To the memory of my parents
Preface

This book is, of course about complexity. The title of the book, as you may recognize was motivated (excuse me for using this very mild expression) by Daniel Dennett’s Consciousness Explained [130]. Dennett’s intention was to explain consciousness as the emergent product of the interaction among constituents having physical and neural character. The goal of this book is to explain how various types of complexity emerge due to the interaction among constituents. There are many questions to be answered, how to understand, control, decompose, manage, predict the many-faced complexity. After teaching this subject for several years I feel that the time has come to put the whole story together.

The term “complex system” is a buzzword, but we certainly don’t have a single definition for it. There are several predominant features of complexity. Complex processes may show unpredictable behavior (which we still try to predict somehow), may lead to uncontrolled explosion (such in case of epilepsy, earthquake eruptions or stock market crashes). One of the characteristic feature of simple systems is, that there is a single cause which implies a single effect. For large class of complex systems it is true that effects are fed back to modify causes. Biological cells belong to this class. Furthermore they are open to material, energetic and information flow by interaction with their environment, still they are organizationally closed units. Another aspect of complexity is the question how collective phenomena emerge by some self-organized mechanisms. Thomas Schelling’s model, which suggests that strong racial prejudice is not needed to generate urban segregation, is paradigmatic.

There is a remarkable and unique statistical feature of certain complex systems. Generally we expect that there is an average, (say, the average height of people), and the deviation from this average is symmetric. Biologists have found that the Gaussian distribution can be applied in many, many cases. In a large number of social systems (but not only there) we see another type of pattern, occasionally called as the 80/20 rule. About eighty percent of the income is made by twenty percent of people, eighty (well, seventy, or eighty-five) percent of flights are landing on twenty percent of the airports, while there
are many small airports with a few flights per day. A large number of scientific papers are written by a small number of scientists, and so on. Such kinds of phenomena, which don’t really have a characteristic size, are described by an asymmetric (skew) so-called power law distribution. The brilliant best-seller of Douglas Hofstadter on Gödel, Escher and Bach published in 1979 emphasized self-reference and loops, actually he calls a strange loop. Loops, specifically feedback loops were studied by cybernetics, an abandoned scientific discipline, which emphasized that effects may feed back to influence causes. Such kinds of systems, which are characterized by “circular causality” certainly could be qualified to be called as complex.


John Casti’s “Paradigms lost” [94] showed me that it is possible to mention different fields in the same book from philosophy of science via molecular biology and origin of life, theory of evolution, sociobiology, linguistics, cognitive science, foundation of mathematics, to quantum physics and cosmology. I have a somewhat overlapping list.

I learned from Michael Arbib’s “The Metaphorical Brain” [18] how to use and not use mathematical formalism. Some pages of his book are filled with equations, and then you may find fifty pages without any formulas. So, I extracted the implicit message to be “Don’t be afraid to use math when it helps to explain your ideas, and don’t be afraid to avoid mathematics when you can convey your ideas without it.”

I have heard about the notions of complex systems, simulation methods, and thinking in models in the late sixties from my undergraduate mentor, Pál Benedek, and later had numerous conversations about the complexity of the brain with János Szentagothai.

It happened that this has been my sixth year to teach complex systems and related fields at Kalamazoo College for undergraduates. Kalamazoo College was awarded by a Henry R. Luce Professorship, and I have had the privilege to serve here to build a program about complex systems. I learned (hopefully) a lot during these years, and the book grew up from my class notes. I benefited very much from the interaction with my colleague Jan Tobochnik. We have a mutual interest in understanding and making others understand problems, many of them are related to complex systems.

Previously I taught a History of Complex Systems Research class at the Department of History and Philosophy of Science at Eötvös University, Budapest (Hungary), when I served there as a Széchenyi professor, and the plan of writing a book about complexity emerged in that period.
I am particularly indebted to two of my Hungarian graduate students, Gábor Csárdi, Balázs Ujjalussy, who helped a lot in preparing the text and figures. Zsófi Huhn, Tamás Nepusz helped to complete specific sections.

I deliberately adopted/adapted texts, figures, ideas from works published earlier with a large set of coworkers, such as Ildikő Aradi, Michael Arbib, George Barna, Fülöp Bazsó, Tamás F. Farkas, Csaba Földy, Mihaly Hajos, Tamás Kiss, Matt Lengyel, Gergő Orbán, Zoltán Somogyvári, Kátherine Strandburg, Krisztina Szalisky, János Tóth, Ichiro Tsuda and László Zalányi.

I acknowledge the discussion of many details with George Kampis and József Lizár. The latter also helped to tell some Hungarian anecdotes etc. in English. I am grateful to Kati Pető and Péter Bruck for their explicit and implicit contributions. Comments from Michael Arbib, Jancsi (Chaim) Forgacs, Viktor Jirsa, Robert Kozma, Ichiro Tsuda, and Günter Wagner are acknowledged. Francesco Ventriglia kindly read the whole manuscript, and made a lot of comments.

I got a lot of help from my students at Kalamazoo. Trevor Jones and Andrew Schneider accepted the painstaking task to correct the grammar. I enjoyed very much numerous conversations among others with Dan Catlin, Griffin Drutchas, Brad Flaugher, Richard Gejji, Elizabeth Gillstrom, Justin Horwitz, Hannah Masuga, Elliot Paquette, Bobby Rohrkemper, Clara Scholl and Jen Watkins.

I would like to thank to Thomas Ditzinger, the editor of the Springer Verlag to encourage me to write the book in the style I chose. Comments from Christian Caron also acknowledged.

