Rainer Feistel, Werner Ebeling

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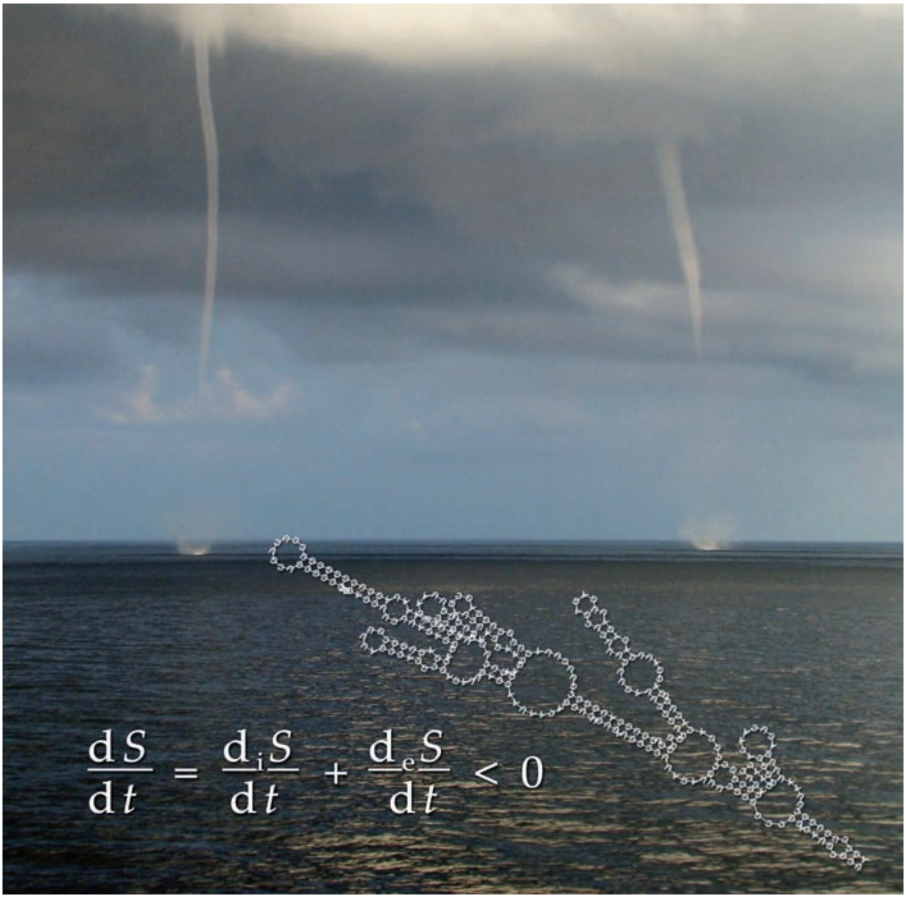
Physics of Self-Organization and Evolution



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Preface

The wall had developed a crack, and a strip of sunlight was dancing right through it.
Erich Kästner: The Schildburghers

At one time Latin was close to the universal language of what we now call "science". Then French took over followed by German and at long last English. Both the English and the Americans are infamous for being monolingual. If you don't publish in English, your work is likely to go unnoticed.
David Hull: Science and Language

The first German edition of this book was written in the years 1978–1980 in Rostock, Moscow, and Berlin, about 10 years before the fall of the Berlin wall, Figure 1.

In contrast to the general expectation of politicians, in particular of the various so-called east experts in the West, that the sudden implosion of the eastern political system was a completely unpredictable event, these authors believe, based on own experience, that already since the 1970s "something was in the air." Preceding the "perestroika" and the related social turnover after 1989, there was a developing spirit of enlightenment, similar to the "Aufklärung" in Germany and the "Siècle des Lumières" in France, before the revolutionary events happened in Europe in the eighteenth and nineteenth century. In retrospect, expressed in the language of physicists, the dawn of the phase transition was accompanied by internal fluctuations with increasing amplitudes.

