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Introduction to the Field of Self-Organization

Becoming is the transition from being to nothing and from nothing to being
Georg Wilhelm Friedrich Hegel: Science of Logic

1.1

Basic Concepts

Our world is the result of a long process of evolution that took between 10 and 20 billions of years. Evolution is based on self-organization (SO); this insight we owe to great scientific results of the nineteenth and twentieth century which will be represented and discussed in this book. Our everyday experience and scientific investigations of natural and social processes have taught us that many complex systems have the ability of self-structuring and SO. The most remarkable examples for this statement are the evolution of life and society on our planet in the last 4 billion years. Although this conclusion seems to be obvious, the scientific interpretation of this process is very difficult and requires contributions from virtually all branches of science, including concepts of philosophers such as Hegel, developed already two centuries ago (Figure 1.1). The main aim of this book is to present in a concise form the most important contributions physics may provide to the solution of the conundrum of evolution.

Our key point is the concept of SO. To start with a kind of definition, under SO we understand an irreversible process, that is, a process away from thermodynamic equilibrium which through the cooperative effects of subsystems leads to higher complexity in spatial structures and temporal behavior of the system as a whole. Self-organization is the elementary step of evolution, while evolution consists of many such steps as shown schematically in Figure 1.2.

The importance of SO and evolution for all natural and social processes is quite evident and is subject of scientific investigations at least since the works of Kant, Hegel, Marx, and Darwin. In physics, several problems of evolution were studied first by Helmholtz, Clausius, Boltzmann, Einstein, Friedman, and Gamow. These



Figure 1.1 Memorial to the great philosopher Hegel, 1770–1831, who developed a deep understanding of evolutionary processes, at the Dorotheenstadt cemetery in Berlin. (photo by authors Dec. 2010).

great scientists created the first physical models for the evolution of the Universe. In the last 50 years, we observe the development of a new branch of physics, the physics of SO processes, which is mainly based on the work of Schrödinger, Turing, Prigogine, Eigen, Haken, and Klimontovich. As we mentioned already in the Preface to this book, many scientists from places all over the world, and in particular those in the former socialist countries, studied the new branch of science with great

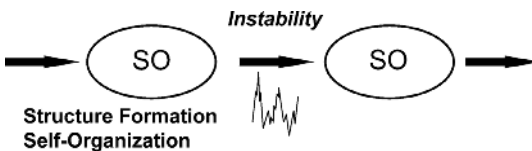


Figure 1.2 Evolution as a sequence of many subsequent SO steps. Each period of SO leads to some structure formation and after its ripening, eventually to an instability that drives the system away from its previous quasiequilibrium state and ultimately leads to another phase of SO.

excitement. The books of the pioneers were printed in large editions, were translated into many languages (see, e.g., Glansdorff and Prigogine, 1971, 1973; Nicolis and Prigogine, 1977, 1979; Haken and Graham, 1971; Haken, 1978) and several popular presentations found a wide public (Prigogine, Nicolis, and Babloyantz, 1972; Nicolis and Portnow, 1973; Ebeling, 1976a, 1979; Haken, 1981; Prigogine, 1980; Nicolis and Prigogine, 1987; Prigogine and Stengers, 1993; Ebeling and Feistel, 1994).

It was in particular the “magic year” of 1971 when the seminal publications on *dissipative structures* (Glansdorff and Prigogine, 1971), *molecular evolution* (Eigen, 1971), and *synergetics* (Haken and Graham, 1971) appeared almost simultaneously and elucidated the physical theory of SO from rather complementary perspectives. Those concepts by themselves represented an innovation, a “critical mutation” in the evolution of physical science; in an accelerated phase of social SO, new working groups were established in universities and research institutes, numerous subsequent articles and books were published, and conferences were held which propagated and amplified the new ideas and theories. The authors of this book were among those who were fascinated and inspired by this new physical picture of the world. The novel “excitation mode” included not only physicists but also mathematicians, chemists, biologists, social scientists, geoscientists, and even philosophers and politicians. Personally, the authors are aware of only one earlier, similar, self-organized development; that was when engineers and mathematicians developed the concepts of cybernetics, self-regulation, automata, learning systems, and roboters (Turing, 1937; Wiener, 1952; Steinbuch, 1961; von Neumann, 1966), which also spread into philosophy (Klaus, 1968) and inspired famous science-fiction authors such as Stanisław Lem, Isaac Asimov, or Karel Čapek, who once coined the term “roboter,” derived from the Slavic word for “worker.” The understanding of nonlinear feedback mechanisms was a key to the later theories of SO.

The summit of this development took perhaps place in the 1970s and 1980s of the last century, immediately before the dramatic social and political turnover in Eastern Europe and in many other parts of the world. The authors of this book had the opportunity to listen to the excellent lectures held by Ilya Prigogine, Hermann Haken, Manfred Eigen, and others in Moscow, Berlin, Halle, and elsewhere. We were much impressed by the excitement of many people, even beyond the field of science, about the ideas of SO. So our statement is that the reception of the ideas of SO contributed to the atmosphere of revolutionary changes that were dawning at the end of the 80s of the last century (see, e.g., Ebeling, 2010). And in fact the events that happened in the eastern societies appeared to be instructive examples for kinetic phase transitions and SO in complex systems, proceeding in real life (Haken, 1981). Critical fluctuations in the society became amplified to macroscopic structures and processes; randomly formed nuclei grew exponentially to mass demonstrations. Previous symmetries with respect to private and public ownership were suddenly broken. With the establishment of the different social structure, similar to Figure 1.2, fluctuations faded away and were finally slaved by the new master variables and dominating dynamical modes.

In this book, our topics are the scientific foundations rather than the social implications of SO. In fact, the theory of SO and evolution is based on many disciplines such as:

- thermodynamics of irreversible processes in open systems,
- nonlinear mechanics, electronics, and laser physics,
- chemical kinetics, far from equilibrium,
- nonlinear population dynamics and theoretical ecology,
- nonlinear systems theory, automata theory, cybernetics,
- theory of information, languages, sequences, complexity,
- probability theory, random noise, statistical methods, and so on.

This list shows already the interdisciplinary character of this field of science. So we may raise the question: What are the chances of physicists to contribute substantially to the science of SO and evolution? Gregoire Nicolis and Ilya Prigogine write in their book (Nicolis and Prigogine, 1977; here translated from the German edition):

In some sense we are in the position of a visitor from another planet who first encounters a house in a suburb and tries to understand its origin and function. Of course the house is not in contradiction to the laws of mechanics, otherwise it would collapse. But this is not the key question; of central interest is the technology available to the constructors, are the needs and requirements of the residents, and so on. The house cannot be understood without the culture in which it is embedded.

In order to develop our basic concepts, let us start with the notions of “elementary” and “complex.” When we want to understand our world as a whole entity, the fundamental question arises: what is the relation between the laws for the elementary aspects and the complex ones? Several reasonable answers on this question are discussed (Simon, 1962; Anderson, 1972). The world outlook of physics relies on laws that physicists consider fundamental. The term fundamental in this context means that these laws cannot be reduced to more basic laws. They are the laws that regulate the attributes and dynamics of elemental particles and fields. Furthermore, they include the laws that formulate even more general rules of exclusion of certain processes, such as the first and second laws of thermodynamics and the Pauli principle. Summarizing we state (see also Ebeling and Feistel, 1994; Ebeling, 2006):

- 1) The fundamental laws of physics cannot be violated; they are valid without restrictions for complex systems as well.
- 2) Complex systems may have emergent attributes, the whole is more than the sum of its parts, and symmetry breaking plays a fundamental role.

The terms “emergent irreducible properties” and “emergent values” play a central role in our concept. As a first irreducible property of physical systems, we understand the *irreversibility of macroscopic processes*. This cannot be deduced in a simple way from the laws of motion of the microscopic constituents (Ruelle,

1993; Hoover, 2001; Lieb and Yngvason, 1999; Ebeling and Sokolov, 2005). As a second fundamental property of macroscopic systems, we understand the ability to show SO under certain conditions. We may define “SO as a process in which individual subunits achieve, through their co-operative interactions, states characterized by new, emergent properties transcending the properties of their constitutive parts.”

Among the points we have to understand are the role of symmetry breaking, of order parameters and phase transitions, of fluctuations and kinetic transitions. Further we have to study the role of different time scales and of slaving of variables in processes of SO. A point of special interest for our picture is the role of *values*, which are indeed among the most relevant emergent properties. In Chapters 6–9 we will discuss the value of a species which means the fitness in the sense of Darwin. We will show that competition is always based on some kind of valuation. This way valuation is a central concept in the theory of evolution and is deeply connected with the origin of life. We will come back to this point at the end of this chapter and in Chapters 6–9.

Another key point is the *origin of information*. As we will see, it is quite easy to measure the amount of information, but it is extremely hard to say something about its value. This is a point which needs a careful discussion. Looking back on our list of key points, we see that it is already quite long and we have a lot of things to discuss.

At the end of this introductory paragraph, let us make the statement that we should not be “overly anthropomorphic” in our views on evolution. Just in order to illustrate this point of view, let us make a longer quotation from a wonderful science fiction book written by the Polish author Stanislaw Lem who spent most of his lifetime in the Polish town Cracow. Lem describes in his science fiction novel what the researcher Giese found on a newly detected planet Solaris:

Giese was an unemotional man, but then in the study of Solaris, emotion is a hindrance to the explorer. Imagination and premature theorizing are positive disadvantages in approaching a planet where – as has become clear – anything is possible. It is almost certain that the unlikely descriptions of the ‘plasmatic’ metamorphoses of the ocean are faithful accounts of the phenomena observed, although these descriptions are unverifiable, since the ocean seldom repeats itself. The freakish character and gigantic scale of these phenomena go too far outside the experience of man to be grasped by anybody observing them for the first time, and who would consider analogous occurrences as ‘sports of nature,’ accidental manifestations of blind forces, if he saw them on a reduced scale, say in a mud-volcano on Earth.

