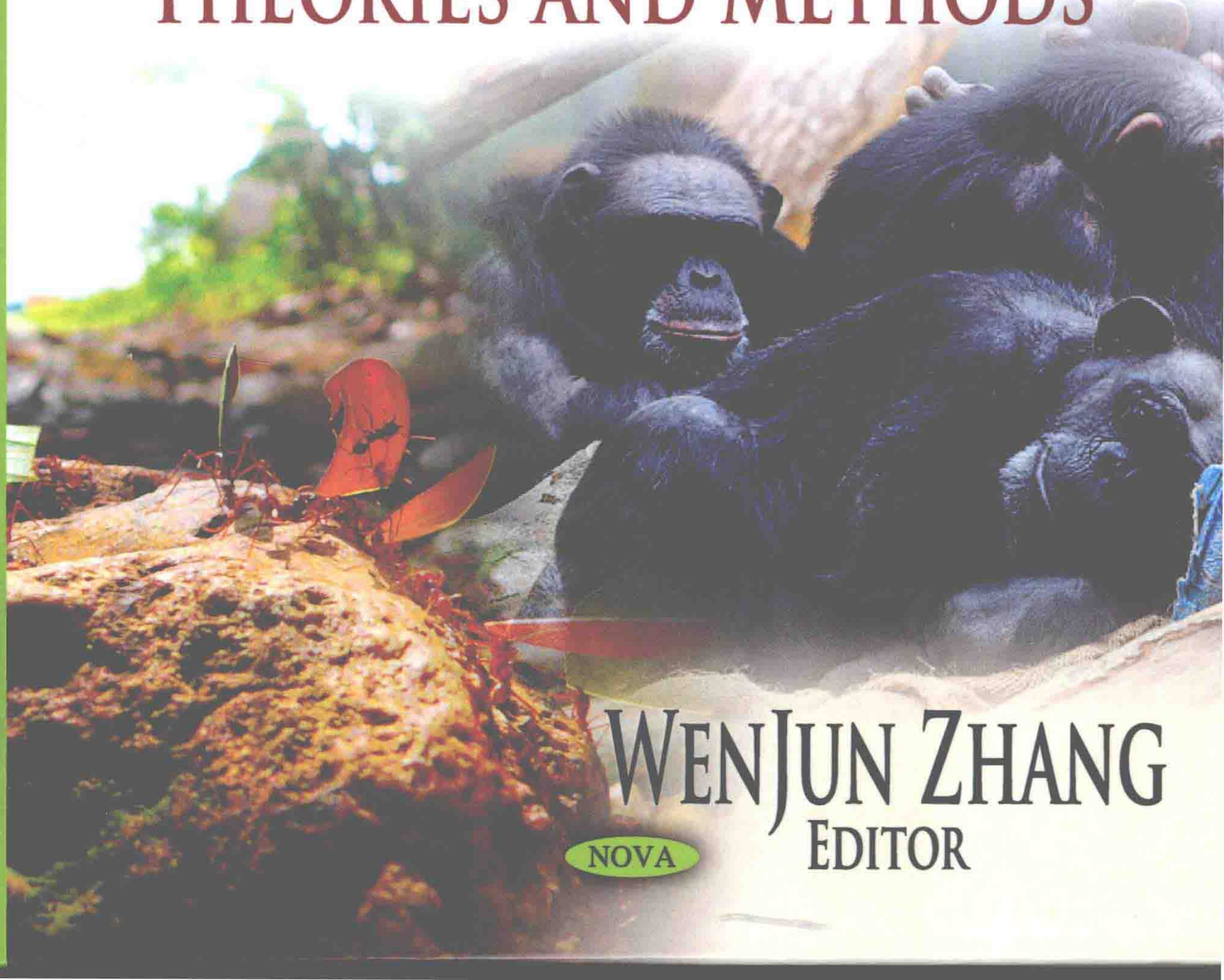
Mathematics Research Developments

SELF-ORGANIZATION

THEORIES AND METHODS



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PREFACE

Self-organization is a universal mechanism in nature. In the past thirty years, numerous phenomena, theories and methods on self-organization have been founded around the world. The book, Self-organization: Theories and Methods, is published to present recent achievements in theories and methods of self-organization. This book includes such theories and methods of self-organization as ant algotithms, particle swarm algorithm, artificial neural network, motion and migration algorithms, self-adaptive Kalman Filter, finite state approximation, etc. Chapters are contributed by more than 20 scientists from China, Italy, Spain, Japan, Russia, Serbia, India, Turkey, in the areas of mathematics, computational science, artificial intelligence, aeronautics and astronautics, automation and control, and life sciences. It will provide researchers with various aspects of the latest advances in self-organization. It is a valuable reference for the scientists, university teachers and graduate students in mathematics, natural science, engineering science, and social science.

