SYSTEM THEORIES: SYNERGETICS

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Summary

S. has links to many fields of the natural sciences, to technology and to the humanities. The outstanding feature of S. is its goal to unearth common features in the macroscopic behavior of a great variety of otherwise quite different systems. As this article witnesses, this goal has been achieved by means of central concepts, such as instability, order parameters and the slaving principle. A price must be paid, however, for this generality, and there are a number of aspects to be discussed further. The price consists in confining the study of the systems' behavior to situations close to instability points. The obvious question is: how close? The detailed study of numerous systems has shown that the range of validity of the synergetic approach may range widely. Mathematically, a minimum range can be guaranteed by the slaving principle. But some examples show that the order parameter concept can hold in a much wider range still to be explored.

In some systems it may be difficult or even impossible to find a well-defined instability - such systems may undergo continuous qualitative transformations that cannot be characterized by order parameters. To study such problems - again under a unifying viewpoint - further research is needed.

The search for unifying laws or principles has been a central problem of science since ancient times as is witnessed by Newton's mechanics, Einstein's theory of relativity, Maxwell's electrodynamics – to mention a few outstanding examples in physics. Now we are beginning to recognize that there exists a whole class of laws of a new type that apply to a much wider range of fields. In view of the vast number of systems and their often incredible complexity, the human mind will be able to cope with them only if it finds general principles. This is not only a philosophical question, but far more importantly, a question of economy of thinking. S. may be considered as a first step towards that direction.

1. Review of Subject Articles

1.1 The contribution "History and Philosophy of the Systems Sciences: The Road Toward Uncertainty" by Ch.O. François, takes a broad view and provides the reader with a deep insight into the interwoven net of ideas and their originators. Only a few topics can be mentioned here.

The main part deals with the search of a new coherence, starting with a discussion of von Bertalanffy's work, who introduced new principles of organization of living systems (e.g. his concept of flux equilibrium of energy). Chaos theory, initiated by the mathematician Poincar\'{e}'s studies and rediscovered in a new context by the meteorologist Lorenz is discussed. François outlines the work of Prigogine in the extension of thermodynamics towards its application to biology and mentions the different approach by Haken's synergetics.

1.2 "General Systems Theory" by Anatol Rapoport. The author, one of the founders (von Bertalanffy, Gerard, Boulding, Rapoport) of the "society for general system theory" conceived as central task the discovery and exploitation of formal isomorphisms between theories characteristic of different scientific disciplines. He discusses several central problems, e.g. in biology the question of equifinality, i.e. that a system reaches a final state irrespective of perturbations. A general answer can be found by the notion of basins of attractors in dynamic systems theory of which Rapoport gives a special example. An important discussion relates to reductionism vs. holism. He considers the planet as a system and points at the threats of destructing homeostasis.

1.3 "Living Systems Theory" by G.A. Swanson, James Grier Miller. This theory defines living systems as concrete open systems with purposes and goals. It identifies a hierarchy of eight levels from cells to supranational systems and discusses the role of matter, energy, and information. A central role is played by the fray-out principle, the central thesis of the theory that tries to explain how higher-level living systems evolve from lower-level ones. With respect to the role of entropy, the reader is referred to Haken's comments on entropy theory below.

1.4 "Entropy Systems Theory" by Kenneth D. Bailey. This article is concerned with the role the entropy concept plays in general systems theory and in social entropy theory with special emphasis on life support systems ("sustainable systems"). Entropy is defined as a measure of the degree of disorder or uncertainty in a system and its various mathematical definitions in thermodynamics (Clausius), statistical physics (Boltzmann), and information theory (Shannon) are discussed. For the applications of entropy to social entropy theory, a society is defined as a population having certain levels of information, technology, etc. treated as macrovariables. Corresponding microvariables are also discussed. A general comment by Haken that concerns both this article as well as a number of other articles is of general concern. In physics, entropy plays a double role:

1. as a measure of disorder,
2. as a Lyapunov function of a dynamical system whose dynamics drives a system to a maximum of entropy (minimum of Lyapunov function). Thus the gradient of entropy acts as a force (cause) of the system's change. (Depending on specific constraints, entropy may appear in other functionals, e.g. the free energy, as well.)

While in social entropy theory 1. remains valid, 2. must be replaced by dynamic equations (Weidlich's socio-dynamics as mentioned in Haken's contribution). These remarks apply quite generally to open systems including those of biology.

