Evolutionary Constructive Approach for Studying Dynamic Complex Systems

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1. Introduction

In this chapter, we introduce a scientific methodology called "evolutionary constructive approach". This approach is suitable for studying dynamic features of complex systems. At first, we identify two types of simulation methodologies, realistic and constructive. The latter is especially needed to clarify complex systems, since the complex systems have distinct characteristics from objects of conventional scientific studies. We characterize such characteristics as "undecomposabilities". We show three example simulation studies using the evolutionary constructive approach. They are about 1) dynamic change of social structures, 2) language change and displacement, and 3) dynamics of communication.

These days, computer simulations have been getting popular in science and engineering. For example, the Earth Simulator developed in Japan has been producing interesting results for meteorology and environmental science (Sato, 2004). Multi-agent simulations, or agent-based simulations, are an enterprise of new method in social science (Conte et al., 1997; Gilbert & Troitzsch, 2005).

The simulation techniques are expected to contribute for understanding and prediction of the future of our world. But our world is not so easy to comprehend and to deal with. We have reached good understanding of some parts of the world, when simple sub-parts can be extracted as systems. Complex systems in which extracting simple sub-parts or breaking down into simple systems are very hard have been still remaining untractable for us. If we try to use modeling and simulation for understanding such complex systems, we should establish the way of thinking, the methodologies and the approach to model the complex world.

The purpose of this chapter is to discuss if constructive approach, especially, evolutionary constructive approach, can contribute to understand the complex world. The constructive approach is a scientific methodology in which an objective system is to be understood by constructing the system and operating it. In evolutionary constructive approach, evolutionary operations, not only genetic evolution but also lifetime development, individual learning and social learning, are incorporated to construct models.

This chapter organizes as follows. In section 2, we describe some seminal constructive studies not limited to works using computer simulations. In section 3, we explain how complex systems are characterized as a preparation to discuss if the constructive approach is suitable for studying complex systems. The important concept to view complex systems is “undecomposability“. In section 4, we explain evolutionary constructive approach in detail. Section 5 is devoted to show examples of simulation studies taking the evolutionary constructive approach. We summarize this chapter with discussion about the future direction of the evolutionary constructive studies in section 6.

2. Two Types of Simulation Methodologies: Realistic and Constructive

We can identify two types of methodologies in simulation studies, one is realistic simulations and the other is constructive simulations. The former tries to make operational copies of actual phenomena as possible as realistic in order to predict what occur in the target phenomena. The latter constructs rather simplified non-realistic models in order to extract essential features and to understand underlying mechanisms and logics of the objective phenomena.

A typical example of the realistic simulation is “the Earth Simulator” (Sato, 2004). In the Earth Simulator, the Navier-Stokes equation, the fundamental equation for fluid dynamics, is calculated with approximation such as finite element method but as possible as accurate using parallel computers. In order to realize the high accuracy, the surface of the earth is divided into square areas as possible as small. Therefore, massive computational power is required. One of the main purposes of the Earth Simulator is to predict the state of the atmosphere of the Earth. An outcome of such effort is depicted in Figure 1(left). This is not a satellite image but the simulation result of a typhoon approached Japan in August, 2003.

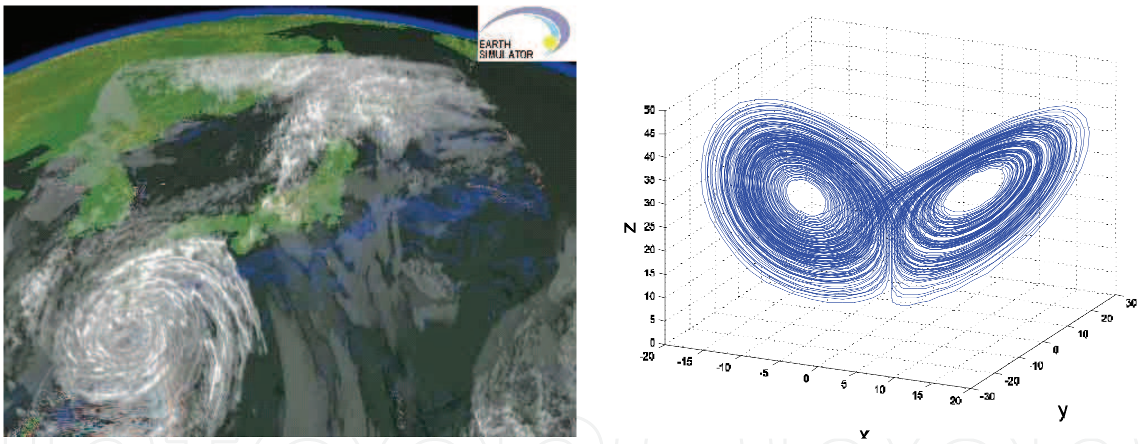


Figure 1. Simulation results from the earth simulator (left) and the Lorenz attractor (right). Both are derived from the same equation but with the completely different methodologies. The former is cited from the Home Page of Multiscale Simulation Research Group, The Earth Simulator Center (http://www.es.jamstec.go.jp/esc/research/Mssg/index.ja.html)

On the other hand, the Navier-Stokes equation is often calculated using different approximation called modal decomposition. Lorenz was one of such meteologists. He extracted five modes of the equation and calculated using a computer in 1950‘s. After some period of calculation, he restarted the numerical simulation starting from the printed results. After a while, he found that the result was not the same as the first calculation. He could find neither any bug of the computer program nor any glitch in the computer. What he found was the sensitivity to initial conditions. The initial condition of the first and second calculations was slightly different, since the printed result was truncated at some digits. In some nonlinear systems, such as fluid dynamics, very small difference can be grown into the system size. Lorenz (1963) called the phenomenon “deterministic nonperiodic flow“, which was named *chaos* later (Li & Yoak, 1975).

Lorenz (1963) studied a more simplified system having the sensitivity to initial condition with three dimensional differential equations, now called Lorenz system. Figure 1(right) is a trajectory of the numerical simulation of the system. This geometrical structure is called the Lorenz attractor. He clarified such unstable and complex dynamics is induced by stretching and folding in the phase space.

This study can be thought of as a constructive simulation. Lorenz constructed a more simplified and more non-realistic model than the Earth Simulator and extracted the essential features in the dynamics of atmosphere. Although, using the Lorenz model, we cannot forecast weather at all, the underlying mechanisms, stretching and folding, of complex dynamics of climate was understood and logics of the objective phenomena why weather forecast is fundamentally impossible was comprehended.

The other classical examples of constructive studies are von Neumann’s self-reproducing automata (von Neumann, 1963) and Turing pattern (Turing, 1952).

Taking notice of the self-reproduction as one of the essential features of life, von Neumann (1963) propounded the question, “whether a machine can reproduce itself”, and considered by what kind of logic the self-reproduction would be possible. By constructing an abstract machine, composed of three parts: a universal constructor, a blueprint and a copier of the blueprint, that actually carried out self-reproduction, he proved that self-reproduction is possible for machines.

On the way of construction he found two important logics in self-reproduction. One is that the self-reproducing machine should have a static description of the machine, since the system has to observe itself in order to reproduce itself but the action of observation inevitably affects both the object and the subject of observation. This is a self-referential problem. This problem can be resolved by preparing a blueprint that is stable for observation. The second point is that the content of the blueprint is used twice in the different manners, interpreted and uninterpreted. When the blueprint is used at the first time, the universal constructor should appropriately interpret the information content that is the way to construct the machine. At the second time, the copier reads the blueprint literally and copies all the letters on the blueprint accurately. What is interesting is that these two points were proved to be realized in living organisms. Especially, the structure of the machine and the two distinct manners of information utilization are critical to make the machine evolvable. von Neumann did not perform simulation of the machine, since the computational power was not enough to calculate his self-reproducing machine at his time.

Turing was also interested in life. Having spatial patterns, most of them are static and some dynamic, is one of the essential features of living organism. Turing (1952) proposed a simple reaction diffusion system for morphogenesis, partial differential equations with two variables. In this system, he supposed an interaction between two imaginary chemical substances, called morphogens. He proved that a particular character of the morphogens and particular manner of interaction realized various stable patterns from spatially uniform state. We can produce such various patterns as stripes and dots in numerical simulations by adjusting parameters of the system. This system is not a model abstracted from precise observation of real concrete phenomena, but Turing constructed the system from the bottom-up by introducing imaginary substances. While chemical substances precisely corresponding to the morphogens have not been found, we can understand the logic and the sufficient conditions for the emergence of nonuniform spatial patterns from uniform initial conditions.

