Complexity and Complexity Theories: Do These Concepts Make Sense?

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Abstract In light of the recently published book *Complexity 5 Questions*, edited by Carlos Gershenson, I discuss some of the Complexity theories (including my own field "Synergetics") with respect to their applicability to cities. This book, with contributions by 24 leading scientists, shows that there is no general consensus on "Complexity". Nevertheless, I believe that there is some common ground for an approach to what one might call a "theory of a city", even if it remains an open ended story.

Keywords Complexity sciences • Information adaptation • Synergetics

1 Introduction: Is "Complexity" a Science?

Two years ago, in 2008, Carlos Gershenson edited a little book entitled *Complexity—5 Questions*. He had invited 24 leading scientists from different backgrounds, including physics, economics, engineering, philosophy, computer science, sociology, biology, mathematics, and chemistry to send their opinions on complexity in brief contributions. Let me start here with a brief introduction formulated by Gershenson (2008) in his preface:

> Etymologically, complexity comes from the Latin *plexus*, which means interwoven. A complex system is one in which elements interact and affect each other so that it is difficult to separate the behaviour of individual elements. Examples are a cell composed of interacting molecules, a brain composed of interacting neurons, and a market composed of interacting merchants. More examples are an ant colony, the Internet, a city, an ecosystem, traffic, weather, and crowds. In each of these systems, the state of an element depends partly on the states of other elements, and affects them in turn. This makes it difficult to study complex systems with traditional linear and reductionistic approaches.

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One of the main features – and problems – of complexity is that it can be found almost everywhere. This makes its study and understanding very appealing, since complexity concepts can in principle be applied to different fields. However, its generality makes it difficult to define, and it is sometimes too distant from practical applications, which may lead to its dismissal by pragmatic researchers.

One of the most debated aspects of complexity in this book (edited by Gershenson) is its status as a science. Some people agree that it is already a science. Some believe that it is too early to call it a science, but that with time it will mature and become a rightful science on its own. Others think that complexity will never become a science, due to its vague nature. In any case, the study of complexity has scientific aspects to it, but also has been applied as a method to solve problems. Moreover, concepts developed within complexity have been absorbed by well-established fields. Still, these are not referred as "complex biology" or "complex physics". It might be the case that all fields will soon absorb complexity concepts. Will they use the term "complexity" to refer to them? It does not matter, that is just a convention.

2 In Search of Unifying Principles

When browsing through the articles of the authors of the book, edited by Gershenson, it becomes apparent that there is no general consensus on the answers to the questions mentioned by him above. Therefore, in a first step to prepare an answer to these questions, I'll start from my own experience. Some 40 years ago, I initiated an interdisciplinary field of research that I called "Synergetics", and in one sense or another can be considered to be the forerunner to the field "complexity" (Haken 1983a,b). Like a number of other approaches, my approach had been inspired by physics. The reason for this lies probably in the fact that, at least intuitively speaking, physical systems are less complex than, say, those studied by biology or sociology. In addition, in the past, physics had supplied us with concepts and mathematical approaches to deal with systems that are composed of many individual parts and that may be able to produce specific structures. The keyword here is 'self-organization'. What might be the goal of such an endeavour? In science, we may distinguish between two main trends, namely the collection of data and the search for unifying principles. Usually, the discovery of unifying principles has been considered to be a considerable achievement in science. Examples are Mendelejew's periodic system of elements in chemistry or Mendel's discovery of the laws of inheritance in biology. Physics is well known for its basic unifying principles, e.g. Maxwell's theory that unifies the laws of electricity and magnetism, or Einstein's theory of general relativity that concerns the relation between matter and space-time.

3 Synergetics

Synergetics can be considered as an attempt to find principles that govern the behaviour of complex systems. The systems may be composed of many elements, parts or subsystems that may be the same or different. The systems studied may belong to a variety of disciplines which range from physics, chemistry, biology, to economy and ecology, psychology and psychiatry. Quite clearly, the individual elements may be of quite different nature, depending on the systems considered.

Fig. 1 The formation of cloud streets

In order to find universal principles for the behaviour of all such systems, we had to pay a price. It consisted in confining the analysis to those situations in which systems change their behaviour dramatically at a macroscopic level. Examples are the formation of cloud streets by the individual parts of the water molecules in water vapour (Fig. 1), the recognition of faces by groups of neurons of the human brain, or the phenomenon of the laser beam; all of these are described below.

