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Synergetics and computers

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Abstract: Synergetics deals with complex systems composed of many subsystems and the way these systems form spatial, temporal, or functional structures via selforganization. Though the systems may belong to e.g., physics, chemistry, biology, sociology, economy, close to situations where the structure change, the structures are determined by the same basic principles, briefly outlined in this article. We then discuss possible exploitations of these principles and phenomena in the design of computer hardware.

Keywords: Complex systems, synergetics, synergetic computer.

What is synergetics about?

Since the audience to which these proceedings apply may not be familiar with synergetics, a few introductory remarks may be in order.

I coined the word 'synergetics' about 15 years ago in order to characterize the new interdisciplinary field of research I invented (or discovered?) at that time [1–4].

In science we all are used to the general method by which we decompose systems of our study into their individual parts in order to learn about the structure or functioning of these systems. Thus a physicist decomposes a crystal into its atoms, a biologist, at least in principle, decomposes animals into organs and cells and still further, or a sociologist considers a society as composed of its individuals. Quite often we recognize that the function or action of a total system does not result from a mere superposition of the actions of the individual parts of the system. Rather, quite often the system acquires new qualitative features by means of the interaction of its individual parts. This leads to the question in which way the interaction between the individual parts can produce new qualitative features. The basic idea of synergetics is to search for principles which are valid for systems irrespective of the nature of their subsystems which may be electrons, atoms, or photons in physics, molecules in chemistry, cells in biology, animals or humans in societies. In view of the great variety of the subsystems such a question may seem to be absurd, but the fulfillment of this task was indeed possible provided we focus our attention on qualitative macroscopic changes of systems. It is needless to say that such unification can be done only at a sufficiently high level of abstraction and it may be that at this point some learning process is needed because otherwise we will get trapped by too superficial analogies.

Since numerous conferences and publications have been devoted to this field over the past decades (there are about 30 volumes of the Springer Series in Synergetics) it will certainly not be

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possible for me to exhaust this field in any adequate manner. But in these introductory remarks I shall try to give the reader at least a feeling what the phenomena treated are and what kind of approaches are used. To this end let me first list a few examples.

Physics

When a liquid in a vessel is heated from below it may spontaneously form specific patterns of fluid motion, e.g. in the form of rolls or hexagons. In plasmas, under the impact of electromagnetic fields and heating, specific wave forms can evolve. In the light source 'laser' the uncorrelated emission by atoms can become completely correlated giving rise to coherent waves.

Chemistry

In chemistry chemicals can react in such a way as to form macroscopic ring patterns or moving spirals, or they can exhibit regular oscillations where the color changes, for instance, from red to blue to red etc.

Biology

In biology undifferentiated cells in a tissue can differentiate in order to form organs, fur patterns etc. There may be abrupt changes in gaits of horses and other animals or there may be correlated motion in flagella.

In animal populations we may observe oscillations or irregular oscillatory patterns of the population density.

Sociology

In sociology the cooperation of groups of people gives rise to specific forms of employment or formation of political opinions and parties.

Economy

In an economy we observe well correlated flows of money, goods etc., a mostly self-organized formation of an economic system, i.e., with specific actions of business men and consumers.

How synergetics proceeds

In physics and to some extent in chemistry we may start from the fundamental laws, i.e. from first principles, so that e.g. we describe a liquid by the motion of its individual atoms. For many practical purposes it is, however, advantageous to proceed to the next level, the so-called mesoscopic level. At this level we treat the liquid as being composed of little droplets described by temperature, density etc. In many other disciplines, e.g. in sociology, the mesoscopic level is the appropriate starting point where one may speak of the number of people with a specific profession or attitude [5]. This resembles the procedure in chemistry where the densities of molecules of a specific kind are introduced as the dynamical variables.