Genius and mediocrity alike are dumbfounded by the teeming diversity of the oceanic formations of Solaris; no man has ever become genuinely conversant with them. Giese was by no means a mediocrity, nor was he a genius. He was a scholarly classifier, the type whose compulsive application to their work utterly divorces them from the pressures of everyday life. Giese devised a plain descriptive terminology, supplemented by terms of his own invention, and although these were inadequate, and sometimes clumsy, it has to be

admitted that no semantic system is as yet available to illustrate the behavior of the ocean. The “tree-mountains,” “extensors,” “fungoids,” “mimoids,” “symmetriads” and “asymmetriads,” “vertebrids” and “agilus” are artificial, linguistically awkward terms, but they do give some impression of Solaris to anyone who has only seen the planet in blurred photographs and incomplete films. The fact is that in spite of his cautious nature the scrupulous Giese more than once jumped to premature conclusions. Even when on their guard, humanbeings inevitably theorize. Giese, who thought himself immune to temptation, decided that the “extensors” came into the category of basic forms. He compared them to accumulations of gigantic waves, similar to the tidal movements of our Terran oceans. In the first edition of his work, we find them originally named as ‘tides.’ This geocentrism might be considered amusing if it did not underline the dilemma in which he found himself.

We hope after this long quotation, our idea is becoming clear now. In order to understand evolution, we need more than just systematics; we need some fresh and unconventional look.

Our guidelines are the ideas of the great pioneers. Among them was, for example, Robert Mayer, who was the first who understood the *Sun as the driving force of the evolution* on our Earth. Further we mention the contributions of Alexander von Humboldt, who was one of the first researchers who took a *global view* on the processes on Earth as well as the contributions of Rudolf Clausius, Hermann von Helmholtz, and Ludwig Boltzmann, who looked first at the Universe from the point of view of physics. The problems about the history of the Universe which these researchers posed were to some extent solved in the twentieth century by other pioneers as Albert Einstein, Alexander Friedman, Edwin Hubble, and George Gamov. These contributions paved the way to the science of SO processes which started as far as we see with Erwin Schrödinger’s (1944) Faustian question “What is life?” and Ilya Prigogine’s (1947) dissertation “Etude thermodynamique des phenomenes irreversibles.”

1.2

History of Evolution as a Short Story

Our Earth is very special and – as far as we are aware – is the only place where life is embedded in the Universe. The Universe is the system of stars and galaxies, so the evolution of the Earth is part of the evolution of the Universe. This book is mainly devoted to the story of the evolution on our planet even though we are not experts in astrophysical theories. Therefore we will only briefly discuss the evolution of the metagalaxy, which provides the general frame for the evolution of our Earth. At present, most experts seem to accept the hypothesis that the evolution of the metagalaxis started with a catastrophic event at about 10–20 billion years ago, which was a kind of explosion, the so-called *Hot Big Bang*. We follow this hypothesis since it seems to explain most, but not all, of the known facts about the Universe surrounding us.

It does not make much sense to ask what was before. Any history has to start with some moment which is given by records, with at least some data beyond speculations. In our case, this is in the first line the red shift interpreted due to an expansion of our cosmos, observed first by Edwin P. Hubble in 1929. The second fact is the so-called background radiation, which was first predicted theoretically in 1946 by George Gamov on the basis of an assumed cosmic expansion, and nearly 20 years later in 1964 observed by Arno Penzias and Robert Wilson. The third fact is given by the relative abundances of protons and neutrons (3:1) and the estimated abundances of the elements, in particular the ratio between hydrogen and helium in the Universe. These three observations as well as other ones are interpreted now as connected with some singular event which happened more than 10 billion years ago. By the way, the experiments with the Large Hadron Collider in CERN and elsewhere are approaching now temperatures of $T \approx 10^{13}$ K and generate extremely dense matter (Aad *et al.*, 2010; Aamodt *et al.*, 2010). This makes it possible to check several predictions of the Big Bang model experimentally in near future.

So let us take the Big Bang event similar to the opening of a box by the ancient Greek women Pandora which, according to the Greek mythology recorded by Homer and Hesiod, was created by Hephaistos, one of the 12 Greek Gods residing in the Olympus. When Pandora opened her box, many sins escaped and only hope remained. In our case, the box of Pandora released a relativistic, optically transparent quantum gas of extremely high density and high temperature which started to expand. Modern researchers do not believe in Greek mythology, but strangely enough they believe in thermodynamics and in relativistic theory. So let us assume following the standard assumption that the relativistic quantum gas observed the relation between temperature T and density ϱ , which is valid for ideal adiabatically expanding gases (another very strong assumption),

$$T \approx \text{const } \varrho^{1/3} \quad (1.1)$$

Since the density varies with some scaling distance $R(t)$ in the form

$$\varrho(t) \approx \text{const } R(t)^{-3} \quad (1.2)$$

we find

$$T \approx \text{const } R(t)^{-1} \quad (1.3)$$

In other words, we expect that the temperature is falling with the reciprocal scaling distance $R(t)$. The solution of Einstein's general relativistic equations for an expanding (radiation) cosmos found by Friedman provides us for the initial stage of some quantum gas of massless particles with the following time dependence (Dautcourt, 1976; Neugebauer, 1980; Zeldovich, 1983; Greene, 2004; Hoynig, 2006):

$$R(t) \sim \sqrt{t}, \quad \varrho(t) \sim \frac{1}{t^2}, \quad T(t) \sim \frac{1}{\sqrt{t}} \quad (1.4)$$

Introducing here some known facts, such as the knowledge that nowadays, after more than 10 billion years, the radiation has a temperature of about 3 K, we find as an

estimate that the temperature decreased since the Big Bang approximately, according to the rule of thumb

$$T(t)[K] \sim \frac{10^{10}}{\sqrt{t[s]}} \quad (1.5)$$

Of course this is a very rough estimate based on several serious assumptions, in particular:

- the whole process is assumed to be adiabatic in the thermodynamic sense and
- the matter in the Universe is ultrarelativistic and radiation-dominated.

Let us briefly sketch now the scenario of what happened after the Big Bang, in the form of a short story consisting of 12 parts (Feistel and Ebeling, 1989; Ebeling, Engel, and Feistel, 1990a). So we divide the cosmic evolution into 12 epochs. The story is about the expansion of matter, which was very hot and dense at the “beginning” and cooled down during the later adiabatic expansion process.

1st Epoch: Physical vacuum and space–time field foam

There is not much known about this early epoch, sometimes called the Planck era, which ends with the formation of what we know as space and time at the so-called Planck time $t \approx 10^{-43}$ s.

In the Higgs-field hypothesis, all elementary interaction forces were still unified and their carrier bosons were massless similar to photons today.

2nd Epoch: Mining the vacuum

The epoch of mining the vacuum is the story about the formation of the primary soup which is a fluid form of matter with a high density and a very high temperature

$$T \approx 10^{32} \text{ K}$$

This period extends up to a time

$$t \approx 10^{-33} \text{ s}$$

At the beginning of this epoch, the Universe expanded extremely rapidly; this expansion was named “inflation.” In the currently widely accepted inflation theory, it is assumed that the early Universe expanded within $\Delta t \approx 10^{-35}$ s by a factor of at least 10^{30} in its diameter, much faster than light (Greene, 2004). Driven by temporarily repulsive gravity, this process is thought of as a sudden phase transition of a subcooled Universe, similar to the explosive growth of a supercritical nucleus, during which fundamental symmetries between elementary particles were broken, the Universe was flattened, and initial quantum fluctuations were frozen in, and gave rise to the presently visible lumpy structure of galaxies and their clusters. The perhaps most convincing observational evidence for this theory is the fact that the angular correlation of temperature fluctuations of the cosmic background radiation that was

measured by the COBE and WMAP satellites has a complicated shape but is perfectly consistent with related theoretical predictions carried out for acoustic oscillations of a dense quantum gas (Smoot, 2006). Thus, the present background radiation appears as a frozen-in image of the dense universe prior to the inflation event.

The primary soup, which was left at the end of the second epoch, consisted of quarks, antiquarks, leptons, photons, and other particles. At the end of the second epoch, the soup had cooled down to

$$T \approx 10^{28} \text{ K}$$

These are the starting conditions for the third epoch.

3rd Epoch: Quark–gluon soup

In this epoch, the Universe is a kind of quark–gluon plasma of high density, perhaps more similar to a “soup” than to a gas. The high temperature supported a state wherein the constituents of atomic nucleons – quarks and gluons – existed unbound. In an experimental effort to recreate such conditions, several researchers collided gold ions using the relativistic heavy ion collider (RHIC) and in recent experiments at CERN using the large hadron collider (LHC) they collide lead ions. The results were analyzed by the two groups – the ALICE collaboration and the ATLAS collaboration. Both groups concluded that the quark–gluon plasma is like a strongly interacting liquid (Aad *et al.*, 2010; Aamodt *et al.*, 2010). However many questions remain still open in this field; further experiments have to be carried out and analyzed. But let us return to our story of the primary soup.

At the end of this third epoch, the soup had cooled down to

$$T \approx 10^{15} \text{ K} \approx 1000 \text{ GeV}$$

The corresponding time is about

$$t \approx 10^{-12} \text{ s}$$

At the characteristic energy of this epoch which is in the order of 1000 GeV, one observes the breaking of the electroweak symmetry, according to the Weinberg-Salam theory. This change of symmetry leads to a change in the composition of matter due to quark annihilation, which leads to the next epoch.

