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Editorial

In memoriam Hermann Haken: synergetics and self-organisation in complex systems

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1 Introduction

With this special issue the Guest Editors commemorate the physicist Hermann Haken who passed away in August 2024 and who was one of the foremost researchers in theoretical physics and complex systems since the beginning of the 1960s. He was the first to describe the solid-state laser by quantum field theory and then ingeniously extended the deep physical insights gained from the laser to diverse complex systems in hydrodynamics, chemistry, biology, neuroscience as well as psychology, sociology, economy and philosophy, thus founding the interdisciplinary research field *Synergetics*. Several of his students, former colleagues and various other researchers influenced by Hermann Haken's work pay tribute to this work in this Memorial issue. They describe recent developments that build on the repercussions of Hermann Haken's legacy and extend his ideas to new directions. This Memorial issue, which consists of 30 articles, demonstrates the strong significance and breadth of Hermann Haken's insight in fostering the massive progress in theoretical physics and complexity science of recent and future times. We subdivided these contributions into four broad research areas.

1.1 Dynamics in physics, chemistry and active matters

Frequency-locking is a prominent state in nonlinear systems. Semiconductor lasers in that state combined with time-delayed optical feedback are paramount examples for exploring the universal properties of nonlinear systems with two competing frequencies. Meineke and Lüdge [1] study the spatio-temporal emission of such lasers while focussing on short feedback delay-times of the same order of magnitude as the corresponding laser cavity round-trip time.

Excitons consist of a positively charged hole and a negatively charged electron and represent the solid-state analog of the hydrogen atom. Motivated by the well-established semi-classical description of the hydrogen atom, Ertl et al. [2] derive quantum defects in the excitation of cuprous oxide by a semi-classical description. Finally, considering the probability distribution of the exciton in momentum space leads to order parameters describing the different angular momentum manifolds. Since the order parameter concept is fundamental in complex systems theory, this work demonstrates nicely the association of quantum effects and Synergetics.

The Bose–Einstein condensation is a macroscopic quantum phenomenon, which is well-understood today and frequently employed in various experimental platforms. Specifically, the photon Bose–Einstein condensation is a prominent variant, which was first realized in a dye-filled microcavity at room temperature and emerges from

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an equilibrium phase transition. In their work, Krauß et al. [3] extend the standard equilibrium description of such a photon Bose–Einstein condensation by non-equilibrium elements. With this it is investigated how the non-equilibrium nature of the photon Bose–Einstein condensation affects the validity of the equilibrium approximation.

Phase interfaces, e.g. between solids and gases, are complex systems and their implicit chemical processes may yield structural spatial patterns. In 2007, Gerhard Ertl received the Nobel Prize in Chemistry for his outstanding research on surface chemistry. In his contribution to this special issue [4], he remembers his time as a student of Hermann Haken in Stuttgart and details the relations of his later work to Synergetics.

Chemical reactions on single crystal surfaces are known to exhibit structural patterns. Despite the undoubted success of the theoretical description of these phenomena, it is still doubtful that these results are of any significance to industrial catalysis. Imbihl states in his article [5], that both seemingly distant research fields *self-organization* and *industrial catalysis* are in fact closely connected via the dynamics of reaction systems and by conditions far from thermodynamic equilibrium.

Active matter involves individual units, which continuously extract energy from their environment and obey self-propelled dynamics. Their thermodynamic description is rather complex due to the constant consumption of energy yielding a state out of thermodynamic equilibrium. Schweitzer et al. demonstrate clearly in their work [6], that research on such systems is related to Synergetics, and they show how synchronization in active matter may emerge. The authors state that their model under study serves as a playground for understanding the emergence of complex patterns in non-equilibrium systems that combine agents' activity and their interaction.

