H. Haken

# Synergetic Computers and Cognition

## A Top-Down Approach to Neural Nets

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With 163 Figures



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# Preface

This book will be of interest to graduate students, researchers and teachers in the computer sciences, in the cognitive sciences and in physics. It provides the reader with a novel approach to the design and study of neural nets. The applicability of this approach is shown explicitly by means of realistic examples. In addition, detailed models of the cognitive abilities of humans are included and compared with the performance of the synergetic computer presented in this book.

The work presented here would not have been possible without the important help of my coworkers. Dr. Arne Wunderlin has helped me in many respects over many years and has made essential contributions, in particular to the slaving principle of synergetics. Drs. Michael Bestehorn, Rudolf Friedrich and Wolfgang Weimer have applied the methods of synergetics to spontaneous pattern formation in fluids and have further developed these methods. Armin Fuchs has not only implemented my algorithm on a VAX computer, but has also made his own important contributions, in particular to pattern recognition that is invariant with respect to translation, rotation, and scaling. Thomas Ditzinger, Richard Haas, and Robert Hönlinger have contributed within the work on their diploma theses to the application of our approach to a number of problems that are shared by humans and computers in the field of pattern recognition. I wish to thank all of them. Chapter 14 is the result of a most fruitful cooperation with my colleague and friend Scott Kelso to whom I am most grateful, also for highly stimulating discussions on a variety of problems in sensory-motor control, and for his constant encouragement. I extend my thanks to Ms. Irmgard Möller, who has not only prepared various versions of the manuscript with great diligence, but also helped very efficiently in a variety of ways to bring the manuscript into its final form. I am indebted to Karin Hahn and Maria Haken-Krell who assisted me in many respects. Last but not least I owe thanks to the staff of Springer-Verlag for their excellent cooperation, in particular to Dr. Angela Lahee, who made numerous highly valuable suggestions for the improvement of my manuscript.

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*H. Haken*

# Contents

# 1. Goal

The purpose of this book is at least three-fold.

1) It presents a new computer concept with explicit examples of its applications.
2) It shows how synergetics leads us to the idea that pattern recognition and, more generally, cognitive processes can be conceived as spontaneous pattern formation.
3) It provides the reader with new models of cognitive processes.

In this way the book will offer new insights into the principles used by nature in the inanimate and animate world, and it may help us to construct novel technical devices. Let us discuss these goals in somewhat more detail.

## 1.1 Why a New Computer Concept?

Up to now, the field of computers has been dominated by serial computers based on the concept of the universal Turing machine and on the von Neumann architecture. Serial computers may process numbers as well as symbols and they are thought to be universally applicable, at least in principle. In practice, however, there are some limitations, which become evident when certain specific tasks are to be fulfilled by computers. For instance, in vision an enormous number of bits must be processed and, if real time processing is required, even our fastest computers are far too slow. Quite evidently biology has mastered this problem. In spite of the fact that neurones are slow, having processing times of the order of milliseconds, we can recognize patterns within a fraction of a second. Thus the brain works by means of a different principle, which can only be parallel processing. So the question arises of how to find the basic ideas for the construction of parallel computers. A possible answer is provided by the Hillis machine (or the hypercube) but this has the drawback that it requires heavy programming. As nature teaches us, there must be realizations in which learning, or in other words self-programming, takes place rather easily. This has led scientists to devise neural computers constructed in a manner analogous to the nets of neurones of human or animal brains.

Present day concepts rely heavily on the model of McCulloch and Pitts (1943) who represented neurones as two-state elements which receive inputs and have outputs. A neurone is activated only if the sum of the input signals exceeds a specific threshold. Early attempts to realize these basic ideas, in particular by Rosenblatt, who constructed the perceptron, were not followed up for a while because Minsky had shown that the perceptron cannot learn certain logical tasks such as the "exclusive or". Over the last decade, however, there has been an enormous revival of this field initiated by several groups of researchers. Their concepts are still based on the fundamental idea of McCulloch and Pitts but with some slight modifications; in particular, with respect to the shape of the threshold curve. At present, no unique opinion exists among the experts as to how far this approach may go. On the one hand, there are some beautiful results, for instance, those of Sejnowski, who trained a neural net to learn spoken language so that the net could perform like children in the first one or two years of school. On the other hand, there is no general theory of what a network can really do, or of how it can be trained in a reliable and fast manner. In fact, learning is still a major problem and, at present, predictions for the future of these devices are difficult to make. Thus the novel concept of a synergetic computer must be viewed against this background.