The main contents are included as follows:

Chapter 1-In this chapter, concepts, theories, and methods of self-organization are briefly overviewed.

Chapter 2-Classification is a data mining functionality that assigns instances in a collection to target classes. The goal of classification is to accurately predict the target class for an unlabelled sample by learning from instances described by a set of attributes and a class label. Conventional classification methods specified in literature are less efficient in classifying very small datasets with repeated attribute values. To overcome this drawback, the study explores a classification method by mining similar patterns among the instances in very small datasets. Classification by Mining Patterns (CMP) algorithm is proposed to predict the class label of the unlabelled sample by mining similar patterns among the instances in the dataset. To mine similar patterns, the instances in the dataset belonging to the same class label are grouped. The instances in each group that differ by one attribute value are merged. Such merged instances form mined patterns. To predict the class label of the unlabelled samples, the attribute values in the mined patterns are compared with the corresponding attribute values of the unlabelled sample. The count of number of attribute values in the mined patterns matching with that of the unlabelled sample gives the attribute match count. The mined patterns having the maximum attribute match count are grouped and the majority class label of the mined patterns is predicted as the class label of the unlabelled sample. To choose the attributes in the mined patterns for comparison, an Ant Colony Optimization based Feature Selection Mined Patterns (ACOFSMP) is proposed. Simulation results are shown to prove that the CMP algorithm is efficient for classifying very small datasets with repeated attribute values.

Chapter 3-This chapter aims to present a study on auto-organisation in the context of Ant Colony Optimisation (ACO) metaheuristic. Heuristic optimisation algorithms should decide how to share efforts between exploration of newer solutions, and the exploitation of those previously discovered. In classical ACO algorithms this decision is taken beforehand, by setting up the algorithm parameters values. Usually it is necessary to change them every time a new problem is tackled. The purpose is to introduce in ACO a self-organisation dynamics that allows to balance the exploitation and the exploration. Inspired by the biological studies on the organisation of the real ant colonies, two kinds of ants are defined: one dedicated to the exploration, and the other assigned to the exploitation. Besides, it is defined a population dynamics to establish a relationship between both populations. This allows to self-regulate the populations between them according to the quality of the solutions found. The ultimate outcome is the Ant Colony Extended (ACE), a new algorithm with the capability of self-organise, which eliminates the necessity of using parameters. The chapter is focused on the population dynamics and its influence on the algorithms behaviour. The results are promising and encourage further investigation of how to apply this approach to other heuristic optimisation algorithm.

Chapter 4-In this chapter, a generalization of the popular and widely used Particle Swarm Optimization (PSO) algorithm is presented. This novel optimization technique, named Generalized PSO (GPSO), is inspired by linear control theory. It overcomes some typical flaws of the classical PSO, enabling direct control over the key aspects of particle dynamics during the optimization process. The basic idea of this algorithm with its detailed theoretical and empirical analysis is presented, and parameter-tuning schemes are proposed. GPSO is also compared to the classical PSO and Genetic Algorithm (GA) on a set of benchmark problems. The presented results demonstrate the effectiveness of the proposed algorithm. Finally, two practical engineering applications of the GPSO algorithm are described, in the area of optimal gear design and architecture and urban design.