In contrast to the physical discipline of 'thermodynamics', which treats physical and chemical systems close to their thermal equilibrium, Synergetics deals with systems that are driven away from equilibrium by a continuous (or discontinuous) input of energy, matter and/or information. The external influences are modelled by means of *control parameters*. The general strategy of Synergetics is the following: We consider a state that has been established under a set of fixed control parameters. One or several of these control parameters are then changed and we study the stability of the former state. When the state becomes unstable, at least in large classes of systems, one or only few configurations of the system can grow, whereas all others, even once generated, will die out. The growing configurations are governed by one or few *order parameters*. These order parameters may compete with each other to win the competition and thus govern the behaviour of the whole system. In other cases, order parameters may cooperate or coexist. The winning order parameters determine the behaviour of the individual parts or, in other words, using a *terminus technicus*, they *enslave* the individual parts of the system; hence the notion of the *slaving principle* that is central to synergetics. This explains the fact that highly ordered structures may arise.

The order parameters may be compared to puppeteers who let the puppets dance in a specific, well-organized fashion. However, in contrast to this image, the individual parts generate the behaviour of the order parameters through their coordinated action. Thus, in all self-organizing systems, we are dealing with the principle of *circular causality*. The individual parts determine the behaviour of the order parameters which, in turn, determine the behaviour of the individual parts. While the individual parts are in general numerous, the order parameters are small in number. Thus, by means of the concept of order parameters and the slaving principle, a considerable reduction of information is achieved. When we focus our attention on the role of the order parameters, the behaviour of the system is governed by only a few of them. On the other hand, when we consider the individual parts it seems as if a consensus has been reached between them so as to produce an organized behaviour. In a number of cases the behaviour of order parameters can be classified, e.g. when there is only one order parameter, close to instability points, the system may undergo strong fluctuations and it may relax only very slowly to its equilibrium state. Such instability points characterize a crisis. In the economy we observe these phenomena, such as large fluctuations of critical quantities of economy as well as their slow return to equilibrium, which may actually be quite different from the one the system had previously occupied.

The theory of synergetics was developed by reference to several paradigmatic case studies that refer to, and illustrate, the various facets of the theory. They are the *laser paradigm* that originated in physics but was applied also to other domains such as sociology, the *pattern recognition paradigm* that is specifically associated with cognition, and the *finger movement paradigm* that suggests interesting insights to the study of human behavior. Here is a short description of each.

3.1 The Laser Paradigm

The phenomenon of the laser beam provides a paradigmatic case study of the above interplay between the control parameter(s), the parts of the system, the emerging order parameter(s), the slaving principle and the process of circular causality.

Let us consider the model of a gas laser (Fig. 2). A cylindrical glass tube contains the laser atoms. In each of them, an electron is orbiting around its nucleus and can occupy either a ground state or an excited state—we assume only one. An electric current sent through the tube excites the electrons and they go from the ground state to the excited state. Hereafter each excited atom emits a light wave of finite length (a wave 'track') independently of the light emission of the other atoms. The light field emitted from all excited atoms is a superposition of such *uncorrelated* wave tracks—it looks like Italian noodles. However, when the strength of the electric current (which acts as control parameter) exceeds a critical value (the laser threshold) a totally different light emerges (*emergence of a new quality*):

A single, practically infinite, *coherent* wave appears; the Italian noodles are replaced by a single, giant noodle. What has happened? According to Einstein, a light wave impinging on an excited atom (its electron in the excited state) can force that atom to reinforce precisely that wave. If several atoms are excited, a light wave avalanche results. In the beginning of laser action, such avalanches (which may differ with respect to their frequency ('colours') are triggered time and again. They *compete* for the support from the energy present in the excited atoms.

