A Computational Aspect of Autopoiesis

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Abstract

Autopoiesis is a neologism, introduced by Maturana and Varela to designate the organization of a minimal living system[9]. Maturana produced the theory of autopoiesis based on his works on visual nervous systems, and then Varela developed his own system theory. Later, Luhmann applied autopoiesis to the theory of social systems[8]. Recently, this theory has been applied to not only sociology but also psychopathology.

However, there are still few mathematical or computational models that represent autopoiesis itself because of its novelty and originality. In this paper, we introduce a recent situation for mathematical and computational descriptions of autopoiesis, and discuss its implications in system science.

1 Aspect of Autopoiesis

1.1 Properties of Autopoiesis

Autopoiesis gives a framework in which a system exists as an organism through physical and chemical processes, based on the assumption that organisms are machinary. An autopoietic system is one that continuously produces the components that specify it, while at the same time realizing itself to be a concrete unity in space and time; this makes the network of production of components possible. An autopoietic system is organized as a network of processes of production of components, where these components:

1. continuously regenerate and realize the network that produces them, and
2. constitute the system as a distinguishable unity in the domain in which they exist.

Maturana gives a car as a representative example of non–autopoietic systems and claims the following[9]: The self–maintenance of a car as itself is realized only when there is a relation between inputs from a driver and outputs of the car. On the other hand, living systems self–maintain themselves by repeatedly reproducing the components and not by actions from others. Although they take nutritious substances from the outside, the organization is not determined corresponding to the substances. The processes for self–reproduction exist firstly and foremost, and the nutritious substances are subordinate to these processes.

The characteristics of autopoietic systems Maturana gives are as follows:

1. Autonomy:
   Autopoietic machinery integrates various changes into the maintenance of its organization. A car, the above example of a non–autopoietic system, does not have any autonomy.
2. Individuality:
   Autopoietic machinery has its identity independent of mutual actions between it and external observers, by repeatedly reproducing and maintaining the organization. The identity of a non–autopoietic system is dependent on external observers and such a system does not have any individuality.
3. Self–Determination of the Boundary of the System:
   Autopoietic machinery determines its boundary through the self–reproduction processes. Since the boundaries of non–autopoietic systems are determined by external observers, self–determination of the boundaries does not apply to them.
4. Absence of Input and Output in the System:
   Even if a stimulus independent of an autopoietic machine causes continuous changes in the machine, these changes are subordinate to the maintenance of the organization which specifies the machine. Thus, the relation between the stimulus and the changes lies in the area of observation, and not in the organization.

Moreover, Kawamoto positions dynamical stable systems which self–maintain themselves through metabolism to the outside, self–organizing systems such as crystals which grow while morphing themselves according to their environment, and autopoietic

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systems, as the first, the second, and the third generation systems, respectively [6]. Kawamoto particularly focuses on the fourth item among the above characteristics of autopoiesis, i.e., absence of input and output in the system.

When we consider the "absence of input and output", important is the view where the system is understood based on the production processes. Kawamoto claims the following: the view of the relation between inputs and outputs in the system is one from external observers and it does not clarify the organization or the operation of the production in the system. A living cell only reproduces its components and does not produce the components while adjusting itself according to the relation between itself and oxygen in the air. Although the density of oxygen affects the production processes, external observers decide the influence and the cell does not. As long as the system is grasped from an internal view of the cell, the system does not have any "inputs and outputs".

The gist in the concept of autopoietic systems Kawamoto gives involves the following:

1. The set of components of a system is determined by the operation of the system.

2. The operation of the system precedes the initial condition.

3. The operation of the system is executed only to succeed itself and does not aim to produce by–products.

4. In the operation of the system, the things that happen in the system clearly differ from the things that external observers discriminate.

1.2 Development of Autopoiesis in a Variety of Research Areas

The most important characteristic of autopoiesis is its development in not only life system theory but also a variety of research areas such as sociology, cognitive science, phisiology, sociology, and psychopathology.

Luhmann applied autopoiesis to the theory of social systems, developing his own interpretation of it[8]. In his theory of autopoiesis, the concept of communications is introduced to solve a problem on complex systems of autopoietic systems, that is, whether social systems as complex systems of human mental systems can be autopoietic systems. In his theory, a social system is not a whole system having human mental systems as its subsystems, but an autopoietic system having communications as its components. Mental systems are autopoietic systems having thoughts as their components by themselves and are coupling with social systems, that is, each system is operationally closed and they are mutually linking.