4th Epoch: Quark annihilation

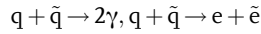
At the beginning of the time interval,

$$10^{-11} \text{ s} < t < 10^{-6} \text{ s}$$

quarks were still dominant in the Universe. However, near the end of this epoch the temperature went down to

$$T \approx 10^{13} \text{ K} \approx 1 \text{ GeV}$$

This corresponds to a particle energy at which the annihilation of quarks becomes possible, including the reactions between quarks and antiquarks



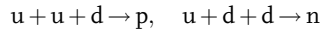
In this epoch, nearly all quarks were annihilated except for a small number of surplus quarks.

5th *Epoch: Formation of a nucleon–lepton–photon plasma*

The time interval

$$10^{-6} \text{ s} < t < 10^{-3} \text{ s}$$

is the epoch of the formation of nucleons. Due to the attracting chromodynamic forces between the quarks, the remaining quarks could form nucleons – either protons or neutrons



Beside nucleons, in the fifth epoch, the metagalaxy was filled with electrons, positrons, photons, and neutrinos. Due to further cooling down according to $T \propto 1/\sqrt{t}$, the temperature was about 30 MeV at the end of the fifth epoch.

6th *Epoch: Neutrino decoupling*

We consider now the time interval

$$10^{-3} \text{ s} < t < 1 \text{ s}$$

Due to further expansion and decrease in temperatures, the mass density and the temperature approached the values

$$\rho \sim 10^8 \text{ g/cm}^3; \quad T \sim 10^{10} \text{ K}$$

At such conditions, the neutrinos became uncoupled from the other particles. As we know from many experiments, in the dense matter on our Earth neutrinos have very large mean free pathways and may fly over very large distances. This started already in the sixth epoch; this was the source of an ocean of neutrinos which are filling our Universe.

7th *Epoch: Breaking the neutron–proton symmetry*

The age of the Universe is now already about 1 s and the temperature around 1 MeV corresponding to $T \sim 10^{10}$ K. So far the number of protons and neutrons was nearly equal. However, due to temperatures below 1 MeV, from now on a certain part of the neutrons changed into protons which have a smaller mass. Finally the relative abundances were 75% for the protons and 25% for the neutrons. These are the abundances of protons and neutrons which we observe today, and this is one of the correct predictions of the Big Bang model.

8th *Epoch: Synthesis of helium and other nuclei, fixation of element abundances*

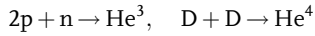
We speak now about the time interval

$$10^2 \text{ s} < t < 10^4 \text{ s}$$

and temperatures approaching

$$T \approx 10^9 \text{ K} \approx 100 \text{ eV}$$

Then the following reactions become possible:



The abundances of the chemical elements became fixed due to the insufficient plasma temperature for other nuclear fusion reactions. Note that the heavier elements beyond helium, which we find now on Earth, were formed only in later epochs.

9th *Epoch: Atom formation and photon decoupling*

Together with electrons, protons, and nuclei of He produced in the previous epoch then formed a typical highly ionized plasma, which is intransparent for photons. So, in this phase photons had a rather short mean free path. However, when the temperature was further lowered to $T \approx 10,000\text{--}100,000 \text{ K} < 1 \text{ eV}$, the formation of H atoms and He atoms became possible. When the temperature approached 1000 K, nearly all electrons were caught by nuclei and atoms formed a neutral gas. Since neutral gases are transparent for light, we observe from now on a decoupling of the photon gas from the heavy matter. This resulted in an independent evolution of the two subsystems – heavy matter and the ocean of radiation. In the forthcoming phase, the radiation was further cooling down. Due to the low density of the gas and the long free path, some of the photons were able to travel for long times and over extremely large distances without significant scattering events. Further cooling down independently of the heavy matter, at the end the photons reached the level of 2.7 K observed today and formed the ocean of background radiation discovered by Penzias and Wilson. The story of heavy matter was much more complicated and requires the opening of a new chapter of our story.

10th *Epoch: Self-structuring of heavy matter*

About a million years after the Big Bang, the metagalaxy consisted of three extended and nearly independent subsystems:

- 1) the neutrino ocean,
- 2) the photon ocean, and
- 3) the system of heavy matter.

It is impossible to describe here in detail the complicated processes which led to the basic structures which are the constituents of our metagalaxy, the formation of stars and planets. The self-structuring of heavy matter and the formation of stars and planets is based on the action of gravitational forces. Starting from an initially uniform gas of hydrogen and helium atoms with a temperature below 1000 K, due to the attractive character of gravity, clusters of matter were formed. This way the homogeneity and isotropy of the distribution of heavy matter was lost. The new symmetry breaking is due to gravitational instabilities which tend to form condensed droplets of matter, similar to what we know from van der Waals gases. In the cosmos, the long-range gravitational

forces between massive objects take over the role of the attractive short-range van der Waals forces between molecules. The dense droplets of heavy matter are heated up again due to an adiabatic compression caused by the gravitational forces (van Dokkum, 2011). In the interior of very dense clusters of matter, nuclear fusion was ignited again. Stars were born which started to radiate with a surface temperature of about

$$T \approx 10^4 \text{ K}$$

Some of the stars were accompanied by smaller clusters, the planets with surface temperatures

$$T \approx 10^2 - 10^3 \text{ K}$$

This two-temperature system was imbedded into the big sea of background photons with a temperature now below

$$T \approx 10 \text{ K}$$

Between the three systems of different temperatures in the metagalaxy, a new mechanism comes into action which works like a Carnot machine and is driving from now on the process of evolution.

11th Epoch: *The photon mill*

The so-called photon mill is the most important mechanism responsible for the SO of the terrestrial (and may be other) biosystems. The idea demonstrated in Figure 1.3 is that the steady flow of photons from the

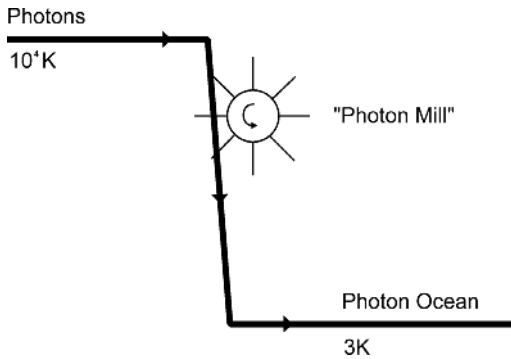


Figure 1.3 The steady photon flow from the temperature level of $T \sim 10,000 \text{ K}$ corresponding to the surface of stars, possibly passing through an intermediate station on

planets and ending finally at the level $T \sim 3 \text{ K}$ corresponding to cosmic background radiation, is the driving force for the terrestrial evolution.

temperature level $T \sim 10,000$ K, corresponding to the surface of stars, passing through a possible intermediate station on planets with $T \sim 100\text{--}1000$ K, and finally ending at the thermal level of the sea of cosmic background radiation, is the thermodynamic driving force of evolution. We will come back to this fundamental mechanism several times in this book.

12th Epoch: Self-organization on Earth

Above we have given a short story sketching the complicated processes which led to the basic structures which are the constituents of our meta-galaxy, the formation of stars and planets. We are interested here mainly in what happened on the particular planet Earth which was formed about 4–5 billion years ago. The first process of SO that occurred on our planet was the formation of geological structures. From the thermodynamic point of view, the driving force responsible for the formation of geological structures in the crust is based on the flow of heat coming from the hot interior of the Earth and flowing outward. This process occurs on a very long time scale. In the atmosphere, we have a more complicated interplay between heat flows from the interior and radiation flows from the surrounding, giving rise to structures such as climate and weather. The driving flows of heat are demonstrated in Figure 1.4. It will be discussed in detail in Chapter 3. The physical effects which finally led to the evolution of the Earth's crust and to geological structures also influence the climatic processes by hydrodynamic instabilities such as the Benard and Marangoni instabilities (Nepomnyashchy, Velarde, and Colinet, 2002), as will be discussed later.

The third and most complicated process of SO on Earth is the evolution of biological organisms. The processes which eventually led to the evolution of life on Earth are in the first line driven by the photon mill shown in Figure 1.3 but are also strongly influenced by geological and climatic factors. To model some of these processes, which are understood only in part so far, is the main topic of this book.

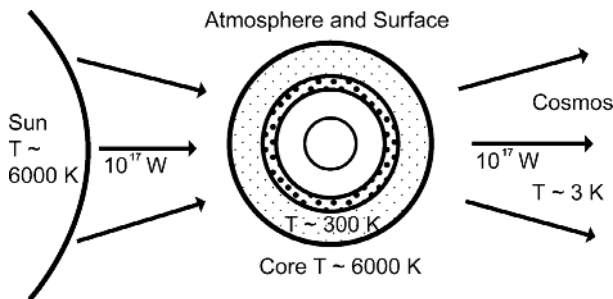


Figure 1.4 The evolution of geological structures is driven by a second mechanism connected with the flow of heat from the interior of the Earth to the surface crust, and from there to the atmosphere and to the ocean of cosmic background radiation, as will be discussed in detail in Chapter 3.

1.3

Structure, Self-organization, and Complexity

As a result of the SO in the 12th epoch of the evolution of the universe, many structures of different kinds were formed. Taking for a moment a more formal view, in some respect all the structures in nature and in society around us are relations between elements. In nature we study atoms made of electrons and nuclei, gases, liquids, and solid states made of atoms, and biological beings that are complex entities made of many atoms or molecules. The relations between objects in the realm of life, that is, biological or social objects, are more complicated; their relations may be characterized with the term “networks,” at least on the formal side. In order to deal with evolutionary processes, we have to go beyond physics and study more general types of structures. Typically, biological, ecological, and social networks consist of many ties, connections, group attachments, meetings, and other events or activities that relate one individual to another. From the abstract point of view, bioecological and socioeconomic networks are also “structures.” As we will describe later in detail, it is possible to give an abstract presentation of such structures by means of mathematical tools. The mathematical idea of structure stands in close relation to the terms *element, set, relation, and operation*.