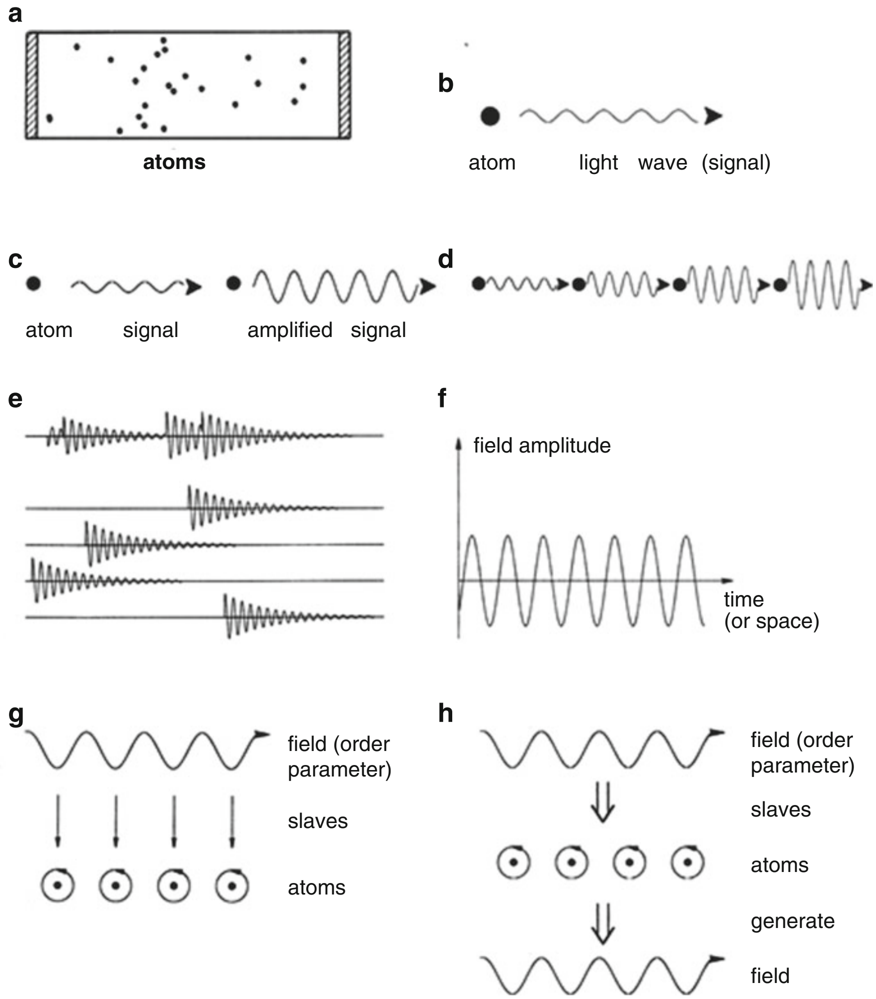

Fig. 2 The laser paradigm. (**a**) Typical setup of a gas laser. A glass tube is filled with gas atoms and two mirrors are mounted at its end faces. The gas atoms are excited by an electric discharge. The laser light is emitted through one of the semi-reflecting mirrors. (**b**) An excited atom emits light wave (signal). (**c**) When the light wave hits an excited atom it may cause the atom to amplify the original light wave. (**d**) A cascade of amplifying processes. (**e**) The incoherent superposition of amplified light waves produces still, rather irregular light emission (as in a conventional lamp). (**f**) In the laser, the field amplitude is represented by a sinusoidal wave with practically stable amplitude and only small phase fluctuations. The result: a highly ordered, i.e. coherent, light wave is generated. (**g**) Illustration of the slaving principle. The field acts as an order parameter and prescribes the motion of the electrons in the atoms. The motion of the electrons is thus 'enslaved' by the field. (**h**) Illustration of circular causality. On the one hand, the field acting as order parameter enslaves the atoms. On the other hand, the atoms, by their stimulated emission, generate the field

The wave (avalanche) that can grow fastest, wins the *competition*, survives, and all other types of waves die out—their 'nutrition' eaten up by the winner, under the principle of *winner takes all*. The winner acts as an *order parameter* in (at least) two ways: First, it describes (represents) the *macroscopic* laser light. Second, it *enslaves* the individual electrons of the atoms. They must behave in such a way that they keep the order parameter 'alive' (the laser wave leaves the glass cylinder continuously and must be maintained).

Thus we arrive at the following scheme:

1. The order parameter enslaves the behavior of the atoms
2. The atoms generate the order parameter by their coordinated behaviour.

This is the principle of *circular causality*.