1.5 "Actor-System Dynamics Theory": by Tom R. Burns, Thomas Baumgartner, Thomas Dietz and Nora Machado. This theory deals with model building in social system analysis, whereby it defines social actors and interactions, institutional and cultural formations regulating social interactions. It stresses the capacity of human agents to construct institutions and technologies without necessarily fully understanding how the systems will perform and evolve. The article underlines problem solving and transformative processes that differentiate a socio-cultural theory of evolution from biological evolutionary theory. The authors discuss several problematiques, e.g. "what to do in face of bounded knowledge and limited control".

1.6 "Ethics as Emergent Property of the Behavior of Living Systems" by

Gianfranco Minati. This article focusses on the ethics of social systems (societies, companies, schools, etc) emergent from the interaction among people (social agents). Rules of interaction among components of social systems are assumed to be, if formalized, the normative ethics of the components themselves. He discusses how to manage, drive and control emergent ethics. The strategy is to act on the context, the environment, on the interactions rather than on the single elements. Remarkably, synergetics (Haken) comes to the same conclusions of self-organizing systems. As it appears, ethics as discussed by Minati, can be interpreted as an order parameter in the sense of synergetics. As Minati says, with respect to the effectiveness of an ethics is given by its ability to keep together a social system, whereby he discusses the role of ethics for growth, evelopment and sustainable development in economic systems. The relationship between quality standards and normative ethics is seen as very close.

1.7 **"Axiological Systems Theory"** by Francisco Parra-Luna. This article stresses the role of human beings with their needs (factor of motivation) and their valuesystem (factor of satisfaction) as crucial elements of society. (A general model of universal needs and therefore of common values exists in UN's 1948 Universal Declaration of Human Rights.)

The concept of value is operationalized as prime material in axiological theory. Societies' global performance should be judged in terms of the measure to which ideals are reached. Acquiring the best possible understanding of such measure is the fresh new task of axiological theory. The author shows how quantification can be achieved (an example is Parra-Luna's list of indicators adapted to a large medium sized company (1993)) and the formation of axiological profiles be established. This makes it possible to measure organizational efficiency, to perform deviation analysis, and to study social progress and regression. Also ethical behavior becomes quantifiable.

1.8 **"Evolutionary Complex Systems"** by Iris. Balsamo. With focus on the problem of sustainability, the author discusses basic concepts of complex systems, such as structure, organization, complexity, self-organization, and elucidates the various aspects of the concept of evolution with its multiplicity of meanings and cognitive functions.

1.9 **"Epistemological Aspects of Systems Theory Related to Biological Evolution"** by E. Tiezzi and N. Marchettini. This article uses thermodynamics and in particular nonequilibrium thermodynamics to understand the dynamics of biological systems and ecosystems. The authors recall the seeming contradiction between the increasing disorder according to the second law of thermodynamics and the increasing order of biological systems, an aspect that is also alluded to in several other articles. While entropy plays a fundamental role in thermodynamics of systems in and lose to thermal equilibrium, the authors quite correctly point out that time evolution of many physical systems is governed by nonlinear evolution equations containing control parameters. This s entirely in agreement with the insights gained by synergetics (cf. Haken's article). In accordance to this, the authors develop the new concept of ecodynamics as an evolutionary physics. The authors stress the concept of Gestalt considering transitions.

1.10 "Socio-Technical Systems: History and State-of-the Art" by E. Hanappi-Egger. This insightful article studies the crucial role organization of work plays in economics. While "Taylorism" focusses mainly on the work process as a sequence of tiny single steps, the "process approach" stresses the importance of human skills and the interplay between the technical and social systems, where both components have to be optimized. Particular attention is paid to information and communication technologies.

1.11 "The Geometry of Thinking" by Curt McNamara. This article is based on Buckminster Fuller's work on the structure of space and its correspondence to human thought processes. It discusses concepts, such as "universe" in the sense of the combined set of all humanities' knowledge and experience, the concept of a system and of structure. Geometric objects are brought in analogy to specific events as action and reaction, etc. It contains also Fuller's definition of synergy as "behavior of a whole system unpredicted by the behavior of their parts taken separately". At this occasion it should be stressed that the fields of "synergetics" have been introduced and defined independently and quite differently by two authors, namely by Buckminster Fuller as some kind of geometrical theory as elaborated in McNamara's article, and by Haken as an analytical mathematical theory of self-organization, which is presented below. While it seems that Fuller's approach works by means of analogies, Haken's approach works by the solutions of mathematical evolution equations.

1.12 "Systemology: Systemic and Non-Systemic Entities" by N. Bulz. This rather formal article that contains numerous quotations to important contributors to the whole field of general system theory, presents four varieties of systemic thinking as conceived by four great philosophers: Decartes (analytic), Platon (holistic), Bacon (experimental), Bergson (experiencial). Having the concept of life support systems in mind, the author brings equilibrium and metaequilibrium in connection with specific contributions of Spinozaa, Russell, Goethe, Leibnitz, and Cusanus.