Ciompi applied cybernetic system theoreis including autopoiesis to psychopathology[2]. He argued that cognitive elements and affective elements in human mind are indivisible and correspond to polar states in a system called "affection–cognition schema". Then, he constructed a model in which individuals' mental systems and family systems with them as their elements mutually interact. Based on this model, he analyzed schizophrenics caught in "double bind situations" [1] and human relations in the families that maintain the situations (in this sense, Ciompi used dynamical stable systems in his model and autopoiesis is explicitly not used). Moreover, Kawamoto and Hanamura applied the theory of autopoiesis to models of schizophrenia extending the definition of autopoiesis[7].

2 Difficulty in Interpretation of Autopoiesis

In interpreting autopoiesis within the conventional system theories, there is a difficulty to image systems based on the verbal description mentioned in the previous secions.

2.1 A Shift of Viewpoints

How systems are grasped from the view of external observers is interpreted as separating the observers from the environment including the system, distinguishing between the system and the background in the environment, and verifying the relation between the system and the distinguished background, that is, the outside of the system. Autopoiesis forces us to give up this view, that is, to put our view in the system, not in the outside of the environment.

Kawamoto gives the following statement as an example of this shift of views: If a person is fast running on the ground like drawing a circle, the person just continuously reproduces the action of running, although an external observer decides that the person is determining the boundary of the system. When the person stops running, the boundary vanishes.

However, this shift of view is not easily acceptable in the contemporary situation where the view of external observers is still major in natural science. If a person bounded to this view observes an autopoietic system, the view shifts towards the outside of the environment and the system is grasped as a static map or dynamical system in a state space. Even if the view shifts towards the inside of the system, the production processes of the components themselves are grasped as the object of the observation and the view of external observers is not completely given up. In the above example of a running person, the observer produces an image of the relation between the person as the object of the observation and the space where the person is running.

2.2 Precedability of Operations to Elements and State Spaces

Moreover, as long as the view of external observers is not given up, the above gist of Kawamoto, in particular, the determination of the set of components by the operation and the precedability of the operation with the initial condition in the system cannot be understood. In the conventional system theories, state spaces where the operation is defined firstly exist, the initial condition is determined independent of the operation, and the properties in the state spaces by the operation such as time evolution are discussed.

A person bounded to the view of external observers cannot imagine the situation where the operation determines its domain and initial condition. Thus, such a person can imagine just self–organizing systems such as hyper–circles, which belong to the second generation systems Kawamoto claims.

3 Descriptions of Autopoiesis

Because of the novelty and originarity of autopoiesis shown in the previous sections, there are still few mathematical or computational models that represent autopoiesis itself. A machine learning model inspired by autopoiesis was proposed to do tasks such as pattern recognition[3], but this model does not represent autopoiesis itself. Moreover, although there are some cases where autopoietic systems are represented by simulations using the method of computational chemistry[10], these are specialized for models of living cells and do not represent mathematically integrated formulations of Maturana's original autopoiesis.

In this paper, we introduce some recent models of autopoiesis and discuss problems in them.

3.1 Quasi–Autopoietic Systems

Metabolism–Repair Systems ((M,R) systems) are a mathematical system model introduced by Rosen to abstractly formalize the functional activities of a living cell – metabolism, repair, and replication[12]. This system model maintains its metabolic activity through inputs from environments and repair activity. The simplest (M,R) systems represent the above aspect in the following diagram:

$$A \xrightarrow{f} B \xrightarrow{\phi_f} H(A,B) \xrightarrow{\Phi_f} H(B,H(A,B)) \quad (1)$$

Here, A is a set of inputs from an environment to the system, B is a set of outputs from the system to the environment, f is a component of the system represented as a map from A to B, and ϕ_f is the repair component of f as a map from B to $H(A,B)$ ($H(X,Y)$ is the set of all maps from a set X to a set Y). In biological cells, f corresponds to the metabolism, and ϕ_f to the repair. If $\phi_f(b) = f$ ($b = f(a)$) is satisfied for the input $a \in A$, we can say that the system self–maintains itself.