So far I have presented the basic features of a *single mode* laser. Laser theory deals with more phenomena, such as coexistence of order parameters (corresponding to ecological niches), ultra short laser pulses etc.

3.2 The Pattern Recognition Paradigm

Pattern recognition (e.g. recognition of faces) is conceived as the action of an associative memory. An example of such a memory is provided by the telephone book; it associates a telephone number to a given name. In abstract terms: an associative memory completes a set of incomplete data to a full set in a well defined manner. But instead of using a list (such as the telephone book or dictionary) we use a dynamical system realized in a net. Such nets were introduced by Hopfield using an analogy with spin. By contrast, our approach (Haken 1991) uses the concept of order parameters and the slaving principle. (In this way typical drawbacks of Hopfield nets, such as "ghost states", are avoided). The basic idea of our 'synergetic computer' (SC) is as follows, leaving aside the question concerning hardware or software realizations. The SC consists of N elements, the (model) neurons of which pairs or quadruples are connected by synapses. Their strengths can be directly implemented by the programmer or learnt by the SC. To this end the individual patterns (e.g. faces) are decomposed into small elements ('pixels') with either respective gray or colour values. Using the specific algorithm of the SC, they yield the synaptic strengths. After this an *order parameter* is attached to each such 'prototype pattern'.

In this way, each 'thinkable' pattern can be represented as a superposition of *prototype patterns*, each multiplied by its *order parameter* (plus an eventually unimportant rest term). When a 'test pattern' (i.e. the pattern to be recognized) is 'shown' to the SC, the initial states of all order parameters are fixed, and the dynamics of the SC leads to a *competition* between the order parameters, which is won by the one whose prototype pattern is most similar to the test pattern. Since the number of pixels of a pattern is (at least in general) much larger than the number of prototype patterns, the identification of a single order parameter means

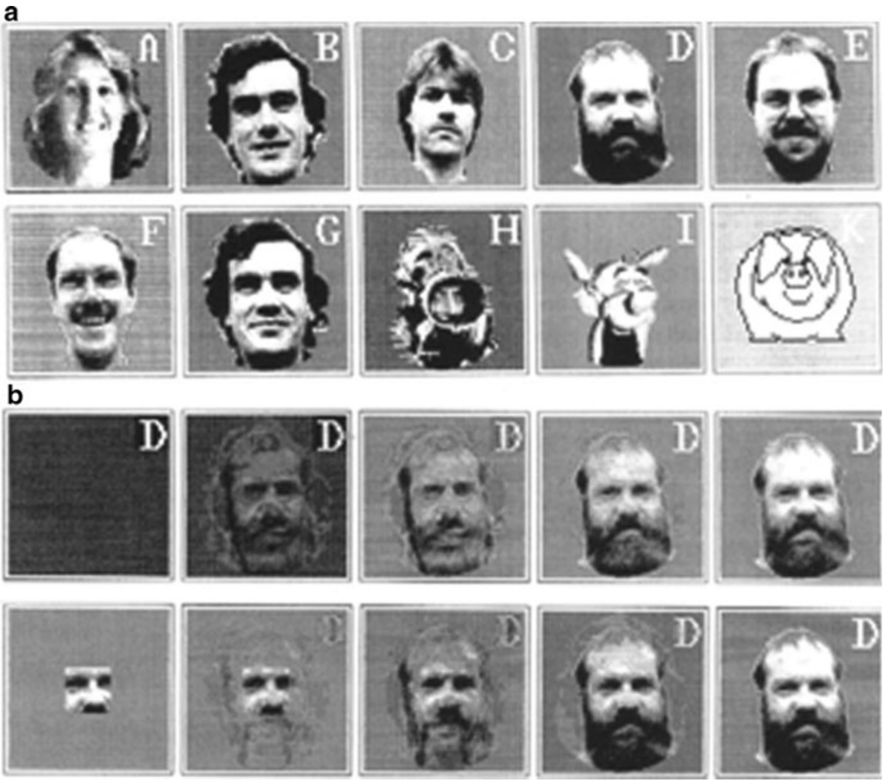

Fig. 3 The pattern recognition paradigm. *Top*: The faces (and other figures) that are stored as prototype patterns with letters encoding the names or identifying the figures. *Bottom*: When a letter from one of the patterns, or part of a face, are offered, the synergetic computer can restore the whole face or figure

considerable *information compression*. On the other hand, a known order parameter can invoke its associated pattern (*information inflation*). The interplay between these two mechanisms leads to *information adaptation*, according to J. Portugali and H. Haken (in preparation). In this way (and in others) the concept of the SC is of relevance to error corrections, categorization, etc. Figure 3 represents a typical process of pattern recognition by means of the SC. For more details of the SC, such as recognition of complex scenes, preprocessing etc. see Haken (1991).