The further procedure in synergetics can be divided into several steps. After the variables of the mesoscopic level characterizing the system have been fixed, equations describing their temporal change must be established. Since in most cases the systems are subjected to internal or external fluctuations, a stochastic treatment is appropriate. This leads us to the formulation of nonlinear stochastic differential equations of the following type

$$\dot{\boldsymbol{q}} = \boldsymbol{N}(\boldsymbol{q}, \alpha) + \boldsymbol{F}(t). \tag{2.1}$$

$\boldsymbol{q}$ is a state vector, the components of which may be for instance densities of various kinds, α are control parameters by which the system is controlled from the outside and $\boldsymbol{F}(t)$ are fluctuating forces.

If the fluctuating forces depend on the variables of the system we must replace these equations by stochastic differential equations of Stratonovich or Îto type. Instead of starting with the equations (2.1) we may equally well introduce the master equation or, in the case of a continuous Markov process, the Fokker–Planck equation,

$$\dot{f} = Lf,$$

where f is a distribution function depending on the state vector $\boldsymbol{q}$ and on time and L a linear operator.

When we assume the general question of synergetics, namely whether there are general principles irrespective of the nature of the subsystems we may come to a first, though somewhat superficial, statement at the level of these stochastic differential equations in their various disguises.

To take a primitive example think of a flow in a liquid on the one hand and the monetary flow in economy on the other. In both cases we may have sinks and sources so that we may be led to certain analogies between these processes because the equations of these processes are practically the same, though the interpretation of the quantities is quite different.

A further example is provided by the analogy between chemical reactions and population dynamics because chemical reactants may migrate and they may, say, undergo transformations as members of a population may change professions.

Quite clearly a number of analogies between physical and chemical processes on the one hand and processes in sociology and economy on the other can be worked out provided a clearcut translation scheme has been established.

While such a procedure may be quite helpful, the central aim of synergetics is farther reaching, namely we want to unearth common features and basic principles of systems even if the interaction processes and the equations describing them are of quite a different nature. This is achieved by studying those situations where the qualitative behavior of the system changes at a macroscopic scale. Since the essential steps have been described in two previous books and numerous papers of mine [3,4] I do not want to repeat them here in detail.

The basic steps are: We first change external parameters such as energy input in a physical system, or change external conditions for a population (e.g. utilities) and study whether the old state becomes unstable. If an instability occurs, usually one or few specific collective motions or states tend to grow, whereas all other states tend to die out, at least in the linearized stability analysis.

In the nonlinear analysis the dying out modes introduce an interaction between the originally growing modes which are called ‘order parameters’. It may be shown by means of the slaving principle that all the damped modes can be eliminated exactly [4]. This theorem actually contains a number of theorems known in mathematics, as special cases for instance the center manifold theorem.

In this way it turns out that the occurrence of spatial, temporal, or functional structures is governed by very few variables. The corresponding order parameters obey equations which can be grouped into specific classes so that it becomes now evident that quite different systems may behave in precisely the same manner because their order parameter equations belong to the same class. In this way it becomes possible to consider the behavior of quite different systems from the unifying point of view.Then in a next step one may draw efficient analogies between the behavior of quite different systems. As I suggested some years ago, in this way one may easily predict the occurrence of chaotic phenomena in economy (in the technical sense of the word 'chaos' as used in mathematics).

Thus in order to conclude this part of my contribution I may state the following. In synergetics it has become possible to establish general principles governing the behavior of quite different complex systems provided they undergo qualitative macroscopic changes. In particular the evolving structures or patterns are governed in general by few order parameters and can be calculated quantitatively [3,4].

In the final part of my contribution I want to produce some ideas how one may try to invert the procedure of synergetics in order to develop some new ideas on the construction of computers.

Some aspects of computing

Can we exploit the insights we have gained in synergetics to either construct computers or to program them adequately? My following remarks are by no means meant as being exhausting. Rather I want to solicit some reflections on the exploitation of analogies.

First let us consider some building principles of *analogue computers*. Let us consider a chemical process giving rise to a spatial pattern described by one or several order parameters. The evolution equation (2.1) can be decomposed into one part describing reactions and another one describing diffusion i.e. the transport of chemicals.