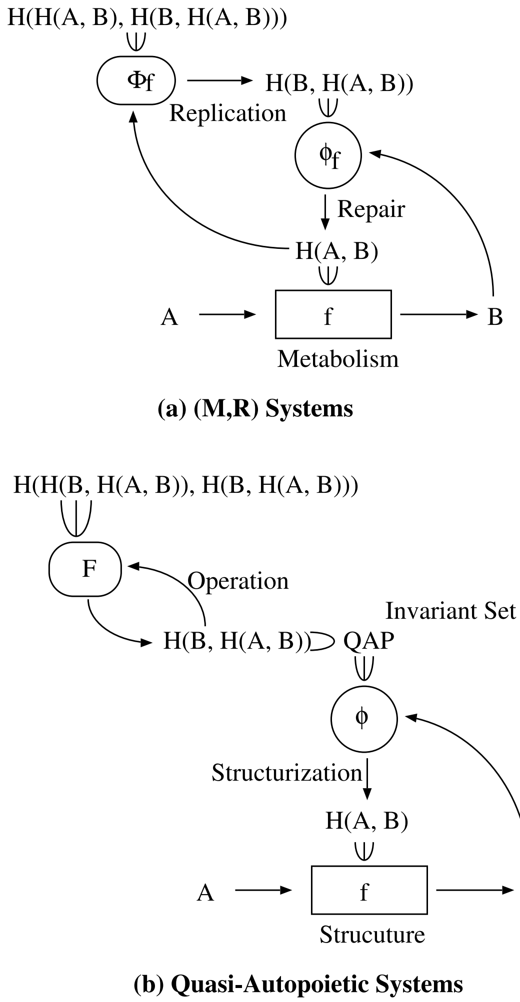

Figure 1: (M,R) Systems and Quasi–Autopoietic Systems

By using this framework of (M,R) systems, we proposed a model of autopoiesis, called "quasi–autopoietic systems"[11]. Our description of a quasi–autopoietic system is as follows:

$$A \xrightarrow{f} B \xrightarrow{\phi} H(A,B), \quad (2)$$

$$H(B,H(A,B)) \xrightarrow{F} H(B,H(A,B)) \quad (3)$$

Instead of the replication map from $H(A,B)$ to $H(B,H(A,B))$ in (M.R) systems, this system has an iteration map on $H(B,H(A,B))$. This map determines the system's self by defining it as an invariant set with a kind of ergodicity property for the map; that is, its self QAP is defined as follows:

$$QAP \subset H(B, H(A,B)),\ F(QAP) = QAP, \quad (4)$$
$$^{\forall}\phi, \phi' \in QAP,\ \ ^{\exists}n \in \boldsymbol{N}\ s.t.\ F^n(\phi') = \phi \quad (5)$$

Figure 1 shows aspects of (M,R) and quasi–autopoietic systems.

3.2 Constructive Dynamical Systems

In both (M,R) and quasi–autopoietic systems, the main subject is the nature of relations between functions in the systems, and the origin of the functions and relations between them is not considered. As a method to represent the origin of systems, Fontana and Buss proposed constructive dynamical systems by abstract chemistry, in which chemical processes are abstractly represented in terms of λ–calculus[4, 5].

In the conventional dynamical systems such as differential equations, the objects of which the systems constitute are given in advance and the systems themselves are represented as quantitative variables and relations between these variables that represent properties of the systems. Thus, the objects themselves do not appear in the description of the systems and the systems are understood as the temporal or spatial change in the numerical value of the quantitative variables. In other words, the conventional dynamical systems cannot directly represent the change of objects and relations between them. Constructive dynamical systems represent dynamics of objects of systems themselves by corresponding chemical reactions to applications of functions in λ–calculus and representing abstract chemical processes by simulations.

Figure 2 shows a λ–calculus flow reactor based on constructive dynamical systems. In this framework, one molecule corresponds to one expression, and one chemical reaction by collision of two molecules to the result of an application of one expression to another and reduction to a normal form. A chemical process is simulated by preparing a finite number of expressions in the reactor as an initial state, then executing a reaction by random collision of two expressions, adding the result into the reactor as a molecule, and removing other molecules, repeatedly. It is shown that there are a variety of self–organized structures such as mutual production and syntactical regularities among expressions as objects in the system in the limit set of the above dynamics. The limit in the above dynamics represents a kind of reactant equations in a chemical process. In other words, constructive dynamical systems are a wider framework including the conventional dynamical systems.