The concept of the synergetic computer stems from the interdisciplinary field of synergetics which we shall discuss below. The synergetic computer utilizes far-reaching analogies between spontaneous pattern formation and pattern recognition. In this book we shall become acquainted with the basic equations of the synergetic computer. These equations may be solved on a serial computer, but they also provide us with the construction principle of a new type of parallel network, in which the individual nodes or neurones have quite different properties to those of the previous neural computers in the sense of McCulloch and Pitts. The most prominent feature of our approach will be the following: We can treat the behavior of our network rigorously in the mathematical sense so that we know precisely what its performance will be. In particular, there are no so-called spurious states which are unwanted and in which the system can become trapped. This difficulty, which occurs in both pattern recognition and learning, and which has been a major problem in traditional neural computers, does not appear in the synergetic computer. In contrast to the bottom-up approach of neural computers, where one starts with the properties of the individual neurones, and then tries to fix the links between them in such a way that the network performs specific tasks, the approach to the construction of a synergetic computer is top-down. One first identifies the desired properties and then an algorithm is established which eventually leads to a technical realization.

We shall provide the reader with a number of explicit examples of the performance of our synergetic computer. We use the example of associative memory and pattern recognition and present results on the recognition of faces and city maps. We will show how recognition can be made invariant with respect to position, orientation, and the size of the objects to be recognized. Scenes composed of several faces can also be recognized. A number of further applications which relate to psycho-physical experiments or to the performance of logical operations will be pesented in Parts II and III of this book.

## 1.2 What is Synergetics About? Pattern Recognition as Pattern Formation

Because the synergetic computer relies heavily on basic concepts and methods of synergetics and utilizes the analogy between pattern recognition and pattern formation, a few words about synergetics may be in order. (More details will be given in Chap. 4.) The word synergetics is taken from Greek and means cooperation. Thus synergetics is an interdisciplinary field of research which deals with the cooperation of the individual parts of a system. This cooperation may lead to the formation of spatial, temporal, or functional structures.

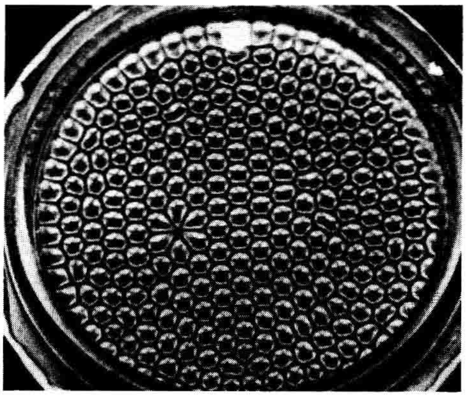

**Fig. 1.1.** Top view of a liquid in a circular vessel. When the liquid is heated from below and the temperature gradient exceeds a critical value, hexagonal cells are formed. In the middle of each cell the liquid rises, sinking back down at the edges of the hexagon. From Koschmieder (1977)

**Fig. 1.2.** Formation of spirals in a chemical reaction. (Winfree, private communication)

A simple example is the case of a fluid heated from below which may spontaneously form patterns in the form of hexagons or rolls based on an upwelling of the fluid (Fig. 1.1). Further examples are provided in physics by the production of the coherent light of lasers, in chemistry by the macroscopic rings or spirals formed in chemical reactions (Fig. 1.2), and in biology by morphogenesis during the growth of plants and animals. Another example is in behavioral patterns which may range from the gaits of horses to specific movements of human beings. In all these cases the systems acquire their structures as a result of rather *unspecific* changes of their environment, for instance when the fluid is heated more strongly or when the concentration of a chemical is changed, etc. In other words, the structures evolving in the system are not prescribed in a specific manner from the outside. More precisely, the system forms its new structure by *self-organization*. In a more abstract sense, the formation of a structure can be interpreted as the emergence of new properties of a system. As was shown in synergetics, there are a great variety of phenomena in physics, chemistry, and biology where the spontaneous formation of patterns or the emergence of new properties by means of self-organization is governed by the *same basic principles*. In Chap. 5 we shall show how these principles may be used to formulate our approach to a synergetic computer.

## 1.3 Cognitive Processes and Synergetic Computers

The simulation or, still better, the understanding of human behavior by means of machines has a long tradition. Just think of clockwork dolls built to mimic human motions such as dancing, etc. We live in an age in which the simulation and understanding of human activities, especially of cognitive processes, is undergoing a revolution that began with the advent of the electronic computer. Because it was soon recognized that computers cannot only process numbers but also symbols, simulations of the tasks performed by humans, for instance playing chess, or the solution of the tower of Hanoi problem were tackled by means of electronic computers. Cognitive processes were modelled by strings of symbols which were processed consecutively. Among the early pioneers, Herbert Simon and Allen Newell as well as Marvin Minsky may be mentioned. After an initial period of great enthusiasm we are presently witnessing a rather critical debate about the success of their concept of Artificial Intelligence. I am sure that a similar debate will occur about connection machines, i.e. "neurocomputers", (and synergetic computers) in the future, especially if we are making far fetched claims about their role in *fully* understanding or simulating human intelligence. It was at the time AI was defined that connection machines, in particular the perceptron, came into existence, were then abandoned, and are presently experiencing an enormous revival. We shall not discuss this exciting development here (but see references cited in Sect. 1.1).