Chapter 5-Artificial neuronets (AN), especially with error back-propagation (BP) training algorithms, have been widely investigated and applied in various science and engineering fields. However, BP-type neuronets, which are self-adaptive systems, have shown some inherent weaknesses, such as, the possibility of being trapped into local minima, the difficulty in choosing appropriate learning rate, and most importantly, the inability to determine the optimal neuronet structure. To solve the inherent weaknesses of AN, lots of improvements for BP-type algorithms have been investigated. However, as researchers (including the authors) realize and experience quite frequently, the inherent weaknesses of BP-type neuronets still exist. In this chapter, differing from others algorithmic improvements on the training procedure, the authors way about the problem solving exploits some elegant structure design, parameter-setting, pseudoinverse and numerical optimization techniques. In other words, a new type of AN using linearly-independent or orthogonal polynomials as activation functions, is presented and analyzed by us (the authors). These finally lead us to propose a weights and structure determination (WASD) method, which is based on a weights-direct-determination (WDD) method, for the authors presented feed forward AN. Based on the authors' previous work, single-input neuronets equipped with the WASD method have successfully overcome the above weaknesses. To investigate and verify two- or multiple-input neuronets equipped with this method, the authors firstly put forward various novel neuronets based on different activation functions. Then, corresponding WASD algorithms are proposed for the presented neuronets. For better performance (e.g., more efficiency and conciseness in self-organizing systems), the authors further propose pruning techniques in the neuronet structure determination. Finally, based on various target functions, numerical results further substantiate the efficacy of the proposed neuronets equipped with the corresponding WASD algorithms, which shows the better performance in terms of training (or say, approximation or learning), generalization (or say, testing or validation) and prediction.

Chapter 6-Humans produce adaptive locomotion through dynamic interactions among the nervous system, the musculoskeletal system, and the environment in a self-organized manner. A human musculoskeletal system has more degrees of freedom (DOFs) than necessary for locomotion and humans solve the redundancy problem in some way to establish locomotion.

It has been suggested that individual DOFs are not manipulated independently, but some DOFs are functionally connected by object tasks to reduce the number of DOFs. These relationships among DOFs appear as low-dimensional structures in the DOFs. This chapter shows such low-dimensional structures in joint movements and muscle activities (kinematic and muscle synergies) during human locomotion based on the analysis of measured data. In addition, it shows a constructive approach using a computer simulation with a neuromusculoskeletal model based on anatomical and physiological findings to examine the functional roles of the low-dimensional structures that generate adaptive locomotor behaviors through dynamic interactions among the nervous system, the musculoskeletal system, and the environment.

Chapter 7-This chapter discusses the self-organized movement of a set of some individuals. It is adopted that individuals perceive reality as its projection on coordinate system that is firmly attached to the individual. The movement of individuals is interpreted as the movement of points in this coordinate system according to the algorithms by which each individual is equipped. The projection of reality and other individuals simultaneously changing the parameters of algorithms and simultaneously impose constraints on the movement of these points. The set of individuals moves so that each individual performs arbitrary motion within the allowed constraints on one of two ways: a) individuals follow one or more leaders, b) individuals preserve system configuration during movement, i.e. not change some typical magnitude of set. Motion of individuals or of set of individuals from one position to another always takes place according to the functions of natural impulses. Short was given comparison between function of the natural impulse and other custom-fit functions.

Chapter 8-Habitat diversity is an important mechanism for species migration and distribution. A stochastic model for species migration in heterogeneous environment is described in this chapter. This model is used to describe various dynamics types in biological process such as periodic oscillation, monotonic increase and decline, and fluctuation. The species extinction likelihood in migrated area largely determines the dynamics and pattern of species migration. There is a significant difference in species migration between heterogeneous and homogeneous habitats. Higher fitness to species will lead to a faster migration and higher percentage of migrated areas. Existence of boundary areas may retard species migration.

Chapter 9-In this chapter a Robust Self-Adaptive Kalman Filter (RSAKF) algorithm with the filter gain correction is developed for the case of sensor/actuator malfunctions. The proposed RSAKF utilizes time variable factors in order to reduce the effect of the faults on the estimation procedure. In this sense, the procedures with single and multiple factors for the

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Chapter 1

An Overview on Theories and Methods of Self-Organization

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Abstract

Self-organization is a universe mechanism in nature. Self-organizing systems are the systems which can evolve and improve the organizational behavior or structure by themselves. In a self-organizing system, the system evolves automatically to form an ordered structure based on some compatible rules. Without any external instruction and force, the self-organizing system emerges only from the interactions between the basic components of the system. In this chapter, theories and methods of self-organization are briefly overviewed.