While the book is dedicated to the memory of my parents, I think they would have suggested me to do it to my children. Zsuzsi and Gábor, the book is dedicated also to you.

We have a long experience with my wife, Csuti, to cope with the complexity of life. I benefited very much from her support, love and wisdom. I am not sure I could have completed this book without her deep understanding. It is difficult to express my gratitude.

Kalamazoo, Michigan and Budapest-Csillébérc

Péter Érdi

June 2007
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1

COMPLEX SYSTEMS: THE INTELLECTUAL LANDSCAPE

1.1 The century of complexity?

“I think the next century will be the century of complexity.”
Stephen Hawking (Complexity Digest 2001/10 March 05, 2001.)

The term “complexity” became a buzz-word in the last decade, or so. We see that the science of complexity has roots both in natural and social sciences. The term “complex” appears as an adjective in very different contexts. “Complex structures”, “complex networks”, “complex processes”, “complex information processing”, “complex management”, etc.

One aspect of complexity is related to the STRUCTURE of a system. In elementary chemistry the most fundamental organization is the structure of molecules, where the elements are atoms, and the relations are chemical bindings between them. Biologists study structures at very different levels of hierarchical organization, from molecular biology via the brain to population dynamics. The neuronal network of the brain consists of neurons connected by synapses (though extrasynaptic communications cannot be excluded). Food webs describe the relationship among species: living creatures should eat other living creatures to survive. An example of structures studied by psychologists is the so-called semantic memory. Semantic memory describes abstract relationship among concepts; e.g. Cairo is the capital of Egypt. In our mind there is a network of words connected by associations. Nodes of the networks are concepts, they are connected by associations, which are the edges of a network. Computer scientists adopt measures to characterize the static structural complexity of software. Programs, containing more cycles, are supposed to be more complex. The selective, functional and evolutionary advantage of the hierarchically organized structures (composed of subsystems, again com-
posed of their own subsystems, etc.) was emphasized by one of the pioneers of complexity, Herbert Simon (1916–2001) [466].

Structuralism was one of the most popular approaches (with a peak in the nineteen sixties) in a bunch of social scientific disciplines, such as linguistics, anthropology, ethnography, literary theory, etc. Its fundamental aim was to describe the relationship among the elements in a system. A predominant contribution to the initiation of the idea of structuralism was Ferdinand de Saussure’s (1857-1913) approach, [128] who considered language, as a system of its elements. Claude Levy Strauss, and his structural anthropology [313] was motivated by structural linguistics. Interestingly, he was also influenced by celebrated mathematical methods applied in cybernetics, and information theory, which were flourished in the nineteen-forties and fifties. To analyze the structure of social groups (first the native Bororo tribes in Brazil), he used the terms “elementary and complex structures and even semi-complex structures”.

Another emblematic scientist, Jean Piaget (1896-1980), a Swiss psychologist, applied structuralism to mental development. The human mind (and brain) is certainly an extremely complex structure. Piaget classified the child development to four classes, the last one around 11 years is characterized with the ability of abstract thinking. The transitions between the stages is driven by errors. The accumulated errors require the reorganization of the cognitive structure. Please note, that Piaget was concerned with development, so he was interested not in static, but dynamic structures. Also, Piaget assumed (and he was right), that knowledge is not only acquired from outside but constructed from inside. We shall return to this topic a few hundred pages later, after we have discussed the structural, functional and dynamic complexity of brain and mind.

---

1 There once was two watchmakers, named Hora and Tempus, who manufactured very fine watches. Both of them were highly regarded, and the phones in their workshops rang frequently. New customers were constantly calling them. However, Hora prospered while Tempus became poorer and poorer and finally lost his shop. What was the reason?

The watches the men made consisted of about 1000 parts each. Tempus had so constructed his that if he had one partially assembled and had to put it down – to answer the phone, say – it immediately fell to pieces and had to be reassembled from the elements. The better the customers liked his watches the more they phoned him and the more difficult it became for him to find enough uninterrupted time to finish a watch.

The watches Hora handled were no less complex than those of Tempus, but he had designed them so that he could put together sub-assemblies of about ten elements each. Ten of these subassemblies, again, could be put together into a larger subassembly and a system of ten of the latter constituted the whole watch. Hence, when Hora had to put down a partly assembled watch in order to answer the phone, he lost only a small part of his work, and he assembled his watches in only a fraction of the man-hours it took Tempus.
1.1 The century of complexity?

The late mathematician of Yale University, Charles E. Rickart (1914-2002) [429] carefully reviewed structuralism from the perspective of mathematics, which “does not mean a formal mathematical treatment of the subject”. While structuralism was an intellectually challenging, optimistic movement, it “has often been criticized for being ahistorical and for favoring deterministic structural forces over the ability of individual people to act” [1].

The most important mathematical technique to represent the structural relationship among the elements of natural and social systems is graph theory. Graph theory offers a natural way to represent systems with individual nodes and connection between nodes. Chemists use graphs to represent their molecules, having the atoms as nodes, and chemical bonds as edges. To represent three-dimensional objects by two-dimensional graphs (in order to visualize molecules on paper, blackboard and/or computer screen) some geometric information (as distances, and angles) are sacrificed, while the topological information (i.e. the existence and non-existence of bonds between atoms) is preserved. Graph theory proved to be very successful in analyzing structures in many disciplines. There is a single mathematician, Frank Harary (1921–2005) who, in addition to his contribution to the development of graph theory itself, had papers on the application of graph theory to anthropology, biology, chemistry, computer science, geography, linguistics, music, physics, political science, psychology, social science. Harary investigated many problems which are nowadays reanalyzed in terms of network theory.