3.3 The Finger Movement Paradigm

The finger movement paradigmatic case study is of relevance to biology, movement science and medicine (and possibly to other fields) depending on the level of abstraction and on application. The underlying experiment, performed by Scott

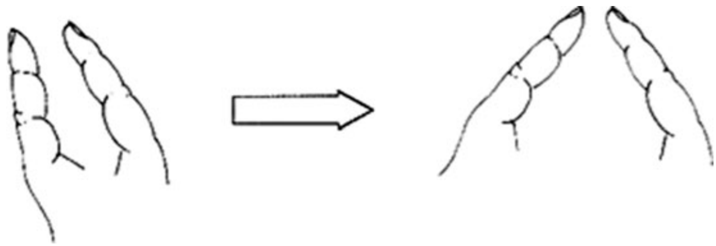

Fig. 4 Kelso's finger movement experiment. While initially people can move their index fingers in parallel, beyond a critical speed of the finger movements the relative position of the fingers switches involuntarily to the antiparallel, i.e. symmetric position

Kelso (Kelso 1995; Haken 1996) runs as follows (Fig. 4): A subject is instructed to move his or her index fingers in parallel according to the speed of a metronome. When the speed is slow, the subject can perform this task. When, however, the speed is increased beyond a critical frequency, the behavior changes qualitatively (think of the laser threshold). Suddenly, a new *coordination pattern* appears: namely a *symmetric* finger movement. This phenomenon was quantitatively modeled by Haken et al. (1985) in the spirit of synergetics. The relative phase between the two index finger serves as an *order parameter* whose 'movement' can be visualized as that of a ball in a hilly landscape—the 'potential landscape'. Actually, both the behaviour of laser light as well as the SC process can be treated and visualized with the help of appropriate potential landscapes. In the finger experiment, the speed (or frequency) of the finger movement is identified as *control parameter*.

Its change causes a deformation of the potential landscape. While at the beginning the ball representing the order parameter sits in a valley, with increased speed (change of control parameter) this valley disappears and the ball can roll to another, deeper valley: the order parameter, and thus the whole movement pattern, changes dramatically. A *phase transition* (both in the sense of thermodynamics or synergetics and movement coordination) happened.

Numerous further experiments on pairwise coordination (e.g. arms and legs) obey the same fundamental order parameter equations. Furthermore, *gait changes* of quadrupeds (ponies, horses, camels etc.) were modeled this way.

In my opinion, the results of this 'order parameter approach' have a number of important implications. What we modeled is the *behaviour* of a *highly complex system*: a human composed of numerous muscles and bones, and myriads of cells including nerve cells. But the highly coordinated behaviour of all these parts (and even their constituents) is not only described but governed (via the *slaving principle*) by a few relevant variables, the order parameters, that in many cases are even measurable. It is thus tempting to model brain activity (or the action of the human mind) by means of the dynamics of appropriate order parameters that, for instance, verify sensation and action, or that represent both a specific neural action and the 'corresponding' thought.

4 Chaos

The above-mentioned results of Synergetics, with its rather extended mathematics, have found further developments in recent years. One is chaos theory (under which terminus former results of Synergetics concerning pattern formation are quite often subsumed). Chaos theory rests on a result of Synergetics, namely that complex systems may be governed by only a few variables. In fact, chaos theory starts with the behaviour of a small number of variables, in general three in the case of continuously changing systems (with respect to discrete time dynamics two variables are sufficient). As computer simulations have shown, such systems can exhibit seemingly irregular behaviour, e.g. characterized by largely fluctuating time series. On closer inspection it could be demonstrated that there are pronounced regularities. When a control parameter is changed continuously, the system may run through a series of instabilities, each characterized by a new kind of temporal behaviour of the system. For instance, a system with a rhythm of one specific period may undergo a transition to double period, fourfold period, etc. (period doubling cascade). This is just one, but well known, example of such chaotic systems.