Keywords: self-organization; principles; theories; methods

1. Mechanisms and Principles of Self-Organization

Organization can be classified into two basic categories, i.e., self-organization and external-organization. The major difference between the two categories of organizations is whether the organizational instructions/forces come from outside the system or from inside the system. The organization with organizational instructions/forces from inside the system is self-organization. In other word, a system is called self-organizing system if there is any specific intervention from outside in the process of evolution (Foerster, 1960; Heyligen, 2002; Zhang, 2013). The stronger a system's self-organization capacity is, the stronger the system's ability to generate and maintain new functions is.

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Self-organizing systems are those systems which can evolve and improve the organizational behavior or structure by themselves. Self-organization is a process to describe the system's global state. In a self-organizing system, the system evolves automatically to form an ordered structure according to some compatible rules. Unlike other organizations, the self-organizing system arises only from the interactions between basic components of the system, without external instructions and forces. In the process of self-organization, several structural components can interact and cooperate to produce the behaviors that only a group will have. The dynamic interactions between low-level components typically include attraction and repulsion, that is, positive and negative feedbacks.

Generally, self-organization arises from the increase in complexity or information. According to the thermodynamic laws, this situation will only occur in the open systems far away from equilibrium. For most systems, this means the energy supply to the system is needed for generating and maintaining a certain mode. In an abstract sense, self-organization is a process that makes the system's entropy increase in the absence of external forces (i.e., a dynamic process that from disordered to ordered states) (Glansdorff and Prigogine, 1971; Nicolis and Prigogine, 1977).

From the perspective of systematic theory, self-organization is an irreversible dynamic process. From the view of mathematics and physics, self-organization means the dimension reduction of state space or the reduction of degrees of freedom, i.e., the system converges spontaneously to one or more steady states (i.e., attractors). In such a system, the local interactions between the basic components of the system can change the modes of system's organization, and the global behaviors of the system cannot be understood intuitively. They cannot be understood by simply observing existing laws and behaviors of between-component interactions (Zhang, 2012). The complex patterns and behaviors of self-organizing systems are thus often called "emergency". In a word, the global properties of self-organizing systems are not predictable.

Self-organization usually requires to be based on three elements (Bonabeau et al., 1999): (1) strong nonlinear and dynamic interactions, even though they do not necessarily relate to the positive or negative feedbacks, (2) a balance between development and exploration, and (3) complex and diverse interactions.

Self-organization is ubiquitous in nature and human society, which covers many fields as physics, chemistry, biology, economics and society. One of the most important examples of self-organization is the nonlinear processes in physics (Glansdorff and Prigogine, 1971; Ansari and Smolin, 2008; Brau et al., 2011). Self-organization is also chemical-related, which is often considered to be synonymous to self-assembly (Kim et al., 2006; Coleman et al., 2011; Harada, et al. 2011). It is very important for the description of biological systems at both sub-cellular level and ecosystem level (Hess and Mikhailov, 1994; Misteli, 2001; Camazine, 2003; Clyde et al., 2003; Motegi et al., 2011). It can also be found in the mathematical systems, like cellular automata (Zhang, 2012).

1.1. Thermodynamic Basis of Self-Organization

The spontaneous formation of new structures, for examples, crystallization process, Bénard phenomenon, and Belouzov-Zhabotinsky reaction (Sun and Lin, 2004), are all self-organizing processes. In other word, the formation of a structure or a mode does not need to be given any external force. The components of those systems seem to be arranged into a more ordered pattern by themselves. At first glance, self-organization violates the second law of thermodynamics. This law holds that the entropy of an independent system can only increase rather than decrease. In other word, the second law of thermodynamics means that an isolated system should evolve in a uniform, simple, difference-eliminating way, which is substantially an evolution to a low-level organization.

In the example of crystallization process, the randomly moved molecules that have been bonded into a crystal structure and thus have been fixed will transmit their kinetic energy to the liquid they are dissolved. Thus, the reduction in the entropy of crystallization process is just offset by the increase in the entropy of liquid. The entropy of the whole system has actually increased, and therefore it is coincident with the second law of thermodynamics.