In this context, the particular nature of the elements does not play any role with respect to the structure model. In contrast, the nature of the relations between the elements determines the specificity of a structure. In that sense, structure means the manifold of interactions between the elements. In the most general context, we speak about SO if the structures formed out by the elements are not determined by external influences but by the internal interactions and relations. As we will show later, there is a deep difference between SO in equilibrium and in nonequilibrium systems.

In other contexts, the nature of the elements is relevant. So, in the general case, the nature of the elements and of the relations is relevant. Later we will see that another essential factor is the dynamics of the elements, which may lead to even more complicated structures, to real complexity. So far, we follow first a more abstract and general approach. By using such a general level, we create methodologically the opportunity of respecifying the definition of both the elements and the relations for any application area one might think of.

The abstract idea of a “structure” is of great importance in our life – both in reality and in science. This is particularly obvious when social structures are analyzed. What does “structure” mean in the original sense? On the one hand, we have our conventional understanding of structure – understanding of structure in our real life. Alternatively, we may formulate a precise structure model in terms of mathematics, in system theory, and in the structural part of the theory of SO (Laue, 1970; Görke, 1970; Casti, 1979; Ebeling, Freund, and Schweitzer, 1998; Helbing, Herrmann, and Schreckenberg, 2000; Pyka and Küppers, 2002; Pyka and Scharnhorst, 2009):

Under a structure we understand the composition of elements and the set of relations respectively operations which connect the elements.

The German philosopher, Kröber (1967), writes about the idea of structure in real systems:

Each system consists of elements that are arranged in a certain way and are linked to each other by relations. We understand by the “structure of a system” the kind of arrangement and connections of their elements . . . Of what kind the elements are we do not consider in this respect. If we speak about structure, we are not interested in the elements of the structure. We only consider the manifold of relations. In this respect the structure of a system is a well-defined connection between the elements of the system. These elements, which are arranged in a determined manner and connected by determined connections can be necessary or random, universal or unique, relevant or irrelevant.

With the famous book *The Elements of Mathematics*, the scientists group Bourbaki gives an example for systematically constructing mathematics as the science of such “structures.” In the following section, we will give a short description of important concepts of the mathematical theory of structures. Especially we will give a summary of the theory of relations, graphs, and matrices to the extent we need it here, with the purpose to apply this abstract theory to socioeconomic networks. In ecological and in socioeconomic systems, the elements of structure are individuals or groups of individuals in different institutional and organizational forms. The socioeconomic connections between these elements are relations in the sense of this abstract theory of structure. Their description can be given graphically by a system of vertices, which model the elements (individuals, groups, firms) and of edges, which describe the relations (connections). Vertices and edges can be weighted. Edges can have a direction. This way we can include quantitative aspects. The decisive aspect of SO of networks is the formation of new connections, which generate new structures. In the following, we want to show that the instruments of the mathematical theory of structure in connection with the ideas and concepts of the theory of SO can contribute to the description of the connections of different groups of the complex socioeconomic network of the global world.

Socioeconomic systems are complex systems which on the one side consist of many connections between the elements. Therefore complexity is an additional idea to be defined. Together with Freund and Schweitzer, one of the authors proposed the definition (Ebeling, Freund, and Schweitzer, 1998):

As complex we describe holistic structures consisting of many components, which are connected by many (hierarchically ordered) relations respectively operations.

The complexity of a structure can be seen in the number of equal respectively distinct elements, in the number of equal respectively distinct relations and operations, as well as in the number of hierarchical levels. In the stricter sense, complexity requires that the number of elements becomes very large (infinite).

Here we are especially interested in the origin of complex structures. We are interested in the development of order (information) for the corresponding basic

situation. At the end, we have to answer the question which parameter relations (order parameters) determine the qualitative behavior of the system. As already mentioned, pioneering work in the investigation of self-organizing systems was done by Ilya Prigogine and his coworkers (1970, 1977). Further important work in this field has been done by Eigen (1971) and together with Peter Schuster (Eigen and Schuster, 1977, 1978) by developing the hypercycle model. The mechanism of SO is clearly worked out by Prigogine. He also gives a stringent physical and mathematical formulation for these processes, in particular with respect to the energetic and entropic aspects. The investigation of such systems shows that the formation of order in complex systems can be associated with physical processes that occur far away from equilibrium conditions (Ebeling and Feistel, 1982). We underline that biological processes, just as socioeconomic processes, can be investigated with the help of the theory of SO because they obey the valid physical and chemical laws. However, processes which include real life (biological and socioeconomic systems) also obey additional rules and laws that are not determined by physics alone. This is evident already from the very general character of the structures we consider here. As discussed above, we formulate the idea of structure mathematically and refrain from the subjective side of this idea. As mentioned before, we need an abstraction in order to describe real systems with the help of graph theory. This will be explained later in more detail in Section 4.4.

By formulating our ideas in a mathematical language, we have the advantage to have access to the vast potential of formal tools and methods available in this field. An important basic approach is to generally start from the theory of sets. As pointed out above, the connection between element and set is the first and most important aspect of a structure. Furthermore we introduce relations and operations. This idea of structure reflects abstract properties of a system. Due to the abstract character, most of the ideas and results can be translated to other systems and comparisons are possible. In general, we distinguish between spatial, temporal, causal, and functional structures.

To illustrate the structures, we will use graphs which represent the elements and their connections by geometrical symbols (Harary, Norman, and Cartwright, 1965; Laue, 1970; Gardner and Ahsby, 1970; Casti, 1979; Ebeling and Feistel, 1982; Jain and Krishna, 2003; Hartmann-Sonntag, Scharnhorst, and Ebeling, 2009). Just to give an example of a complex network, we present an economic network with four levels in Figure 1.5. This graph represents the flow of materials and outcomes in a production process. The economic picture just serves as a schematic example; in later sections we will discuss mostly examples from biology and ecology.

As our example nicely shows, in economics the relations between economic agents, in particular the flow of commodities, can be represented in a network form. Similarly, information flows, for example, price signals between market participants, are exchanged. The structure of the network then describes a situation with local interaction (not every agent is informed about all other agents but the agents do not act isolatedly either) (Pyka and Scharnhorst, 2009). Socioeconomic networks can also describe a variety of different actions of agents that influence other agents (Saviotti, 1996; Saviotti and Mani, 1995; Saviotti and Nooteboom, 2000). The diffusion of

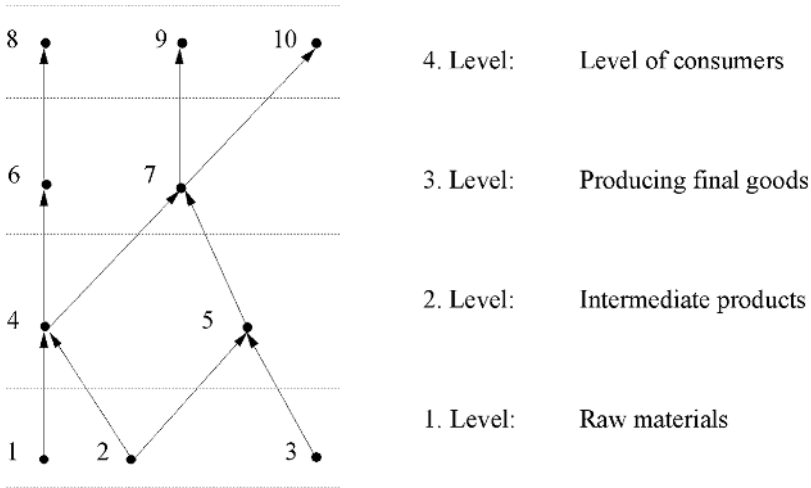


Figure 1.5 Schematic graph of a socioeconomic network with four levels: (1) raw material such as airts, fossils, plants, and so on; (2) intermediate products such as steel, coal, corn, and so on; (3) producing final goods; and (4) level of consumers.

technologies over firms can be described as a network of actions from the formation of a company (with a certain technology) over knowledge transfer between companies (in form of imitation or merging) to the exit of companies due to technological competition. We will come back to such a network interpretation in later sections for examples taken from chemistry, biology, ecology, and economy. We are especially interested here in the origin of complex structures, and in the development of order (information). In the end, we have to answer the question which parameter relations (order parameters) determine the qualitative behavior of the system.