Research on active matter comprises a class of non-equilibrium systems within statistical physics, e.g. when a large number of self-propelled interacting particles evolve in time driven by additive stochastic forces. Steinhöfel et al. [7] consider a Fokker–Planck approach to study the evolution of particles, but map the Fokker–Planck equation into a Schrödinger equation. They show that this transformation is straightforward for reciprocal interactions, while it can be extended to the case of non-reciprocal interactions. Moreover, this extension provides novel insights into the nature of the system's steady state.

1.2 Nonlinear dynamics

Ma et al. [8] analyzed important aspects of the structure of airfoil, which are crucial for flight safety. In particular, they investigated the influence of a harmonic and a long-range correlation random load, which is described by a fractional noise component. They found a bistable system in their conceptual model that can undergo unexpected stochastic transitions due to the long-range correlation of the noise component. These vibration patterns present a significant threat to the structural integrity of the airfoil, which in turn puts the safety of the entire aircraft at risk.

As one of the key infrastructures of our modern society, the power system is of utmost importance. Meanwhile, as the largest and most complex man-made system in the world, its dynamics is quite complicated and hard to grasp. This holds specifically true in particular modern power systems with renewable energy as a main body. In the work of Hou et al. [9], the stability of power systems is studied based on complex network science. Inverters typically cause highly unwanted synchronous-frequency oscillations. This contribution reveals that the dynamics of the transmission line, which is usually ignored in traditional power system analysis, actually plays a dominant role in synchronous-frequency oscillations.

Ramazanov et al. [10] studied the interaction between two parametrically excited van der Pol–Mathieu–Duffing oscillators. They explored the influence of parametric impact and cubic nonlinearity on the synchronization of oscillators. They found interesting and complex phenomena due to the influence of these parameters, especially a fractal structure which is formed on the boundary of the synchronization area.

Based on Hermann Haken's basic research on the influence of noise on complex systems, Semenov [11] showed that nonlocal coupling provides a way of controlling collective noise-induced dynamics in the stochastic resonance regime. He demonstrated this phenomenon for coupled overdamped bistable oscillators. In particular, it was established that increasing the coupling radius and coupling strength allows one to enhance or suppress the effect of stochastic resonance. Moreover, nonlocal coupling was considered as an intermediate option between local and global (pairwise or higher-order interactions) coupling topologies, which were also discussed in the context of stochastic resonance control.

Rybalova et al. [12] explore the influence of different kinds of noise on an inhomogeneous network of Rulkov maps. They distinguish the effects of classic white noise and the more realistic Lévy noise. They identify, for the first time, interesting types of coherence resonance, a basic constructive noise-induced phenomenon. In particular, they find solitary states and phase chimeras there and determine their emergence in dependence on the noise parameters. This offers a new way of generating such structures also for engineering systems.

Dynamic component analysis (DyCA) was developed by the group of Christian Uhl, a former doctoral student at Hermann Haken's institute who worked on similar topics under the excellent supervision of Rudolf Friedrich in the 1990s. In their contribution, Warmuth et al. [13] generalized this method to create a version that is robust with respect to additive noise and missing data. They introduced a continuous variational approach that couples

DyCA's least-squares minimization with a L^2-based regularization. This enables simultaneous data reconstruction and extraction of dynamical components. The authors present proofs of the existence of minimizers and the well-posedness of the underlying operator equations. The contribution concludes with the results of applying this technique to electroencephalographic data from absence seizures.

In laser theory, Hermann Haken and Robert Graham were the first, who derived a macroscopic model description of the laser dynamics by applying center manifold-like techniques, which led finally to the development of the more general slaving principle in nature. In the following decades, this approach was generalized successfully to other applications and established the field of Synergetics. Settmacher et al. [14] apply related techniques in the field of neuroscience, where thousands of model neurons are coupled and define a high-dimensional microscopic model as well as low-dimensional macroscopic behaviour emerges as action and cognition. Central in such a method is the approximation of the dynamic behaviour on the low-dimensional attractive slow invariant manifold for constructing the macroscopic dynamics in a reduced model order. The aim of the proposed technique is to approximate the macroscopic dynamics of a microscopic high-dimensional neural network system of integrate-and-fire neurons.

