Von Neumann finally constructed a stable description and successfully separated a machine from a tape. But 10 years after von Neumann's work, such separation has proved to be unnecessary in order to have self-reproduction (3). Also, the concept of universality of self-reproduction was discarded by C. Langton (4) because such universality is not essential to life itself. However, what we want to emphasize here, and what we think von Neumann really was driving at, concerns the problem of evolution. At first glance, self-reproduction in the sense of "making a same object," and evolution in the sense of "making a different object" sounds very inconsistent. How can we reconcile the two? When we are faced with this problem, the separation of machines and tapes again comes into play. Separation is necessary for self-reproduction in the first place, but at the same time it is necessary for evolution: separation is to evolution as language is to creativity.

By describing an object by language, we can modify the object without modifying the object itself, and we

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can analyze non-existence objects and paradoxical matters. For example, there is no "false chemical reaction," but there is "false logic." By putting objects into linguistic codes, we can deal with the difference of matters true and false. Or, we can deal with paradoxical sentences. Acquisition of such linguistic codes, therefore, means to have the autonomy of description free from any physical or chemical constraints.

To acquire such linguistic code, it is necessary to separate machines from tapes. In fact, such acquisition has occured in biology. We can say that protein can synthesize new protein by acquiring linguistic codes (e.g., using DNA sequencing). A new protein can be called a "false" protein since it has not existed before acquiring a description. Therefore, the separation of machines from tapes is essential not only for stable self-reproduction; it is also necessary for perpetuating the evolutionary process. But not only mere evolution becomes possible by acquiring separation; evolution of evolvability (5) is obtained at the same time. Evolvability is not just a simple way of adapting to a given environment. It is defined as a meta-adaptability which adapts the method of adaptation itself (i.e., Bateson's deuterolearning (6)). We will discuss the possibility of having evolvability based on our simple computer simulations (8; 9).

A Model of Machines and Tapes

Our system consists of two different objects – tapes and machines. A tape has a bit string of a circular form (7-bit in this simulation). A machine consists of three different parts: a head, a tail, and a transition table. Each head and tail is expressed by a 4-bit string, whose pattern is compared with various tape binary patterns. If a pattern matches, a tape is replicated (with some modification by the machine) on the tape with the transition table. A synthesized tape is translated into the machine which is encoded by the tape pattern.

After introducing an ensemble of tapes and machines, we carry out a machine-tape reaction process. All machines and tapes have a maximum value N. Assuming that there are plenty of materials to make machines and tapes, we let them react in proportion to their numbers in a system. A pair of new machines and tapes are generated, and aged machines and tapes are removed, in order, from the system. Reaction between a pair of machines and tapes is represented, as well as a chemical reaction,

$$\mathbf{M}_i + \mathbf{T}_j \Rightarrow \mathbf{M}_k + \mathbf{T}_l + \mathbf{M}_i + \mathbf{T}_j \qquad (1)$$

where the machine $\mathbf{M}_i$ reads the tape $\mathbf{T}_j$ and the tape $\mathbf{T}_l$ is generated. From this tape, the machine $\mathbf{M}_k$ is translated out.

Here we define two different mutations. The first mutation is caused by external noise, which cannot be controlled by machines or tapes. In this sense, we name it **passive mutation**. This mutation only occurs on the bits which the machine reads. The second mutation is caused by a machine's rewriting process. Some tapes are frequently rewritten, but some are not. Since this rewriting process is completely determined by a machine, we name it **active mutation**. A passive mutation is measured by the frequency of "bit flipping," and an active mutation is measured by the frequency of rewritten bits.

Using this abstract machines and tapes system, the following is noted:

— We initially prepare a random set of machines and tapes in a system. External noise breeds autocatalytic structures, called core networks, in the system. Once the core networks are formed, they are stably replicated as a whole even without external noise. Core networks have general structures, whereas machines as well as tapes are globally replicated in the network. It should be noted that the Eigen's Hypercycle (7), where tapes are replicated only locally, is a special case of the core network.

— Core networks which include a variety of machines emerge for an adequate level of external noise. Too small or too large external noise leads to either a simple autocatalytic core networks, or total extinction. The obtained structure of core networks reflect the property of external noise; namely, a random pathway induced by an external noise is mimicked deterministically in a machine's rewriting processes.

Evolvability of Core Network

If we have one pool of machines and tapes, a single independent core network emerges in the pool, and the core network is maintained by the mutually translating process of the machines. What happens if we have interaction between different core networks? In trying to answer this, we introduce a cell assembly of core networks; that is, machines and tapes which are contained in a cell structure. These cells can exchange machines, but not tapes, with other cells.

We assume two different levels of replication. One is replication of machines and tapes within a single cell, and the other is simply replication of cells. If a condition is fulfilled by the cell, it divides to leave a same number of machines and tapes to the daughter cells. Therefore, there emerge two identical cells at division time. The division condition is assumed to be determined by the degree of stability multiplied by the degree of diversity. In practice, we measure the stability by the number of mutually catalyzing machines, and the diversity by the total number of different machines. At the same time, cells which largely fail to satisfy the condition are removed from the pool. A non-responding time is also prepared: once a cell divides, it cannot divide during the non-responding time.

