Introduction to Focus Issue: Design and Control of Self-Organization in Distributed Active Systems

Alexander S. Mikhailov1 and Kenneth Showalter2
1Abteilung Physikalische Chemie, Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, 14195 Berlin, Germany
2Department of Chemistry, West Virginia University, Morgantown, West Virginia 26506-6045, USA

(Received 1 June 2008; accepted 1 June 2008; published online 27 June 2008)

Spatiotemporal self-organization is found in a wide range of distributed dynamical systems. The coupling of the active elements in these systems may be local or global or within a network, and the interactions may be diffusive or nondiffusive in nature. The articles in this focus issue describe biological and chemical systems designed to exhibit spatiotemporal dynamics and the control of such dynamics through feedback methods. © 2008 American Institute of Physics.

In this issue, attention is focused on a broad class of systems that are encountered in different fields of science. The common property of such systems is that they consist of many elements capable of autonomous activity and, through interactions between these elements, produce complex but ordered collective activity patterns. These coherent patterns do not result from some external forces; they emerge intrinsically through a self-organization process. To a certain extent, they can even resist external influences and maintain their integrity despite environmental variations. As the conditions are changed, a stable organization pattern can be replaced by a different one through a dynamical bifurcation.

The architecture of interactions between elements is essential for the emergence of collective coherent patterns. In the simplest case of globally coupled systems, each active element interacts with any other element in the ensemble and all interactions are identical. Such situations typically arise when interactions between elements are not direct but go instead through some “mass medium” that is common for all of them. The opposite situation is that the interactions between the elements are local and restricted to their immediate neighbors in the physical coordinate space. The elements can sit then at the nodes of a regular or an irregular lattice. Continuous active media also belong to the latter kind of system, because they can be viewed as consisting of individual volume elements that locally interact.

Between these two extremes, distributed active systems with networks of interactions are found. There, interactions are not localized, and even elements well separated in space may efficiently communicate. On the other hand, such non-local interactions are addressed and specific for each pair of elements, in contrast to what is characteristic for the globally coupled systems.

Distributed active systems are ubiquitous in nature and in the man-made world. In chemical reaction-diffusion systems, nonequilibrium reactions in small spatial volumes can lead to dynamical bistability, excitability, and oscillations. Diffusion of chemical species across the volumes leads to local interactions and can result in the appearance of traveling waves and other types of spatiotemporal self-organized patterns. Some biological systems, such as slime mold or cardiac tissue, are very close in their properties to active reaction-diffusion media, although local interactions are not then necessarily of a diffusion origin. In the heart, for example, electrical interactions between neighboring cells play a dominant role.

The classical example of a network-based distributed active system is the brain. Its neurons interact electrically, as in the heart, but the synaptic interactions can extend over long distances, and their properties are specific for each neuron pair. At the level of a single biological cell, genetic expression and metabolic networks, as well as the signal transduction networks based on protein interactions, are of fundamental significance.

Human society provides a rich variety of self-organization phenomena. It is a hypernetwork formed by interacting active agents and network aspects are obviously important for its understanding. However, global coupling and local interactions are also characteristic for some forms of social organization.

While an understanding of naturally existing distributed active systems is already a principal challenge, one can go further and consider how such systems can be efficiently controlled and artificially designed. New modes of behavior now become possible, as well as the development of entirely new systems with desired properties. Experimental studies have shown that interactions between relatively simple processes with elements of feedback can lead to the formation of complex spatiotemporal patterns that are highly sensitive to conditions and may be dramatically transformed in response to small but carefully targeted perturbations. The control of self-organizing dynamical systems differs from methods based on traditional engineering principles. Small, purposeful perturbations can be designed to influence the nonlinear processes that are responsible for self-organization, effectively steering the dynamics of a system toward a desired state. The application of large perturbations or rigid controls would disrupt the delicate balance of the self-organizing dynamics and prevent any possibility of reaching a desired dynamical state. Instead, the inherent dynamics of a system can be directed by small perturbations or feedback designed to subtly influence the system’s natural spontaneous activity.
There are many possible approaches for designing and controlling spatiotemporal dynamics. The inherent sensitivity of nonlinear systems to perturbations allows efficient control using feedback techniques, and algorithms can be designed to stabilize desired unstable states or destabilize undesired stable states with very small perturbations. The latter is relevant to studies aimed at suppressing the maladies of epileptic seizure and Parkinson’s disease that result from pathological periodic dynamics. A wide range of new spatiotemporal patterns arises when global feedback is incorporated into the dynamics of distributed systems. Completely new spatiotemporal behaviors may also arise that are not observed in autonomous systems, and some, such as localized structures, may have practical potential for information storage. Local feedback, where the signal imposed on the system has spatial as well as temporal components, offers the possibility to expand the range of spatiotemporal dynamics in distributed systems. Periodic forcing offers another means for influencing the inherent dynamics of a system or for generating completely new modes of spatiotemporal behavior. Spatiotemporal turbulence, for example, can be suppressed or promoted by slightly varying the forms of periodic forcing.

Sophisticated experimental techniques have been developed to study the evolution of scroll waves in excitable chemical media. The controlled initiation of scroll rings and their evolution monitored by optical tomography are described by Bánsági and Steinbock in this Focus Issue. Depending on conditions, scroll ring filaments shrink, eventually leading to vortex annihilation, or grow, with instabilities developing that give rise to turbulence.

