Synergetics: An Introduction

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How do complex systems organize? What are the underlying mechanisms in such systems that let emerge new phenomena that cannot be explained by isolated subsystems? Synergetics (after the Greek expression *synergeon*: science of cooperation) is an interdisciplinary research field that provides answers to these essential questions. The discipline Synergetics was founded by H. Haken about 50 years ago. Today, it covers a huge range of research fields ranging from natural sciences through medical sciences to economy and social sciences.

Complex systems are heterogenous and hierarchical in the sense that they are built up of interacting subsystems that are built up of subsystems themselves and so on. The various subsystems may be of different nature, e.g., may evolve on different spatial or temporal scales or may represent physical or more abstract entities. The interaction of subsystems may lead to emergent self-organization phenomena that cannot be explained by separated subsystems. An obvious example for a complex system is the brain that is built up of interacting brain areas, such as visual or motor areas, which in turn are built up of nerve cells and connecting fibers, which in turn exhibit complex substructures of interacting molecules. Synergetics asks about the general principles of self-organization of such complex systems, irrespective of the nature of the individual entities, cf. chapter ► "Synergetics: Basic Concepts."

To approach this goal, it is advantageous to focus on such situations where the macroscopic system state changes qualitatively. Indeed, it is an outstanding fact that few fundamental concepts allow us to cover a great variety of self-organization phenomena from a unifying point of view. Examples for such concepts are stability, instability, control parameters, order parameters, the slaving principle, and the circular causality.

Today Synergetics is a meeting place between bifurcation theory, the theory of stochastic processes, phase transition theory, and synchronization. In physics, it has become possible to start from first principles. For instance, in quantum optics, the coherence properties of laser light were derived in every detail based on Heisenberg equations of motion for operators. In the present book, K. Lüdge and B. Lingnau show their recent experimental and theoretical results on quantum dot and quantum well lasers in the presence of delayed feedback in the chapter ► "Laser Dynamics and Delayed Feedback." The authors reveal the bifurcation criteria for emerging chaotic dynamics. Another example is fluid dynamics where an energetically excited fluid may run through a hierarchy of spatio-temporal patterns with increasing degree of excitation. At comparatively low excitation levels, well-defined patterns evolve. While regular patterns stand in the foreground of the chapter ► "Fluid Dynamics, Pattern Formation" by M. Bestehorn, the chapter by L. Pismen ► "Patterns and Interfaces in Dissipative Dynamics" emphasizes defects and interfaces. At higher excitation levels, turbulence comes into play, cf. the chapter ► "Fluid Dynamics: Turbulence" of R. Friedrich and J. Peinke. The authors provide a broad overview of the corresponding research field while discussing both the deterministic chaotic and stochastic dynamics of turbulent systems.

In general, chaotic and stochastic processes are two descriptions to formulate mathematically seemingly rather irregular system behavior. Their relation and even coexistence is demonstrated nicely in chapter ► "Recent Advances in Quantum Chaos of Generic Systems" by M. Robnik. The author reviews the fundamental concepts of quantum chaos in Hamiltonian systems. In general, Synergetics applies classical mathematical tools to describe stochastic processes such as generalized Langevin equations, the FokkerPlanck equation and the density matrix equation. In the chapter ► "Linear and Nonlinear Fokker-Planck Equations," the author T. Frank

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follows up the method of the Fokker-Planck equation and provides a deep insight into self-organizing stochastic systems whose probability density obeys nonlinear Fokker-Planck equations. Stochastic processes may also induce phase transitions as demonstrated by A. Hutt and J. Lefebvre in chapter ▶ "Additive Noise Tunes the Self-Organization in Complex Systems." Here, the authors apply both a path-wise stochastic analysis and the probability-based Fokker-Planck analysis.

Although, historically, Synergetics had started by studies motivated by phenomena observed in physical systems, its concepts have been applied to diverse phenomena in other research fields. Bifurcation theory represents a valuable concept to describe chaotic dynamics in natural systems. For instance, neural information processing is based on brain cells and their network interactions. Each cell exhibits diverse dynamic operation modes, such as regular spiking, bursting, or chaotic behavior. In chapter ▶ "Chaotic Dynamics in Neural Systems," A. Pusuluri, H. Ju, and A. Shilnikov show detailed bifurcation analysis of various high-dimensional phase space models of brain cells. Brain networks may inherit the single cells behavior or show new emergent self-organized dynamic patterns that in turn again may exhibit chaotic dynamics. Macroscopic biological brain networks can be observed by several experimental techniques, such as electroencephalography (EEG). The authors C. Uhl and B. Seifert demonstrate in chapter ▶ "Shilnikov Chaos in Epilepsy" that experimental EEG may obey the dynamics of a chaotic attractor.