From the mathematical point of view the reaction term implies addition, subtraction, multiplication, and division of variables at a certain site of the chemical reaction provided we discretize the system. That means in each discrete cell computational processes are going on with inputs and outputs to or from the neighboring cells. In this way the chemical reaction provides us with a model of a parallel computer.

But by an analogy with processes dealt with in synergetics we gain a deeper insight, namely we may conceive now a parallel computer whose output is a specific macroscopic pattern which can be read off by a macroscopic measuring apparatus.

Another type is provided by the laser model in which information between the individual laser atoms is transferred via the electric field which is then the carrier of information and the individual transition processes within atoms can be considered as computational processes whose results are exchanged via inputs and outputs.

Both models lead to the definition of a synergetic computer in which many coupled individual computers produce macroscopic coherent outputs of a specific nature depending on a specific initial input given to the individual computers. Some inputs may (or must) be even random.

After I have presented this talk at Geilo [6], I have learned that such principles have been applied by Shimizu [7] to construct a model computer for pattern recognition. Here the individual computer elements are fed with states denoting orientations of line segments. The computers are coupled in such a way that they resonate the more, the more line segments build up to a whole straight line. By a suitable feedback mechanism the occurring lines and their orientations can then be identified as macroscopic patterns. Of course, this present model is still at a rather initial state but I think it shows the feasibility of computational processes in analogue computers based on synergetics, i.e. on macroscopic patterns evolving from local attractors.

A further possibility of exploiting ideas of synergetics arises, when we put the patterns formed by chemical reactions of physical processes in liquids in analogy to specific distributions of tasks over computers in a computer network (without a master computer). For instance we may consider instruction and data flows with sinks, sources and transformations and let the computers form global patterns of their activities.

Since we have learned how patterns arise in synergetics and can be selected and controlled in a global, i.e. unspecific fashion it seems promising to let computers selforganize the distributions of tasks by building in mechanisms in computers which allow a competition between collective modes of behavior.

Let us finally consider a synergetic process which might be of interest to those working on the *computer hardware*, namely how to establish connections between computer elements via selforganization, i.e. without external planning or manipulation. A beautiful example is provided by the establishment between retina and cortex in some animals.

Experiments indicate that these connections are not established genetically by means of some kind of a blueprint but that they are established in a functional manner, i.e. via competition and cooperation of growing nerve fibers, growing from the retina to the cortex. Those pairs or aggregates which stem from the same part of the retina and thus receive practically the same signals grow to the same spots on the cortex while incorrect fiber connections are eliminated. The mechanism can be described as that of competing order parameters where only one order parameter wins and with it the specific spatial pattern [8].

If we plot, in a one-dimensional model, the starting points of the fibers versus the end points, we observe the specific pattern of a diagonal. From an abstract point of view a connection with the concept of Hebb's synapse can be constructed. These synapses are reinforced by their appropriate use for instance by the repeated receipt of the same signals. It seems to me that such principles can be applied to computers.

If one allows for a specific learning period and then manages to solidify or freeze in the surviving connections it becomes possible to construct a logical network without planning it before hand. I do not think it will be too hard to find physical systems which can show solidification of connections or perhaps the opposite, i.e. melting of unnecessary connections.

A second, still more interesting possibility will be that one keeps such connections active for the while desired and then let them die out and activate other ones. It may be premature to elaborate on these latter ideas at the present moment.

In conclusion I should like to state that the exploition of basic principles of synergetics in computer construction and programming seems to me promising, though I am fully aware of the fact that the remarks I made here are of a rather preliminary character.

Note added in proof

For a recent publication on construction principles for a synergetic computer see

H. Haken, in: H. Haken, Ed., *Computational Systems — Natural and Artificial*, Proc. Internat. Symp. Synergetics, Schloss Elmau, 1987 (Springer, Berlin/Heidelberg/New York, 1987).

The corresponding algorithm allows for the recognition of faces irrespective of orientation, size, and location and even if the faces are incomplete. The algorithm allows the recognition of specific scenes (e.g. several faces which are partly hidden) and explains oscillatory perception of ambiguous figures.

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