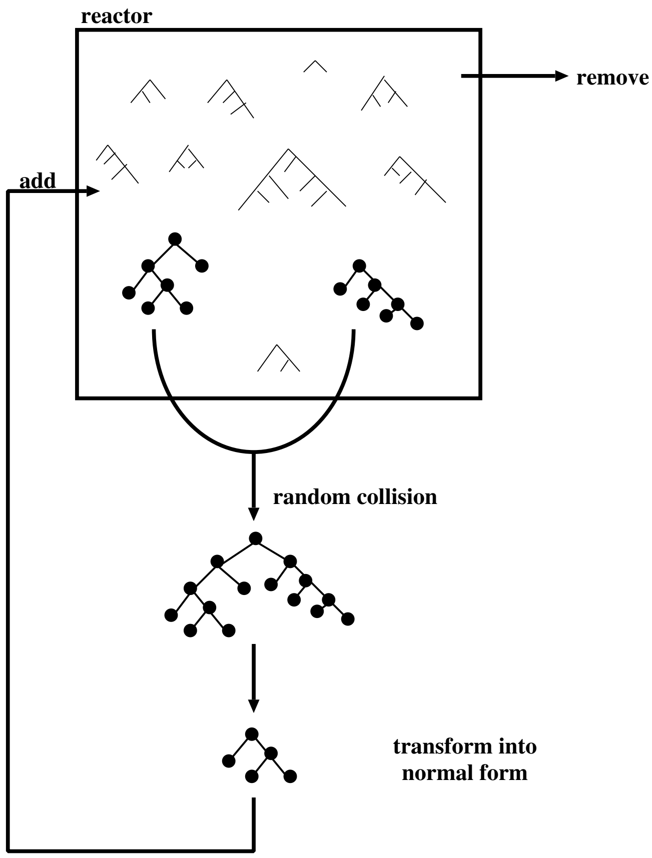

Figure 2: A λ–Calculus Flow Reactor based on Constructive Dynamical Systems (Fontana and Buss, 1996))

3.3 Deductive Hyper Digraphs

Tsujishita argued that λ–calculus approaches are inappropriate for the nature of mutual actions in life systems because it is normal that things operating and things to be operated are not distinguishable in the systems, and in chemical reactions by λ–calculus the roles of them are determined. Then, he used "deductive hyperdigraphs" to represent autopoiesis[14].

For a set of components of a system X, the set of the following relations is called a hyperdigraph:

$$\Gamma\ :\ a_1,\ a_2,\ \ldots,\ a_n\ \longrightarrow b\ \ (a_1, \ldots, a_n, b \in X) \qquad (6)$$

Here, the above equations mean that components a_1, …, a_n generate another component b. The left figure in Figure 3 shows that b and c generate a and a generates b. The right figure shows that b and d generates all the components when a is given.

A hyperdigraph is called "deductive" when it satisfies with the following conditions:

1. each element generates itself,

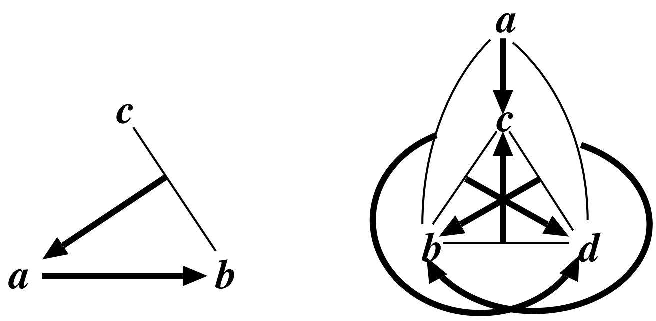

Figure 3: Examples of Hyperdigraphs (Tsujishita, 1998)

2. If a_1, ..., a_n generate b, then a, a_1, ..., a_n generate b for any $a \in X$.

3. If Γ_i generates b_i $(i = 1, \ldots, n)$ and b_1, ..., b_n generate c, then Γ_1, ..., Γ_n generate c.

Deductive hyperdigraphs are a kind of abstract algebraic structures for representation of relations between components on generation. The above deductive conditions mean a closed situation where each component is generated by other components in the hyperdigraph. This closed situation corresponds to operationally closed nature of autopoiesis.

4 Discussion

In order to represent autopoiesis as mathematical or computational models, it is necessary to find machanism that a system creates the space where it exists and the boundary between it and the environments by itself. In the models introduced in the previous section, however, some important characteristics are lost.

