Frank Schweitzer:
Self-Organization of Complex Structures: From Individual to Colletive Dynamics - Some Introductory Remarks
in: *Self-Organization of Complex Structures: From Individual to Collective Dynamics* (Ed. F. Schweitzer)
Gordon and Breach, London 1997, pp. xix-xxiv

Self-Organization of Complex Structures: From Individual to Colletive Dynamics - Some Introductory Remarks

Frank Schweitzer

Institute of Physics, Humboldt University,
Unter den Linden 6, 10099 Berlin, Germany

e-mail: frank@physik.hu-berlin.de

In a world of fast growing population, global traffic and intercontinental trade relations, and an ever increasing demand for new supply systems for a developing society, the unterstanding of structure formation and evolutionary processes is one of the major challenges at the doorstep into the twentyfirst century. This challenge is also pointed to natural sciences on their way to a new responsibility for complex phenomena.

The emergence of complex behavior in a system consisting of interacting simple elements is among the most fascinating phenomena of our world. Examples can be found in almost every field of today's scientific interest, ranging from coherent pattern formation in physical and chemical systems [3, 8, 12], to the motion of swarms of animals in biology [4, 21, 26] and the behavior of social groups [22,25]. In the life and social sciences, one is usually convinced that the evolution of social systems is determined by numerous factors, difficult to grasp, such as cultural, sociological, economic, political, ecological etc. ingredients. However, in recent years, the development of the interdisciplinary field "science of complexity" has lead to the insight, that complex dynamic processes may also result from simple interactions. Moreover, at a certain level of abstraction, one can also find many common features between complex structures in very different fields.

These investigations lead to the hypothesis, that there is a common level to describe the formation of these structures. It is the basic dynamics of structure formation, which creates these analogies, regardless of the different sub-entities involved, and we are convinced that the theory of self-organization provides a suitable quantitative approach to it. This may shed some new light on the established ideas about hierachical planning and control in social, economic or urban evolution. However, this is not only a question of developing new theories, it is challenged by the pressure resulting from the problems of our evolving world. Confronted with these realities, there could be a quest for the system-immanent forces which allow the generation of structures in a new way.

In order to reveal the dynamics of these self-organizing processes in nature and society, a dialogue is needed between natural and social science. This dialogue should help to overcome the gap between natural and social science (i) by providing methods of the natural sciences, which could be adapted for solving problems in the social or life sciences, and (ii) by increasing among natural scientists the sensitivity for problems in the social sciences. Genuinely, it is the aim of this book to contribute to this dialogue, and it is the wish of the editor, that it will set some new perspectives for future collaboration.

About the Conference

The two volumes of this book consist of a selection of papers which have been presented at the International Conference "Self-Organization of Complex Structures: From Individual to Collective Dynamics", held in Berlin, Germany, 24. - 28. September 1995. The conference attracted some 150 scientists from 15 countries. During the five days meeting, 18 plenary talks, 34 talks in parallel sessions and 40 poster contributions have been presented [28].

Regarding the scientific approach, the Berlin conference continued conference series as "Irreversible Processes and Self-Organization" (IPSO 1-4, Rostock, 1977, Berlin, 1982, Kühlungsborn, 1985, Rostock, 1989) [5,6] and "Models of Self-Organization in Complex Systems" (MOSES, Gosen near Berlin, 1990) [7], which already gained an international interest. The scientific committee of the recent Berlin Conference included A. Hübler from the Center of Complex Systems Research of the University of Illinois, Urbana, and W. Ebeling, L. Schimansky-Geier from the Institute of Physics of the Humboldt University, Berlin, which I would like to thank for their cooperation. Financial support for the conference was provided by the "Deutsche Forschungsgemeinschaft" (Bonn).

The recent Berlin conference was, of course, not the first conference dedicated to the problem of collective dynamics. Already the title of the conference might have remind someone on the workshop "From Individual To Collective Behavior in Social Insects" [21], which was devoted to specific problems of organization in ants and bees societies. Among the recent conferences, dealing with self-organization and complexity, some have confined themselves basically to physical problems [3,12,19], others focused especially to the problems of artificial life [15,18,23]. Contrary, the Berlin conference, as these proceedings reflect, aimed to link the discussion about complex phenomena in natural science, such as physics or biology, in particular to those in life science, such as sociology, economy or regional planning. One of the challenges of the conference was to reveal cross-links between the dynamic models used in the specific fields, in order to find out pieces for a common theory of self-organization and evolution of complexity.