The concept of order parameter is a major feature in Synergetics. It represents the quantity that allows us to describe the essential dynamics of a system. This order parameter may be an amplitude variable or a synchronization measure. It is well established that the brain encodes and decodes information by synchronization and A. Daffertshofer and B. Pietras consider a phase synchronization measure as order parameter in brain models in chapter ▶ "Phase Synchronization in Neural Systems". They describe how such a measure provides deeper insight into the underlying brain mechanisms. Since synchronization represents a primary mechanism of neural information coding, P. Tass, G. Hauptmann, and C. Popovych consider external stimulation protocols in clinical patients to tune the synchronization between brain cells. Their chapter ▶ "Brain Pacemaker" explains that highly synchronized brain states may reflect a pathological state in certain brain areas and the authors demonstrate how external electrical stimulation may de-synchronize the brain state and thus alleviate the health situation of patients.

Going beyond the description of specific mesoscopic complex biological systems, such as brain cells or the brain signal EEG in the examples given above, Synergetics concepts have been applied to more macrosopic systems. As a first step, one may relate mesoscopic dynamics to macroscopic observations. For instance, self-organization in the brain may be observed as mental states, cognitive abilities, or behavior. Clinical psychology knows the concept of *Gestalt* that represents a certain pattern in perception, behavior, or social interactions. The chapter ▶ "Self-Organization in Clinical Psychology" by G. Schiepek and V. Perlitz bring together Gestalt theory and the Synergetics concepts of self-organized patterns. The chapter shows nicely how methods of mathematical analysis enter more and more the field of psychiatry and how this allows doctors to monitor the mental and behavioral state of patients.

Another macroscopic self-organized pattern observed in humans and animals is ▶ "Movement Coordination" as pointed out by A. Fuchs and S. Kelso. They can show how a large class of transitions in movement coordination can be described by the Synergetics concept of order parameter equations although humans and animals are highly complex systems.

More general, human and animal behavior consists of sequences of actions that are the results of free choices as to what kind of behavior the subject would like to perform next. These sequences are the result of internal, e.g., neurobiological, conditions and external circumstances. Since these conditions and circumstances in turn are the consequences of prior actions, behavior, and experiences, behavior is determined by laws. The chapter ▶ "Determinisms of Behavior and Synergetics" by T. Frank presents Synergetics as a mathematical and conceptual framework that allows us to describe switches between actions and behavior in mathematical terms.

The latter studies consider quantifiable observations that can be modeled explicitly, such as index variables of behavior in clinical psychology, movement frequency, amplitude, and phase in movement coordination or determined behavioral motor actions. The situation is even more complex in cognition, where thought and behavioral patterns or intentions are hardly quantifiable. Nevertheless, W. Tschacher has been undertaking this challenge and shows in chapter ▶ "Intentionality: Steps Towards Naturalization on the Basis of Complex Dynamical Systems" how mental processes can be linked to material processes. Here, the author tackles the long-standing problem of intentionality and relates it to circular causality and self-organizing pattern formation which can be formalized by concepts of Synergetics.

Extending the view from the self-organization in single individuals to self-organization of a population of individuals, it is obvious that the same Synergetics concepts can be applied due to the hierarchical structure of complex systems. From this point of view, J. Portugali takes a closer look at cities. In the chapter ▶ "Self-Organization and the City," he discusses the interrelation between human individuals and their ability to form social groups as a process of self-organization. Another complex system built up of several different human populations is the financial market, cf. the chapter ▶ "Financial Market Dynamics: A Synergetic Perspective" by L. Borland. This system is highly complex due to the heterogeneity of human populations, their underlying market psychology, and their diverse financial interests. The traders represent the interacting subsystems, their actions, feed back into the financial market, and macroeconomic phenomena may contribute to the dynamics as well. The order parameters in such systems are traded quantities, such as the price of shares. The author relates the market dynamics to dynamics well-known from other Synergetic systems. At last, the even more global view of the world's ▶ "Industrial Society's Natural Future" presented by H.G. Danielmayer and T. Martinetz considers the subsystems industry, economy, human nature and finance, and their interactions. The authors follow the concept of Synergetics and provide a unified description of these four, until now, separated academic disciplines. They undergird the work's prediction by large datasets and hence, once again, demonstrate the power of Synergetics as discipline.