For self-organizing systems, which are not in their equilibrium, it is hard to determine whether the second law of thermodynamics is true or not. Prigogine started to study the systems far away from equilibrium states since the 1950s and proposed the theory of dissipative structures (Glansdorff and Prigogine, 1971; Nicolis and Prigogine, 1977) in which the most used models to explain dynamic self-organizing process are Bénard cells and the Brusselator. The theory of dissipative structures tried to address such questions as, under what conditions a system will be able to evolve from the disordered to the ordered, and form a new, stable, and internally-dynamic structure. Such a structure must be an open system, i.e., there are energy/matter flows in the system; the system will continuously generate entropy, but at the same time the entropy will be actively dissipated from the system or output from the system. Thus, at the cost of environmental ordering, the system will be able to increase ordering of its own. The system will be able to follow the second law of thermodynamics simply by removing its excess entropy. This dissipation can be mostly found in life systems. Plants and animals obtain energy and matter by absorbing light or food with low entropy, and then output energy and matter by draining the metabolic waste of high entropy. This will reduce its internal entropy to offset the degradation process required by the second law of thermodynamics.

The output of entropy cannot explain why and how self-organization happened. Prigogine held that self-organization would mostly occur in the nonlinear systems far away from equilibrium.

1.2. Principles of Self-Organization

The first symposium on self-organization was held in 1959. In this symposium, the British cybernetic expert, Ashby, proposed "the principle of self-organization" (Ashby, 1947). He believed that a dynamic system, ignoring its classification or composition, always tends to move toward an equilibrium, or the "attractor". This theory reduced our uncertainty in the state of system and solved the problem of entropy in systematic science. This is equivalent to self-organization, which finally reaches the equilibrium and the final equilibrium can be considered to be a state with mutually adaptation of all components in the system. Another cybernetic expert, Heinz von Forster, proposed the principle of order from noise (Foerster, 1996). He believed that the larger a system is subject to random interference, paradoxically, the quicker it performs self-organization (i.e., become more ordered). This idea is very simple: The larger the state space that a system moves through is, the faster it reaches the attractor. If the system stays at its initial state, it will not reach the attractors, and self-organization will thus not occur (Foerster, 1996). Generally, there are multiple attractors in a nonlinear system. The attractor theory holds that the behavior trajectories of complex system in the state space can be represented by the dynamic equations. These dynamic equations are always determined by a set of “attractors”. What attractor the system will move toward depends on the attraction domain that the initial state falls into. What attractor the system eventually reaches is uncertain. Some small fluctuations will cause the system to move toward an attractor rather than another attractor. Prigogine thus proposed a related principle, i.e., order arises from fluctuations.

1.3. Fundamental Theories of Self-Organization

So far, self-organization theory is generally believed to mainly consist of three parts, the theory of dissipative structures (Glansdorff and Prigogine, 1971; Nicolis and Prigogine, 1977), synergetics (Haken, 1978, 2004), and catastrophe theory (Saunders, 1980). However, the basic thoughts and theoretical kernel of self-organization can be derived entirely from the theory of dissipative structures and synergetics.

(1) The theory of dissipative structures. Prigogine officially proposed the theory of dissipative structures in 1969 (Nicolis and Prigogine, 1977). The theory mainly aimed to explain the exchange of matter and energy between the system and the environment and its effect on the self-organizing system. The structure established from the exchange of matter and energy between the system and the environment is a dissipative structure, such as city, life, etc. Far away from equilibrium, the openness of system, and nonlinear mechanism between different components of system, are three conditions for the formation of a dissipative structure. Far away from equilibrium refers to that the distribution of matter and energy in different areas of a system is extremely uneven. The theory of dissipative structures is mostly used to discuss the evolution of complex systems. It uses two levels of approaches, i.e., deterministic and stochastic approaches in the discussion of system evolution. Deterministic approach uses macro-physical variables to describe system dynamics and features. Stochastic approach treats macro-physical variables as the average of corresponding random variables. Analyzing random variables will not only obtain the averaged values but also help understand fluctuation characteristics of the system.