1.4

Entropy, Equilibrium, and Nonequilibrium

Entropy is one of the central terms of this book. This term plays a central role in the modern science of our days. Its significance reaches from physics to probability theory, the theory of information, computer science, economics, psychology, just to give a few examples. What does entropy mean? If we consult Wikipedia first, we read there: “In physics, entropy, symbolized by S , from the Greek μετατροπή (metatropi) meaning ‘transformation’, is a measure of the unavailability of a system’s energy to do work.” We consider this as a good and quite useful definition. However, this is not the only way to define entropy. There exist now many publications on the topic of entropy; there is a special journal *Entropy* and on the Internet one may follow an ongoing and never-ending discussion on what entropy actually is. Entropy is something that has a Janus face; one can look at it from many perspectives and it might always look quite different. The term entropy was coined in 1865 by

Rudolf Clausius (1865) who played the most important role in the history of the two fundamental laws of thermodynamics. On page 390 of his seminal paper, he wrote:

*Sucht man für S einen bezeichnenden Namen, so könnte man, ähnlich wie von der Größe U gesagt ist, sie sey der Wärme- und Werkinhalt des Körpers, von der Größe S sagen, sie sey der Verwandlungsinhalt des Körpers. Da ich es aber für besser halte, die Namen derartiger für die Wissenschaft wichtiger Größen aus den alten Sprachen zu entnehmen, damit sie unverändert in allen Sprachen angewandt werden können, so schlage ich vor, die Größe S nach dem griechischen Wort $\eta \tau\rho\sigma\pi\eta$, die Verwandlung, die **Entropie** des Körpers zu nennen. Das Wort Entropie habe ich absichtlich dem Worte **Energie** möglichst ähnlich gebildet, denn die beiden Größen, welche durch diese Worte benannt werden sollen, sind ihrer physikalischen Bedeutungen nach einander so verwandt, dass eine gewisse Gleichartigkeit in der Benennung mir zweckmäßig zu seyn scheint.*

(In English: If one looks for a term to denote S , one could, similar to what is said about the quantity U that it is the heat and work content of the body, say about the quantity S that it is the transformation content of the body. Since I prefer to borrow the name for quantities so important for science from the old languages to permit their unaltered use in all languages, I suggest to name the quantity S the *entropy* of the body, after the Greek word $\eta \tau\rho\sigma\pi\eta$, the transformation. Intentionally I have formed the word *entropy* as similar as possible to the word *energy* because the two quantities denoted by those words are so closely related with respect to their physical meaning that a certain similarity in their nomenclature appears appropriate to me.)

Let us continue with a few additional historical remarks about the work of Clausius and the history of the second law (Ebeling, 2008). After studying physics in Berlin, Clausius taught for some years as a teacher at the Friedrich-Werdersches Gymnasium in Berlin and was a member of the seminar of Professor Magnus at the Berlin University. When at this time Clausius' fellow Hermann Helmholtz published his work about the first law, Professor Magnus asked Clausius to give a report about the essential news in that work. We do not know why Magnus asked Clausius rather than Helmholtz directly. Anyhow, this was a very good idea, since the extremely careful Clausius began with the roots of that science. More precisely, he studied first the nearly forgotten works of Clapeyron and Carnot. This way Clausius was able to find the link between Carnot and Helmholtz and could proceed to a higher level. Clausius' report on Helmholtz's fundamental work, given at Magnus' colloquium, was the beginning of a deep involvement with thermodynamical problems.

Building on the work of Helmholtz and Carnot, Rudolf Clausius developed, and published 1850 in Poggendorff's *Annalen*, a completely new law, the second law of thermodynamics. Clausius was fully aware of the impact of his discovery. The title of his paper explicitly mentions "laws." His formulation of the second law, the first of several later formulations, that *heat cannot pass spontaneously from a cooler to a hotter body* is expressing its essence already very clearly. Unlike Carnot and following Joule,

Clausius interpreted the transfer of heat as the transformation of different kinds of energy, in which the total energy is conserved. To generate work, heat must be transferred from a reservoir at a high temperature to one at a lower temperature. Clausius introduced here the concept of an ideal cycle of a reversible heat engine. In 1851, William Thomson (Lord Kelvin) formulated independently of Clausius another version of the second law. Thomson stated that it is impossible to create work by merely cooling down a thermal reservoir. The central idea in the papers of Clausius and Thomson was an exclusion principle: “Not all processes which are possible according to the law of the conservation of energy can be realized in nature.” In other words, the second law of thermodynamics is a selection principle of nature. Although it took some time before Clausius’ and Thomson’s work was fully acknowledged, it was fundamental for the further development of physics, and in particular for the science of SO. In later works, Clausius arrived at more general formulations of the second law. The form valid today was reported by him at a meeting of the “Züricher Naturforschende Versammlung” in 1865. There, for the very first time, he used the term “entropy” and introduced the quotient of the quantity of heat absorbed by a body and the temperature of the body as the change of entropy. We will discuss the details of the thermodynamics theory in Chapter 2 but give already here a preliminary version of the two basic laws of thermodynamics.

First Law of Thermodynamics: There exists a fundamental extensive thermodynamic variable, the energy E . Energy can neither be created nor be destroyed. It can only be transferred or transformed. Energy is conserved in isolated systems.

Here, *extensive* means that the energy of a system is the sum of the partial energies of arbitrary subdivisions of that system. The energy production inside a system is zero. Any process is connected with a transfer or with a transformation of energy. Energy transfer may have different forms such as heat and work, and possibly chemical energy. This is expressed by the formulae

$$dE = d_e E + d_i E \quad (1.6)$$

where the internal change is

$$d_i E = 0 \quad (1.7)$$

and the exchange part is

$$d_e E = d'Q + d'A \quad (1.8)$$

Here we introduced an infinitesimal heat transfer $d'Q$ and an infinitesimal work transfer by $d'A$. The infinitesimal change of energy of a system equals the sum of the infinitesimal transfers of heat and work. The basic SI unit of energy is $1 \text{ J} = 1 \text{ N m}$, corresponding to the work needed to move a body 1 m against a force of 1 N.

Work may be expressed in terms of a bilinear form, in the simplest case just by $(-p dV)$, that is, pressure multiplied with change of volume. The hypothesis that the infinitesimal heat can also be expressed in a bilinear form led Clausius to the entropy

concept. He assumed that $d'Q$ may be written as the product of an intensive quantity and an extensive quantity. *Intensive* quantities are those which take equal values for arbitrary subdivisions of a given homogeneous system. The only intensive quantity which is related to heat is temperature T , and the related conjugate extensive quantity Clausius denoted by S . This way he introduced entropy as an extensive quantity that is conjugate to the temperature, $d'Q = TdS$. This equation may alternatively be written by division by the temperature; this takes us back to our first equation which was invented by Clausius:

$$dS = \frac{d'Q}{T} \quad (1.9)$$

This says the differential of the state variable entropy is given by the infinitesimal heat, $d'Q$, divided by the temperature T . In more mathematical terms we may say, the temperature T is an *integrating factor* of the infinitesimal heat. To make more transparent what this means, we write the first law, Equation 1.6, in the form of a *Pfaffian differential equation*

$$d'Q = dE + p dV \quad (1.10)$$

In general, no smooth mathematical function “heat,” $Q(E, V)$, exists as an integral of Equation 1.10 with the properties $\partial Q/\partial E = 1$, $\partial Q/\partial V = p(E, V)$ for any given function $p(E, V)$. It is known that for Pfaffian forms of two independent variables such as Equation 1.10, there exists always a function, $\beta(E, V)$, termed the integrating factor, such that Equation 1.10 turns integrable after multiplication with β , and that the infinitesimal quantity $\beta \times d'Q$ is an exact differential (Stepanow, 1982). Clausius could prove that the reciprocal temperature, $1/T(E, V)$, is such a factor, Equation 1.9, and that a function $S(E, V)$ exists which satisfies the two equations

$$\frac{\partial S}{\partial E} = \frac{1}{T}, \quad \frac{\partial S}{\partial V} = \frac{p}{T} \quad (1.11)$$

For clarity, we must add that Equations 1.9 and 1.11 are strictly true only for reversible processes; in that case the change of entropy, dS , in the system equals the flux of entropy through the boundary, as explained below. The basic SI unit of entropy is 1 J/K. One can easily see that entropy is in general not conservative, that is, Equation 1.9 is only a special case rather than being universally valid. Let us consider for example two bodies of different temperatures being in contact. Empirically we know that there will be a heat flow from the hotter body to the cooler one. When the heat flows down a gradient of temperature, it produces entropy. The opposite flow against a gradient of temperature is never observed. A generalization of this observation leads us to the following formulation of the second law:

Second Law of Thermodynamics: Thermodynamic systems possess an extensive state variable termed entropy. Entropy can be produced, but never destroyed. The change of entropy in reversible processes is given by the exchanged heat divided by

the temperature, Equation 1.9. During irreversible processes, entropy is produced in the interior of the system. In isolated systems entropy can never decrease.

We only mention here the deep relation between irreversibility and chaos (Schuster, 1984, 1995; Ruelle, 1993; Lanius, 1994a, 1994b; Lieb and Yngvason, 1999; Landa, 2001).

By splitting the entropy change into a part due to exchange and a part due to internal production, we arrive at the following mathematical formulation of the second law (details will be explained in Chapter 2)

$$dS = d_e S + d_i S \quad (1.12)$$

where the internal production part cannot be negative:

$$d_i S \geq 0 \quad (1.13)$$

and the exchange part is related to the heat transfer, (1.9),

$$d_e S = \frac{d'Q}{T} \quad (1.14)$$

or to other forms of entropy fluxes.

The next step in understanding the role of entropy is connected with the work of Ludwig Boltzmann and Max Planck. Both these great scientists were fascinated by the entropy concept. Ludwig Boltzmann found first a connection between entropy and the distribution function of molecules in a gas. Max Planck, who originally was not an enthusiast of the atomistic view, became also interested in the statistical foundations of entropy at the end of the nineteenth century. In fact, he was the first who introduced the “Boltzmann constant” when he explicitly wrote down the famous formula

$$S = k_B \log W \quad (1.15)$$

which connects the entropy with the number of microscopic states W that are consistent with a given macroscopic state (Klimontovich, 1982). This way it became clear that entropy is not only a thermodynamic quantity, but it is also related to the probability of states, and is a measure of disorder. Disordered states have the highest probability: thermodynamic equilibrium corresponds to states of maximum disorder (Figure 1.6). Entropy is like the head of Janus; there is still another meaning of entropy, which later has to be discussed: according to Hartley and Shannon, entropy is (up to a constant) a measure of information corresponding to the uncertainty removed by exploring the actual state of the system (Shannon, 1951; Jaglom and Jaglom, 1984; Hoover, 2001).