A recent (nonclassical) development of the constructive simulation is Kaneko's coupled chaotic maps (Kaneko, 1986, 1990). He tried to understand high dimensional chaos, but no handy model existed. There are many good models in low dimensional chaos such as the logistic map, Hénon map, Lorenz system, Rössler system (Alligood et al., 1996). Thus, his idea to make a high dimensional system was to connect many low dimensional chaotic maps. Basically, there are two types of coupled chaotic systems. One is a coupled map lattice which consists of chaotic maps with a local coupling (Kaneko, 1986),

$$x_{n+1}(i) = (1-\epsilon)f(x_n(i))+(\epsilon/2)\{f(x_n(i-1))+ f(x_n(i+1))\}\ , \tag{1}$$

where n is the index for time and i for space, and x is the value of the state, that is, $x_n(i)$ represents the state of the ith map at the nth time step. Each element receives the influence of adjacent elements. The strength of the influence is controlled by a parameter ϵ. The function f(x) is a chaotic map, e.g. the logistic map $f(x)=1-ax^2$, where a is a nonlinear parameter. The other type is called globally coupled maps, which is a system of chaotic maps with a mean field coupling (Kaneko, 1990),

$$x_{n+1}(i) = (1-\epsilon)f(x_n(i))+(\epsilon/N)\sum_j f(x_n(j))\ , \tag{2}$$

where N is the number of maps. The average of all elements affects each element. Thus the larger value of the coupling constant, ϵ, makes the system uniform, and the large value of nonlinearity, a, makes the system disordered. In computer simulations of the systems, we can find fruitful complex dynamic phenomena, such as spatio-temporal chaos, dynamic clustering, pattern dynamics and chaotic itinerancy, by adjusting the parameters.

The chaotic itinerancy is a remarkably dynamic motion, in which a trajectory chaotically transits among varieties of low dimensional ordered states through high dimensional unordered states; or transits among low dimensional dynamical states including fixed points, periodic and chaotic motions through high dimensional chaotic motions (Kaneko & Tsuda, 2003). We depict an example of chaotic itinerancy observed in globally coupled maps in Figure 2. This graph shows dynamics of effective dimensionality, that is the degree of freedoms, of a system of globally coupled maps with 10 logistic maps. The system has 10 dimensionalities at most, since it consists of 10 one-dimensional maps. The maps continue to synchronize with other maps and to desynchronize. When all elements synchronize, that is thought of as a state with complete order, the effective dimension is 1. When they desynchronize at all, that is an unordered state, the effective dimension is 10. A state with mid dimensionality is a partially ordered state. Figure 2 demonstrates that the effective dimensionality changes with time. The system moves between full ordered state, the effective dimension is 1, and full disordered state, the effective dimension is 10, with chaotic fluctuations. This change does not cease forever.

The coupled map lattice and the globally coupled maps are not models in its rigorous sense, since they do not represent any concrete phenomena. They are realizations of pure abstract concept of high dimensional chaos. In other words, an object of study is created by the coupled chaotic system. While the coupled chaotic system is an abstract mathematical object, it is utilized to study actual concrete phenomena of life, especially diversification of the cells (Kaneko, 2006).

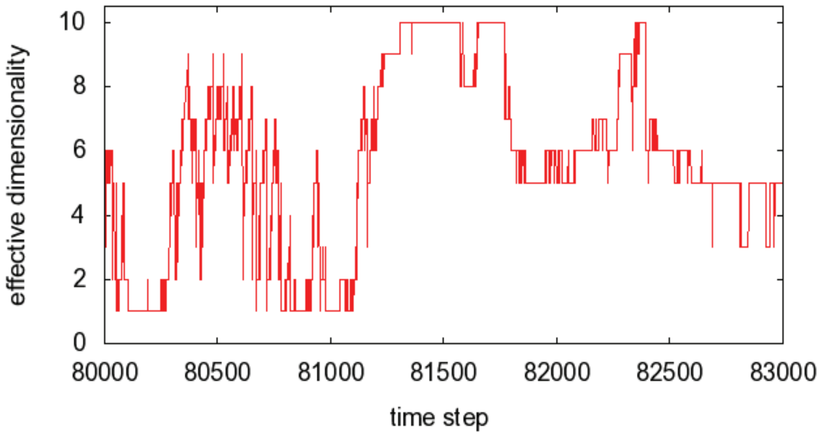


Figure 2. Example of chaotic itinerancy in a system of globally coupled chaotic maps. The effective dimensionality of the system fluctuates with time

3. Characteristics of Complex Systems

Above mentioned constructive studies are concerned with complex phenomena, such as chaos and life, in which dynamics and interactions play important roles. This fact is not by a mere chance. Constructive approach is suitable for studying complex dynamical systems. Before explaining the (evolutionary) constructive approach, we discuss the characteristics of complex systems.

Complex systems are not the same as complicated systems. A system composed of mere vast amount of elements or having mere entangled relations may be identified as complicated but not as complex. We claim that complex systems are characterized by three *undecomposabilities* (Hashimoto, 2007). Conventional scientific methodology has made premise three types of decompositions. They are decompositions or separations between operators and operands, between parts and whole, and between observations and observed objects. Most objects of complex systems studies refuse some or all of such decompositions.

Conventional descriptions are likely to divide an objective system into states and fixed functions governing the behavior of the states, or into a black box having certain functions and inputs to/outputs from the black box. Suppose that there is an unidentified machine with several buttons and we are going to know how it works. We may try to give the machine some inputs, for example, pushing the buttons, and then wait responses to the inputs. Here, we presuppose that the machine has some states and some functions that are evoked by pushing the buttons. The functions are operators acting on the states and the state changes are brought by the operators. If we can describe good correspondences between the inputs and the outputs, we will feel that we are approaching understand of the objective machine. The objective system is made to resolve into operators, what act on something, and operands, on what the operators act, and the operators are supposed not to change by the operation.

This decomposition is not necessarily obvious for systems with self-referential and self-modification features. In such systems, the movement of the system may act on the system (self-reference) and change the system itself (self-modification). Namely, the systems can work both as an operator, acting on the system, and an operand, the object of the action, at the same time. This characteristic is called the undecomposability between operators and operands. This undecomposability brings the systems "rule dynamics", i.e., rules describing the dynamics of the systems have dynamics.

Biological evolution has this characteristic. Biological evolution is defined as changes of the gene frequencies in a group of organisms with respect to their environment for adapting to a fitness landscape. In classical view of neo-Darwinian evolution, the organisms unilaterally changes to fit to the environment. The environment selects organisms which can survive in the environment (natural selection). In this view, the environment is an operator and the organisms are operands. But actually, the organisms are not so passive but often modify their environment actively. The environmental change brought by the organisms persists for several generations, and thus the environmental change affect the natural selection. The process to modify the environment or to make a new environment to live is called niche construction (Odling-Smee et al., 2003). In the view of niche construction, biological organisms are both operators and operands. The evolutionary dynamics must be understood from such dynamic viewpoint.

Complex dynamical systems such as language and social institutions are other examples with the undecomposability between operators and operands. Language can be thought of as a system for making and understanding utterances. Any language continues to change with our use of the language. A dead language which no one uses is not subject to change. Social institutions are habits in the ways of thought common to social members. The institutions seem to regulate behavior of the social members. But the institutions are seldom static. Once a social institution established, it is not continue forever. Most of people conform to the institution, the change of the institution occurs often from within the society. Namely, social institutions change with the behavior of the social members, that is regulated by the social institutions. This is a representative of the rule dynamics.

In reductionism, temporal and spatial levels of an object of study are restricted, and it is often said that the whole is the sum of all parts. More macro level than the focusing level is often thought of as closely analogous to static. More micro level than the focusing one is likely to be approximated as random. However, if a small change arisen in one of parts of the objective system is expanded and spread to the whole system, the decomposition of levels and the reduction into partial systems become impossible. It is commonly conceded in many literatures that complex systems do not accept such decomposition. Chaotic systems have this undecomposability. The behavior of the system sharply depends on initial conditions. A small change in the initial conditions or in the state of a partial system may make the state of the system completely different, as described in the previous section.

When a small fluctuation is expanded into the system level, another conventional decomposition between observation and an object of the observation is collapse. Since any observation inevitably perturbs the object, the influence of the observation may become apparent in such system. If a system composed of an observer and an observed object has the undecomposability between operator and operand, that is, the observer is the operator and the object is the operand, the undecomposability between observer and observed object is also induced. In social systems, it is recognized that observation and description, or investigation and its publication, may affect the behavior of the objective social systems. Thus, a methodological problem has been pursued in social science. Several methods different from natural science are devised in social science, such as participatory observation, ethnomethodology, and action research. The difficulty comes from the fact that biological organisms have subjective agency. They may react differently to the same situation. Therefore, reproducible observations become difficult for biological and social systems.

4. Evolutionary Constructive Approach

A new scientific approach is required so as to progress understanding of dynamic complex system which have the undecomposabilities described above. Here we introduce "evolutionary constructive approach" (Kaneko & Tsuda, 1998; Kaneko & Ikegami, 2000; Hashimoto, 2002; Asada & Kuniyoshi, 2006). It is a methodology in which we try to understand an object through *constructing and operating* the object.

We make a model, often mathematical or computational, of an object and implement the model using some media. This is construction. In making a model and constructing a system, individual concrete phenomenon of the object is not necessarily modeled realistically. As exemplified in section 2, the logic, not materialistic details, to realize the target phenomena is focused on. The systems constructed should consist of elements and factors which are considered to be essential to the objective system. As for the media of construction and operation, we use hardware, such as robots, software, such as computer programs, and wetware, such as biochemical molecules.

In trying to construct a complex object, we may be perplexed by a paradox:

> In order to construct something, a blueprint is required. In order to draw the blueprint, the object must be analyzed and understood well. This is a deadlock situation. Therefore, constructive understanding is impossible for an object which is difficult for analysis and description.