DYNAMICAL complexity is about temporal processes. Here is an arbitrary list of related concepts: clockwork Universe, heat death, arrow of time, time reversal, eternal recurrence, biological clock, heart beat, neural rhythmicity, weather prediction, epilepsy, . . . . Irreversibility and periodicity are recurring themes. There is no strict correlation between structural and dynamical complexity. Robert May published a paper in 1976 in Nature with the title “Simple mathematical models with very complicated dynamics” [334], which clearly explained a mechanism of the emergence of chaos in simple mathematical equations: models even with simple structure may lead to complicated dynamics.

The ALGORITHMIC INFORMATION complexity (introduced by the legendary mathematician Andrey Nikolaevich Kolmogorov (1903–1987) and extended by Gregory Chaitin) of some computable object is the length (measured in number of bits) of the shortest algorithm that can be used to compute it. So, the shorter the algorithm, the simpler the object.

The notion of COGNITIVE complexity has been related to personality theory [272]. It has been used as a basis for discussion on the complexity of personal constructions of the real world (and particularly of other people) in psychology. People have mental models about their social environment. A
subject should rate a number of people around her on a number of attributes, 
generally in a bipolar axis. The complexity of the world view of a subject can 
be measured by this test. A subject, who assigns to all their friends positive 
attributes and to their enemies negative attributes would have a less complex, 
 basically one-dimensional mental model of their acquaintances. (S)he has only 
friends and enemies. A subject with the ability to see people as a mixture of 
“good” and “bad” characteristic properties has a higher “cognitive complexity”.

There are many more disciplines related to complexity issues: (such as, say 
computational complexity, ecological complexity, economic complexity, orga-
nizational complexity, political complexity, social complexity), just to mention 
some of them. Browsing the web you may see that almost all of them have 
their journals, conferences, etc. So, it would be difficult to deny that complex-
ity theory has become very popular.

Roughly speaking we know that the big success stories of twentieth century 
science are related to the reductionist research strategy. Particle physics and 
molecular biology were the most fortuitous disciplines, both apply predom-
inantly the reductionist research strategy. Reductionism is a coherent view, 
which suggests that chemistry is based on physics, biology is based on chem-
istry, psychology on biology, and sociology on (bio)psychology. A more ex-
treme view claims that finally everything is “physical”, any aspect of life and 
mind is basically a physical thing. Molecular biology emerged in search for the 
structure of genes, and the application of the reductionist strategy implied big 
progress in reducing genetics to molecular biology.

While the differences between the twentieth century sciences and complexity 
are significant, neither one has a hegemony. The former, including biology, 
were dominated by mechanistic reductionism.

Mechanistic reductionism suggested, that the universe, including life, were 
considered as “mechanisms”. Consequently, understanding any system re-
quired the application of the mental strategy of engineering: the whole system 
should be reduced to its parts. Knowing the parts was thought to imply the 
complete understanding of the whole.

The science of complexity suggests that while life is in accordance with 
the laws of physics, physics cannot predict life. Therefore, in addition to re-
ductionism, a more complete understanding of complex dynamical systems 
requires some holism. The (w)holistic approach is interested in organization 
principles. One of the most important key concept of this approach is the 
notion of “emergent properties”: system’s properties emerge from the interac-
tion of its parts. Holists like to tell, that the whole is somehow (?) greater 
than the sum of its parts. In extreme form, holism not only denied that life
can be understood by physical-chemical laws, but suggested the existence of some “non-material agent”.

1.2 Characteristics of simple and complex systems

1.2.1 System and its environment

A system is a delineated part of the universe which is distinguished from the rest by a real or imaginary boundary (Fig. 1.1). The system approach integrates the reductionist and the holistic approaches. There are **closed systems** which are maintained by internal forces, and not influenced by external forces. A piece of stone is an isolated system, and its shape is preserved by increasing a force to threshold, when it might be subject to disintegration by rupture. The properties of the stone can be studied by neglecting its interaction with the environment.

The founder of the “General systems theory”, Ludwig von Bertalanffy (1901–1972) emphasized that, as opposed to stones, and to other isolated systems, the majority of biological and social systems are **open systems**. The behavior of an isolated system is completely explainable from within. Living structures, and other open systems, should be considered, as systems being in permanent interaction with their environment to ensure normal performance.
Systems theory is always concerned about the boundary between a system and its environment. It is clear where the boundary of a stone is. Also, we might intuitively expect that the chemical composition of a stone will not change for tomorrow. But its temperature is influenced by the sunshine. Roughly speaking a piece of stone is closed for material flow, but it is subject to energy flow. The stone is not really an isolated system, since it has the same temperature as its environment. They are in thermal equilibrium. More precisely, the change in the temperature of the environment implies an energy flow to equilibrate the temperature difference. Our temperature is not the same as that of our environment, and our internal processes ensure to maintain the temperature difference. We are “open systems”, dynamic structures maintained by permanent material, energetic and information flow with our environment.

To give an appropriate description there are three concepts we should know: a system, its environment and the interaction between them. So from the perspective of system theory, we should know how to characterize the state of the system, the properties of the universe, which affect the system excluding the system itself, and the interactions/relationships between the system and its environment.

1.2.2 Simple systems

What are simple systems? Here are some characteristic properties of simple systems:

- Single cause and single effect
- A small change in the cause implies a small change in the effect
- Predictability

Common sense thinking and problem solving often adopts the concept of “single cause and a single effect”. It is probably not a very big exaggeration to say that both the classical engineer’s and the medical doctor’s fundamental approach was based on this concept. Common sense also suggests that small changes in the cause imply small changes in the effect. It does not literally mean (as sometimes is mentioned) that there is a linear relationship between the cause and the effect, but it means that the system’s behavior will not be surprising, its behavior is predictable. With a somewhat more technical terminology, small changes in the parameters (or in the structure of the system)
do not qualitatively alter the system's behavior, i.e. the system is “structurally stable”.