When in 1970 Ilya Prigogine, Figure 2, presented his great lecture on self-organization in Moscow, this was appreciated by the audience as a kind of theoretical revolution. One of these authors was a witness of this outstanding event. The lecture room in the Moscow Academy of Science was overcrowded, the excitement was enormous. While most people supported the new ideas, a few also protested against them. The related emotional impression is well reflected in the text by the German poet Erich Kästner that we used as our motto above. Kästner (1899–1974) had a difficult life and was badly treated by the Nazi regime because of his protest against the militaristic German policy and the Second World War.

Figure 1 Crack in the Berlin wall, virtually foreseen already in 1954 by Erich Kästner, in the motto of this chapter. Photo taken in November 1989 in Berlin, courtesy of Jörg Hildebrandt.

The vivid resonance which the ideas on self-organization found among the public in particular in the former socialist countries resulted in the immediate translation to Russian of all books on self-organization available at that time. A similar response was observed after the lectures of Manfred Eigen and Ilya Prigogine at the end of the 1970s in Halle/Saale, presented during public conferences organized by the oldest German Scientific Academy, Leopoldina. As a matter of fact, Leopoldina strongly promoted the distribution of the ideas of self-organization in both parts of Germany. As well, Hermann Haken's books on Synergetics also played an important role for the emergence, propagation, and development of the new physical discipline. Nearly the same what had happened in Moscow in 1970 took place again in 1982 after an excellent lecture of Prigogine on "The Arrow of Time," given at the Pergamon Museum in East Berlin. In addition to physicists, chemists, mathematicians, and biologists, also many philosophers and journalists participated in the discussion, and Prigogine's ideas were transmitted on the radio to a broader public.

Figure 2 Ilya Prigogine during a lecture in the 1980s. (from the archive of the authors).

The original edition of this book was inspired by the feeling of this exciting atmosphere of the emergence of something "New" in those unique years. This way our first book was mainly a reaction to a widespread interest of the community in ideas of self-organization and evolution. These authors were very happy to get in close contact to scientific pioneers such as Ilya Prigogine, Herrmann Haken, and Manfred Eigen, as well as to various other experts in that field such as Conrad, Nicolis, Klimontovich, Romanovsky, Stratonovich, Velarde, and Volkenstein.

It was at the Heraeus Seminar on "Evolution and Physics – Concepts, Models, and Applications" in Bad Honnef in January 2008 when these authors decided to publish an English edition of the German "Physik der Selbstorganisation und Evolution" of 1982, almost exactly 30 years after the writing of the original manuscript had begun. During the meeting the impression prevailed that even after three decades the presentation given in the old book might still be worth to be made available to a wider public than to just the German readership. The quick first idea of an almost literal translation was soon dismissed; in the meantime, too much research was done and too many discoveries were made to be left completely unappreciated in the revision. The first and second German editions appeared in 1982 and 1986 in the Akademie-Verlag in Berlin. Rather than straightforwardly producing an English version of the original monograph, in discussions with the legal successor of the publisher we eventually decided to accept the challenge and largely rewrite the text in order to bring it to a modern state that reflects more recent developments both in the field and in the viewpoints of the authors. The following reasons motivated us to write an essentially new manuscript:

1) The revolutionary changes in the former GDR and in the other East European countries substantially changed our view on the evolution. On the other hand, it

occurred also that many of the essential statements were confirmed by the evidence of life. In particular, we have in mind a statement on page 209 of the first edition: "Refusal of innovation is virtually an optimal tactic, but ultimately it is a fatal strategy, as biological evolution has shown." Being used to read and write "between the lines" at that time, this was a critical formulation. Having in mind the experience from the last 22 years we may now better say "as was shown by biological and social evolution."

2) Our professional careers after "the wall had developed a crack" led one of us (R. F.) to Baltic Sea research and correspondingly to fields of oceanography and geosciences. The second author (W.E.) was founding speaker of a German collaborative research center on "Complex Nonlinear Processes – SFB 555" and later – already as a pensioner – in several new collaborations with foreign partners such as in Cracow, Madrid and Moscow. This experience as well as the contacts with new friends, colleagues, and collaborators widened our views and introduced new topics into our research which are in part reflected here.
3) In the last 30 years, the worldwide situation changed dramatically, new problems such as the warming climate, destruction of environment, and global financial crises have arisen which pose real dangers to the future of humankind. Similar to an earlier popular book (Ebeling and Feistel, 1994), also in this general book on evolution we felt some necessity to gather and review certain material regarding the past and the future of evolution on Earth, without claiming to be exhaustive in any way. We hope that some of our perspectives provide interesting alternatives to commonly discussed viewpoints.