As these articles demonstrate, General Systems Science is playing a fundamental rule both in basic and in applied science challenged to solve vital problems of our modern human society. In this endeavor, both hard data (cf. Parra-Luna's article) and concrete approaches are needed. The latter are provided by dynamic and stochastic approaches that carefully discuss the boundaries of the system considered with respect to flows of energy, matter and information, and take care of the relevant internal processes.

2. Definition of Synergetics

On the basis of the previous twelve articles, a redefinition of Synergetics (S.) will be attempted. S is an interdisciplinary field of research initiated by H. Haken in 1969. It deals with systems that are composed of several or many subsystems (elements, parts) that interact with each other in a more or less complicated fashion. The subsystems and their interactions may be subject to prescribed external or internal conditions. S. studies the spontaneous formation of spatial, temporal, or functional structures, or of immaterial constructs via self-organization. Self-organization means that the structures evolve without specific interference from the outside. S. searches for basic principles of self-organization irrespective of the nature of the individual subsystems. In doing so, it develops a common language and operational approaches. One may distinguish between microscopic S., macroscopic S., phenomenological S., and semantic S.

3. Goals and General Approaches

Microscopic S. starts from the individual behavior of the subsystems. (See *Actor-System-Dynamics Theory*). In the next step the interaction is taken into account and the state of the total system is determined under specific external or internal conditions described by so-called control parameters. The central problem of S. is then the study of how this state of the total system changes, when one or several control parameters are changed. In general, between two situations can be distinguished, namely nemesis

1. the system adapts smoothly, i.e. without qualitative changes;
2. the system undergoes dramatic qualitative changes on macroscopic scales (critical situation).

The central goal of S. is the study of the system's behavior at those critical situations. As the general analysis reveals, close to such "critical points" in control parameter space, the dynamics of the system is, at least in general, governed by few variables, the so-called order parameters. Once the dynamics of the order parameters is known, the slaving principle of S. allows the explicit determination of the behavior of the individual subsystems. In these considerations both deterministic as well as stochastic processes can be included. The approach by microscopic S. can be described as bottom-up, because it starts from the individual parts. A further goal is to look for universality classes of the behavior of order parameters, i.e. to look for common features of the dynamic behavior irrespective of the nature of the individual systems. Phenomenological S. uses the general results of microscopic S. that close to critical points the behavior of complex systems can be described by means of, in general, few order parameters. Phenomenological S. aims at identifying control and order parameters and at formulating phenomenological dynamical equations for the order parameters that may contain both deterministic as well as stochastic influences. Macroscopic S represents a systematic approach to derive order parameters and their dynamics from macroscopically measured data. This approach is based on the maximum entropy principle in a form formulated by Jaynes and extended by Haken to take care of dynamical processes. (See *Entropy Systems Theory***).**

As may transpire from the above statements, microscopic, phenomenological and macroscopic S. are based on mathematical descriptions and methods. In a number of cases, for instance in sociology, or some biological problems, such a mathematical description may not be available. In such a case we may apply semantic S. that draws on logical relationships as expressed by the concepts of control parameters, order parameters, and the slaving principle.

While there is a large class of phenomena in a great variety of systems that can be dealt with by concepts of order parameters and the slaving principle, the definition of S. is, according to sect. 1, still wider. General approaches to self-organization have been formulated by Per Bak in terms of self-organized criticality and, from a different point of view, by Benoit Mandelbrot in terms of fractals, i.e. in terms of self-similarity at various length scales. Self-similarity with respect to time scales is a basic theme in chaos theory. A detailed presentation of these approaches is, however, beyond the scope of this article.

4. Some Typical Examples

In order to illustrate the concepts of S., we present two examples from the natural sciences and one example from sociology.

4.1 The Laser

The laser may be considered as the standard example of S.. It was also the first case in which the basic concepts of S. were developed. The laser is a physical device, namely a specific light source that allows the production of a new type of light, so-called coherent light, that has properties different from those produced by conventional light sources, such as lamps. While there is a great number of different types of lasers, the fundamental principle can be illustrated by means of a gas laser. It consists of a cylindrical glass tube that bears mirrors at its end faces. One of the mirrors is semitransparent, i.e. it allows the transmission of light to some degree. When light waves are produced in such an arrangement and run in axial direction, they are reflected many times and stay longer in this device than any other waves that are running in nonaxial direction.