The main focus of the recent Berlin conference was the emergence of collective phenomena from individual or microscopic interactions in different fields of applications, which are marked here just with a view key words:

1. *Evolution of complexity*: emergence of dynamical hierarchies, probabilistic approach of complex systems, multi-agent systems, models of pattern formation and interactive structure formation.

2. *Evolutionary optimization*: molecular self-assembly, ensemble search strategies and emergence of collective strategies.

3. *Biological and ecological dynamics*: co-evolution, emergence of functionality, collective phenomena in biological systems.

4. *Dynamics of socio-economic processes*: self-organization in social systems with respect to cultural elements, interacting spatial economies, economic evolution, dynamics of innovation processes.

5. *Urban structure formation and transportation dynamics*: micro and macro models of settlement formation, growth of urban aggregations, traffic flow models and transportation networks.

The conference should demonstrate the transfer and the transformation of approaches to complex systems, which have been developed in physics, chemistry and molecular biology during the past 15 years, into other fields of application. The *intrinsic interdisciplinary outline* of the conference was not just a phrase; ideally, physicists came together with biologists, chemists, economists, sociologists, town planners and transportation engineers. This mutual exchange of ideas among scientists from very different fields was most stimulating. Moreover, these topics do not only gain scientific interest; they also attract a broad public attention in order to manage the challenges and problems of our common future. So, the conference provided a forum of broad-minded and intensive discussions, with ample possibilities to establish new contacts and to organize future collaboration.

Regarding the selection of papers, the two volumes follow the outline of the conference given above.

The Approach of Self-Organization

In these introductory remarks it is not intended to summarize the fourty-seven chapters of the book, which display the broad variety of applications of self-organization. Before going into the details, one may wish to get a comprehensive definition of "self-organization". Despite the fact, that a broad spectrum of theories and methods has been developed to explain structure formation in complex systems, there is no commonly accepted definition of "self-organization" or "complexity". However, we know about conditions regarding the dynamics and the boundary conditions of systems to be capable of self-organization or to perform complex behavior, which should not be repeated here [8, 10, 11, 17, 20].

In order to point to the relation between self-organization and the transition from individual to collective dynamics, the following short definition might be useful: "Self-organization is the process by which individual subunits achieve, through their cooperative interactions, states characterized by new, *emergent properties* transcending the properties of their constitutive parts. " [2] This explanation, which focuses on the dynamical aspects of the process, includes, in a general sense, also processes of structure formation which occur via a relaxation into a (thermodynamic) equilibrium state, such as the formation of lipid membranes, liquid cristals, snow flakes etc. For the latter processes, the term "conservative self-organization" has been suggested [11].

Another heuristic definition of self-organization was proposed by the Collaborative Research Department "Natural Constructions"(SFB 230, Stuttgart, Germany), which, from 1984 to 1995, coordinated an interdisciplinary research project of biologists, architects, civil engineers, physicists, and philosophers about structure formation [27]: "Self-organization is defined as spontaneous formation, evolution and differentiation of complex order structures forming in non-linear dynamic systems by way of feedback mechanisms involving the elements of the systems, when these systems have passed a critical distance from the statical equilibrium as a result of the influx of unspecific energy, matter or information. " This description tempts to include also the conditions, which may distinguish "conservative" from "dissipative" self-organization processes.

Recently, the physical approach to self-organization has provided special tools for both an analytical description and simulation capabilities. Considering different levels of description, we have to distinguish between a microscopic level of locally interacting elements with a microscopic eigendynamics and, on the other hand, a macroscopic level of global patterns with a macroscopic eigendynamics. The key question of how the system properties on the macroscopic level depend on the microscopic interactions, is one of the major problems in predicting complex systems. Following the approach of Synergetics [10], a scenario can be derived which describes this process as an interplay of local interactions and global boundary conditions. Here, the interacting elements, due to their eigendynamics and their specific interactions, commonly create order parameters, which in turn feed back to the dynamics of the elements, resulting in a circular causality. Additionally, evolving systems effect their environment, which in turn also influences their further development.