Following the great pioneers, we consider here *entropy* as the central statistical concept: entropy is a measure of uncertainty of the microscopic state. Later we will see that there is also a fundamental connection to the ideas of dynamic instability: in particular we will explain in Chapter 4 that the instability of the microscopic trajectories generates uncertainty of the thermodynamic state, that is, of entropy and of other macroscopic properties.

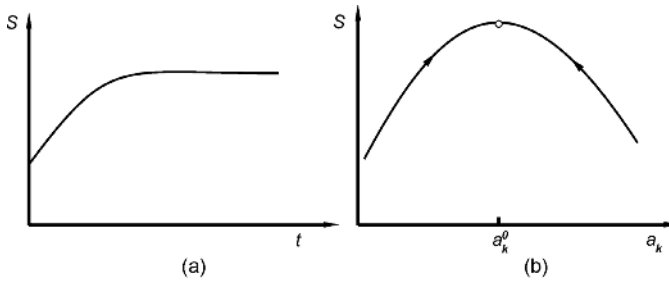


Figure 1.6 The tendency of entropy to approach the state of the highest entropy, corresponding to thermodynamic equilibrium and maximum disorder. (a) Entropy increases as a function of time. (b) Entropy as a function of parameters; the state with maximum entropy corresponds to equilibrium.

From our new point of view, structures may be classified into the two large categories of *equilibrium structures* and *nonequilibrium structures* (Klimontovich, 1982, 1991, 1995).

The theory of SO shows how the emergence of structures is associated with a decrease in entropy (Glansdorff and Prigogine, 1971; Nicolis and Prigogine, 1978; Ebeling and Feistel, 1982). The concept of “structure” is closely related to the term *information (entropy)*. Information is already a more difficult problem which we will discuss later (Ebeling, Freund, and Schweitzer, 1998). Now we are going to explain several of these aspects in more detail.

In order to prepare states which (at given energy) have an entropy lower than the entropy of the equilibrium (which is maximal in comparison to all other states of the system at the same energy),

$$S(E, X) < S_{\text{eq}}(E, X) \tag{1.16}$$

we need boundary conditions which permit a lowering of the entropy. Let us split the entropy change into two parts – the external change and the change due to internal irreversible processes, (1.12),

$$dS = d_e S + d_i S \tag{1.17}$$

The second law requires that the second term is always positive or zero. This implies that in order to have an increase in order by decrease of entropy, we need to export entropy

$$dS = d_e S + d_i S < 0 \tag{1.18}$$

This is the thermodynamic condition for SO. To express this condition in a different way, we have to satisfy the inequality

$$-d_e S > d_i S > 0 \tag{1.19}$$

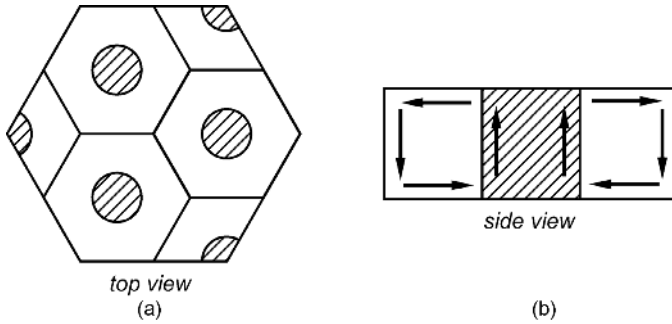


Figure 1.7 Benard cells in a liquid layer heated from below. (a) View at a Benard system from above; the shaded parts show the upwelling regions, the blank parts show the downwelling regions. (b) Vertical cross section showing one cell with ascending liquid in the center.

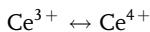
In other words, to lower the system's entropy we have to export more entropy than is produced by internal irreversible processes. Let us consider several examples. First we consider a liquid layer in a gravity field heated from below. Let T_1, T_2 be the temperatures below and above, respectively, and Q be the heat flow per unit of the surface and per unit time. Naturally we have $T_1 > T_2$ and therefore for the entropy production,

$$-\frac{d_e S}{dt} > \frac{d_i S}{dt} = \frac{Q}{T_2} - \frac{Q}{T_1} > 0 \quad (1.20)$$

We have shown above that the entropy export in a Benard system is positive. This means SO is possible. However, our criterion is only a necessary rather than a sufficient condition. The experiment displayed in Figure 1.7 shows that beyond some critical value of the temperature difference, the liquid starts to organize itself; it forms roll cells (Ebeling, 1976a, 1978a; Nepomnyashchy, Velarde, and Colinet, 2002). Self-structuring due to thermal convection is the most important form of dissipative structures in geophysics (see Chapter 3).

As another example from chemistry, we show a photograph of the Belousov–Zhabotinsky reaction, one of the classical examples of SO (Agladse *et al.*, 1989; Linde and Zirkel, 1991; Linde and Engel, 1991), see Figure 1.8.

The Belousov–Zhabotinsky reaction is a rather complex redox reaction with the central part



which occurs in the presence of sulfuric acid, malonic acid, and potassium bromate (Agladse *et al.*, 1989; Linde and Zirkel, 1991). In the presence of a redox indicator (here, ferroin), the reaction can be visualized by observation of the color (red means more $3+$ ions and blue means the $4+$ ions dominate).

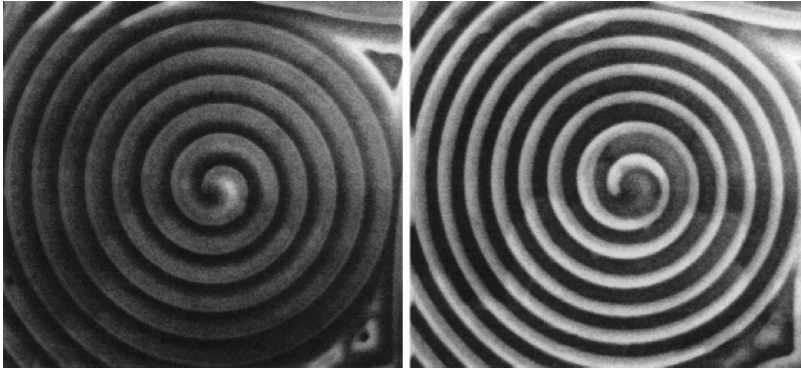


Figure 1.8 Snapshots of a Belousov–Zhabotinsky reaction showing spiral structures. (courtesy of Hartmut Linde).

As a final example for a structure formation due to SO, we show in Figures 1.9 and 1.10 the flow structure at an interface due to Marangoni effects (Linde, Schwarz, and Gröger, 1967; Nepomnyashchy, Velarde, and Colinet, 2002; Bestehorn, 2006).

Solitons are an example for localized structures, in our example moving fronts, which are relatively stable against perturbations, collisions, and so on (Nepomnyashchy, Velarde, and Colinet, 2002).

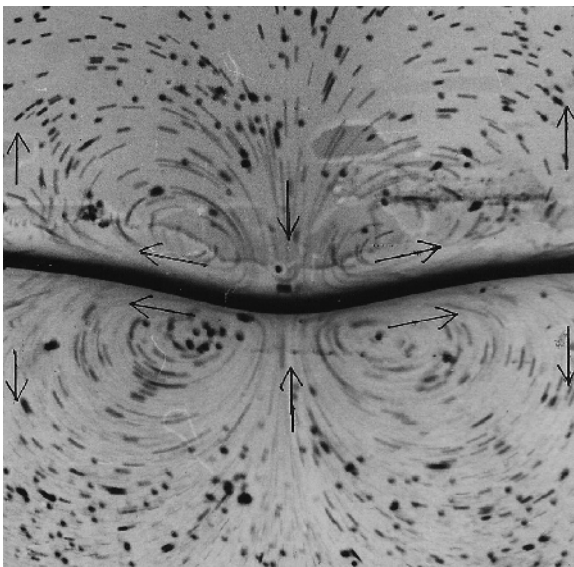


Figure 1.9 Structure formation (roll cells) at an interface due to the Marangoni instability. The arrows show the directions of the hydrodynamic flows. (courtesy of Hartmut Linde).

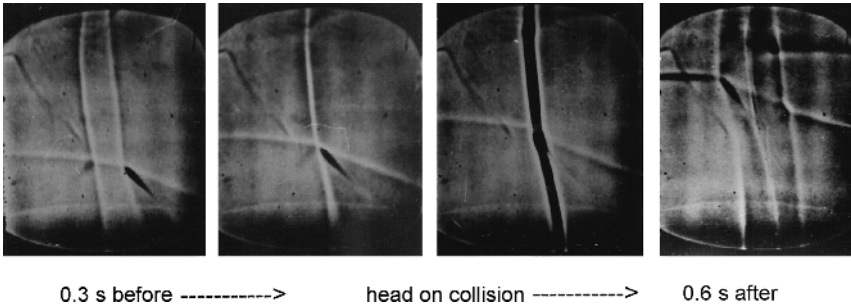


Figure 1.10 Soliton structures including collisions which are due to the Marangoni effect at an interface. (courtesy of Hartmut Linde).

1.5 Dynamics, Stability, and Instability

In the previous section, we demonstrated several examples for the dynamics of SO. Here we will explain in brief several concepts which are basic for the approach of physicists to the theoretical modeling of SO phenomena. More details and applications will be discussed later and the formal part will be developed in particular in Chapter 4. At first we introduce the notion of state space, dynamical models, and trajectories. In fact this is a view going back to the great pioneers of modern science Nicolaus Copernicus (1471–1543), Galileo Galilei (1564–1642), Johannes Kepler (1571–1630), and Isaak Newton (1643–1727). In the sixteenth and seventeenth century, these pioneers developed the idea of orbits for the description of planets which follow some rules or laws; in particular, they could show that the motion of all bodies is determined by gravitational forces. The very essence of this view appears in Newton's law in the form of differential equations. In the modern version which was basically formed by the pioneers of theoretical mechanics, Lagrange, Jacobi, and Hamilton, the geometrical description of all mechanical motions was developed as an extremely elegant mathematical tool. This beautiful theoretical construction was completed by Poincaré (1854–1912) by introducing the ideas of stability and instability of trajectories and by Helmholtz and Rayleigh by introducing the idea of self-sustained motions. All these ideas played an important role for the later concepts of SO which will be explained in detail in this book. Here we will briefly consider several formal aspects, notions, and mathematical tools, along with several physical concepts which led to the modern nonlinear dynamics on which the understanding of SO and evolution is grounded.