For about one century, the concept of an order parameter in complex systems has provided important insights into order–disorder transition of alloys, fluid convection, solid-state lasers or even biological networks. Hermann Haken and colleagues demonstrated theoretically for various thermodynamically open systems that the system dynamics collapses to the evolution of few order parameters at phase transitions. These concepts resemble well the concept of the thermodynamic theory of dissipative structures of Ilya Prigogine. In self-organizing systems, phase locking is a known observed phenomenon, for which, however, no order parameter has been developed yet. Newman et al. [15] propose such a new order parameter, which is similar to the well-known Kuramoto order parameter reflecting phase synchronisation. Applications to network models of various degrees of complexity illustrate the new order parameter.

A key aspect of Synergetics is the reduction of high-dimensional systems to rather low ones, in other words finding order parameters on low-dimensional manifolds. In certain complex systems, this reflects slow, dominant modes, which dictate the evolution of fast, microscopic fluctuations. This reduction principle makes phase space analysis particularly insightful. Such an interaction of slow and fast modes may imply complex recurrent dynamics. In their work [16], Marwan et al. explored how diffrent ways of quantifying recurrences serve as powerful tools to analyze phase space dynamics within this synergetic perspective. They show how recurrence-based methods uncover evolving patterns, transitions between regular and chaotic behaviour, and characteristic time-scale separations that govern complex dynamics.

The already mentioned dynamical component analysis (DyCA) aims to identify low-dimensional dynamics from high-dimensional multivariate data, in the spirit of Haken's Synergetics. Orth et al. [17] applied this technique to a marker-based whole-body gait data to extract relevant dynamics. They demonstrated the applicability of DyCA to gait data and obtained promising initial results. The authors compared the decomposition to principal component analysis (PCA) methods and obtained comparable results as well as features, that often remain obscured in conventional variance-driven methods.

Recurrent neural networks play a key role in the field of machine learning when it comes to problems involving sequences of data, such as learning of natural language or time series. Rather complex tasks, like large data or real-time processing, require high amounts of computing resources and energy, thus limiting their application in several fields. Semenova [18] considers analog recurrent networks built in hardware and investigates the impact of hardware noise on hardware echo-state networks. The noise processes taken into account originate from photonic recurrent neural network realized in hardware.

1.3 Neuroscience, behavioral science and psychology

Various brain disorders, including Parkinson's disease, typically exhibit abnormally high degrees of neuronal synchronization in specific brain regions associated with the diseases. For example, patients with late-stage Parkinson's disease (PD) experience various motor and non-motor complications that significantly diminish their quality of life. To remedy such pathologies, deep brain stimulation (DBS) has been developed to treat PD patients who do not respond to medical therapy. Although it is highly effective for well-selected PD patients, conventional DBS does not adequately improve all pathologies and may be ineffective or even induces adverse effects. To address the limitations of DBS, Chauhan et al. [19] propose extensions of coordinated reset (CR) stimulation, which represents an alternative to conventional DBS. CR was developed to specifically counteract abnormal synchrony deploying methods borrowed from Synergetics, statistical physics and nonlinear dynamics. The authors demonstrate how to minimize the total amount of stimulation ensuring minimal harm and adverse side effects to the brain.

The brain decodes and encodes information transiently in time and thus exhibits transient neural activity. There is a strong indication, that such transients represent sequential switches of meta-stable states and thus reflects switches between neurons or groups of neurons. The meta-stable states are supposed to represent transient self-organized neural states. In dynamical systems language, such sequences of meta-stable states represent

heteroclinical orbits. The work of Korotkov et al. [20] study the conditions for the existence of such heteroclinic cycles with a specific focus on multi-dimensional Lotka–Volterra systems.