However, in evolutionary systems like life, cognitive system, language, economic and social systems, which have their own intrinsic dynamics, the final complex state is not needed to be designed for construction. Instead, as illustrated in Figure 3, we design a simpler state which has the possibility to attain the final state as a result of change, or which is thought of as the origin of the object; and incorporate mechanisms of change, such as genetic evolution, individual learning, social learning, development or diversification. We call this methodology "the evolutionary constructive approach". This approach releases us from the paradox that what is too complex to understand cannot be constructed. This approach has another merit. We can observe the changing processes in which initial states arrive at the target state through the process of complexification and structuralization. The mechanisms of change are usually not easy to implement in hardware construction and are not easy to control in wetware construction. Therefore, software construction may be suitable for this approach at the present.

We operate the system constructed. For software construction, computer simulations are performed extensively by testing the varieties of the settings, parameters, initial conditions and algorithms of change. We investigate which setups result in what kind of consequences and observe processes to complexify and structuralize. Through the operation and analysis, we try to clarify what occurs inevitably, in what kind of logic the objective phenomenon occurs, what the sufficient conditions for the objective phenomenon are.

We may observe changing processes or final states that differ from those seen in the actual world, depending on the setups. In this case, knowledge about the "could-be" state of the target phenomenon is obtained. In order to establish the theory of evolution, it is necessary to attain integrative comprehension including evolutionary paths which possibly might exist. Therefore, recognizing the "could-be" states is important. Experiments of the evolutionary paths in various setups can be repeatedly conducted usually. Besides, many variables of the system are measurable. Therefore, we can treat phenomena of which empirical observation is difficult and objects with historical dependency or a one-time-only nature. Accordingly, the evolutionary constructive approach is an effective method for the comprehension of origin and evolution.

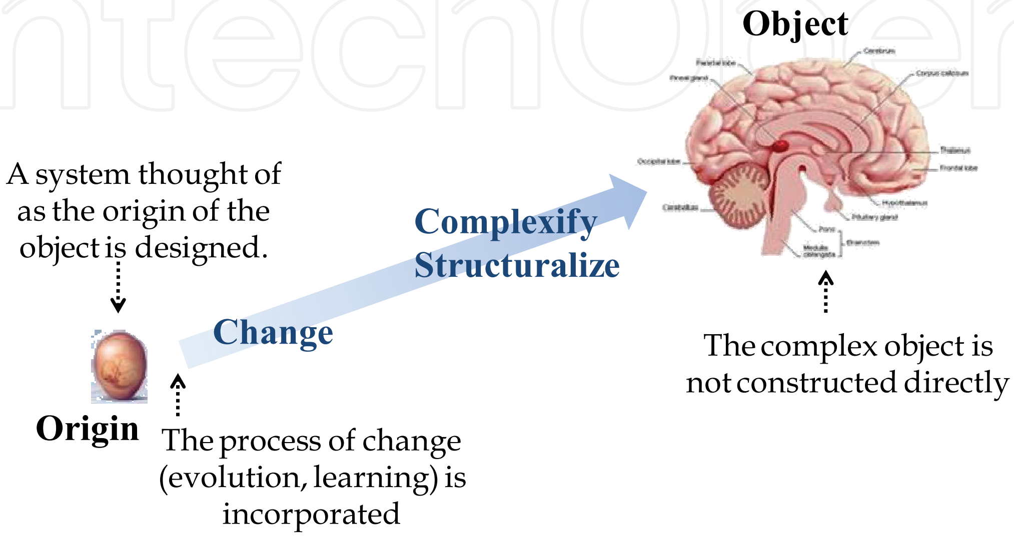


Figure 3. Evolutionary constructive approach

Another effective aspect of the constructive approach is the specification of the details of ideas. When we make a model which can be operated actually in simulations or in robotic systems, we must make every fine features clear and detailed. In the process of specification, we need to formalize the important concept, to determine the relationships among subparts of the model and the idea. We sometimes find a missing link in the logic to form the target phenomena which was overlooked before actual modeling. We may also find such a missing link during operating the model by observing unexpected results. In particular, in cases where multiple causalities and logics work simultaneously, which is usual in complex dynamical systems, we are not good at following such multiple flows of causalities and logics without mathematical or computational thinking tools. In some research areas, researchers often rely on verbal theorizing, even based on empirical evidence. When the objective system is so complex that the verbal theorizing may easily lead us astray, the constructive approach can be used to corroborate or to suspect the reasoning.

The constructive approach concerns to engineering. We construct systems using some media with technologies, often high technologies. In contrast to engineering, the constructive approach may be considered as a scientific methodology, since the purpose of constructive studies is mainly to understand some objects. In engineering, something designed based on conceptualization – be it experiential or theoretical - is constructed and utilized for the world. Therefore, engineering has the directionality "from the concept to the world", namely, we realize in the world what is conceptualized. On the other hand, science has the directionality "from the world to the concept", namely, we conceptualize and understand the world. In constructive studies, the methodologies of these two directionalities, engineering, “concept → world”, and science, “world → concept”, are connected as “concept → world → concept“.

The constructive approach is basically a hypothetico-deductive method. At the first “concept” stage, we have a working hypothesis based on knowledge so far about the objectives. A system is constructed based on the idea that “certain phenomena and process should occur according to existing knowledge and a working hypothesis”. If the process and the phenomena currently assumed are actually realized as results of the operation of the system, it means that the hypothesis was verified in part. Here, the deductive stage is executed through the operation of system constructed. We modify the hypothesis and reconstruct the system, when the assumed consequence is not obtained.

When assumed consequence is realized, we should analyze thoroughly which settings or which part of hypothesis bring the consequence. This analysis may give us a new insight about the core of the problem and the important part of the hypothesis. If we intend to understand further fundamental mechanism of the target phenomena or to study the origin of the objective system, we try to construct a new system in which the setting that brings the assumed consequence in the previous construction is not incorporated as a model. Such setting forms a new object and we search for a hypothesis that realizes the setting as a consequence of evolution in operating the new system.

A nontrivial consequence which was not considered initially may be observed as the result of the operation. This is an *emergence* for a researcher. It is necessary to ask why such a consequence comes out and what kind of significance it has in the target phenomenon, and to clarify the mechanism in which the nontrivial consequence occurs. Accordingly, the emergence must not be left as it is. We have to advance our understanding so that the emergence is resolved as reasonable. By this activity, a new light is shed on the object, generation of a new hypothesis is brought about, and further comprehension progresses. Therefore, the constructive approach plays the role of hypothetical generation and is a tool of thought as well as hypothetical verification.

The new object and new hypothesis leads us the second “concept“ stage, and the process of construction and operation continues as “concept → world → concept → world → ···“. In evolutionary constructive approach, new features are added to a system constructed at the later constructions. The accumulative addition of new features is also considered as a kind of evolutionary process.

We should notice that, in the constructive approach, while finding sufficient conditions may be possible, a necessary condition cannot be acquired. Even if the target state can be attained starting from a certain setting and condition, there may always be a possibility that the setting and the condition are not indispensable to attain the state, because other settings and conditions may bring about the target state. It will, however, be possible to narrow sufficient conditions by repeating experiments with various setups and elaborating models. Moreover, it is also impossible to answer the question concerning origins straightforwardly by this approach, i.e., “when” an event occurred in the actual world. The constructive approach can contribute to find essential logic, that is, the “how” question, while the “when” question must be clarified by empirical evidences. One possible course to approach the “when” question in constructive studies is to clarify strict conditions for the event to occur and to propose reasonable hypotheses, about the conditions for the event to come into being, which should be provable with empirical evidence.

5. Examples of Evolutionary Constructive Simulations

In this section three example studies taking the evolutionary constructive approach are introduced. The examples are concerned with institutional change and language dynamics. As we saw in section 3, they are typical objects of complex systems study. Concretely, we describe the simulations about 1) Endogenous dynamics of macro social structure, 2) Meaning change and displacement in evolution of language, and 3) Dynamics of communication.

5.1 Endogenous Dynamics of Macro Structure

We apply the evolutionary constructive approach to dynamic social phenomena (Sato, 2005; Sato & Hashimoto, 2007). The target phenomenon of the study introduced in this sub-section is the endogenous changes of social structures/institutions. We ask how the dynamics of macro structures in a society, such as institutions, occurs endogenously. Social structures and social institutions are often considered as equilibria, especially in neo-classical economics. If a society is really in an equilibrium and is not given an exogenous shock, no change occurs in the society. In actual fact, however, we often experience changes in the social structures and institutions. We think that not all of the changes are induced by external sources.

The key ideas for the endogenous social dynamics are the internal dynamics of individuals and the micro-macro loop. The internal dynamics is autonomous change of the individual's internal states. We think social individuals have internal states and the states change dynamically, especially in humans, even without any change in the outside of the individuals. The internal dynamics can explain the diversity and the consistency of human behavior. Individuals can act differently under the same environmental state, if they have various internal states. If the states change dynamically, not random, the behavior may have some causal relationships. The micro-macro loop is a mutual relationship of dependences or influences between micro and macro levels in a society (Shiozawa, 1999). The micro-macro loop should be discriminated from micro-macro couplings. There are many macro variables in a society which are decided by actions of the social members, for example, the stock prices, GDP, the average income, and so on. Some of them are just the sum or the average of all members' variables and affect the actions of social members. We regard such interactions between the micro and macro *variables* as the micro-macro coupling. On the other hand, the micro-macro loop is structural relationships between micro and macro *structures*.