4.1 On Quasi–Autopoietic Systems

We can interpret that quasi–autopoietic systems satisfy with Kawamoto's gist in section 1.1 by regarding F as the systems' operations and ϕ as their components[11]. In these systems, however, the space where the operations and components exist is given in advance. Thus, quasi–autopoietic systems cannot represent autopoiesis in the sense that the systems create the spaces and the boundaries by themselves.

This problem is deeply related to the concept of "closure of efficient cause" in "relational biology" Rosen proposed[13]. In relational analysis, a system is regarded as a network that consists of components having functions. Then, he compared machine systems with living systems to clarify the difference between them, based on the relationship among components through entailment. In other words, he focused his attention on where the function of each component results from in the sense of Aristotle's four causal categories, that is, material cause, efficient cause, formal cause, and final cause. Rosen's conclusion is summarized as follows:

1. Machine systems are described with their states. This fact results from considering the category of formal models for the system.

2. If all the components of a machine system must be entailed in the sense of efficient cause, there must be a larger system entailing them. This causes an infinite regress.

3. In a machine system within which all the components are entailed in the sense of efficient cause, an infinite decomposition of the state space happens, thus this also causes an infinite regress.

4. Thus, any machine system is not closed under efficient cause.

Then, Rosen claimed that *a material system is an organism if and only if it is closed to efficient causation.* (M,R) systems satisfy the above condition "closure under efficient cause" in the sense that the replication map Φ_f is entailed in the system by b, that is, the output of the metabolism f [12]. However, quasi–autopoietic systems do not because just the operation map F is not entailed in the system. If the condition of closure under efficient cause is required for models which represent autopoietic systems, we must find the way in which the operation map is constructed in the system by f and/or ϕ.

4.2 On Constructive Dynamical Systems

On the other hand, constructive dynamical systems look like closed under efficient cause, that is, each object in the limit is entailed by other objects based on applications of λ–calculus. Moreover, the limit in the above dynamics represents a kind of reactant equations in a chemical process. In other words, the state space for the equation is generated through interaction among objects.

However, the set of all the possible objects in the systems are given in advance and the functions of the objects are also given in advance based on the definition of the objects. In other words, constructive dynamical systems do not represent self–creation of the space. Moreover, since constructive dynamical systems are originated based on chemical processes, their application is limited to models like cells (in fact, the description of autopoiesis by McMullin and Varela[10], which is also a model simulating chemical processes, is limited to cells).

4.3 On Deductive Hyperdigraphs

Deductive hyperdigraphs are useful for relational analysis, that is, abstractly representing relations among components on generation without mentioning to statial structures where components are defined. Thus, it is more abstract than (M,R) and quasi–autopoietic systems and useful for describing the way for mutual actions of components. For examples, Figure 4 shows representations of (M,R) and quasi–autopoietic systems by hyperdigraphs. The figure clarifies the following facts: as far as a is given in (M,R) systems, all the other components mutually generate, and quasi–autopoietic systems are not closed because no things generate F in the systems.

In the same way as (M,R) and quasi–autopoietic systems, however, deductive hyperdigraphs do not clarify either the origin or change of relations of components on generation, which are dealt with in constructive dynamical systems.

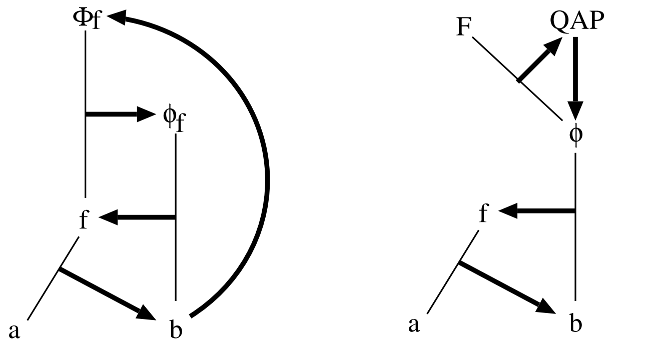

Figure 4: Representations of (M,R) and Quasi–Autopoietic Systems by Hyperdigraphs

5 Conclusion

In descriptions of autopoiesis within the conventional mathematical frameworks, important characteristics are lost because of a kind of uncertainty on spaces, that is, the fact that spaces where systems exist are determined by the operations. This kind of uncertainty differs from that in fuzzy theories, which is deal with as the degree to which each element in a given set belongs to a subset in it. Nevertheless, and thus, descriptions of autopoiesis require a new mathematical framework and system science. As a result, it may happen a paradigm shift in engineering perspective for real adaptive systems.

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