Intuitively it seems to be obvious that there are simpler and less simpler patterns of binary strings. A very simple pattern is 01010101, which shows biperiodicity. Assuming some “continuity hypothesis”, the behavior of the continuation of the pattern is predictable. It is not predictable, however, how to continue a randomly generated string. There are patterns, which are not simple and not random.

**Simple versus complex systems and the Deborah number**

Marcus Reiner, the founding father of rheology defined a non-dimensional number, the Deborah number $D$, as

$$D := \frac{\text{time of relaxation}}{\text{time of observation}}$$

(1.1)

The difference between non-changing “solids” and flowing materials “fluids” is then defined by the magnitude of $D$. If the time of observation is very large, or, conversely, if the time of relaxation of the material under observation is very small, you see the material flowing. On the other hand, if the time of relaxation of the material is larger than your time of observation, the material, for practical purpose is solid. The name resembles us to Prophetess Deborah [424], who sang (even before Heraclitus’s “panta rei”) “The mountains flowed before the Lord”. Deborah knew that not only that everything flows. She also knew that with the infinite observation time God can see the flowing of those objects what the man in her short lifetime cannot see.

We may conclude that the complexity of a stone should increase with the length of its observation.

**1.2.3 Complex systems**

Here are some characteristic properties of complex systems:

- Circular causality, feedback loops, logical paradoxes and strange loops
- Small change in the cause implies dramatic effects
- Emergence and unpredictability
Circular causality

Circular causality in essence is a sequence of causes and effects whereby the explanation of a pattern leads back to the first cause and either confirms or changes that first cause; Example: A causes B causes C that causes or modifies A. The concept itself had a bad reputation in legitimate scientific circles, since it was somehow related to use “vicious circles” in reasoning. It was reintroduced to science by Cybernetics (see Section 2.2.2), emphasizing feedback. In a feedback system there is no clear discrimination between “causes” and “effects”, since the output influences the input.

Feedback

Feedback is a process whereby some proportion of the output signal of a system is passed (fed back) to the input. So, the system itself contains a loop. Feedback mechanisms fundamentally influence the dynamic behavior of a system. Roughly speaking negative feedback reduces the error or deviation from a goal state, therefore has stabilizing effects. Positive feedback which increases the deviation from an initial state, has destabilizing effects. Natural, technological and social systems are full with feedback mechanisms (Fig. 1.2).

![Fig. 1.2. Systems with feedback.](image-url)

Systems with feedback loops are used by engineers (to serve them more justice) to stabilize the operation of plants. They use sensors and actuators to measure and control their system. The Greek Ktesibios, who lived in Alexandria, revolutionized the measurement of time by building a water clock. To achieve his goal he had to invent a regulator valve to maintain the level of the water in a tank at a constant level. Maybe he was the first who consciously used feedback control. (see later, such as Fig. 3.4). The toilet uses negative-feedback to fill itself up with water when flushed. In this case an impairment of the control system may show positive feedback, which implies non-required overfill. A simple example of feedback inhibition is a connected thermostat-heater system. A sensor detects the temperature, and when the temperature...
reaches a predetermined value, the thermostat signals the furnace to switch off. When the temperature drops below an other predetermined value, the furnace is turned back on.

For chemical reactions, positive feedback is related to the concept of **auto-catalysis**. Autocatalytic reactions have a specific property: \( n \) components generate \( n + m \) components, \( m > 0 \). For such reactions there is a self-amplifying mechanism between the concentration of a component and its velocity of formation: the velocity is increasing function of its own concentration.

In the “simplest case” the velocity is proportional with the concentration. “Simplest case” means that \( n = 1 \) and \( m = 1 \), so one component (molecules) produces two molecules by using some other component \( A \):

\[
\text{Linear autocatalysis:} \\
A + X \rightarrow 2X, \quad \text{velocity} = k[A][X].
\]

There are higher-order autocatalytic reactions, too. Quadratic autocatalysis:

\[
A + 2X \rightarrow 3X, \quad \text{velocity} = k[A][X]^2.
\]

Chemists often use a different terminology. They (we) call “linear” autocatalysis as “quadratic” and “quadratic” autocatalysis as “cubic”, respectively to reflect the *molecularity* of the reaction. Two molecules collide in the first case, three collide in the second.

There is a big qualitative difference in the behavior of the linear and the quadratic autocatalytic system. The first reaction is just equivalent to the model of population growth posited by Malthus more than two hundred years ago. The *assumption* of the model is that the rate of the increase of the population is proportional to the actual size of the population. The model leads to exponential growth (Fig. 1.3). It means that in the limit of infinite time the population size will be infinite. By modifying the assumption a little, and assuming that the encounter of two individuals is necessary to have a third individual leads to super-exponential behavior, specifically to “explosion”. The

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2 Any models are based on assumptions. Model builders like to play the game to study the effects of changes in the assumptions.
term “explosion” here means that during finite time period the population size will be infinite (Fig. 1.3).

Autocatalytic reactions have an important role in getting so-called exotic chemical behavior (as periodicity or deterministic aperiodicity (chaos) in the concentration, as it will be discussed later in several contexts. We shall return to the difference between exponential and super-exponential dynamics in the subsection 9.3.6.