Understanding the macroscopic dynamics of the brain, e.g. observed experimentally as encephalographic data, may involve understanding how it results from microscopic activity, e.g. networks of single neurons. Typically, the mathematical description of single-neuron activity addresses the generation of single-action potentials (single-fire events) or the firing rate of neurons. The Lighthouse model developed by Hermann Haken at the end of the twentieth century describes single action potentials in single neurons while offering a bridge between single action potential generation and firing rate descriptions. Coombes [21] illustrates the Lighthouse model for neurons in a spatial network and points out by mathematical analysis its elegance in deriving new complex activity patterns, such as traveling waves and spatial stripes as well as spatially localized bumps.

The brain exhibits transient dynamics, which may be observed by transient power surge or power drop in specific frequency bands and are called event-related synchronisation (ERS) and event-related desynchronization (ERD), respectively. Their neural origins are not understood. Hutt [22] proposes explaining ERS and ERD by changes of underlying endogenous activity, which has been experimentally found in previous studies to adjust cognition. This work considers a random network model subjected to additive noise and detailed analytical analysis utilizing the order parameter concept demonstrates how transient additive noise tunes the stability and spectral properties of the network.

Healthy sleep is a major condition for a healthy life, while sleep problems, such as insomnia or apnea, may produce or reflect mental decease. Sleep stages like non-REM sleep and REM-sleep are supposed to reflect certain self-organized brain states, which exhibit characteristic spatio-temporal brain activity as observed by multi-electrode electroencephalography (EEG). Sergeev et al. [23] consider electroencephalographic data observed during human sleep as graph-structured networks, which allows to represent spatio-temporal brain activity as time-evolving networks and corresponding network features characterize the brain states in sleep stages.

The mathematical description of drug addiction promises insight into the dynamics of addiction evolution. In this context, it is necessary to distinguish psychological versus physiological aspects. Frank [24] proposes how to involve both aspects from the Synergetics perspective. Previously, synergetic concepts have been shown to improve our understanding of epidemiological and virus dynamic models and the dynamics they describe. The presented work introduces a drug addiction order parameter, which is defined analytically. Its role is discussed together with time-dependent eigenvalues and explained-variance scores recently introduced in the context of epidemological of disease outbreaks.

Insights into movement coordination have progressed by developing the corresponding mathematical models, such as the Haken–Kelso–Bunz (HKB) model. This conceptual model and its many extensions in research laboratories around the world constituted the foundation of a mechanistic science of coordination called coordination dynamics which extends across a range of disciplines and phenomena. Kelso [25] suggests that the HKB model may not only represent a description of biological coordination but also provides important insight into the link between mind, matter, and movement. The contribution details how this perspective and interpretation involves an intimate connection between fluctuations, i.e. as physical causes, and intentionality typically viewed as mental causes.

1.4 Econophysics, social sciences and philosophy

Urban road networks are prototypical complex systems and one of their important features is their sensitivity to local perturbations. Such perturbations have been shown by Haken to induce transitions to new dynamic states. In their contribution [26], Wassmer et al. quantify how marginal changes in free-flow travel times affect the social cost of traffic, i.e. the flow-weighted sum of travel times over all edges of a traffic network. Applications to synthetic and real-world urban networks demonstrate how self-organized traffic patterns emerge from the interplay of network topology, its link characteristics, and traffic participant behavior.

In his contribution, Portugali describes the historical development of a comprehensive synergetic theory of cities [27]. In doing so, he sheds light on various aspects of the fundamental principles of complexity: Hermann Haken's theory of synergetics, Lorenz's theory of chaos, Prigogine's theory of dissipative structures, and Mandelbrot's theory of self-similarity. He argues that the urban form results from bottom-up processes rather than from top-down design alone. Therefore, planning is seen as acting within an already dynamic system with a limited ability to directly control outcomes. The author emphasizes the importance of information flows and the cognitive processes of urban stakeholders in shaping spatial structures. In his contribution, moreover the author advocates for planning approaches that establish flexible frameworks, acknowledge uncertainty, and utilize simulation tools, such as cellular automata and agent-based models, to explore potential urban evolutions.