In this sense, the self-organized structure formation can be considered as the opposite of a hierarchical design of structures, which basically proceeds *from top down to bottom*: here, structures are *originated* bottom up, leading to an emerging hierarchy, where the structure of the "higher" level appears as a new quality of the system. For the prediction of these global qualities from local interactions fundamental limitations exist which are discussed e.g. in chaos theory. Moreover, stochastic fluctuations also give unlikely events a certain chance to occur, which in turn effects the real history of the system. This means, the properties of complex systems cannot be determined by a hierarchy of conditions, the system creates its complexity in the course of evolution with respect to its global constraints. Considering, that also the boundary conditions may evolve and new degrees of freedom appear, co–evolutionary processes become important, and the evolution may occur on a qualitatively new level. The understanding of co-evolution, however, is among the unsolved problems in complexity science, tackled from different perspectives.

Particle-Based Models of Self-Organization

In order to gain insight into the interplay between microscopic interactions and macroscopic features in complex systems, it is important to find a level of description, which on one hand considers specific features of the system and is suitable to reflect the origination of new qualities, but on the other hand is not flooded with microscopic details. An approach which fulfills these criteria is given by individual- or particle-based models used for computer simulations. In a very general sense, the elements of the system are treated as *multi-agents*, relatively autonomous entities which have a set of different rules to interact with each other. Which of the rules applies for a specific case, may also depend on local variables, which in turn can be influenced by the (inter)action of the multi-agents. By changing the rules of interaction or the influence of the environment during the simulation, one might be able to observe different kinds of collective dynamics and the emergence of new system properties not readily predicted from the basic equations.

In the science of complexity, today different variations of multi-agent models are applied to simulate adaptive behavior, ranging from ecology to engineering and to artificial life [1,4,14–16,18,23]. However, individual-based models are not restricted to the social and life sciences, they are also useful in physics in cases when continuous approximations are less appropriate. The discrete approaches to structure formation range from lattice gas models in hydrodynamics to stochastic cellular automata and models of active walkers or active Brownian particles. The advantage of a particle-based approach to physico-chemical structure formation is given by the fact that it is applicable also in cases where only small particle numbers govern the structure formation. Here, partial differential equations are not sufficient to describe the behavior of the system. The final pattern is path-dependent, which means it is intrinsically determined by the history of its creation and irreversibility and early symmetry breaks play a considerable role. Hence, a stochastic description is needed which considers fluctuations in the system. In many physico-chemical applications, a particle-based approach provides a quite stable and fast numerical algorithm for simulating structure formation even for large density gradients.

So, individual- or particle-based models provide a flexible tool to describe self-organization in complex systems, suitable to reflect the origination of new qualities, the unfolding of complexity, and the limited predictability of the future. Different applications of these models in natural and social sciences can be found in the following chapters of this book.

At the end of these short introductory remarks, I would like to address a problem which implicitely points to the application of self-organization concepts. Compared to the reductionistic approaches in science, self-organization theory is often interpreted as a holistic approach which conquers the classical reductionism. However, self-organization itself is a phenomenon which is only visible from a certain perspective. This means that self-organization models are also based on certain reductions regarding the system elements and their interactions. On the way toward a generalized self-organization theory, we have to understand carefully the nature of these reductions, especially when turning to the social and life sciences. Self-organization in social systems is confronted with the mental reflexions and purposeful actions of their elements, creating their own reality. While we are, on one hand, convinced that the basic dynamics of self-organization originates analogies between structure formation processes in very different fields, regardless of the elements involved - we should, on the other hand, not forget that there are really differences between these elements, especially between humans and physical particles. Thus, a deeper understanding of self-organization has to include also a better insight into the reductions, which only allows the construction of the concept of self-organization. The problem is open for discussion, to find the answer, however, is an interdisciplinary enterprise.

References

Note: This small selection of references is not intended to be complete or representative. Rather, I have chosen a few (English) books and review articles, which may open the door to the more specific journals and articles in this expanding field.

[1] Andersen, P.W., Arrow, K.J., Pines, D. (Eds.) (1988): The Economy as an Evolving Complex System, Reading, MA: Addison Wesley.

[2] Biebricher, C.K., Nicolis, G., Schuster, P. (1995): Self-Organization in the Physico-Chemical and Life Sciences, EU Report 16546.