Biological networks use feedback in all hierarchical levels of the organization. Jacob and Monod outlined a network theory of genetic control in prokaryotes (prokaryotes are simple cells, which don’t contain nucleus, while eukaryotes do) in 1961 [357, 255]. The Operon model is the classical model for the cellular metabolism, growth and differentiation (for the legacy and historical analysis of this seminal work see [361]). Now there are detailed mathematical models [577] which by taking into account the network structure of the lactose operon regulatory system (Fig. 1.4) are able to reflect the fundamental bistable property of the system.

Bistability occurs in many natural, social and technological systems, when a system is able to exist in either of two, so-called steady states, and when there is an abrupt jump from one state to the other. Bistability is a property of certain nonlinear systems, and such kinds of phenomena were demonstrated and analyzed in different fields, such as from phase transition in physics to jumps in the oil price and to interpretation of ambiguous figures etc. We shall return to this topic in Section 2.2.3. Abrupt jumps from one state to the other were subjects of interdisciplinary studies, what we shall discuss later under names of “phase transition”, “synergetics” and “catastrophe theory”.

Fig. 1.3. Exponential growth (linear autocatalysis) and explosion (quadratic autocatalysis). Left: linear scale. Right: logarithmic scale.
A simple example for positive feedback in economics is the relationship between income and consumption. By increasing income per capita there is an increase in consumption. Increased consumption has of course a positive effect in income (if nothing else changes, or “ceteris paribus” using a favorite term of economists).

Interestingly, Brian Arthur, who took the lion’s share in popularizing complex systems thinking in economics, and specifically to use positive feedback (or increasing return, using again the terminology of economists) [25] was strongly influenced by the Monod-Jacob feedback model in molecular biology, and the theoretical studies on autocatalytic reactions, which proved to be important ingredients of producing oscillatory patterns in chemical and biological systems.3

The sociologist Merton coined the term “Matthew effect” [351] as a mechanism for amplifying small social differences. He paraphrased the Gospel of

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3 “I started to read about enzyme reactions and the writings of Jacques Monod, a French molecular biologist and Nobel Prize winner. He had written a book called Chance and Necessity where small events could get magnified by positive feedbacks and lead to different enzyme reaction paths. I began to realize that the counterpart in economics to positive feedback was increasing returns. I started reading the physics of positive feedback, and particularly the work of the German Hermann Haken at Stuttgart and the Belgian Ilya Prigogine, a man I am very fond of…” http://www.dialogonleadership.org/Arthur-1999.html
St. Matthew 25:29 to explain why and how already established scientists are able to dramatically increase their resources compared to others.

The stability and occasionally abrupt change in governmental policies and institutions can be explained by negative and positive feedback processes (see Baumgartner and Jones 2002), [51]. Negative feedback processes ensure the stability of institutions, while positive feedback, i.e. self-amplifying processes may help to diffuse new ideas. The more politicians talk about an issue, such as health-care system or prescription drug coverage, the more the public will be concerned with it. Examples of actions implying stability: counter-inflatory effects of the Federal Reserve, unemployment compensation, price supports for farmers, etc. ... The political scientists Baumgartner and Jones cite the mathematician-economist Brian Arthur to explain, that the “increasing return” mechanism also operates in politics. (It is interesting to see the propagation of ideas through disciplines: Arthur’s economic theory was motivated by physical-chemical and biochemical models, while his economic models fertilized thinking in political science.)

One mechanism of the decision-makers is based on mimicking others behavior, a strategy labeled as “go with the winner”. Nobel prize winner (2005) Thomas Schelling [457] (go with him) set a celebrated model of segregation. In his model there are two types (say, red and blue, or white and black) of agents, who live in a two-dimensional grid. The agents may choose to remain or to move to a free space. With the model it is possible to investigate the effect of different rules. Schelling concluded that even without having a racist attitude, a slight preference to live “among your owns” may lead global segregation. Schelling models will be discussed in Section 4.7.1.

Schelling studied a variety of social phenomena, where the individual decision was determined by the behavior of the others in the group. We are ready to cross the street when the light is red, if others around us do the same, we buy similar goods as our neighbors, and so on. Schelling intuitively has foreseen that there are situations, which basically have two outcomes, i.e. they show bistability; adopting Schelling’s terminology, two macrobehaviors (which emerged from the micromotivations of the individuals). Either all people cross the street, (since the positive feedback among the people amplified the action), or everybody decides to wait. Either everybody starts to applause after a performance, or a weak applause decays very rapidly. Which of the two possibilities will be realized, it is determined by the number of people involved.

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4 “To him who hath shall be given and from him who hath not, shall be take away even what he hath”, from the parable of the three servants”
If it is larger than a critical mass than (well, almost) everybody will do the same.\textsuperscript{5}

**Logical paradoxes**

Logical paradoxes are also intimate ingredients of complexity. While this subsection will speak about paradoxes, first let’s discuss a case which turns out to be non-paradoxical. The so-called liar paradox goes back to Epimenides, who lived in the sixth century BC. He wrote: A person from the island of Crete asserts:

\begin{center}
All Cretans are liars.
\end{center}

We can conclude that if he is telling the truth, then he is lying. One might believe that if he is lying, then he is telling the truth. But the statement is not paradoxical at all: if there has ever been a Cretan who made a true statement then Epimenides’s sentence is simply false without implying its own truth. This is a paradox only if Epimenides is the only Cretan.