Here we do not initiate any external noise. Instead,

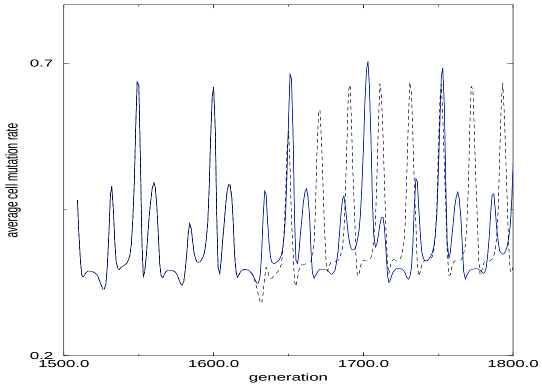

Figure 1: During inhibition of machine inter-cellular exchanges, we see that, after a short period of time, the unstable oscillations of active mutation rates (solid lines) become stable periodic oscillations (broken lines).

machine flows from the other cells play the role of external noise. Machines which are not generated in a core network, perform unknown rewriting events to the core network.

Initially, we prepare several cells and place machines and tapes randomly. These machines and tapes do not constitute the core structure, but emerge from inter-cellular interactions. We set the division condition so that cells with only oscillating core networks can divide. An oscillating core is defined as a core whose network topology is temporally changing, as well as its active mutation rate.

We noticed that there are two different cell lines: one is a stable cell line which leaves an identical core network when it divides, and the other is an unstable cell line which leaves unstable, non-identical core networks. Whether the cells have identical core networks is measured by the average active mutation rates introduced earlier. Similar core networks may have similar values of active mutation rates. In the stable cell lines, both mother and daughter cells have almost identical, regularly oscillating active mutation rates. Conversely, unstable cell lines exhibit irregular and thus non-identical oscillating patterns.

After a given period of time, we turn off the inter-cellular interaction. We then find that the unstable cell assemblies are sustained by the stable cell assemblies. Shortly afterward, we turn off the inter-cellular interaction, and the stable cells increase their population exponentially. On the other hand, unstable cells are soon lost after the turning-off procedure (Fig.1). These unstable cells transition into stable cells without inter-cellular machine exchanges.

Under the inter-cellular machine exchanges, these unstable cells can remain. Also, such "instability" of these cells is inherited by the offspring. This inheritance is not

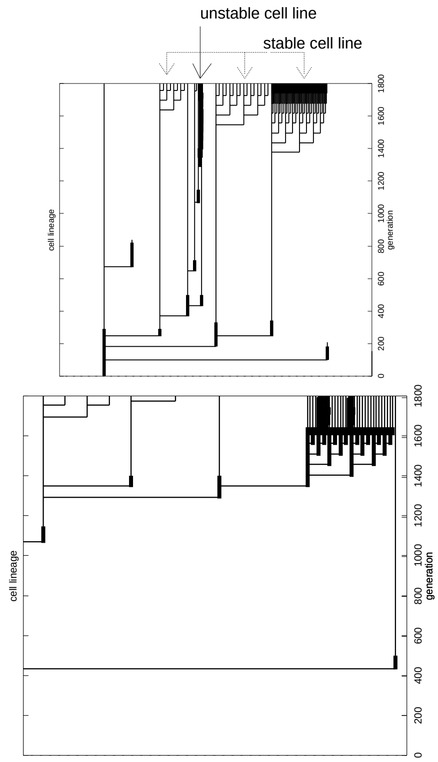

Figure 2: By quantifying the unstable oscillation, we draw the unstable cell line in red. The vertical line corresponds to the cell generation number. The bottom figure (b) is a scale up of the top figure (a) of the later generations of unstable cell lines.

strictly deterministic, but the offspring can inherit the seed of this instability. Once it is lost from the mother cell, the instability is difficult to be recovered by the cell lines. In Fig.2, we have overlaid the instability quantity on a total cell phylogeny. The figure shows that the instability is indeed transferred to the offspring. However, the environment which sustains this instability transfer is prepared by the stable core networks. In other words, there is a stable environment which can sustain an ensemble of unstable replicators. Finally, it should be noted that what is inherited is not the patterns of tapes, but rather the way machines read tapes. We call this an example of "replication of evolvability," as it transfers at least a meta-level of description, i.e., how to read and rewrite tapes.

Discussions

Fontana's Alchemy (10; 11) shares common features with our system. He uses λ-calculus instead of our machines and tapes. His level 0 system corresponds to our simple fixed-state core, and a level 1 corresponds to stable core structures. Instead of meta-inhibition of self-copying in Fontana's model, we have introduced external noise to breed core structures. A level 2 corresponds to the present model, an inter-cellular interacting system. What Fontana calls "glue" corresponds to machine exchanges between different core networks. Inter-cellular interactions produce such glue machines in our example.

Recently, K. Kaneko and his colleagues have shown that cells which contain fixed but complicated chemical networks exhibit a variety of cell differentiation based on cell division and competition dynamics for a common energy source. Their model inspired our construction of cellular division. Since our motivation is to understand the necessity of the machine/tape separation in the context of evolution, we have studied the machine's rewriting process on tapes instead of pure dynamical systems modeling. As a result, we have succeeded in studying the evolution of the network as well as its evolvability.

However, the inheritance of different cell types (i.e., different dynamical state with the same core network) is observed in pure dynamical systems modeling without being introduced to the separation of machines and tapes. Therefore, in order to show more clearly the necessity of separation, we have to deal with the essentially language-like situation where the difference of a true or false description has an effect; namely, we have to come back to the problem of the interference between data and program. Success of separation opens the way to the general-purpose computer. But complete separation is virtually impossible. Contrary to the prevailing attitude which tries to suppress the impossibility of separation by putting into place numerous syntactical rules (13), we have to analyze the impossibility of separation itself.

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