The behaviour of such systems shows quite a number of self-similarities. Typical examples of self-similarity are provided by the theory of fractals, which is intimately related to chaos theory. Using a mathematical procedure called 'iterated maps', fractal theory produces arrangements of points e.g. on a plane, where the arrangements appear as patterns. When a pattern is looked at through a microscope, a *similar* pattern appears, but now at a smaller scale. This procedure can be continued ad infinitum, thus revealing a law of 'self-similarity'.

Chaos theory also uses geometric representations of movements of bodies or temporal changes of systems. As an illustration, consider the elliptic orbit of Earth around the sun. When we change the momentary position and/or velocity of Earth, another ellipse will be followed by the body. When we change parameters such as initial position or velocity continuously we will find a bundle of ellipses, so that a rather regular pattern of orbits results. As had been observed by Poincaré at the turn of the last century, such movements can become quite irregular if there are three or more celestial bodies involved. To mention one important result discovered by E. N. Lorenz (1963): in a model belonging to meteorology even a small change of initial conditions (e.g. position, velocity) can change the course of the trajectory dramatically. I usually illustrate this result using the following picture (Fig. 5): let a steel ball fall on a vertical razor blade. Then the path of the ball will follow quite different trajectories, depending on whether the tip of the razor blade is hit by the steel ball a little more to the left or to the right. This observation has many important consequences in weather forecasting, economics and in numerous other fields. Because of the just mentioned so-called 'sensitivity to initial conditions', the further evolution of the system cannot be predicted satisfactorily over a somewhat extended period of time.

When dealing with economy, but also with related fields, different approaches may be used. One is the methodology of Synergetics. Another important one is that

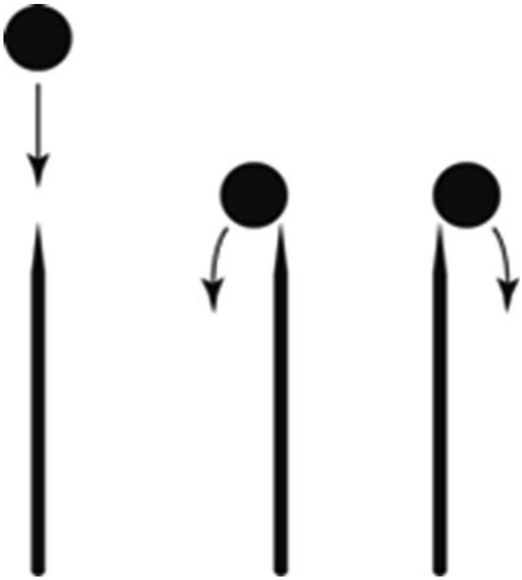

Fig. 5 Illustration of chaos as 'sensitivity to initial conditions'

of game theory as founded by John von Neumann and Morgenstern many decades ago. Here the player's strategies which lead to success are investigated. A well known example of intricacies is that of 'prisoner's dilemma'.

5 Turing Machine

The concept of complexity is a well known research topic in mathematics. To get a handle on this concept, let us consider the *Turing machine* which is the prototype of any digital computer. It consists of a computing head which runs along an infinite tape, divided into boxes (Fig. 6). Using the dual number system, each box can carry either a zero or one. First, the program and an initial state are encoded on the tape by a specific sequence of zeros and ones. Then, by moving the head one step forward or backwards, the tape is read and the result of this reading is processed by the head whereupon it proceeds one step forward or backward and prints the result on the tape.

The concept of the Turing machine allows us to define a measure for the complexity of a given system whose state (or perhaps process) can be described by a sequence of bits (zeros or ones) on the Turing tape. Then, however, the following question arises: what is the smallest number of bits we need to write down the program and initial state that generate the given state of a system as described previously? The length of the shortest sequence would then describe the complexity of a system. Unfortunately, it can be proven that there exists no general algorithm which allows us to determine this shortest length. There are deep