A paradox may emerge if the sentence is self-referential: A man says that he is lying. Is what he says true or false? The core of this paradox is:

\begin{center}
This sentence is false.
\end{center}

A self-referential sentence talks about itself. Another form of the paradox is when a single sentence is not self-referential, but it refers to the next sentence, which refers back to the first one, in a controversial way:

\begin{center}
The next sentence is false.  
The preceding sentence is true.
\end{center}

\textsuperscript{5} Phil Ball [40] enthusiastically popularizes how the concepts of physics can be used to predict the collective behavior of a large group of people.
Russel’s Barber Paradox:

In a small town, a barber cuts the hair of all people who do not cut their own hair, and does not cut the hair of people who cut their own hair. Does the barber cut his own hair? Suppose he does cut his own hair. But by the second half of the first sentence, he does not cut the hair of people who cut their own hair, including the barber himself. Contradiction. Suppose he does not cut his own hair. Then by the first half of the first sentence he does cut the hair of people who don’t cut their own, including the barber himself. Contradiction.

Strange loops

Probably the (sorry, not too young) Reader will agree with me, that the most popular (which certainly does not mean that the most extensively read) book on complexity issues (though this terminology is hardly used in the the book) is Hofstadter’s Gödel, Escher, Bach: an Eternal Golden Braid [238]. The book is about “Strange loops”. Strange loop is a sophisticated version of self-reference. As Hofstadter says: “whenever, by moving upwards (or downwards) through the levels of some hierarchical system, we unexpectedly find ourselves right back where we started”. Escher’s famous Waterfall (Fig. 1.5) is an example for strange loop: the water flows continuously down, still returns again to the top of the waterfall. Our intuitive notion that water flows downhill is challenged.

Hofstadter uses the strange loop as a paradigm to interpret paradoxes in logic, and founds it as a main organizational principle (not his terminology) not only in mathematics and computer science, but also in molecular biology, cognitive science, and in political science.

Feedback cycles, strange loops and iterative algorithms (recursions), are elements leading to complexity. When I checked what Wikipedia writes about it, and found a subsection about recursive humor, I laughed:

Recursion

See “Recursion”.

Recursive algorithms might lead to certain type of complex structures which have the property of self-similarity (Fig. 1.6).
Small changes imply dramatic effects

The expression “butterfly effect” became well-known, even in the popular culture. As we may read in http://www.anecdotage.com/index.php?aid=1358 (checked in June 16th, 2007):

Butterfly Effect
While working on a weather prediction problem one day in 1961, Edward Lorenz, using a computer to model the weather with a system of 12 basic equations, ran a program from the middle rather than the beginning – and entered parameters to three decimal places, rather than the normal six. Lorenz was surprised to see how differently the weather patterns evolved. Such minute changes, he supposed, might be caused by something as trivial as the beating of a butterfly’s wing. Lorenz had discovered the so-called “butterfly effect”, and was soon embroiled in chaos theory …

We know its geographic variations:

- The flap of a Butterfly’s Wings in Brazil sets off a Tornado in Texas.
- A butterfly flapping its wings in Kansas could trigger a typhoon in Singapore or a downpour on your summer party.
- A man sneezing in China may set people to shoveling snow in New York.
- A butterfly flaps its wings in Asia, the action may eventually alter the course of a tornado in Kansas.
- A butterfly flapping its wings in Tokyo could cause a cyclone in the Caribbean.
- A butterfly flapping its wings in South America can affect the weather in Central Park.
- The possibility of large storm in New England may be caused by a butterfly wing flap in China.

Edward Lorenz himself gave a lecture in a session on Global Atmospheric Research Program of the meeting of the American Association for the Advancement of Science in 1972 with the title “Predictability: Does the Flap of a Butterfly’s Wings in Brazil set off a Tornado in Texas?” Somewhat more technically speaking he suggested that certain dynamical systems show “sensitive dependence on initial conditions”, and small errors are subjects of dramatic amplification. Implicitly, the effect of a flap in the reality is similar to a round-off error in his model.
1.2 Characteristics of simple and complex systems

The “butterfly effect” is at most a hypothesis, and it was certainly not Lorenz’s intention to change it to a metaphor for the importance of small event. It is used at least in metaphoric sense to explain stock market crashes, but also political events (how the tiny change in the mind of the designer of the ballot paper in Palm Beach for the US Presidential election in 2000 led to the result, which finally was settled by the Supreme Court).

Dynamical systems that exhibit sensitive dependence on initial conditions produce remarkably different solutions for two initial values that are close to each other. Sensitive dependence on initial conditions is one of the properties to exhibit chaotic behavior. In addition, at least one further implicit assumption is that the system is bounded in some finite region, i.e. the system cannot blow up. When one uses expanding dynamics, a way of pull-back of too much expanded phase volume to some finite domain is necessary to get chaos. This property is also true for linear systems: \( \frac{dx}{dt} = ax, \ a > 0 \), the solutions are written down by \( x(t) = x(0) \exp(at) \), which means exponential separation of the difference of two close initial points. This example is just an unbounded expanding system. The complicated geometry behind the generation of chaos, and the stretching and folding of trajectories leading to divergence will be discussed in Section 3.6.2.

A large class of chaotic motions, which seem phenomenologically irregular, lead to strange attractors as opposed to simpler motions, e.g. damped or sustained oscillations which tends to simpler attractors, such as points, or closed curves. Strange attractors have fractal structure. Fractals often (but not always) are self-similar. Strange attractors have complex structure, but sometimes even simple rules, simple algorithms (such as the logistic difference equation, a very simple example of a first-order difference equation) may lead to such kinds of patterns.

\[
x_{n+1} = rx_n(1 - x_n), \quad x_0 = \xi
\]

where \( r \) is the only parameter, and \( \xi \) is the starting point of the iteration.

The equation is recursive or iterative mapping: the result of the mapping is fed back to the equation, producing a new result, i.e. a new \( x_n \) etc. What is interesting, that depending on the value of the control parameter \( r \), the mapping leads to qualitatively very different results (Fig. 1.7). The general form of the first-order iterative mappings is \( x_{n+1}(r) = f(x_n(r), r), x(0) = x_0 \).