Another contribution [28] dealing with urban development is by Günther Haag. Together with Wolfgang Weidlich, a friend and colleague of Hermann Haken at Stuttgart University, he developed *Concepts and Models of a Quantitative Sociology: the Dynamics of Interacting Populations* [29]. His contribution to the present Special Issue explores self-organized criticality (SOC) in spatial population systems using a synergetic master equation model

for migration between regions. It analyzes how synergistic effects in migration decisions lead to instabilities of a population distribution and uneven settlement patterns. Numerical simulations demonstrate a Pareto distribution of city sizes when the agglomeration parameter reaches its critical value. This critical state acts as an attractor, explaining universal power-law distributions in settlements without fine-tuning parameters. Practical applications involve parameter estimation from migration data, outperforming gravity models in a German districts case study.

Lisa Borland, a former PhD student of Hermann Haken from the early 1990s, reviews financial and economic models and emphasizes that they are all connected to Haken's synergetics [30]. Starting with Lotka–Volterra-type equations that model financial markets as complex systems with competing species and capital, Borland moves on to spin- and agent-based models, stochastic equations, and multi-timescale models. These models explain price formation and capture market complexities, such as volatility clustering, herding, collective stress behavior, spontaneous bubbles or crashes, and asset return features, such as fat-tailed distributions that slowly approach a Gaussian distribution (like turbulence), long-memory volatility, time-reversal asymmetry, and multifractal scaling. Finally, the author reviews her approach to capturing the statistical signatures and behavioral patterns observed during periods of market panic, such as the global financial crisis (GFC), the COVID-19 pandemic, and the current uncertainty surrounding international tariffs.

The study of complex systems involves a certain number of philosophical problems, as Kurt Goedel's incompleteness theorem. This states, inter alia, that complex systems may give rise to phenomena, such as structure formation, that can no longer be simply derived or calculated from their basic building blocks. Harald Atmanspacher elucidates such links between fundamental philosophical aspects and Haken's Synergetics [31], also by recalling personal encounters and deep discussions with him. The contribution demonstrates the broad range of Haken's research work, from solid-state physics over biology and neuroscience to computer science, and its corresponding impact on today's philosophy of science.

1.5 Concluding remarks

The extensive work of Hermann Haken has started in solid-state physics, was later extended to complex systems in physics, chemistry, and biology with a stronger focus on neuroscience up to computer science. It is important to emphasize that, in one of his last books [32] in neuroscience, he proposed the Lighhouse model which is a new spiking neuron model simplifying the bridge between slow (spiking frequency) and fast (single spikes) time scales in the brain. Recent studies of Stephen Coombes et al. [21, 33] extend Haken's original Lighthouse model and demonstrate that it provides a tractable mathematical framework for studying how activity-dependent neural myelination may regulate temporal coordination, synchrony, and communication through coherence in spiking neural systems.

Moreover, as a final remark, we mention another outstanding example of Hermann Haken's ideas ahead-of-histime in computer science: the synergetic computer [34, 35]. Rather than computing a classification, the synergetic computer allows a driven nonlinear medium to self-organize into it—replacing processing power with structure formation. This same principle underlies the Maass-liquid state machine [36] and Jaeger's echo state networks [37], which leads to reservoir computing [38]. Physical representations like in [39] lead to *physical* reservoir computing [40], a hot topic in artificial intelligence research today. This is in line with recent exciting research that replaces artificial neural networks with analog networks of harmonic oscillators [41]. Haken's proposal, dating from the late 1980s, precedes these ideas by one to two decades. The two differ mainly in where the task-specific information resides—designed into the dynamics in Haken's case, trained into the readout in reservoir computing.

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