The reader may recognize that this experience and the new tasks strongly influenced the manuscript and resulted in new views and several completely new topics. In particular, we put much more attention on the evolution of climate and environment, a topic that got a lot of actuality these days. Further we took into account many new results in the fields of nonlinear dynamics, chaos theory, and theory of self-organization. As a result, the emphasis of this edition differs from the original one in various respects. For instance, self-reproducing automata are no longer discussed; their theory did not develop as promisingly as it appeared to us in the past. Complexities and other similarity measures of sequences were a new and hot topic at that time; now the wealth of publications on genetic information and on language evolution issued since then is impossible to be reasonably reviewed in a single chapter. We decided to put more emphasis on the physical question how symbolic information carriers can emerge by mechanisms of self-organization than on techniques to describe and to analyze strings of letters or chains of molecules. On the other hand, elementary questions regarding the climate and the structure of our planet occupy much more space and attention in this book than it did before.

The authors worked many years on thermodynamics, theoretical physics, and dynamical systems. Accordingly, this book is written in the language of physics and makes use of standard tools from thermodynamics and mathematics. The target it aims at is beyond the traditional field of physics; it is the – still fascinating – question of how the fundamental laws of physics are related to the emergence of qualitative newness and the historicity of evolution. Evidently, the forms of life that exist on Earth, the basic laws that govern it, and the amazing diversity of functions and structures it produces including ourselves and the science we are engaged in, represent the main challenge and central problem of this book. Notwithstanding, here the focus is on physical conditions, theories and models that offer a better understanding for the emergence and observed perfection of life.

We like to convey our deep conviction that no mysteries are involved in the appearance and unfolding of life, neither divine beings, intelligent creators, nor extraterrestrial visitors, that is, neither systems that were never practically observed, nor ones that are even unobservable by definition of their human inventors. We share the view of the ingenious Lev Landau that his proverbial "gramophone spirit" is neither a necessary nor a particularly helpful theory for explaining the functioning of a gramophone. Rather, the laborious, meticulous and sometimes erratic search for consistent combinations of observational evidence, theoretical models, and causal explanations is the only promising and defendable scientific approach to reveal the secrets of life, as repeatedly outlined by authors such as Carl Sagan and Richard Dawkins. Accordingly, quite fundamentally, this book is not a place to find any kind of final answer or eternal truth. It is intended as an introduction to the research field for students, and as a review of selected aspects of self-organization and evolution for interested colleagues and other readers who share our curiosity regarding the physical basis of the miracle of life.

At the Rostock university, the research group on nonlinear irreversible processes was established with a special course read by Werner Ebeling already in 1973. Under the impression of the works of Prigogine, Eigen, and Haken, and by the experiments of Belousov and Zhabotinsky on oscillating reactions and chemical waves, as well as of Hartmut Linde on hydrodynamic surface waves, it was a fascinating experience to do research at the borderlines between physics, biology, and social science; quite in contrast to the classical scope of textbook physics. Easy access to the upcoming "personal computers" such as Sinclair ZX81 and ZX Spectrum permitted the investigation of numerical solutions of nonlinear differential equations as well as simulation experiments at so far unprecedented convenience and promptness. It was the emotional experience of passing a secret gate and entering a pristine new world of concepts, models, and theories which stimulated ideas and publications of the group.

Various meetings with other colleagues on workshops and conferences were always very inspiring and informative, in particular the *Conferences on Irreversible Processes* and *Self-Organization* held in Rostock in 1977 and in Berlin 1982, respectively (Figure 3), the first two in a series of four. While the 1982 book was in preparation, the group moved to the Humboldt University of Berlin and grew rapidly, in particular because of its scientific attractiveness to many students and postdocs. By coincidence, we all remember very well the end of the departure day of a workshop held by the group near Berlin when a specific historical "fluctuation" triggered a critical local instability with dramatic and enduring consequences: the Berlin Wall had developed a crack that gradually widened in an irreversible process of self-organization which eventually resulted in the end of the world-wide Cold War.