Scroll waves are believed to play a role in the heart maladies of tachycardia and fibrillation. They are organized around line-like filaments, and their overall dynamics can be understood in terms of the motions and bifurcations of the filaments. Rousseau, Chaté, and Kapral describe detailed studies of scroll filaments in the three-dimensional complex Ginzburg–Landau equation. They focus on the role twist plays in bifurcations to helices and super-coiled helices as well as to complex disordered states.

Propagating pulses in one-dimensional excitable media commonly annihilate on collision; however, examples of systems exhibiting wave reflection from boundaries and on collision with other waves are known. Systems displaying monotonic and nonmonotonic dispersion curves are analyzed by Bordyugov and Engel. Their study shows that pulse interactions are strongly dependent on the features of the relaxation in the wake of the pulse.

There are relatively few chemical systems that exhibit sustained spatiotemporal behavior. The ferrocyanide-iodate-sulfite reaction displays a wealth of interesting dynamical behaviors, including sustained stationary lamellar patterns and self-replicating spots. Szalai and De Kepper report that a key mechanistic feature of this system is the presence of low-mobility weak acid functional groups that alter the effective diffusion of the hydrogen ion autocatalyst. Annular and disc spatial reactors provide complementary information on the three-dimensional structure of the patterns.

Carefully designed interfacial systems may give rise to chemomechanical motion. Sumino and Yoshikawa describe the self-motion of an oil droplet containing iodine that travels on a glass slide immersed in surfactant solution. The self-propulsion is modeled by adsorption and desorption of surfactant, yielding a description of active Brownian motion.

Systematically developed systems that exhibit a wide range of spatiotemporal dynamics and the control of these systems are described by Vanag and Epstein. Experimental approaches for developing new spatiotemporal systems include the use of open unstirred reactors and incorporating chemical variations that give rise to large differences in the diffusivities of critical species. New spatiotemporal behavior arises with the introduction of global feedback and periodic forcing as well as traveling modulation, where moving spatial perturbations are imposed on an active medium.

Stabilized waves in the photosensitive Belousov-Zhabotinsky reaction behave like constant-velocity, self-propelled particles. Interactions between multiple waves can be introduced by excitability gradients that are generated by a feedback algorithm, as described by Steele, Tinsley, and Showalter. Rotational and processional behavior arises for certain interaction strengths, and group behavior including complex multiple-wave orbits is exhibited.

Qiao et al. review their experimental and theoretical studies on control of scroll wave turbulence in the oscillatory Belousov-Zhabotinsky reaction in the presence of spatial gradients. If the gradient is sufficiently strong, a straight scroll spanning the medium becomes unstable and undergoes breakup, leading to the development of defects and, under certain conditions, to the onset of turbulence. The authors show that the application of spatially homogeneous external forcing, implemented in experiments via periodic variations in illumination, can stabilize inherent turbulence of scroll waves. A similar result could be achieved by application of external noise.

Dahlem, Schneider, and Schöll analyze self-organized wave behavior in the brain. During migraine and stroke, pathological events that spread through the cerebral cortex are observed. The cortical spreading depression involves a reaction-diffusion process and the cortical tissue can be modeled as an excitable medium. What prevents propagation of such waves under healthy conditions and permits them in the pathological case? The authors suggest a mechanism for shifting the onset of excitability in this system that involves a failure of a nonlocal or noninstantaneous feedback control.

Complex rhythmic states arising from coupled oscillators are found throughout nature, particularly in living systems, such as heartbeat-respiration oscillations or circadian rhythms. Intricate patterns of oscillatory states in a network representing a multielectrode electrochemical system can be engineered using phase models, as described by Kori et al. The method allows the development of delayed feedback signals that give rise to interaction functions corresponding to desired dynamical behaviors.

Problems of robustness in evolving biological networks are discussed by Kaneko. Through numerical simulations of a simple model, capturing the essence of gene expression dynamics, it is demonstrated that the networks acquire robustness to mutations only when gene expression is sufficiently noisy in the evolutionary process. A quantitative condition, which links robustness to mutations in the evolutionary time scale and robustness to noise in the development on the reproductive time scale, is obtained.
Kaluza, Vingron, and Mikhailov\textsuperscript{12} also discuss the questions of robustness of biological networks. Using a simple model, motivated by characteristic properties of cellular signal transduction networks, they show that the networks, which are functional and at the same time robust against a particular kind of random local damage or noise, can be constructed. Analyzing statistical properties of the designed networks, it is found that their architecture is strongly influenced by the type of perturbations against which they are made resistant.

The papers presented in this Focus Issue describe a diverse collection of distributed systems with a common theme: they have been carefully designed to display self-organizing dynamics or they are dynamical systems under the influence of feedback and control. Self-organizing distributed systems display remarkably rich dynamics, and the range of behavior is significantly expanded when elements of coupling and feedback are introduced. Further advances in the design and control of distributed active systems will occur as new forms of coupling and more intricate feedbacks are introduced that are designed to yield particular desired dynamical behaviors. This collection is not aimed at providing a comprehensive survey of design and control of distributed active systems; however, there are a number of reviews available on these and related topics.\textsuperscript{13–21}