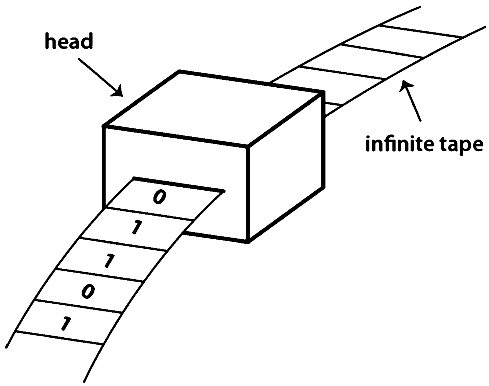

Fig. 6 Turing machine

connections with Gödel's theory on *undecidability*. Having said this, it is important to note that the problem of undecidability does not prevent the definition of complexity measures, e.g. the length (in bits) of a message, to mention a simple example. Such a message can be the description of an object or of a behaviour. However, it is far beyond the scope of the present paper to go into this in detail.

6 Information

Another rather comprehensive theory that deals with systems is Shannon's *information theory* (Shannon and Weaver 1949). In its original form it allows us to define and calculate the capacity of a given information transmission channel or, more precisely, it allows us to calculate the number of bits per second that are to be transmitted through such a channel.

An important concept is *information entropy,* which allows us to calculate the number of microscopic realizations of the macroscopic state of a given system where the state is characterized by so called 'moments', i.e. average values and correlation functions. The application of the maximum information entropy principle has led to a number of insights into the behaviour of complex systems close to their instability points. For example, new light can be shed on the properties of order parameters and enslaved parts. Furthermore, 'unbiased guesses' can be made about processes on which only incomplete data are available.

Information theory as defined by Shannon deals with *closed and simple systems*. Complexity theory is about open systems. In my book *Information and Self organization* I studied two forms of information: *Shannonian information*, which is information without meaning, that is, a quantity; and *semantic information*, which is information with meaning (Haken 2006). Semantic information is a property of open and complex systems. Relations between Shannon and semantic information have been discussed in this book and have been further elaborated by Haken and Portugali (2003) as well as in a new paper (to be published) that emphasizes the concept of 'information adaption'. The latter two studies have applied the notions of Shannonian and semantic information to the domain of cities.

7 Network Theory

In recent times a comprehensive study of networks has been booming. Networks are ubiquitous, e.g. from the Internet, railways, streets, supply centres, down to molecular reaction networks in cells. Studies have been performed by Barabasi (2002), Watts (2004) and others. One general notation is that of 'scale invariant networks' or 'scale free networks'. Here the frequency distribution P_n of nodes is treated as a function of connections to other nodes, where P_n is described by power-laws $P_n \propto n^{\alpha}$ (e.g. in contrast to $P_n \propto e^{-\alpha n}$). An important problem is the determination of the number of pairwise connections n to connect two different nodes. The existence of 'small worlds' in which only a few connections are needed to connect two given nodes a, b is an important result.

A connection to synergetics is relevant when one treats dynamics on networks. An example is provided by neuronal nets where the 'neurons' correspond to the nodes and the synaptic strengths to the links. The interplay between topology and dynamics is a challenging topic, which includes the study of changes of the net due to learning (or forgetting).

8 Fuzzy Logic and Grey Systems

Fuzzy logic: In this approach, initiated by Zadeh (1975), the strict rules of logical connections, in particular by a Boolean algebra, are softened by means of probabilistic connections. This approach is applied, for example, to the automatic steering of trains (e.g. soft breaking).

Grey systems: In China, in particular in the work of Deng (1989) and Sifeng (2004), systems are studied in which the data on systems are either only partly known or not completely reliable.

9 Cellular Automata (CA)

Last but not least, the theory of cellular automata must be mentioned. This theory, originated by John von Neumann, decomposes physical space (or some abstract space), mostly one- or two-dimensional, into cells (labelled by j) which may occupy states (labelled l) $s_{j,l}$ $l = 1, .., M$; ($J = 1, ..N$). The evolution in discrete time steps of occupation patterns is determined by simple rules, e.g. the states of the neighbours of cell j determine in the next time step the state of that cell. A simple example is this: Take the sum of the occupancies of the two neighbours and subtract twice the occupancy of the cell considered. Multiply the result by a constant. This describes a diffusion process. What are the resulting patterns? Among others, periodic or chaotic patterns are found.