Figure 3 Ilya Prigogine at the II. Conference *Irreversible Processes and Self-Organization* in Berlin 1982. From left to right: Roman Ingarden, Yuri Klimontovich (deceased 2003), Rainer Feistel, Dagmar Ebeling, Ilya Prigogine (deceased 2003), Werner Ebeling. (photo from the archive of the authors).

For the research group, Figure 4, but as well for close friends such as Miguel Angel Jiménez Montaño (University of Veracruz at Xalapa, Mexico) and Yuri Mikhailovich Romanovsky (Moscow State University, Russia), Figure 5, with whom the authors frequently met and worked together since the 1970s, one of the most attractive meeting places is the cottage house of the Ebeling family in Born on the Darss Pensinsula.

When telling about the history of the relations between thermodynamics, statistical physics, and nonlinear science, with respect to historical events related to Berlin, Rostock, and Moscow as the towns closely connected with our personal education and careers, some prejudice may be excused by the reader. We cannot claim perfect accuracy of the historical details; this point we prefer to leave to professionals. We are

Figure 4 Autumn workshop 1978 at Ebeling's cottage house in Born, Darss Peninsula. From left to right: Horst Malchow, Jürn Schmelzer, Waldemar Richert, Lutz Schimansky-Geier, Matthias Artzt, Ulrike Feudel, Werner Ebeling, Ingrid Sonntag, Harald Engel, Reinhard Mahnke.

Figure 5 Science-family meeting in 2000 at Ebeling's cottage house in Born, Darss Peninsula. From left to right: Barbara Ebeling, Rainer Feistel, Sabine Feistel, Miguel Angel Jiménez-Montaño, Julia Hildebrandt, Werner Ebeling, Erik Hildebrandt, Yuri Mikhailovich Romanovsky, Stefan Feistel, Jörg Hildebrandt.

more interested in the origin of the ideas and their development than in biographical facts.

This book summarizes the knowledge, viewpoints, and opinions of the authors regarding the physics of self-organization. It is a textbook with some bias regarding the thermodynamics of evolutionary processes including the relations between nonlinear dynamics, statistical physics, and stochastic theory. It paints a physical picture of the origin of life, from the early universe and formation of the planet Earth up to competition and information processes characteristic for life in its various forms. In explaining the main ideas of our approach we prefer the inductive and sometimes the historical perspective. This way, this book is basically intended as an introduction for students of physics of higher semesters and for graduate students in physics and related research fields who search their path across the "jungle" of modern interdisciplinary research. The book's orientation is more on general understanding and illustrative examples than on theoretical or modeling details. Deeper knowledge is available from a wealth of scientific literature that is briefly reviewed in the text. In other words, in the first line our aim is to contribute to the education of students and young scientists, to explain what is holding together physics and natural sciences, and not so much to fill the readers' minds with too many equations. Nevertheless, we also include some original results of research from the group's working since the 1970s at the Rostock University and since 1980 at the Humboldt University Berlin.

This work is in part based on lectures held at universities in Berlin, Cracow, Moscow, Puebla, Riga, Saratov, Torun, and Xalapa on topics such as "Thermodynamics," "Dissipative Structures," "Statistical Physics," "Stochastic Theory," "Brownian Motion," "Nonlinear Dynamics," "Self-Organization," "Entropy and Information," "Physics of Evolutionary Processes," and on related subjects given by the authors in close cooperation with colleagues such as Heinz Ulbricht, Reinhard Mahnke, or Gerd

Röpke at the Rostock University, and Lutz Schimansky-Geier and Igor Sokolov at the Humboldt University Berlin between 1974 and 2010.