One can say that the geometrical interpretation of the trajectories of a dynamical system as orbits in an appropriate state space (phase space) appears to be one of the most important instruments for the investigation of dynamical processes. In fact, these concepts go back to the classical mechanics. Generalizing the concepts of mechanics, Poincaré, Lyapunov, Barkhausen, Duffing, van der Pol, Andronov, Witt, Chaikin, Birkhoff, Hopf, and others laid the basis for the modern theory of dynamical

systems (Eckmann and Ruelle, 1985). Parallel research was started in the biosciences by Lotka, Volterra, Rashevsky, and others. In the second half of the last century, dynamical systems theory was developed quite independently of physics and biosciences and found applications in most branches of science. In particular, the theory of dynamical systems is also the heart of the science of synergetics founded by Haken starting from laser physics (Haken, 1970, 1978, 1981, 1988) and the theory of SO developed by Prigogine, Glansdorff, and Nicolis, mostly backing on the concepts of irreversible thermodynamics (Glansdorff and Prigogine, 1971; Nicolis and Prigogine, 1977).

We will merely touch the surface here and will discuss only a few basic notions and examples. Let us consider a dynamical system, assuming that its state at the time t is given by a set of time-dependent parameters (coordinates). We consider this set as a vector and write

$$\mathbf{x}(t) = [x(t_1), x(t_2), \dots, x(t_n)]$$

The set of state vectors, $\mathbf{x}(t)$, spans a vector space, \mathbf{X} , which will be termed the *state space* or phase space of the system. Let us assume now that the state at a time t_0 , given by $\mathbf{x}(t_0)$, and the state at a later time $t > t_0$, given by $\mathbf{x}(t)$, are connected in a causal way. We assume that the current state is a function or a more general mapping of the initial state and certain additional parameters which we denote by the vector

$$\mathbf{u}(t) = [u_1, u_2, \dots, u_m]$$

The set of all possible parameter values \mathbf{u} forms the *control space* of the system. The parameters \mathbf{u} take into account the influence of the environment and possibly also actions of external control. We assume that the connection is given by a map \mathbf{T} ,

$$\mathbf{x}(t) = \mathbf{T}(\mathbf{x}(t_0), \mathbf{u}, t - t_0) \quad (1.21)$$

The set $\{\mathbf{X}, \mathbf{T}\}$ is referred to as the *dynamical model* of the system (Anishchenko *et al.*, 2002; Landa, 2001; Ebeling and Sokolov, 2005). The choice of the phase space is not unique; there are many possibilities to make a choice for the phase space, depending on the model's details and convenience of representation. The existence of a dynamical map, \mathbf{T} , which defines the state at the time t , by means of the state at an earlier time, expresses the causality of the dynamical process under consideration. In the real world, we observe two different cases of causal relations between $\mathbf{x}(t_0)$ and $\mathbf{x}(t)$. If the relation between the two quantities is unambiguous, that is, if the future state is given by the map \mathbf{T} in a unique way by the initial one, we speak about deterministic models. In contrast, if there are several possibilities for the future state $\mathbf{x}(t)$ depending on random effects, we speak about stochastic models.

A typical example for deterministic-type models is given by Onsager's relaxation equations which we will discuss in more detail in Chapter 2. They are a set of first-

order differential equations for certain variables numbered $i = 1, \dots, n$ describing the deviations from a stationary state and read

$$\frac{dx_i}{dt} = - \sum_j \lambda_{ij} x_j \quad (1.22)$$

In this equation there appears a set of relaxation variables, x_i , and a matrix, λ_{ij} , which defines their mutual relations. Newton's equations describing the movements of planets are another example. Further we may think of time series obtained by recording the outputs of some measuring instruments in certain time intervals, and by a stroboscopic observation of continuous trajectories or by periodic reports. There are other processes such as the annual reports on the production of a country, which are intrinsically discrete in time. Examples of models with discrete time will be considered in the later chapters.

Let us discuss here only the simplest case of the relaxation equations. These equations possess stationary states $x^{(s)}$ given by the zeros of the right-hand sides, which lead to a vanishing time derivative of Equation 1.22. There are two kinds of stationary states – stable states and unstable states (Landa, 2001). Deviations from a stable state are followed by a relaxation to the original state.

Deviations from unstable states are amplified, as shown in Figure 1.11. The interplay between stability and instability belongs to the basic features of SO processes. Typical examples of structures created by instabilities we have already seen in Figures 1.7–1.10. In the case of Benard and Marangoni structures shown in Figures 1.7 and 1.9, the uniform state of the liquid at rest is unstable with respect to small hydrodynamic perturbations, which start to grow and bring the system to a new nonequilibrium structure. In the case of Figure 1.8, chemical instabilities give rise to spiral structures. We may consider these examples as concrete realizations of the general schema drawn in Figure 1.2.

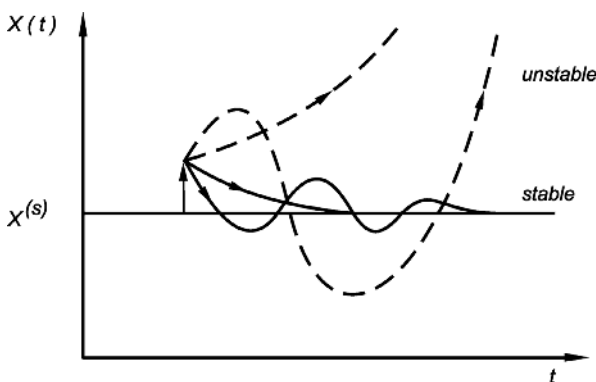


Figure 1.11 Stable and unstable states of a linear relaxation equation. The deviations from a stable state decay (solid curves), but the deviations from an unstable state start to grow (dashed curves).

1.6

Self-Organization of Information and Values

We know that the existence of all living beings is intimately connected with information processing. This we consider as the central aspect of life. We define *a living system as a natural, ordered and information-processing macroscopic system with an evolutionary history*. This may be used even as a criterion for decisions. Let us imagine that we are traveling on a spaceship far from our home-planet Earth. Suddenly we meet another unknown object moving in space, sending signals and doing maneuvers. The foreign spaceship hinders our further flight and takes an attitude which our captain considers as dangerous. He is asking us, the group of scientists on the ship: How should we behave? After some discussion, the scientists recommend to destroy the object if it is not a living being. But now the captain asks the scientist how to distinguish between a living and a nonliving item. After another discussion, the scientists group says: Evidently the foreign object is information processing, so check whether it is the result of a natural evolutionary process. If the answer is yes then we have to respect it, and if it is made just by another intelligence then you are possibly allowed to destroy it. Then the captain says, you are not really helpful, what I need is a more operational criterion, but the scientists answer that there is no other way to decide.

We consider information processing as a special, high form of SO. Information is an emergent property. We see several important problems here:

- 1) What is the general relation between SO and information and how may this relation be expressed in a quantitative way?
- 2) What is the origin of information processing in evolution? How did information processing emerge in the process of SO of biomolecules?

Both these problems seem to be unsolved so far. Key papers which reflect the main tendencies and the directions of search for final solutions were written by Eigen, Haken, and Volkenstein. How did information emerge by SO? Genuine information is symbolic information, needing a source that creates signals or symbols, a carrier to store or transport it, and finally a receiver that knows about the meaning of the message and transforms it into the structure or function the text is a blueprint for. This way symbolic information is always related to an ultimate purpose.

Information-processing systems exist only in the context of life and its descendants: animal behavior, human sociology, science, techniques, and so on. To our knowledge, the very first such system in evolution history was the genetic expression machinery of early life, where DNA triplets were used as symbols for amino acid sequences of proteins to be mounted. However the details, how life appeared, which way symbolic information developed out of nonsymbolic, native one, are hidden behind the veils of an ancient history. Other, later examples for the SO of information are much easier to study, and this was done in a very elucidating manner by Sir Julian Huxley in the beginning of the last century in behavior biology. The evolutionary process of the transition from use activities of animals to signal activities he discovered is termed ritualization." In our concept the transition to "ritualization" or "symbolization" is a

central point. A more detailed view at this transition process reveals rather general features which we consider as a universal way to information processing.

When a process or a structure becomes ritualized (symbolized), its original full form of appearance is successively reduced to a representation by symbols, together with a building-up of its processing machinery, which is still capable of reacting to the symbol as if the complete original were still there. At the end of the transition, the physical properties of the symbolic representation are no longer dependent on the physical properties of its origin, and this new symmetry (termed coding invariance) makes drift and diversification easily possible because of the newly achieved neutral stability. Neutrally stable states are those which do not exhibit restoring forces in response to modification. If symbols are arranged as linear chains in space or time, the information system is regarded as a language (such as genetic information); if not, it is termed a signal system (such as traffic signs or the hormone system).