[3] Cladis, P.E., Palffy-Muhoray, P. (Eds.) (1995): Spatio-Temporal Patterns in Nonequilibrium Complex Systems, Reading, MA: Addison-Wesley.

[4] DeAngelis, D.L.; Gross, L.J. (Eds.) (1992): Individual-based Models and Approaches in Ecology: Populations, Communities, and Ecosystems, New York: Chapman and Hall.

[5] Ebeling, W., Ulbricht, H. (Eds.) (1986): Selforganization by Nonlinear Irreversible Processes, Berlin: Springer.

[6] Ebeling, W., Ulbricht, H. (Eds.) (1989): Irreversible Processes and Selforganization, Leipzig: Teubner.

[7] Ebeling, W., Peschel, M., Weidlich, W. (Eds.) (1991): Models of Selforganization in Complex Systems, Berlin: Akademie-Verlag.

[8] Feistel, R., Ebeling, W. (1989): Evolution of Complex Systems. Self-Organization, Entropy and Development, Dordrecht: Kluwer.

[9] Haken, H. (1978): Synergetics. An Introduction. Nonequilibrium Phase Transitions in Physics, Chemistry and Biology; Berlin: Springer, 2nd ed..

[10] Haken, H. (1983): Advanced Synergetics – Instability Hierarchies of Self–Organizing Systems and Devices; Berlin: Springer.

[11] Jantsch, E. (1980): The Self-Organizing Universe. Scientific and Human Implications of the Emerging Paradigm of Evolution, Oxford: Pergamon.

[12] Kai, S. (Ed.) (1992): Pattern Formation in Complex Dissipative Systems, Singapore: World Scientific.

[13] Kauffman, S.A. (1993): The Origins of Order: Self-Organization and Selection in Evolution, Oxford: Oxford University Press.

[14] Lam, L., Naroditsky, V. (Eds.) (1992): Modeling Complex Phenomena, New York: Springer.

[15] Langton, C.G. (Ed.) (1994): Artificial Life III., Proc. Workshop on Artificial Life, June 1992, Reading, MA: Addison-Wesley.

[16] Maes, P. (Ed.) (1991): Designing Autonomous Agents. Theory and Practice From Biology to Engineering and Back, Cambridge, MA: MIT Press.

[17] Maturana, H.R., Varela, F.J. (1979): Autopoiesis and Cognition. Boston Studies in the Philosophy of Science, Boston: Reidel.

[18] Meyer, J.A., Wilson, S.W. (Eds.) (1991): From Animals to Animats, Proc. 1st Intern. Conf. on Simulation of Adaptive Behavior, Cambridge, MA: MIT Press.

[19] Millonas, M. (Ed.) (1996): Fluctuations and Order: The New Synthesis, New York: Springer.

[20] Nicolis, G., Prigogine, I. (1977): Self-Organization in Non-Equilibrium Systems: From Dissipative Structures to Order Through Fluctuations, New York: Wiley.

[21] PASTEELS, J.M.; DENEUBOURG, J.L. (EDS.) (1987): From Individual To Collective Behavior in Social Insects, Experientia Supplementum vol. 54, Basel: Birkhäuser.

[22] VALLACHER, R., NOWAK, A. (EDS.) (1994): Dynamic Systems in Social Psychology, New York: Academic Press.

[23] VARELA, F., BOURGINE, P. (1992): Toward a Practice of autonomous systems. Proc. 1st Europ. Conf. on Artificial Life, Cambridge, MA: MIT Press.

[24] WEI-BIN, Z. (1991): Synergetic Economics, New York: Springer.

[25] WEIDLICH, W. (1991): Physics and social science – the appraoch of synergetics; Physics Reports **204** 1-163.

[26] WILSON, E.O. (1971): The Insect Societies, Cambridge, MA: Belknap.

[27] Evolution of Natural Structures. Principles, Strategies and Models in Architecture and Nature, Proc. 3rd Int. Symp. of the SFB 230, Stuttgart, 1994

[28] The Abstract book of the Berlin conference (123 pp.), which includes the complete scientific program (including poster sessions), the abstracts of all contributions and the list of participants, is available on Internet: http://summa.physik.hu-berlin.de/~frank/index.html.