Many colleagues and friends inspired and improved this book, and assisted in various other ways: Kobus Agenbag, Chris van den Broeck, Dmitri S. Chernavsky, Michael Conrad (deceased), Olivia Diehr, Andreas Engel, Harald Engel, Ulrike Feudel, Jan Freund, Ewa Gudowska-Nowak, Eberhard Hagen, Hermann Haken, Peter Hänggi, Anna-Maria Hartmann, Ingrid Hartmann-Sonntag, Toralf Heene, Olaf Hellmuth, Kevin Hennessy, Hanspeter Herzel, Martin Heß, Günter Jost, Yuri L. Klimontovich (deceased), Jürgen Kurths, Hartmut Linde, Reinhard Mahnke, Horst Malchow, Trevor McDougall, Lutz Molgedey, Frank Moss, Günther Nausch, Gregoire Nicolis, Thorsten Pöschel, Ilya R. Prigogine (deceased), Gregor Rehder, Gerd Röpke, Yuri M. Romanovsky, Ruslan L. Stratonovich (deceased), Andrea Scharnhorst, Lutz Schimansky-Geier, Juern Schmelzer, Frank Schweitzer, Dirk Schories, Igor M. Sokolov, Franz Tauber, Heinz Ulbricht, Norbert Wasmund, Vladimir Vasiliev, Manuel G. Velarde, Mikhail V. Volkenstein (deceased), Yakob B. Zeldovich (deceased), and Christoph Zülicke.

We are particularly and deeply indebted to our families for their multiple assistance, stimulating cooperation, and inexhaustible patience, Barbara Ebeling, as well as Sabine, Susanne, Stefan, and Angela Feistel.

The present manuscript was mostly written in Warnemünde where one of these authors is now involved in Baltic Sea research, and in the village of Born located on the Darss Peninsula near Rostock where the second author enjoys new chances after retirement, and also partially in Berlin in close contact with the colleagues at the Humboldt University.

This book is dedicated to our former students, coworkers, and friends, who helped to work out our ideas in a harmonic but critical and altogether friendly atmosphere.

Berlin, Born, and Warnemünde, in February 2011.

1
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

Physics of Self-Organization and Evolution, First Edition. Rainer Feistel and Werner Ebeling.

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

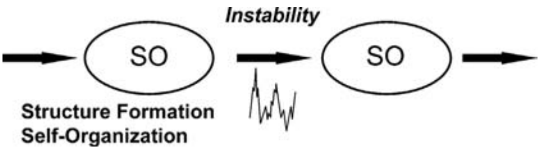

Figure 1.2 Evolution as a sequence of many subsequent SO steps. Each period of SO leads to some structure formation and after its ripening, eventually to an instability that drives the system away from its previous quasiequilibrium state and ultimately leads to another phase of SO.

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-volcanoon 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 workutterly divorces them from the pressuresof 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),

$$T \approx \text{const}\, \varrho^{1/3} \tag{1.1}$$

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

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

we find

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

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; Hoyng, 2006):

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

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

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

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.

1^{st} *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.

2^{nd} *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

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

This period extends up to a time

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

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

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

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

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

The corresponding time is about

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

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,

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

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

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

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

$$q + \tilde{q} \rightarrow 2\gamma, q + \tilde{q} \rightarrow e + \tilde{e}$$

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

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

The time interval

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

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

$$u + u + d \rightarrow p, \quad u + d + d \rightarrow n$$

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.

6^{th} *Epoch: Neutrino decoupling*

We consider now the time interval

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

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

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

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.

7^{th} *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.

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

We speak now about the time interval

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

and temperatures approaching

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

Then the following reactions become possible:

$$2\text{p} + \text{n} \rightarrow \text{He}^3, \quad \text{D} + \text{D} \rightarrow \text{He}^4$$

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.

9^{th} *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 $T \approx 10,000-100,000$ K < 1 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.

10^{th} *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

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

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

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

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

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

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

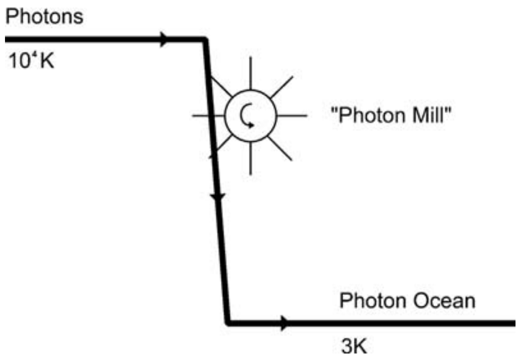

Figure 1.3 The steady photon flow from the temperature level of $T \sim 10{,}000$ K corresponding to the surface of stars, possibly passing through an intermediate station on planets and ending finally at the level $T \sim 3$ K corresponding to cosmic background radiation, is the driving force for the terrestrial evolution.