Let us make now a few remarks on the relation of *chemical information processing and life*: the scenario we propose is mainly based upon the fundamental ideas of Eigen, who first introduced the concept of SO far from equilibrium into the problem of the origin of life, and of Oparin, who proposed the first scientific approach to the problem by underlining the importance of insulated self-assembling droplets (coacervates). Our aim is to formulate an own-standing hypothetical staircase to life, trying to merge Eigens and Oparins ideas to a common scenario under mainly physical rather than chemical or biological aspects. Although many researchers discuss special aspects such as particular molecule types and environmental conditions in detail, we believe those to be only specific circumstances, while the main questions are posed by the succession of steps of SO, of symmetry-breaking, of information processing, the onset of most primitive forms of Darwinian selection.

This concept will be briefly surveyed, since it differs in a few details from the well-known Eigen-Schuster concept. Beside some mathematical points (referring, e.g., to the mathematical formulation of the quasispecies concept and to stochastic effects), the main difference is our emphasis on a very early formation of individual spatial compartments, similar to Oparin's approach. Further, instead of hypercycles, some hypothetical RNA-replicase cycles play the dominant role in our scenario. This argument was based on an estimate of the probabilities for a spontaneous generation of catalytic feedback structures. The theory of random catalytic networks (Chapters 2, 4, 6) suggests that very simple structures such as paths, branching systems, semicycles, and small cycles have much higher probabilities to come into existence spontaneously than larger cyclic structures. Especially the genetic expression machinery, often assumed to be the very first evolving structure which must have been appeared just by chance, is considered here as a result of a long chain of preceding chemical evolution steps (Ebeling and Feistel, 1982).

In our model, six qualitative stages are assumed and characterized in detail in Chapters 8 and 9:

- 1) *Physicochemical SO*: Spontaneous formation of polypeptides and polynucleotides, local increase in the concentration in compartments (coacervates, microspheres, pores, etc.), catalytic assistance of the synthesis in networks and

cascades, first self-reproduction of polynucleotides (RNA) assisted by catalytic proteins (replicases), competition and selection between compartments and between replicative cycles inside compartments.

- 2) *Formation of protocells and of a molecular language*: Genesis of self-reproductive units consisting of RNA and proteins, division of labor between RNA and protein is more and more developing, generation of elements of a molecular language. DNA takes over the role of the memory and RNA is specializing in transcription functions. The building-block principle for the synthesis of proteins is worked out.
- 3) *Genetic code, ritualization, and division of work*: The full coding is successively replaced by a kind of stenography, the first triplet code arises and the direct chemical meaning of a complete sequence is replaced by a symbolic notation (ritualization), the development of the genetic code and the division of work led to the first living “minimum organism” in the sense of Kaplan (1978).
- 4) *Cellular organization*: The triplet code generates more and more complex structures such as membranes that are stabilizing the compartments. Spatial separation and nonlinear advantage leads to a freezing of the code. Controlled division of cells occurs.
- 5) *Genesis of autarkic systems*: A sharp selection pressure generates systems that are able to use primary sources of energy by photosynthesis. Heterotrophy and food-webs appear. Division of labor inside the cells is leading to compartments and especially to the formation of nuclei. Sexual reproduction is invented.
- 6) *Morphogenesis*: Cell associations are formed. The metabolic products take over regulating functions; division of labor between cells creates multicellular organisms. Certain cell groups, neurons, specialize on information processing. The basic mechanisms which were first based on direct chemical or stereochemical relations are replaced by the use of symbols. The corresponding second ritualization transition (symbolization transition) leads to complex nervous systems.

We are convinced that any further progress in the understanding of the origin of life on Earth will depend on the clarification of the points mentioned above.

There is another point which needs a better understanding, namely the problem of *combinatorial explosion*. One of the basic problems of understanding the SO of complexity is connected with a choice among an enormous number of combinatorial possibilities. For example, the number of different possibilities to arrange n monomers belonging to λ types (4 for DNA, 20 for proteins) is given by

$$N_n = \lambda^n$$

This is a very large number and the corresponding probability to find it by a random search

$$P_n = \lambda^{-n}$$

is extremely small. Evolution arguments shed new light on this important problem (Chapters 7 and 8, Feistel, 1990; Krug and Pohlmann, 1997; Ebeling, Freund, and Schweitzer, 1998).

We believe that all these problems are of high importance for any search or design of macromolecular systems with desired properties. In fact, to estimate the chances for a successful search and to envisage a good strategy we need the entropies. In this way, entropy research should be an immanent part of any research program in the field.

We conclude this section with a discussion of the concept of *values as emergent irreducible properties*. As we have pointed out above, we understand SO as a “process in which individual subunits achieve, through their cooperative interactions, states characterized by new, emergent properties transcending the properties of their constitutive parts.” In this respect we would like to stress the role of values, which are indeed among the most relevant emergent properties. An example is the value of a species which means the fitness in the sense of Darwin. Competition is always based on some kind of valuation.

Evidently the concept of values was first introduced by Adam Smith in the eighteenth century in an economic context. The fundamental ideas of Adam Smith were worked out later by Ricardo, Marx, Schumpeter, and many other economists. In another social context, the idea of valuation was used at the turn of the eighteenth century by Malthus. Parallel to this development in the socioeconomic sciences, a similar value concept was developed in the biological sciences by Darwin and Wallace. Sewall Wright developed the idea of a fitness landscape (value landscape) which was subsequently worked out by many authors; in the last few years, many new results on the structure of landscapes were obtained by the group of Peter Schuster.

The concepts of values and fitness landscapes are rather abstract and qualitative. Our point of view is that values are an abstract nonphysical property of subsystems (species) in a certain dynamical context. Values express the essence of biological, ecological, economic, or social properties and relations with respect to the dynamics of the system (Feistel, 1986, 1990, 1991; Ebeling and Feistel, 1994; Ebeling, 2006). From the point of view of modeling and simulations, values are emergent properties. The valuation process is an essential element of the SO cycles of evolution. The existing theory has already anticipated several value concepts such as the value of energy (i.e., entropy), the information value, the selection value in biology and the exchange value in economy. All these value concepts have several features in common:

- 1) Values assigned to elements (subsystems) of a system or to the modes of their dynamics incorporate a certain entirety of the system; they cannot be understood by a mere view of the subsystem without its whole environment. In other words, here the whole is more than the sum of its parts. Values represent irreducible features of the system on its level of complexity.
- 2) Values are central for the structure and dynamics of the entire system; they determine the relations between the elements and their dynamical modes as well as the dynamics of these relations. Competition or selection between elements or dynamical modes are typical elements of the dynamics.

- 3) The dynamics of systems with valuation is irreversible; it is intrinsically connected with certain extremum principles for the time evolution of the values. These extremum principles may be very complex and can, in only a few cases, be expressed by scalar functions and total differentials.
- 4) The necessary physical condition for any form of valuation is the pumping with high-valued energy. Isolated systems show a general tendency to devaluation, which is caused already by the devaluation of the energy in the system, due to the second law.

Only in the simplest case, the value of a subsystem (species) with respect to the competition is a real number. Since real numbers form an ordered set, the species are ordered with respect to their values. In such systems, competition and valuation may be induced by the process of growth of species having high values and decay of species having low values (or the opposite). In many cases, the growth of “good” species is subject to certain limitations. A standard case studied in detail by Fisher (1930) and Eigen (1972) is the competition by average. Here all species better than the average over the total system, $V > \langle V \rangle$, grow and all others that are worse $V < \langle V \rangle$ decay. Because the occupation $N(t)$ is changing, this leads to an increase in the averaged value $\langle V \rangle$ in time. In some cases, the values are given by the distribution itself, for example,

$$V_i = -\log(N_i/N)$$

This valuation favors equal distribution and the averages correspond to entropies. It is interesting to note that in this view, the entropy appears as a special kind of valuation. In physics, according to Boltzmann’s concept, entropy maximization is subject to the condition of constant energy, and the elements are defined by a partition of the phase space of the molecules. The lowering of entropy with respect to its maximum (at given energy) expresses, after Clausius, Helmholtz, and Ostwald, the work value of the energy in the body. The second law of thermodynamics expresses a general tendency to disorder (equipartition), corresponding to a devaluation in isolated systems.

Many competition situations in biology, ecology, and economy are associated with a struggle for common raw material or food. Here, the result of the competition can still be predicted on the basis of a set of real numbers (scalar values). In more general situations, the values are merely some property of the dynamical system rather than well-defined numbers. One may attribute three functions to valuation (Feistel, 1990, 1991):

- 1) Regulating functions, establishing stable attractor states among the winners of the competition,
- 2) Differentiating functions, awarding “better” competitors and eliminating the defeated ones, and
- 3) Stimulating functions, amplifying favorable fluctuations which destabilize the established parent regime.

Valuation is absolutely central to the origin of life; in order to survive, a living creature needs a standard of basic values as food, shelter, protection, comfort, and so on. In modern societies, there exists an exchange value – the money. A role similar to that of a currency is played by adenosine triphosphate (ATP), which is exchanged between the parts of an organism. The generation of values in biological and social societies is deeply connected with the origin of information.

The question of the value of information is a special and very important problem, which raised a never-ending discussion (see, e.g., Volkenstein, 1986; Marijuan, 2003). We will explain our point of view in Chapters 5–9. In short, we see the value of information for a living system in the gain of some of the basic values due to the transfer of information to the system. We will explain examples in Section 5.6. Normally the basic values needed for survival are difficult to achieve, think only about the search for energy-rich molecules in the primary soup, for the recruitment of food, shelter, and protection in ecological systems and in early human societies. Here the information transfer by signals comes into play. It was basically information transfer which increased the access to the basic values and made the explosion of life on earth possible. This way, information value is not a new value per se, but it is the gain of basic values as food, shelter, protection, comfort, money, and so on by transfer of information.

We are concluding this chapter with these rather general remarks. As we will see, in nearly all problems which will be treated later, the real difficulties are in the details, but this is the subject of the following chapters.