One might reasonably ask whether connection machines, or in other words neural computers, can, in a single step, conceptually bridge the enormous gap between microscopic events taking place in the real neurones of the brain and the macroscopic phenomena of cognition, or whether intermediate steps are required. The latter point of view has been clearly expressed by Smolensky. I am also inclined to support this latter view. It is here that the synergetic computer comes in. Being based on a top-down approach we study macroscopic events and try to simulate them by a network which in turn may combine the functions of subunits composed of a greater or lesser number of neurones. Nevertheless, we wish to demonstrate that our approach allows us to make quite specific predictions that can be compared with psychological findings. We shall show how our computer can recognize patterns, and how the process is made invariant with respect to displacements, rotations, and scaling. It will turn out that these invariance properties can be devised in different manners.

A comparison with experimental psychological data will tell us that one of these approaches can be followed up as a model of cognitive processes whereas the other is certainly less applicable (Sect. 12.2). We shall also see how a parameter, which may be directly related to psychological attention, is responsible for the recognition of scenes by a computer. This may shed new light on the way humans perceive complex scenes. The same attention parameters will turn out to be responsible for oscillations that occur in human perception of ambiguous figures such as Fig. 2.5. The application of the synergetic computer to the recognition of movement patterns, for instance the distinction between the different gaits of horses, leads us to ask whether or not humans perceive these patterns in a similar manner.

We have chosen vision as an example of cognitive processes for several reasons. First of all pattern recognition can be easily performed by our computer and the results can be readily compared with those of psycho-physical experiments, even in a quantitative manner. At the same time we believe that vision is a useful paradigm for higher mental processes, such as reasoning, problem solving, etc. Interestingly, this is also mirrored in language by the existence of expressions such as "to gain insight" and "to develop a picture of a situation", etc.

Our approach "sheds new light" on the question of mental maps or mental representations. Surprisingly, the approach allows two interpretations:

1) By a completely parallel network in which mental maps or representations must be stored in the connections or "synapses" between different "neurones".

2) An alternative interpretation in terms of the "grandmother cells" which have occasionally been postulated in brain theories. But most probably our grandmother cells are different from neurones and represent whole assemblies of neurones. We shall also show how we can model assimilation and adaptation and how these two concepts are related to one another. I do not believe that our approach, or any other contemporary approach, will be the ultimate step towards a full understanding of brain functions. On the other hand, I am convinced that it is an important step possessing much future potential.

In many, if not all cases, I believe that the processes of cognition may be thought of as pattern formation by self-organization. This must occur at the abstract level as far as concepts are concerned, and at the material level in cognitive processes related, for example, to firing patterns in neural nets. As the reader will see, a number of our results can be tested experimentally so that a sound basis for future work is established. Our results can also be related to Gestalt-theory. Indeed, more recently psychologists such as Stadler and Kruse have underlined pronounced analogies between the behavior of the systems dealt with in synergetics and phenomena found in perception. As we shall see, a key to cast the concept of "Gestalt" into a rigorous form is provided by the order parameter concept of synergetics.

# Part I

# Synergetic Computers

# 2. What are Patterns?

> One of the most interesting aspects of the world is that it can be considered to be made up of patterns. A pattern is essentially an arrangement. It is characterized by the order of the elements of which it is made rather than by the intrinsic nature of these elements.
>
> *Norbert Wiener*

These sentences by the famous mathematician Norbert Wiener may serve us as a first guideline in defining a pattern. The idea that the nature of the elements is irrelevant for a pattern raises an important issue; namely, a pattern is defined on a specific length scale, on which the nature of the elements is irrelevant. Clearly we may focus our attention on the structure of these elements, but then the elements become the pattern and in turn are composed of still smaller elements. Rather than attempting a final definition of a pattern, let us consider instead a series of examples.

The animate world provides us with a huge variety of different patterns which on occasion may be quite bizarre as is demonstrated by Fig. 2.1. This figure shows the spherical eye of a tropical fly and exhibits the fine hexagonal structure of the facets. Figure 2.2 shows a number of butterflies and moths with their beautifully patterned wings. We recognize these animals in spite of their rather different shapes and their different markings. Apropos shape and coloring: quite often shape and coloring of animals and plants serve special purposes, e.g., to attract a sexual partner or to hide from an enemy by an adequate camouflage or mimicry. Figure 2.3 shows a variety of dogs. We recognize them all as dogs although they may be of different ages, may belong to different breeds, are photographed in different locations, and are in different states of movement or rest. Thus our recognition evidently has a very pronounced capability of categorizing.

Human beings have a highly developed ability to recognize faces, and there is even a specialized center in our brain to do so. Figure 2.4 shows a scene that can be easily decomposed by our brains such that the individual faces can be recognized. There are also patterns that cannot be interpreted in a unique fashion. An example is shown in Fig. 2.5, a drawing by the famous artist Escher. When we consider the white dots as foreground, we recognize angels; when we consider the black dots as foreground, we recognize devils. As we are told by psychologists, and as our own experience teaches us, our perception of these patterns oscillates, i.e. we first recognize the devils for a while, then they are replaced by angels, then the devils will reappear, etc. Patterns need not be static, they may also be dynamic, e.g., when we watch the gaits of horses or dancing people, their movements follow specific patterns. Therefore, one may speak of behav-