5.1.1 Modeling of Agent and Social Interaction

The agent with internal dynamics is modeled by a kind of neural network with recursive connections. The architecture of the neural network, drawn in Figure 4, is equipped with two recurrent connections. One is between a hidden layer and a context layer, which is introduced by Simple Recurrent Network (Elman, 1990). The other is between output and input layers. The system's own past output affects its behavior through the latter connection. We call this architecture Simple Recurrent Network with Self-Influential Connection (SRN-SIC). The hidden layer represents the internal state. In addition to the external stimuli, the network changes its output based on the internal state and its own past output, which forms the internal dynamics. This type of neural network can learn a time series by adjusting the synaptic weights according to teacher signals. We use the back propagation algorithm for the learning.

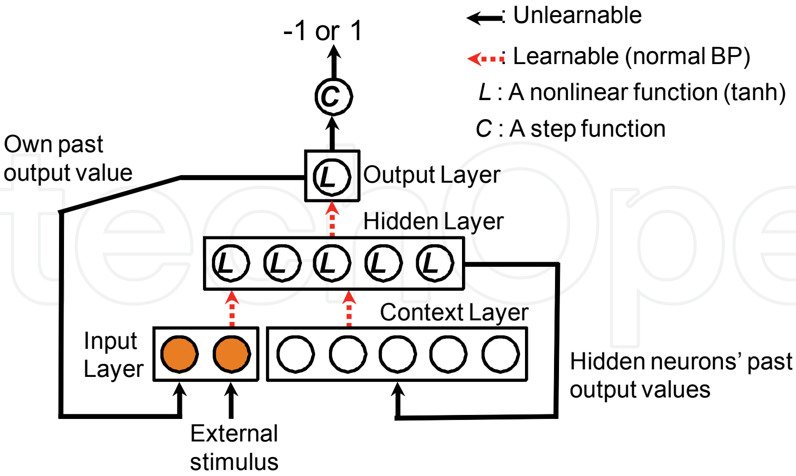


Figure 4. Simple Recurrent Network with Self-Influential Connection (SRN-SIC): Each circle is a neuron. A group of the neurons, a layer, is surrounded by a square. A neuron is added after the output in order to make the outputs from the network rounded to the choices of the minority game. The synaptic weights of the recursive connections are fixed at 1.0

In this study, the social interactions among the agents is modeled by the minority game (Challet & Zhang, 1997) in which players selecting a minority choice from two alternative choices, say -1 and 1, win. This game is the model of a competitive situation for limited resources, which is common in a society, such as market, mating, competition for water and food source, and so on.

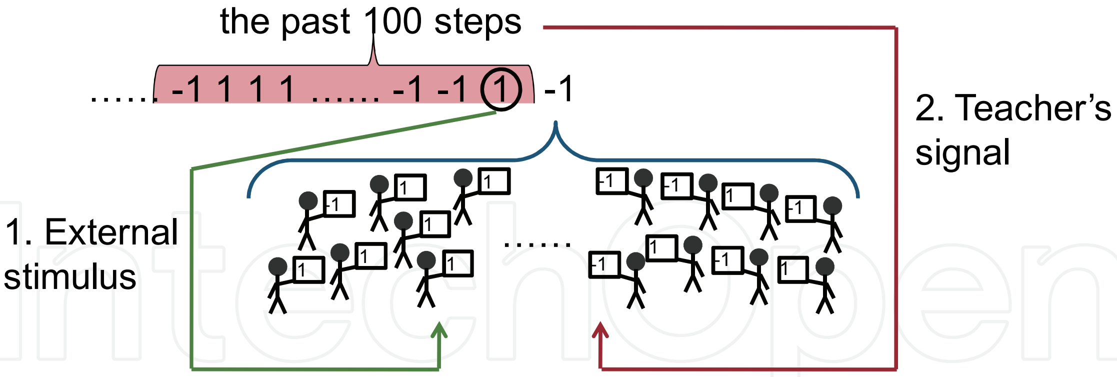


Figure 5. The micro-macro coupling in our system

The micro-macro coupling is explained in Figure 5. The winner of game, that is, the minority side, is the macro variable of the system. This is decided from the choices of all players, which are the micro variables. This is the coupling from micro to macro. We prepare two couplings from macro to micro. One is that the last minority side is given to the agents as an external stimulus. The other is that a past time series of the minority side is given to all agents as a teacher's signal to learn. We consider dynamical patterns in the time series of minority side as the macro structure and the neural network structure shaped through the learning as the micro structure, which represents the behavioral rule of each agent.

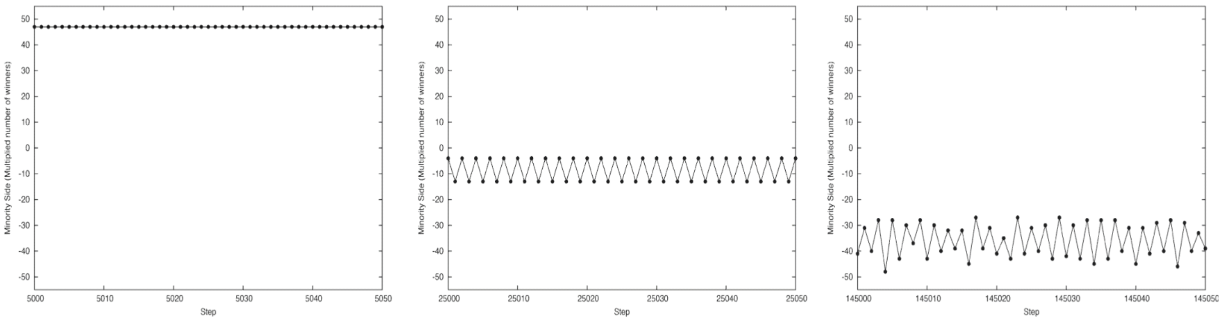
5.1.2 Simulation Results

The computer simulation of this system was done with the following parameter settings:

- The number of agents: 101
- Learning: every 10,000 games
- Teacher's signal: 100 past steps
- Learning rate, momentum coefficient, nonlinearity of neurons: 0.01, 0.8, 0.8
- Initial learnable synaptic weights: uniform random value between -0.5 and 0.5
- Initial input to the input and context layer neurons: 0.0

This system shows the variety of dynamic patterns at the macro level, both in the minority side and in the number of the winners (Figure 6). Among others, the most interesting pattern is Figure 6(d). In this pattern, both the minority side and the number of winners change aperiodically.

(a) Fixed : Fixed (b) Fixed : Periodic (c) Fixed : Aperiodic



(d) Periodic : Periodic (e) Periodic : Aperiodic (d) Aperiodic : Aperiodic

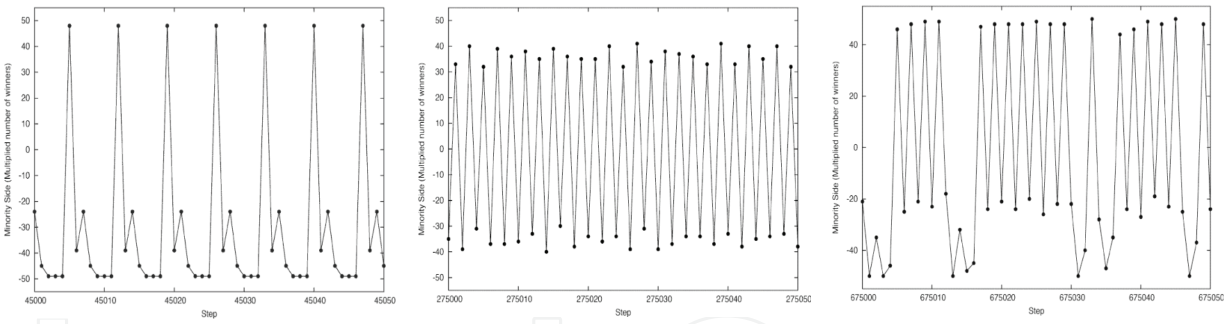


Figure 6. The dynamic patterns at the macro level: The X axis is the steps, the Y axis is the minority side (-1 or 1) times the number of winners. The label above each graph means that the first one is the dynamical state of the minority side and the second that of the number of winners

We closely analyzed this aperiodic pattern. The long term dynamics of the minority side is shown in Figure 7 which is the dynamics of the weighted moving average of the minority side in 20 steps. The ith past step is weighted by 2^{-i}, namely, the older information is more lightly weighted. As we see, the state chaotically change among various ordered dynamical patterns, fixed at 1.0 or -1.0 and periodic cycles with different periods, through aperiodic motions. It is a similar dynamics to chaotic itinerancy (Kaneko & Tsuda, 2003), a spontaneous transition among attractors, which is introduced in section 2. Note that this dynamics occurs in between learning (within 10,000 steps). Therefore no change takes place in the structures of neural networks and no external disturbance exists. We have confirmed that this dynamics does not cease how long the calculation continues without learning.