In this way the axial waves interact more strongly with the atoms or molecules of a gas with which the tube is filled. Consider the simple case of atoms. In a semi-classical picture electrons are orbiting around the nucleus of each atom, like planets around the sun. According to quantum theory, there are only orbits with discrete energies available for electrons. Let us consider a specific electron in its ground orbit. By an electric current sent through the tube, this electron can be excited to an energetically higher orbit. From there it returns to its ground orbit whereby it emits a light wave. It is, as if a pebble is thrown into water, in which case a water wave runs away. In a usual lamp or then in a laser, many atoms with their electrons are excited. When there are few atoms excited, they emit their light waves independently. A microscopically chaotic light field emerges. When there are more atoms excited, the process of stimulated emission, first considered by Einstein, comes into play. Once an atom has emitted a light wave and this light wave hits a second excited atom, it may force the second atom to reinforce this light wave. This process can be repeated whereupon the light wave is more and more amplified, a cascade sets in. In a laser tube different light waves ("species") are possible that differ with respect to their wave lengths (correspondingly their frequencies) and their directions. Such light waves may interact with the atoms differently strongly. Some can utilize the energy stored in the excited electrons more efficiently and thus can be amplified more strongly than other waves – a competition for "resources" sets in. The most efficient wave wins this competition and survives in the laser tube - a mechanism reminiscent of Darwin's principle of the "survival of the fittest". This winning light wave is called the order parameter.

Quite remarkably, the order parameter emerges at a specific critical value of the applied electric current that plays the role of the control parameter. More precisely speaking, laser action starts when the input power enables the amplification rate of the winning light wave to compensate its loss rate due to the transparency of a mirror. To visualize the action of that wave on the electrons, it may be compared with a wave running across a lake on which there are boats. The boats are going up and down according to the rhythm of that wave. Similarly, the electrons move around the atoms according to the rhythm of the order parameter. Thus the order parameter forces the individual electrons, i.e. the subsystems, into a specific motion, or, in other words using a terminology of S., it enslaves the subsystems. On the other hand, the order parameter would die out because of the semi-transparent mirror unless it is reinforced again and again by the light emission of the individual electrons. Thus on the one hand, the order parameter is kept alive by the action of the subsystems, on the other hand the order parameter determines the motion of the subsystems. This is called {\em circular causality}. The transition from the light of a conventional lamp to laser light, when the pump power (applied electric current) is increased, bears a strong semblance to phase transitions in systems in thermal equilibrium. Such phase transitions occur for instance when water freezes to ice or when ferromagnetism sets in. The laser transition shares with those transitions phenomena known as symmetry breaking, critical slowing down and critical fluctuations and is called a nonequilibrium phase transition, because this device operates far away from thermal equilibrium.

The laser is an open system, because it is energetically pumped, in the present example by means of an electric current sent through the glass tube. The laser action described so far is called "single mode operation".

When the energy influx into a laser is increased, a variety of other phenomena can occur, namely for instance the one order parameter is replaced by several, or in other cases, macroscopic chaotic laser light may be generated. These transitions from one kind of activity to another one occur at specific values of the input current. In this way, an instability hierarchy occurs. While in the laser the order parameters are selected from the possible light waves, in many other fields the order parameter is generated by the system itself. We quote as an example the convection instability of fluid dynamics.

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Biographical Sketch

Hermann Paul Joseph Haken, born 1927 in Leipzig, Germany, studied Mathematics and Physics at Universities of Halle and Erlangen, where he obtained his PhD in Mathematics in 1951. In 1956 he became a lecturer in Theoretical Physics at University of Erlangen. From 1960 till 1997 he was full professor at the University of Stuttgart. He was visiting professor or guest scientist at various institutions in Great Britain, the USA, France, Japan, Russia and China. He published 17 text books, monographs and popularizations on *Synergetics*, *Atomic and Quantum Physics*, *Laser Theory*, *Molecular Physics and Quantum Chemistry*, *Quantum Field Theory of Solids*. Many of these books appeared in several languages including English, German, Italian, Spanish, Hungarian, Polish, Russian, Japanese, Chinese, and Czech. Haken published also more than 500 original papers in scientific journals. Among his numerous awards are honorary doctorates of the Universities of Essen, Boca Raton (Florida), Madrid, Regensburg, Munich, honorary professorships at Universities of Xian (China), Shanghai (China), and honorary president of the *Haken Synergetics Institute* in Yunnan (China). Among other distinctions he received the Max Born Preis (Great Britain and Germany), the Albert A. Michaelson Medal (USA), the Max-Planck-Medal (Germany), the Honda Prize (Japan), and he is member of the Order Pour le mérite (Germany).