(2) Synergetics. Haken first proposed the concept of synergy in 1976. Another science on self-organization, synergetics, was thus established (Haken, 1978, 1983, 2004). About synergetics, Haken held that on the one hand, in a system many subsystems interact to produce the structure and function at the macroscopic scale; on the other hand, there are many different scientific disciplines cooperating to explore the general principles for governing self-organizing systems. The order parameters generate and govern subsystems by competition and cooperation between various subsystems. Serving of various subsystems to order parameters reinforces order parameters and further promotes the serving of subsystems to order parameters, so that the system can be spontaneously organized by itself (Haken, 1978, 2004). Competition and cooperation between order variables will result in different forms of evolutions of self-organization. Synergetics mainly discusses the coordination (i.e., synergy) mechanism between internal components of the system studied. It holds that the coordination between various components in the system is the basis of self-organizing process. Competition and cooperation between order parameters of the system are direct forces for the formation of new structures. Because of independent evolution of components in the system, various local and collaborative evolutions, as

well as random inferences by environmental factors, the actual state of system always deviates from the average. The magnitude of such a deviation is called fluctuation. When the system is in its transition from one steady state to another steady state, and the independence evolution and collaborative evolution between system components move into a balance, any small fluctuation will be amplified, and quickly spread to the whole system. The resultant giant fluctuation will promote the system moving into an ordered state. In addition, Harken proposed the concept of functional structure, i.e., the function and structure are dependent for each other. If the energy or matter flow is cut off, the physical and chemical system will lose their structure, while a biological system is mostly able to maintain a fairly long time. Such biological systems seem to combine non-dissipative and dissipative structures together (Haken, 1978, 2004).

(3) Catastrophe theory. Catastrophe theory was first proposed by the French mathematician, Thom R, in 1969. Since the 1970s, Zeeman and other scientists have further developed catastrophe theory and apply it to various aspects of physics, biology, ecology, medical science, economics and sociology, and have produced significant impacts (Zeeman, 1976). This theory was built on the basis of the stability theory. It considers a catastrophe process as a process that transit towards a new steady state through an unsteady state started from an original steady state. In the mathematical view, this means the changes of values of a set of parameters and mathematical functions that denote the states of system. Thus it is a theory to describe the phenomena that the continuous change of parameters lead to the discontinuous change of the states of the system. It treats with the systems that are almost structural stable in the state space but there is some structural instability on some point sets of measure 0. The basic characteristics of catastrophe systems include multiple steady states, reachability, jumping, lagging, and divergence (it reflects the sensitivity of evolutionary trajectory to the path of control parameters). Catastrophe theory holds that different outcomes may occur even if it is the same process that corresponds to the same controlling factors and critical values, and different new steady states may be achieved with different probabilities (Saunders, 1980). Generally, catastrophe theory does not reveal the mechanism to produce catastrophe phenomenon. It provides a reasonable mathematical model to describe the phenomenon of catastrophe in the real world, and categories various catastrophe types. In ecology, there are a lot of applications of catastrophe theory, such as the sudden outbreak or sudden collapse of biological population. In addition, there are also other theories of self-organization, for example, Eigen's super circle theory. Super circle theory is a self-organization theory on molecular evolution. However, it is a scientific hypothesis, the impact is still limited.

1.4. Properties of Self-Organization

Interacting with the environment, the self-organizing system can evolve to form new structures and functions. Unlike ordinary mechanic systems, it has its own peculiar properties. Those peculiar properties can be used as part of the definition of self-organizing systems. For example, there is no centralized control, and continuous adaptation to the changing environment, etc.

(1) Local interactions generate global ordering. The most obvious change in the self-organizing system is the formation of global ordering. Local interactions follow immediately basic physical processes, and any impact from one region to another region must first move through all intermediate regions. When it passes through intermediate regions, all the processes will be disturbed by the turmoil occurred in the intermediate regions. First we assume the system is disordered and all components of system evolve randomly. The impact of any passed will be quickly dispersed and ultimately destructed by these random turbulences. The result is thus that, starting in the chaotic state, the distant parts of system are actually independent, that is, they do not affect each other. During the process of self-organization, all the components of the system are closely linked. Understanding of the structure of a regional component will be valuable to know the structure of components of its consecutive regions.