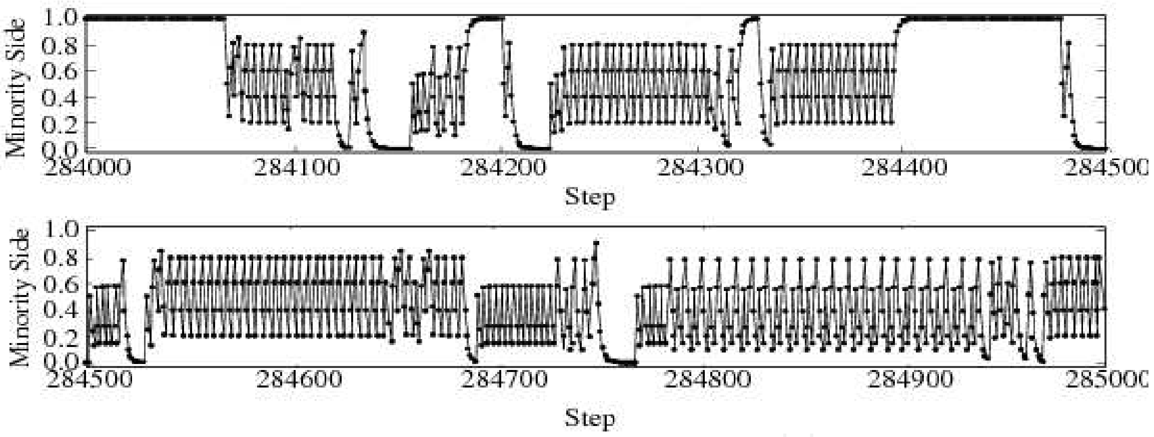


Figure 7. Itinerant dynamics of the minority side: The Y axis is weighted moving average of the minority side

We found that the agent had chaotic internal dynamics under the macro itinerant dynamics. An instance of the internal dynamics of an agent is exemplified in Figure 8 which shows the state change of two hidden and output neurons. This resembles a strange attractor. We measured the correlation dimension and the lyapunov exponent (Figure 9). This measurement proved that the agent structure has low dimensional chaos with weak nonlinearity (the correlation dimension is 0.92, the lyapunov exponent is around 0.02). We also found that when the macro dynamics shows the itinerant dynamics, the micro level is occupied by the agents with aperiodic, maybe chaotic, motions (Table 1).

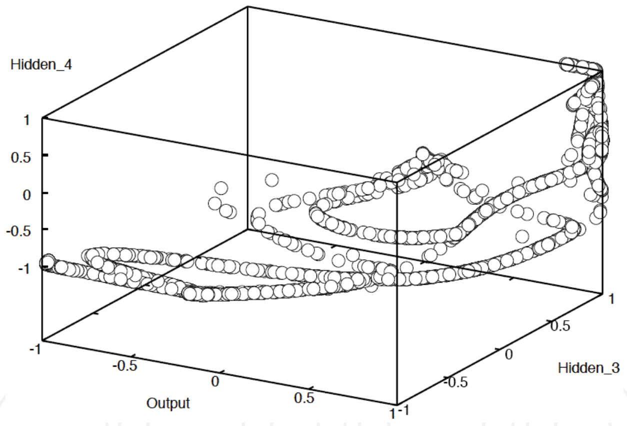


Figure 8. The internal dynamics of an agent when the macro level shows itinerant dynamics: The X and Z axes are the state of some hidden neurons. The Y axis is the state of the output neuron (before rounding)

5.1.3 Discussion: Itinerant Dynamics and Rule Dynamics

The itinerant dynamics (Figure 7), i.e., the continuous transitions among ordered patterns, at the macro level is interpreted as the perpetual changes of social structures, since the fact that the system with many individuals (very high dimension) is in a low dimensional dynamical state implies that the system has some sort of order, that is, structuralized. This dynamics is a kind of rule dynamics. The agents behave with certain order, namely, they seem to share a kind of rules to govern their behavior. These rules undergo changes by their behavior. An important point is that the agents' internal structures do not undergo any change, for no learning takes place in that period. The agents acquire the internal structure that is able to induce the macro changes. This is confirmed by the fact that most agents have chaotic internal dynamics (Figure 9). Chaotic dynamics can expand small fluctuations into the whole system scale. As we discussed in section 3, this situation causes the undecomposability between parts and whole. Since there are many agents with chaotic internal dynamics in the case of itinerant macro dynamics (Table 1), a small fluctuation of one agent transmits to the other agents with expansion and finally the whole structure is modified.

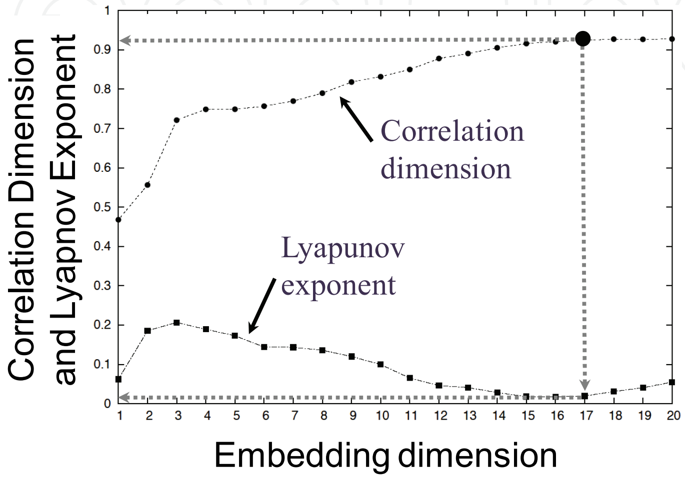


Figure 9. The correlation dimension and the lyapunov exponent of the internal dynamics of an agent depicted in Figure 8

Macro Level		**Micro Level**		
Minority Side	# of Winners	Fixed	Periodic	Aperiodic
Fixed	Fixed	101	0	0
Fixed	Periodic	84	17	0
Fixed	Aperiodic	50	46	5
Periodic	Periodic	63	38	0
Periodic	Aperiodic	20	77	4
Itinerant	Itinerant	8	6	87

Table 1. The number of agents having three types of internal dynamics, fixed, periodic and aperiodic in the various macro dynamical patterns

The competitive interaction implemented in the minority game also plays important role for the rule dynamics. When there is a rule at the macro level, the agents try to play the winner's move by following the rule. But more than half agents go to the "winner's side", the side is no more winner. Thus, the macro rule collapses. Since the macro rule is not a mere operator for the micro behavior, we can find the undecomposability between operator and operand. We have confirmed that the itinerant dynamics is not observed under the cooperative interaction, the majority game (Sato, 2005).

The micro-macro loop is considered to be established in our system. The ordered dynamical pattern at the macro level, which implies the macro structure, is composed of the dynamical patterns in the internal structures of the agents, which are the micro structures. The agents acquire the micro structure through learning of the macro dynamics. We have also confirmed that the removal of the micro-macro loop eliminated the itinerant dynamics (Sato, 2005).

We can conclude that endogenous dynamics of macro structure is likely to be induced by the chaotic internal dynamics, the competitive social interaction and the micro-macro loop.

5.2 Cognitive Modeling for Language Evolution and Displacement

The second topic is the dynamics of language. Humans have cognitive ability not only to acquire and use symbols but also to create them. One characteristic of the human symbol system is displacement. Displacement is to refer something detached from "now, here and I". Namely, it is to be away, in space, in time and in subject, from the place where the body and the mind exist. It is said that the displacement is one of the critical natures that discriminate human communication system from other animals' communication systems. Other important features of the human communication system, such as symolism and syntax, are found in animals' communication systems, for example, of verbet monkey (Cheney & Seyfarth, 1985) and birdsong (Okanoya, 2002). Messages of animal communication are practically about situations that a sender or a receiver confront, especially about biologically fundamental affairs such as survival, danger and reproduction. Considering about displacement is an important issue in the emergence and the evolution of human symbol system, and also of human language. Further, it is straightfowardly understandable that the displacement brings creativity.

The emergence and evolution of the symbol system can be devided into four stages as described in Figure 10. The first stage is articulation, in which object to be referred is singled out as an entity. The second is the stage of labelling or symbolization, in which a sign is asigned to the entity.The sign becomes a symbol. Symbol grounding is concerned with this stage. Next stage is to manipulate the entity referred virtually through minipulating the symbol. Artificial intelligence had aimed at realizing this stage. The last stage is to release static connection between signs and entities, and to make signs represent or to create new entities and new meanings. This stage can be called as symbol expansion or meaning creation.

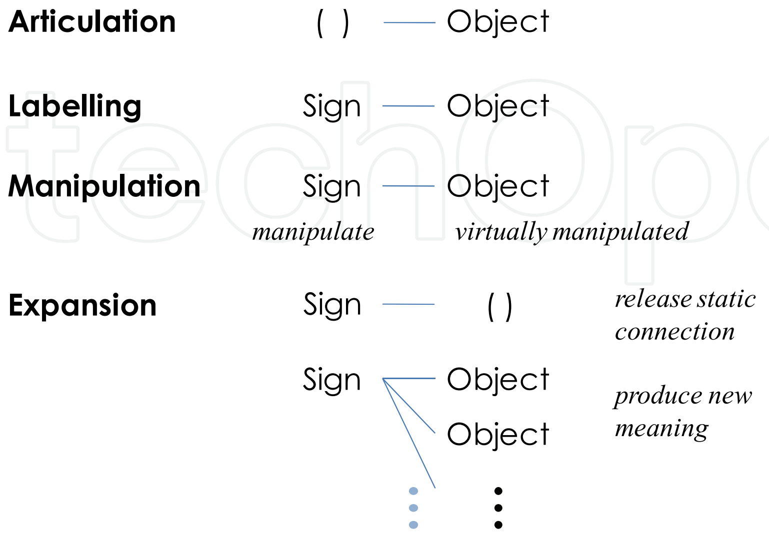


Figure 10. Four stages in the evolution of symbol system

The displacement is related to this forth stage. In this subsection, we study the symbol expansion and the meaning creation by considering a kind of language change processes called grammaticalization with the evolutionary constructive approach.

