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On “Synergetics” by Hermann Haken (1976)

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The idea of cooperation has always been an important element in societies starting from the Ancient Greek and the Byzantine Empire tradition. In fact, already the Ancient Greek cooperative traditions imply the idea of self-organization and can still be found today, for example as trade unions. Self-organized entities, such as communities, cities or even national states, comprise elements in their sub-structure, which interact (typically) in a nonlinear way. Such entities may be called *complex systems*. When the interaction of such sub-elements is strong enough and the environment of the system provides the suitable conditions, the system of interacting elements develops a novel common behavior. This process of new organization is called self-organization. Such self-organizing processes may not emerge only in societal systems (Smith and Stevens (1996)), such as herd behavior or group thinking, but occur also in biological systems as animal stripe and spiral patterns (Turing (1952)), in chemistry as self-assembly of molecules (Lehn (2002)) and in human behavior as movement coordination (Kelso and Schönner (1988)).

Theoretical models of each of such self-organized systems considers the non-linear interaction of certain modes. Such modes capture the system-wide interactions and may represent spatial, temporal or spatio-temporal patterns. Of course, the origin of these modes and their respective coupling is specific for each system. For instance, in physics the quantum-mechanical laser theory (Haken (1983)) has shown that the optical laser beam observed in experiments represents a stationary self-organized system state, which corresponds to a single oscillatory coherent mode. This mode emerges from non-coherent modes by a state transition. Such transitions also describe the emergence of self-organized systems in non-physical systems as pointed out above. The article of Hermann Haken on *Synergetics* published 1976 draws the connection between many self-organizing systems and points out their similar behavior close to the corresponding state transitions. Educated as mathematician and physicist and working on laser theory in the 1960s, he discovered that the state transition in all self-organized systems may obey an identical concept and he named this the *slaving principle*. In fact, this vivid concept finds its equivalent in mathematics as center manifold theory.

Pointing out the importance of the slaving principle in the article *Synergetics* and in his work after, Hermann Haken intended to demonstrate that state transitions in all systems may obey this principle. What is it in detail? To understand this, the notion of the *order parameter* and the *control parameter* is important to explain. As detailed in *Synergetics*, the order parameter describes a certain function, which may evolve in time and which describes the full system's dynamics close to a state transition. The corresponding equation describes the system's evolution, but of course is specific to each system under study and includes a set of specific system parameters. Such parameters reflect the individual system's properties. When modifying a set of control parameters, which are chosen among the system parameters, the order parameter changes its value for a critical value of the control parameter and the system transitions from one state to another. Hence, the control parameters determine the system's state. For instance, a fluid system of mixed chemicals in the Belousov-Zhabotinsky reaction (Cassani et al. (2021)) exhibit spiral waves when put in a petri dish. The order parameter may describe the time evolution of a spatially distributed concentration of a certain chemical in the chemical reaction, like Bromid. One of the fluid ingredients in the Belousov-Zhabotinsky reaction

is a catalyst solution, like cerium. The concentration of this catalyst represents a control parameter. At low catalyst concentration, the Bromid concentration is low, i.e. the order parameter takes low values, and no patterns occur in the petri dish. After increasing the catalyst concentration, i.e. the control parameter increases beyond a certain critical value, the fluid ingredients react to each other and Bromid is generated and oscillates temporally and diffuses in space, i.e. the order parameter oscillates between large and small values. Hence the fluid changes its state from a spatially homogeneous temporally constant state to a propagating spiral wave state.

Such a state transition process has been well known in the literature. Now, what is new and how does the slaving principle come into play? It is the way how the order parameter performs the transition. Mathematical models of self-organizing systems describe the system dynamics by several interacting variables, which evolve on different time scales. Close to the state transition, there are variables, which evolve very slowly in time and others are comparatively fast, while both slow and fast variables are coupled to each other. The slaving principle states that the slow variables represent the order parameters and determine the dynamics of the fast variables or, in other words, enslave the fast variables. These enslaved fast variables couple back to the slaving order parameters. Consequently, in a vivid picture moving a system far from a critical point towards a critical state where a state transition may occur, the system re-organizes close to the transition point by separating into slaving and enslaved modes. There, the enslaved modes support the slaving modes and the enslaving order parameter perform the transition. Obviously, such a transition implies a dramatic reduction of the system's complexity since (typically) only few order parameters describe the system dynamics. In other words, the system becomes highly ordered. Moreover, this picture does not just apply to deterministic systems, but is also valid in the presence of random system fluctuations. In this case, random fluctuations may facilitate or delay state transitions (Hutt et al. (2007)).

The mathematical description of state transitions is individual to each system under study and may be well established in each research domain. In the first years after the publication of *Synergetics* in 1976, the slaving principle has not appeared to provide much insights into research fields, which already understood how to describe mathematically state transitions in their systems. Such research fields were Mathematics itself and Physics. However, in subsequent years it attracted more and more attention in closely-related fields, such as chemistry (Kuramoto (1984)) and biology (Mosekilde and Mouritsen (1995)), and in other less-related research fields such as psychology (Tschacher et al. (1992)), brain science (Jirsa et al. (1999)), economics (Zhang (1991)), societal opinion (Weidlich (1994)) and urbanism and city planning (Portugali (2020)). In sum, the slaving principle represents the methodological backbone of Synergetics, while its application to very diverse complex systems affirms its value. Its power unfolds especially in systems, whose dynamics is less obvious to exhibit the classic features of state transitions, such as time-scale separation, emergence of ordered patterns and critical random fluctuations. For instance, the application of the slaving principle to societal dynamics introduces an interesting perspective on revolutions. In the Peaceful Revolution in the former GDR in 1989 (Childs (2001)), the number of political peaceful demonstrations increased more and more over the year, while the support of the GDR government by the Soviet Union leadership declined. While demonstrations with an increasing number of participants were poorly suppressed by the state

police in 1989 and Hungary and Czechoslovakia opened their borders to the West, the GDR citizens realized the “wind of change”. Identifying the number of participants of demonstrations as the slow order parameter, the single citizens as the fast variables and the GDR government support from the Soviet Union and the political pressure by the increasing number of GDR citizens leaving the country via Hungary and Czechoslovakia as the control parameter, the slaving principle applies: the slowly growing number of protesting citizens convinced (enslaved) the single citizens to join the demonstrations (supporting of the slow slaving order parameter by the fast enslaved variables). At the critical point in Fall 1989, the pressure on the GDR government was that high (the protests were that massive), that a simple internal communication mistake between members in the GDR government (random fluctuations) provoked the government statement to journalists “..to my best knowledge, the Wall is open..” and consequently induced the Fall of the Berlin Wall (state transition).

Of course, such a vivid model of the Peaceful Revolution lacks mathematical foundation, but nevertheless describes heuristically a state transition based on the slaving principle. This model comprises all elements of a state transition without applying mathematics as a description language while it provides insights into the possible mechanism of a revolution. Hermann Haken summarizes in the article: “Synergetics analyses and compares the behavior of systems composed of many subsystems in situations where the macroscopic structure changes qualitatively. [...] Though subsystems may be quite different, the mechanisms by which an old structure is replaced by new ones are the same. Certain collective variables, called order parameters, become unstable, grow, and, by competition or cooperation among each other, establish a new structure. The subsystems then have to obey those configurations of order parameters which have survived the competition. Even the dynamics of quite different systems essentially obeys the same laws. The advantage of analogies is obvious. Once a problem is solved in one field, its solution can be transferred to another field.” The discovery of analogies is still going on until today.

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