Both the theory of CA as well as synergetics aim at a classification of resulting spatio-temporal patterns. But while CA operates on discrete variables, synergetics works with continuous variables and studies their differential equations. The transition from discrete to continuous implies a number of subtleties. Important classification work was done by Chua et al. (2009) in connection with Wolfam's systems (2002).

10 Concluding Remarks

As the reader will note, there are a number of approaches for dealing with complex systems from some unifying points of view, whereby the point of view is determined by the methodology to be applied and which is (hopefully) the most suitable. I think it is safe to say that current complexity theory is not a monolithic theory, but has rather become a tool box for dealing with complex systems, e.g. the growth of cities, population dynamics etc. A prototypical book is that of Juval Portugali (2000): Self-organization and the City.

Many problems concerning complex systems stem from biology and economy. This is witnessed for example by the Complexity Digest, presently edited by Carlos Gershenson and founded by the late Gottfried Mayer. I am proud to say that Gottfried was a former Ph.D. student of mine who then went to the United States and later on to Taiwan. I dedicate my article to his memory. As is obvious from the Complexity Digest, this field is increasingly concerned not only with unifying theories but also with the collection of data on, say, remarkable phenomena from different disciplines.

I think that a close cooperation between experimentalists, observers on the one hand and theoreticians on the other, will be the most important thing for the further development of this field.

In conclusion, I want to mention some more or less early attempts at unifying approaches to what are nowadays called 'complex systems':

1. Cybernetics: A theory of the steering of systems, both in the animate and inanimate world, with fundamental contributions by Norbert Wiener. A prototypical example of this field is the regulation of room temperature by a thermostat.
2. In a more advanced state this field had been treated by Heinz von Foerster who investigated it from the psychological point of view and introduced the notion of self-organization. He presented as a typical example a battle between the American and the Japanese navies in the Second World War. The American admiral's ship was heavily damaged, so each individual ship of the American navy had to find its own target by 'self-organization'. This task is intimately related to the assignment problem in manufacturing where tasks and workers must be assigned to machines (or the other way around) so as to reach an optimal result. While the task-machine problem was solved by the 'Hungarian method', the three partner problem just mentioned is considered to be 'NP' in mathematical terms. Our own approach rests on a generalization of the order parameter equations we introduced for pattern recognition (of e.g. Starke et al. 1999).

3. Von Bertalanffy's (1968) general system theory: The goal of Bertalanffy was to treat different systems from the point of isomorphism. He was looking for similar properties of parts belonging to different systems in order to conclude that these systems behave similarly. Although the idea was nice, its applicability was restricted by the fact that for many systems it is hard to find relevant similarities between their elements. An important concept of von Bertalanffy's was his idea of flux equilibrium, which supplements the conventional idea of equilibrium in a static system. Here, as in biology, systems are treated which are supported by an influx of energy and matter and thus kept in some kind of steady state. General system theory must not be mixed up with the mathematical branch of dynamical systems theory which is of purely mathematical nature, and its formalism must be brought to life by concrete applications.
4. The concept of communication has played a crucial role in the theory of societies by Niklas Luhmann.
5. In chemistry, and in related fields, an early attempt at dealing with open far-from-equilibrium systems from a unifying point, was made by Ilya Prigogine, who introduced the notation of *dissipative structures*. It must be said, however, that his attempt to use concepts of thermodynamics, such as entropy production and excess entropy production, turned out not to be appropriate for the treatment of far-from-equilibrium systems. His student, Gregory Nicolis, and others carried this field further, whereby they switched to concepts originally introduced in Synergetics.

Clearly, this list is by no means exhaustive, but I hope that I have been able to provide the reader with some flavour of 'Complexity'. In current science, this mushrooming field is dealt with in both book series and journals. I would like to mention a few examples: the Springer series in Synergetics has found a sister series called Complexity. Complexity theories are also dealt with in series issued by World Scientific, Singapore, and in numerous monographs, e.g. by Cambridge University Press. Numerous journals also deal with this topic, e.g. The International Journal; Emergence; Complexity and Organization—an international trans-disciplinary journal of complex social systems. A full list of all these series and journals is beyond the scope of this article, however.

How much the topic of 'Complexity' is interwoven with *systems science* is clearly documented by the quite recently published *Encyclopedia of Complexity and Systems Science* by Springer, Berlin.

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