5.2.1 Grammaticalization

Grammaticalization is a type of meaning change in which content words obtain functional meanings (Heine, 2005). The content words represent some contents like nouns, verbs and adjectives. The functional words play some grammatical roles like auxiliary verbs, prepositions and conjunctions. A representative example of grammaticalization is "be going to" in English, in which a content word "go" acquired a functional meaning of future tense. In the process of grammaticalization, meanings of a word often changes from concrete meaning related to a part of body or bodily experiences to an abstract concept such as space or time, and then further abstracted to represent grammatical function. This change is usually unidirectional from content to functional and from concrete to abstract. This unidirectionality is a remarkable feature of grammaticalization. The unidirectionality of grammaticalization progresses from representing concrete experiences to expanding symbol relations into abstract entities. This coincides with the fourth evolutionary stage of the symbol system illustrated in Figure 10. Another important feature of grammaticalization is universality. Similar changes are found in many different languages (Heine & Kuteva, 2002a). The universality and the unidirectionality imply the universal tendency of human cognition.

Grammaticalization is interesting from the viewpoint of language evolution (Heine & Kuteva, 2002b; Hurford, 2003; Newmeyer, 2006). Language evolution is a long term changing process of complexification and stracturalization of human languages from an initial language which is expected to be simpler than the present. The fact that grammaticalization is unidirectional and universal brings an insight that the initial language may be composed of only content words (nouns and verbs) and have comprexified through the processes of grammaticalization (Hurford, 2003).

Further, considering what cognitive structure causes the unidirectional language changes from concrete to abstract will yield knowledge about the origin of language. The origin of language is a biological evolutionary process in which human cognitive abilities related to language emerged and evolved. In order to clarify such evolutionary process, the evolutionary constructive approach is effective, since the process must be complex and empirical evidences are rare. Constructing and operating models of language change and language evolution are to search for structures, settings and conditions for general properties of human language to be possible (Hashimoto & Nakatsuka, 2006).

5.2.2 Cognitive Modeling of Grammaticalization

We explain the modeling of grammaticalization. The description is limited to the important part because of the space limit. The details should be referred to (Nakatsuka, 2006; Hashimoto & Nakatsuka, 2007).

We focus on reanalysis and analogy which Hopper & Traugott (2003) point out as the necessarily processes for grammaticalization. Reanalysis is internal structural change of sentences, which is not apparent at the level of forms. Analogy is to generalize grammatical rules and to apply a rule to forms in which the rule is not applied formerly. We think of them as cognitive abilities of language users and equip agent with the following three abilities:

- Reanalysis : ability to articulate sentences based on contextual information and existing knowledge
- Cognitive analogy : ability to find similarities among situations and among forms
- Linguistic analogy : ability to apply linguistic rules extensively in its own knowledge

We adopt the iterated learning model (Kirby, 2002) as the interaction between agents, which is illustrated schematically in Figure 11. Suppose two agents, a speaker and a learner, look at various situations. The learner attempting to acquire language receives utterances which describe the situations from the speaker who already has linguistic knowledge. The linguistic knowledge is composed of rules to correspond situations or part of situations (meaning) to utterances or part of utterances (forms), category/<meaning> → form. The learner structuralizes its own linguistic knowledge in order to produce appropriate utterances for situations. After a while of learning, the learner becomes to a new speaker and a new learner is introduced. They compose the next generation. The new speaker gives the new learner language inputs based on its knowledge acquired at the learning process. It is a characteristic of the iterated learning model that linguistic knowledge is transmitted and structuralized through generations.

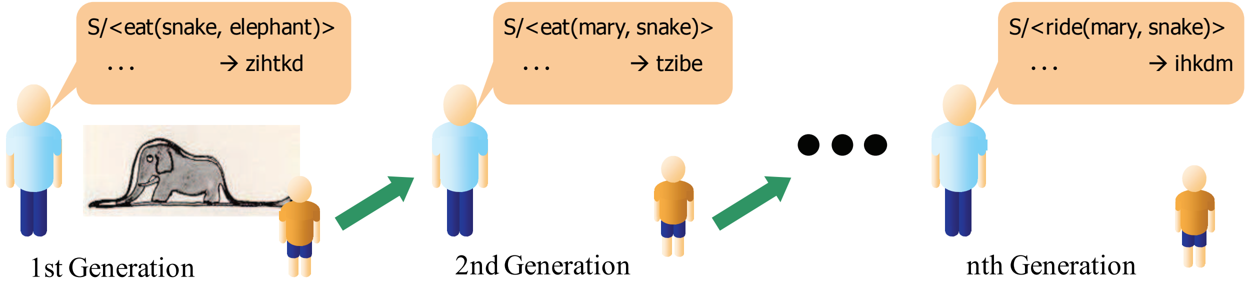


Figure 11. A schematic view of iterated learning model

In this learning process, the learner performs three learning operations, called chunk, merge and replace, to generalize linguistic knowledge. These operations have the following correspondences to the abilities of the agent (Hashimoto & Nakatsuka, 2006): Reanalysis is realized mainly by chunk. Cognitive analogy is premised in all three operations. Linguistic analogy is realized mainly by replace.

We further introduce two designs of meaning space: pragmatic extension and cooccurrence. The former is to make use of a form representing a meaning in order to describe another meaning. The latter is that a meaning often appears with another particular meaning.

5.2.3 Simulation Results

The simulations were done under the following setting:

- Meanings: 5 verbs, 5 nouns, 3 tense meanings, <past>, <present> and <future>
- Pragmatic extension: the speakers can make use of forms for <run> and <walk> to describe the meaning <go>
- Cooccurrence: two meanings <go> and <future> have high probability to appear in the same situations
- The number of utterances in one generation: 50
- Initial knowledge: both a speaker and a learner do not have any rules.

The frequencies of application of the three learning operations, chunk, merge and replace, change with generations as Figure 12 (left). The frequecny of replace operation is much larger than the other two. This operation works effectively for promoting the descriptive power of linguistic knowledge. We made an experiment in which the learners cannot use replace operation. In this case, the application frequency was not compensated by remaining two operations as seen in Figure 12 (right) and the total frequency decreases than the case with replace. The descriptive power does not grow so much. The important finding is that meaning change, that is, a form representing a meaning at some generation becomes to represent another meaning at later generations, is rarely obseved.

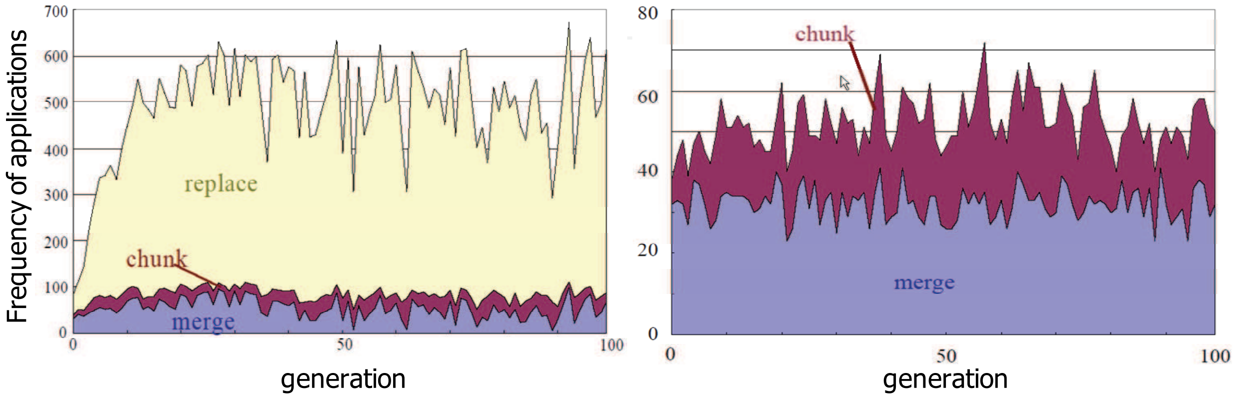


Figure 12. The application frequency of three learning operations with replace (left) and without replace (right)

There are four conditions about introducing the two designs of meaning space. We counted the frequency of meaning change for all four conditions. Figure 13 shows the total frequency of meaning changes. The results of significance testing are written above the bars. The solid and dashed lines mean the difference between two values is significant or not, respectively. It is found from this result that setting the pragmatic extension significantly heightens the meaning change. We then counted the frequency of meaning change concerning grammaticalization, that is, from <go> to functional meanings, <past>, <present> and <future> (Figure 14). In this case, introducing the cooccurrence makes the frequency from <go> to <future> twice than the other changes. From these results, we found that the pragmatic extension promotes the meaning change and the occurrence brings the unidirectionality.