(2) Distributed control. We tend to consider that a highly organized system is instructed and controlled by external or internal forces. This kind control is called centralized control. In a self-organizing system, the control to organization is distributed throughout the system. All components contribute to the final arrangement of the states of system. Despite some of the advantages of centralized control with respect to distributed control, centralized control must be based on distributed control at some levels. For example, the function of human brain is dispersed in the network formed by interacting neurons. Different brain regions perform specific functions, but not a neuron or a group of neurons has all the ability to control brain. This is a result of self-organization.

(3) Nonlinearity and feedback. Nonlinearity means the whole is not equal to the simple sum of its parts, i.e., superposition principle is not met. Referring to the mechanical movement, a linear phenomenon is generally manifested as smooth motion in time and space. It can be described by the functions with good performance, and the functions are continuous and differentiable. The nonlinear phenomenon is a movement from regular motion to irregular motion, with obvious jumping and intermitting features. From the view of disturbance and parameter theory, the response of a linear system is smooth and proportional changes, but nonlinear system will exhibit substantial changes in some of the key points because of the small changes in parameters, and it form and maintain spatially regular and ordered structures. Linear relationship is independent, while the nonlinear relationship is an interactive one, which makes it violate superposition principle and produce gain or loss. In the nonlinear systems, there are feedbacks between system components, and each component affects the others and other components in turn affect it. Positive feedback plays a role similar to the input so that the system's deviation increases, and the system's oscillation is thus amplified. Negative feedback causes reverse outcome compared with input's role, so that the system's output error can be reduced and the system is thus stabilized. In the complex self-organizing systems, there are often several chains of positive and negative feedbacks, so a change can be enlarged in a certain direction but suppressed in the other directions. This will result in the very complex behaviors hard to be predicted.

(4) Far away from equilibrium. Equilibrium is a special state of a system. At this state, the everywhere measurable macroscopic physical properties of the system are

uniform throughout the system (so that there is not any macroscopic irreversible process inside the system). At the equilibrium state, the system follows the first law of thermodynamics: $d_E = d_Q - pd_V$, i.e., the increment of energy inside system is equal to the absorbed heat subtracting by outward work done by the system. It is also coincident with the second law of thermodynamics: $d_S/d_t \geqslant 0$, that is, the spontaneous evolution of system is always toward the direction of entropy's increase. For the system at equilibrium state, it must abandon its extra energy; it will remain in the minimum energy state without the input of external energy. The system far away from equilibrium is more sensitive and more vulnerable to environmental changes due to its dependence on external energy input. But it is more powerful to respond changes. On the other hand, the surplus of external input energy allows the system to amplify the self-organization process, for example, offsetting small turbulences or maintaining positive feedbacks longer in the aid of strong interactions. This makes the system more vigorous and more adaptive to external changes.

(5) Systematic termination and organizational hierarchy. The interactions between individual components of self-organizing system can be, to some extent, defined as an ordered structure. However the ordering does not mean organization. Organization is an ordered structure and can achieve a particular function. In a self-organizing system, this function is to maintain a particular structure under various disturbances. The general characteristics of self-sufficiency can be understood as a closure. A process with causal relationship can be represented as a chain or a sequence: A → B → C → D → ..., where A initiates B, B initiates C, C initiates D, and so on. Overall, this will lead to a continuous change. However, there may be its own termination of a link in the chain, for example, O returns J. So the cycle of the system becomes J, K, L, M, N, O, J, K, L. Thus the corresponding arrangement of the system will always be maintained or recycled. In addition, if the loop is placed in a negative feedback region, it is relatively not affected by the impact of external interference (Foerster, 1960). In a self-organizing system, a lot of autonomous and organization-closed subsystems may generate. Those subsystems will interact in a more indirect way. They will also adapt to the structure for termination and determine subsystems at a higher level. New generated subsystems will contain the original subsystems as their components. Each self-organizing system constitutes a series of subsystems. A self-organizing system thus forms a layered structure. Each self-organizing system belongs to a high-level self-organizing system and contains low-level self-organizing systems. It interacts with other self-organizing systems at the same level. Therefore, the hierarchy is one of the characteristics of self-organizing systems.

2. Algorithms of Self-Organization

2.1. Computer and Mathematical Modeling

Because it is difficult to predict complex behaviors of self-organizing systems, computer simulation and mathematical modeling are useful methods for theoretical experiments of those systems. They also help people understand how these systems work. One method for