How sensitive are the solutions with respect to the control parameter \( r \) and the initial value \( x_0 \)?

Bifurcations analysis seeks answer to the first question. More precisely, it is used for studying the changes in the long term qualitative behavior of the system. Chaos is related both in changes in the parameter value, and
sensitivity to the initial conditions as well. There are parameter windows where chaos may occur, and a basic property of chaotic systems is the sensitive dependence of the solution on initial conditions.

Fig. 1.7. For $r = 2.8$ the system shows a damping oscillatory approach to a fixed point. For $r = 3.3$ there is a non-damping, self-sustained oscillation between two points. For $r = 3.8$ there is a chaotic, irregular behavior. The right bottom part of the figure shows the results of a somewhat longer simulation.

Chaos is a fundamentally important example what we might call dynamic complexity. It became extremely popular in the 1980s. This was the period when personal computers started to be used and simple (or not so simple) equations were solved numerically and the results were visualized. In many labs students and their teachers played with their computers and found that visualization of scientific results is important and possible. For a black-and-white version see Fig. 7.11 in Chapter 7.

Emergence and unpredictability

István Örkény: The meaning of life
If we string up a bunch of red hot peppers, we end up with a wreath of red hot peppers. On the other hand, if we don’t string up a bunch of red peppers, we will not end with a wreath of red hot peppers. The peppers will be just as many, just as red as hot, but they will not be a wreath of hot peppers.

Is it the string? No, it is not a string. The string, as we know is a third-rate factor of little importance. What then?

Whoever falls to thinking about this and makes sure not to let his thoughts stray from true path may come to discover many great truths.

[390] István Órkény, Hungarian writer, wrote among others grotesque with the title “One minutes stories”

The problem of “emergence of complexity” has at least two different levels. First, what parts of a system do together that they would not do by themselves. One molecule of H$_2$O is not liquid, one neuron is not conscious, one amino acid is certainly not alive, one sheep is not a herd, one soccer player is not a team (well, eleven players are also not necessarily a team, as desperate Hungarian soccer fans know these days, more than fifty years after the great period of Ferenc Puskás and his teammates). How do system properties arise from the properties of the parts connected? Sometimes system properties emerge due to the local interactions among the elements, without any external command, so the mechanism is called self-organization. In other case (say, soccer), some external stimulation might help (a little bit). But even the best coach is unable to build a world champion team from a set of ungifted players.

Second, there exists the question about the “evolution of complexity” occurring in phylogenetic time scale. Theory of evolution suggests that there is a mechanism called “natural selection” which explains the development of life forms. While it does not predict precisely the future forms, as the theory is sometimes criticized, Peter Medawar, a Nobel-prize winner biologist answered the critics in 1973:

“...finds Darwinian theory still at fault from a strictly methodological point of view. Darwinians have yet to produce a theory which makes specific predictions possible. I think the justice of this criticism really depends on how specific the predictions have to be. Let us imagine, as is not improbable, that a metabolic product which we shall call gorgonzolin of the mold Penicillium
gorgonzoli is a powerful antibiotic. From what one knows of the genetic system of bacteria it is already quite possible to predict that if strains of streptococci or staphylococci are cultivated in sublethal concentrations of gorgonzolin a new variant will eventually appear which is entirely resistant to the action of gorgonzolin. It is true that gorgonzolin has not yet been discovered, but a great many fungal antibiotics have been, and I predict that what has turned out to be true of all of them would turn out to be true of gorgonzolin also.”

Interestingly, the lack of ability to predict does not imply qualms regarding the relevance of a scientific discipline. While there is some progress in predicting the onset of epileptic seizures, eruption of earthquakes and crash of stock market, or at least it is possible to analyze the limits of predictability, (as we shall discuss in Section 9.3.1) nobody claims that neuroscience, geophysics and economics are not legitimate scientific disciplines.

1.3 Connecting the dots

The intention of our book is to explain complexity, by connecting the scattered dots of concepts. The spirit of complex systems research can be understood by analyzing the ideas, concepts and methods related to different disciplines. While these disciplines sometimes cooperated and competed with others, in other times they neglected each other.

Complex systems research certainly was not mainstream during the incredible success of quantum physics, relativity theory and molecular biology (and the twentieth century physics and biology dramatically changed the world), there were however several scientific disciplines which searched for “organization principles”.

In Chapter two the history of complex systems research is reviewed. Berta lanffy’s systems theory was interested in finding common principles in different disciplines, so he tried to revive the concept of the “unity of science”. He suggested that to explain life phenomena theoretical biology should be based on the notion of open systems. The founding fathers of the general systems did not want to establish a “general theory of everything”, which would not have any content. They hoped to integrate the different perspectives, and also to analyze and synthesize different forms of complexity.

The birth, rise, and fall, or better saying, dissolution of cybernetics, the science of “communication and control in animals and machines”, was about the theory of the computers and brains. The mathematician Norbert Wiener,
1.3 Connecting the dots

and the neurophysiologist Warren McCulloch are the founding fathers of cybernetics. It was an optimistic movement, with some overambitious goals. It used many concepts, which became popular again related to both the science of “complex adaptive systems” around the Santa Fe Institute, and to the discipline of cognitive science.

Cybernetics is striking back now, and many of its ideas appear from brain theory and cognitive science to complex systems theory, see Section 8.6.1.