5.2.4 Discussion: Significance of Replace Operation

We showed that the replace operation is indispensable for meaning change. In order to consider what is the significance of replace operation, we explain this operation. The replace is defined as follows: When a meaning and a form in a rule are included in another rule, the latter is replaced with a new rule having a variable where the former is substituted. For example, suppose an agent has two rules,

N/<john> → ot,

S/<read(john, book)> → swote,

where N represents a category of the meaning <john> belonging to and S represents a sentence. Since both rules have <john> in the left hand side and "ot" in the right hand side, the replace operation can be applied. The latter one is replaced by a new rule

$$S/\text{<read}(x,\text{book})\text{>} \rightarrow \text{sw } N/x \text{ e},$$

where *x* is a variable.

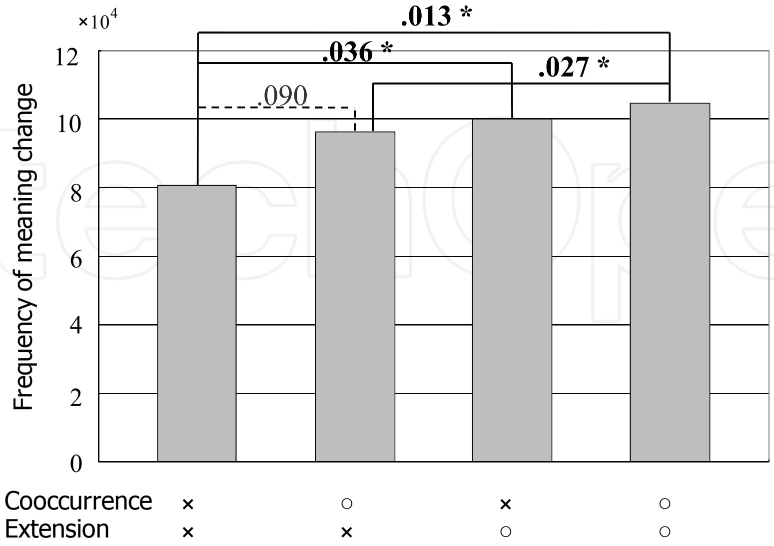


Figure 13. The total frequency of meaning change for four conditions about cooccurrence and pragmatic extension

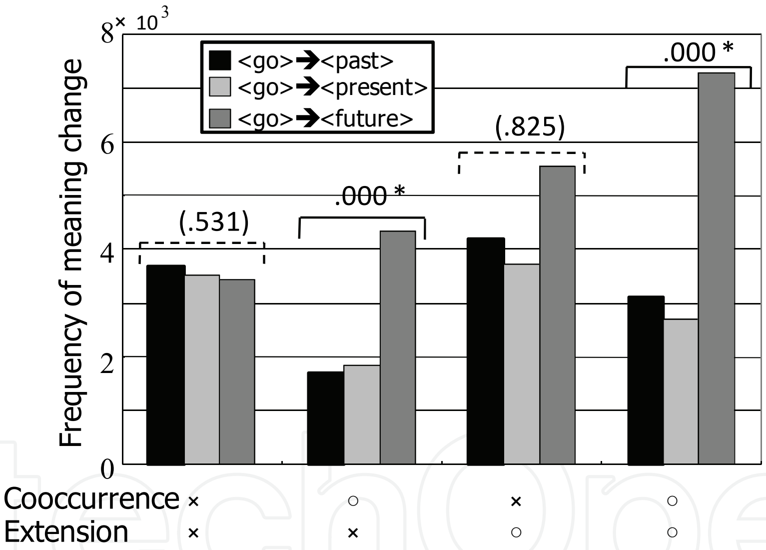


Figure 14. The frequency of meaning change from <go> to functional meaning for four conditions about cooccurrence and pragmatic extension

Note that any rule in the category N can be substituted in the variable. If the agent has other rules in the category N, say N/<elephant> → ir, the agent can produce an utterance corresponding to a situation <read(elephant, book)> using the rule set after the replace operation. The rule before the replace operation is acquired through an experience to watch a situation "John reads a book" and to hear an utterance "swote". But extensive application of the new rule acquired by the replace operation makes new utterances about situations that were not in the agent's experience.

This feature to produce sentences about situations detached from direct experiences is thought of as corresponding to displacement. The replace operation realizes the linguistic analogy. It is suggested that the linguistic analogy in which a linguistic rule acquired is applied extensively to other rules is important for meaning change. We can consider that the significance of the linguistic analogy is caused by learning operation bringing the displacement.

5.3 Dynamics of Communication

Communication is a dynamic process. A symbol used in communication is composed of three terms: form, reference and interpretation (Peirce, 1935). The interpretation is physically unknowable different from the other two terms. Further, people often have different ways of interpretation and the ways are unknowable by other people. Despite of the unknowablility, we communicate with each other. We are engaged in communication under a tacit supposition that the counterpart of the communication must have the same interpretation. Since the difference between interpretations actually remains, however, inconsistency and misunderstanding inevitably become unconcealed and the communication sometimes fails. We try to communicate again by modifying our interpretation under a supposition that this modification should be valid. Namely, communication has the dynamics of success and failure in mutual understandings. In this section, we try to model such dynamic feature of communication (Fujimoto & Hashimoto, 2008).

5.3.1 Modeling Communication Dynamics Based on Language Game

As we have mentioned, communication has the following features:

- Inconsistency of interpretation occurs on the way of communication and we retry communication through modification of interpretation.
- Even if a way of interpretation once leads to successful communication, the success with the same way of interpretation in following communication is not guaranteed.
- Success and failure of mutual understanding continues forever.

We hypothesize that ambiguity and context play important roles for maintaining the dynamics of success and failure in communication.

Our modeling is based on Steels' Language Game (Steels, 1996; Steels & Kaplan, 2002). The Language Game is a model of language evolution, in which an establishing process of the common vocabulary is represented. The basic procedure of the Language Game is the following:

1. Some of objects, discriminated by IDs, are decided (randomly) as an object-set.
2. A speaker selects one topical object from the object-set and utters a name of the topical object according to its own lexicon.
3. A hearer answers an object according to its own lexicon.
4. If the answer is collect, the communication is success. If not collect, the speaker teaches the hearer the selected object and the hearer updates its lexicon by recording the correspondence between the name and the object's ID.

A cycle from the stage 2 to 4 is called one step.

Repeating this procedure, the agents who cannot communicate with each other at first come to be mutual understanding finally. That is a process from failure to success of communication. But after a while they succeed always, if there is no change in the objects or in the communicating members. Namely, the dynamics of communication fades away.

We introduce two features concerning our assumption into the Language Game. One is a mechanism to maintain the ambiguity of symbols, the other is a disambiguation mechanism of the polysemous symbols by utilizing contextual information. We construct two new games. In one game, called game A, hereafter, the following two settings are added:

- Each object has multiple features in addition to ID. The speaker gives particular names to all features and ID. The hearer accepts all utterances as names of the objects' IDs. This device is for ambiguity.
- The hearer reconfigures its lexicon sometimes. In the reconfiguration process, the hearer finds a feature that is common to all objects having the same name and makes the name and the common feature correspond. This process represents a kind of induction to disambiguate polysemous names.

The other one, game B, has the following setup:

- All objects are discriminated only by IDs (no features).
- The number of symbols is restricted. This promotes ambiguity.
- Each object-set has particular objects that appear with high probability. This setting is called "situation". The speaker names each object associated to the situations. Situation changes sometimes but the hearer cannot notice the change of situation.

5.3.2 Simulation Results

The computer simulation of the game A was done with the following parameter settings:

- The number of objects: 50
- Features: 3 features and 3 values for each feature; Form {circle, triangle, square}, Color {red, green, blue}, Size {large, middle, small}
- The number of names: 60
- Lexicon reconfiguration: Every 100 steps or 200 steps (different simulation runs)
- Initial lexicon: Both the speaker and hearer do not have any name.

Name	ID	Form	Color	Size
34	23	Square	Blue	Large
34	41	Square	Green	Small
34	11	Square	Green	Middle
15	50	Circle	Blue	Middle
33	50	Circle	Blue	Middle
1	32	Circle	Green	Small
1	2	Triangle	Red	Small
1	8	Triangle	Red	Small

Name	ID or Feature
34	Square
1	Small
9	34
13	Circle
24	24
5	Red
39	14
32	1
17	7

Table 2. Parts of the hearer's lexicon before (left) and after (right) several times of the reconfigurations in the game A with 100 step interval of reconfiguration

Table 2 (left) shows a part of hearer's lexicon at the 199th steps in the game A with 100 step interval of reconfiguration. This timing is just before reconfiguration. There are some ambiguous symbols, shaded in the table. Namely, the names correspond to plural objects (IDs). The ambiguity was lost through reconfigurations. The right table depicts a part of the hearer's lexicon at the 900th step. Each name makes one-to-one correspondence to an ID or a feature. The communication became full success, the same as Steels's Language Game (Steels, 1996), with the lost of ambiguity as shown in Figure 15. The reconfiguration by induction is so strong in this small lexicon that all ambiguity resolved. No dynamics of communication was found in this game.

Next, we describe the simulation results of the game B. The setting of game B is as follows:

- The number of objects: 30
- The number of symbols (names): 10
- Four of five objects are peculiar to a situation.
- The number of situations: 5
- The situation changes every 5 steps. New situation is randomly selected from 5 situations.

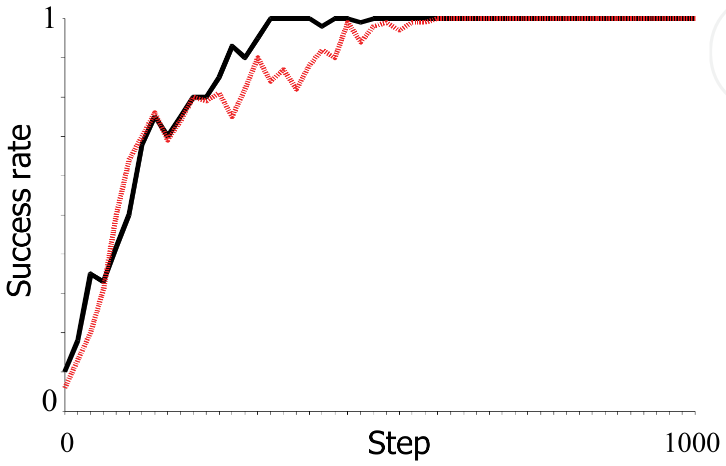
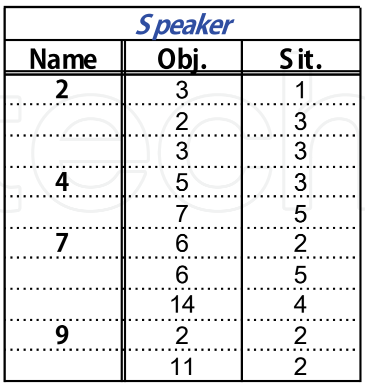
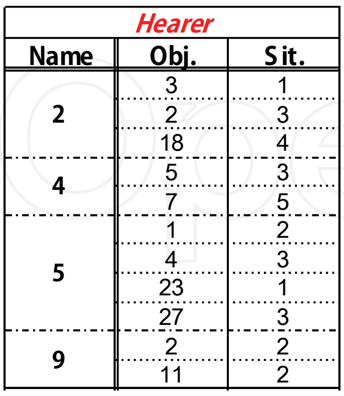


Figure 15. The change of the success rate of communication in game A with 100 step intervals of reconfiguration (solid) and 200 step intervals (broken)

Table 3 is parts of lexicons of the speaker and the hearer at the 200th step. All names in this table are ambiguous, i.e., one name corresponds to plural objects. The success rate of communication changes with steps as shown by the solid line in Figure 16. It grows roughly until around the 100th step (25th situation), but stays around 0.5 with fluctuations after the 100th step. Even after acquiring all names, communication between the agents may fail since the hearer does not know when situation changes. This dynamics does not disappear how long the communication continues.



Speaker		
Name	**Obj.**	**Sit.**
2	3	1
	2	3
	3	3
4	5	3
	7	5
7	6	2
	6	5
	14	4
9	2	2
	11	2



Hearer		
Name	**Obj.**	**Sit.**
2	3	1
	2	3
	18	4
4	5	3
	7	5
5	1	2
	4	3
	23	1
	27	3
9	2	2
	11	2

Table 3. Parts of the lexicons of the speaker (left) and the hearer (right) at the 200th steps

We compare the success/failure between at the beginning and the end of each situation (Figure 17). The bottom graph is apparently dense. This means that the hearer identifies the situation through communication and can decide the meanings of ambiguous names utilizing the information of situation.

The ambiguity sometimes brings "superficial" success of communication. The hearer succeeds communication at the beginning of new situation but fails at the next step in the same situation. Namely, the hearer does not understand the situation at that time. But thanks to the ambiguity of symbols, the agents happen to succeed the communication.

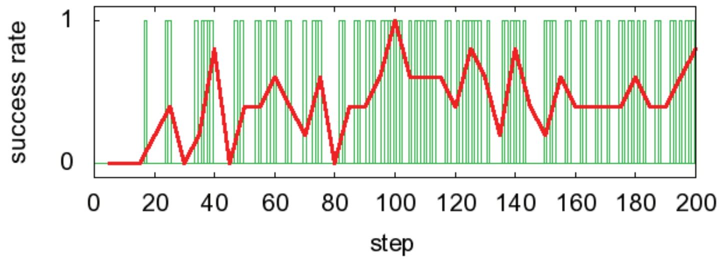


Figure 16. The success rate of communication averaged per each situation (5 steps) (line) and the success/failure of communication at each step (bars). 1 and 0 mean success and failure, respectively

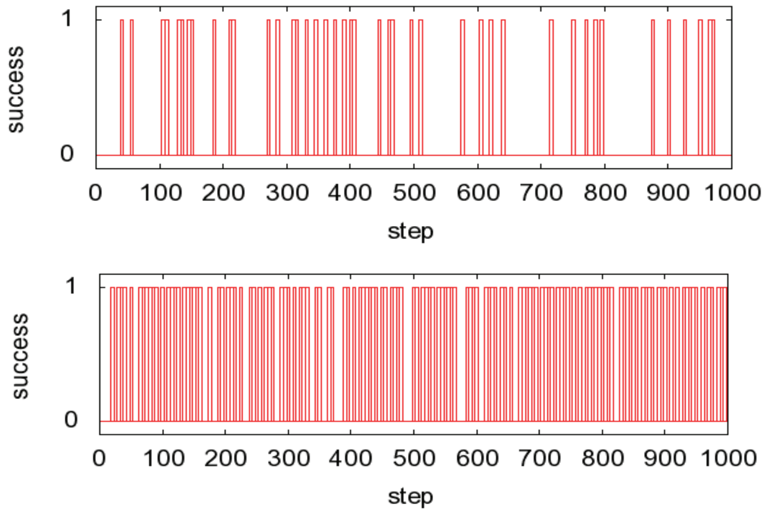


Figure 17. The success and failure at the beginning (top) and the end (bottom) of each situation

5.3.3 Discussion: Role of Ambiguity and Context

We are engaged in communication with indefiniteness and mutual understanding. These two antithetical features make our communication dynamic. In our simulation, we introduce ambiguity and context into Language Game. The indefiniteness is realized by the ambiguity of symbols and the change of the context. But if inductive reasoning is too strong, the ambiguity is disambiguated completely and the indefiniteness may fade away. The mutual understanding is attained by utilizing the contextual information. We found that the ambiguity also works to yield "superficial" communicative success.

We have realized the dynamics of communication by ambiguity and context in our model (game B). Thus, our hypothesis is verified to some extent. The critical point, however, to induce the dynamics of communication is the change of context. If the context does not change, the agents may attain the full success. The change of the context is implemented by hand in our present model. The context change should be endogenous in order truly to realize the dynamics of communication. This means that rule dynamics should be introduced to our model. The context plays as a rule in communication. The progress of communication in a context leads to the change of the context in natural language conversation. This study can be thought of as revealing the crucial importance of the rule dynamics in communication.

6. Conclusion: Towards Embedding Subjectivity in Objective System

In this chapter, we have discussed the evolutionary constructive approach as a methodology to study dynamic complex systems. In the evolutionary constructive study, we construct an objective system including some mechanism of change, and we operate the system. The constructive studies introduced in the previous section are concerned with intrinsic dynamics in social and linguistic systems the endogenous changes of social structures; the displacement causing language change and creativity; and continuing the success and failure of communication. From the viewpoint of complex systems explained in section 3, these themes are associated with rule dynamics, in which the operation of a system induces the change of the system's governing rules, and therefore associated with the undecomposability between operator and operand. The example studies represent that the evolutionary constructive approach has suitability for treating such dynamic complex systems.

Since we often treat the biological, cognitive, linguistic and social issues in constructive studies, the models are usually agent-based and consist of cognitive individuals. The individuals are equipped with internal structure, internal dynamics and mechanisms to change their internal states and internal structures. The individuals change their internal structures according to interactions with the circumstances and other individuals. The individuals develop their own ways to behave in their world, which is a basis of subjectivity and autonomy. We study the whole system consisting of such individuals objectively. Using evolutionary constructive approach, we may be able to embed systems having subjectivity and autonomy or systems having the ability to develop subjectivity and autonomy in a system that is an object of scientific investigation. Conventional scientific methodology is not good at dealing with subjectivity, since scientific research becomes possible by finding an objective entity in which subjective feature is stripped off. But treating subjectivity scientifically is unavoidable, if we are going to deepen our insight about complex systems as we described in section 3. We should develop further the evolutionary constructive approach in order to make such embedding possible.

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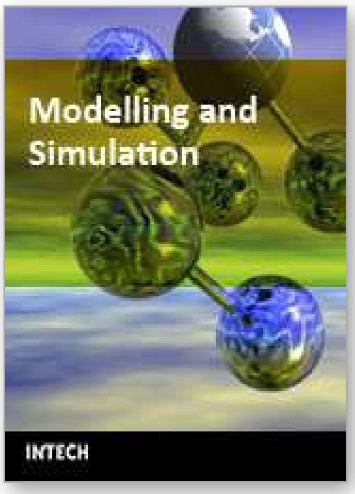

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