In the nineteen seventies three disciplines, each of them with the goal of being interdisciplinary and emphasizing “nonlinearity” became fashionable in Europe. The connotation of the word “nonlinearity” was that “linear” is uninteresting, and nonlinearity leads to different and nice patterns in time and space. I think, three European schools, each of them had leaders with strong personality, dominated the field. The theory of “dissipative structures” grew out from non-equilibrium thermodynamics and was labeled with the name of Ilya Prigogine, and his “Brussels school”. Hermann Haken (Stuttgart) used the term “synergetics” to deal with systems, where order is an emergent property of macroscopic systems due to the interactions of elementary constituents. “Catastrophe theory” is a mathematical theory for classifying abrupt qualitative changes in the behavior of a system due to small changes in the circumstances. It emerged from the works of the French mathematician René Thom. Thom’s approach was deeply deterministic, while the other two schools took into account random effects and fluctuations to get ordered structures.

Chapter three is about the complexity of temporal patterns, i.e. about notions, such as periodicity, reversibility, irreversibility and chaos. The concept of time is strongly culture-dependent, and there is an evolution of the concept from the ancient Mayan cyclic world view via the Newtonian clockwork worldview and pessimistic view of the eventual heat death of the Universe to the modern concept of irreversibility. Mechanical clocks not only measured the passing time but served as the model of the eternal, periodically moving Universe. The collision between the “reversible” mechanics and the “irreversible” thermodynamics led to the birth of statistical physics, which now seems to be a very efficient conceptual and mathematical tool to understand collective phenomena beyond the kingdom of strict physics. Nature and society is full with periodic phenomena. A very popular model of oscillatory changes is the Lotka-Volterra model. It explained, more precisely gave an insight into the mechanism of the prey-predator dynamics. The model was able to describe the periodic change of the quantity of “big” and “small” fishes in the Adriatic sea, under the qualitative assumptions that the small fish has infinite resource (say, plankton), the big fishes’ only food are small fishes, and there is a natural decay of the big fishes. This toy model, and its generalizations, are popular tools in modeling competitive and cooperative interactions, in biological, economical and sociological context. One of the most important ingredients of
any theory of complex processes, as we mentioned earlier, is chaos theory. Chaos theory was a big fashion, although as it happens with any fashion, its popularity is decaying. Chaotic phenomena are, in any case very important, they give a unique insight to understand the mechanism of generating a large class of unpredictable events. There are big universal questions: does biological and even cosmical evolution have an irreversible direction, or are there any arguments that they are cyclic phenomena?

Chapter four illustrates the scope of the dynamic world view, which grew out from mechanics. As in the mechanics of mass points, the state of a point is determined by coordinates, the composition vector of chemical components determines the “chemical state”, a vector, which defines the quantities of the different species. The temporal change of the state due to the interaction among chemical components or among species is described by the laws of chemical kinetics, and the laws of population dynamics, respectively. Such kind of causal modeling approach helps to understand biological and social processes as well, as biological pattern formation, propagation of epidemics and ideas, evolutionary dynamics, opinion formation, attitude changes, business cycle etc.

Chapter five is about the role of deductive and inductive reasoning and strategies in decomposing and constructing complex systems. Cybernetics and artificial intelligence is mentioned in terms of combining different reasoning strategies through the contributions of two intellectual giants, John von Neumann and Herbert Simon. Chapter six is about randomness. Biological variation was dominated by the Gaussian distribution. Deviation from the average behavior (which is in this case equivalent with the “most probable” state) is symmetric. Deviation from average height is symmetric: roughly the same number of people are shorter and taller than the average. Asymmetric (skew) distributions have strongly different properties. The distribution of wealth of people is not symmetric. There are much less people with large income than with a low one. The popular 80-20 thumb rule says that 20% of the population owns 80% of the wealth. There are a set of models, which lead to such kinds of skew distributions, such as lognormal distribution and power law distribution.

In many respects, complex structures are neither purely regular, deterministic nor completely random structures. Chapter seven is opened by discussing structural complexity, and the ways of measuring it. Then self-organizing mechanisms and algorithms are discussed, the interaction between deterministic and random effects are specifically studied. Randomness and complexity in artworks (of Jackson Pollock) are also discussed. Networks have many excellent properties to represent natural, technological, social systems, so it is easy to accept why network theory is so important in analyzing complex systems.
In addition to a brief review of its main concepts, a specific class of networks, i.e. citation networks in technology, will be explained.

In colloquial sense we often say that the brain is the most complex structure. Chapter eight discusses the brain-mind-computer trichotomy. Both the philosophical and experimental backgrounds are briefly reviewed. Then the basic principles of neural organization, and the frameworks of the fundamental computational models are summarized. We argue that the tradition of cybernetics combined with the perspective of complex systems theory offers a framework of a brain-mind-computer theory.

Chapter nine gives some more ideas on how to use complex systems in practice. The comparative analysis of equation-based and agent-based modeling strategies is given. What we can hope now from game theory? Once it was applied for analyzing political conflicts in terms of predicting the outcome of possible strategies depending of the strategies of the other players, and later was successfully applied to evolution. Evolutionary game theory offers causal mechanisms for the emergence of cooperation and social norms. Complex systems theory, in accordance with the ambition of the elder days general systems theory is interested in finding similarities among the (un?)-predictability of such kinds of phenomena, as epileptic seizure, eruption of earthquakes, and stock market crashes.

In the final, tenth Chapter it will be summarized how the ingredients of complex systems contribute to explain complexity. We argue that complex systems research offers a perspective to (well, not to bridge, but at least) narrow the gap between science and the humanities. While the “Age of Reason” is over, the author agrees with those who work on a new, “third culture”, and believe that “bounded rationality” and the acceptance of our fallibility is the only way for mankind to survive ourselves.