Chapter 1

THE BACKGROUND TO SYSTEMICS

1.1 Introduction

This book is devoted to the problems arising when dealing with emergent behaviors in complex systems and to a number of proposals advanced to solve them. The main concept around which all arguments revolve, is that of Collective Being. The latter expression roughly denotes multiple systems in which each component can belong simultaneously to different subsystems. Typical instances are swarms, flocks, herds and even crowds, social groups, sometimes industrial organisations and perhaps the human cognitive system itself. The study of Collective Beings is, of course, a matter of necessity when dealing with systems whose elements are agents, each of which is capable of some form of cognitive processing. The subject of this book could therefore be defined as "the study of emergent collective behaviors within assemblies of cognitive agents".

Needless to say, such a topic involves a wide range of applications attracting the attention of a large audience. It integrates contributions from Artificial Life, Swarm Intelligence, Economic Theory, but also from Statistical Physics, Dynamical Systems Theory and Cognitive Science. It concerns domains such as organizational learning, the development or emergence of ethics (metaphorically intended as *social software*), the design of autonomous robots and knowledge management in the post-industrial society. Managers, Economists, Engineers, as well as Physicists, Biologists and Psychologists, could all benefit from the discoveries made through the trans-disciplinary work underlying the study of Collective Beings.

From the beginning, this book will adopt a *systemic* framework. The attribute "systemic" means that this framework fits within *Systemics*, a thinking movement which originated from *General Systems Theory*, proposed by Von Bertalanffy and from *Cybernetics*, introduced by Wiener and developed by Ashby and Von Foerster (Von Foerster, 1979). A systemic framework is characterized by the following features:

- Focus is placed upon the global, holistic properties of entities qualified as *systems*, which, in general, are described in terms of elements and of their interactions;
- the role and the nature of the *observer*, as well as the *context*, are taken into account, as far as possible, within the description and the modelling of each and every phenomenon;
- the goal is not that of obtaining a *unique, correct* model of a given behavior, but rather of investigating the *complementary* relationships existing between *different* models of the same phenomenon.

In order to better specify the domain under study, we will introduce, distinctions (which could even be considered as hierarchical) between different kinds of systems:

- *simple systems*, where each component is associated (in an invariant way) with a single *label* (which could even be a number), specifying its nature and allowed operations ; a limiting case of simple systems is given by *sets*, in which the individual components cannot perform operations, but only exist;
- *Collective Beings* (Minati, 2001), where each component is associated (in a variable way) with a *set of possible labels*; the association between the component and the labels depends upon the *global behavior* of the system itself and can vary with time; a typical case is a flock of birds, within which each bird can be associated with a single label, specifying both its relative position within the flock and the fact that its operation consists only of flying in such a way as to keep constant its distance with respect to neighboring birds. Such an association, however, holds as

long as the flock behaves like a flock, that is like a single entity; as soon as the flock loses its identity, a single bird becomes associated with a set of different labels, specifying different possible operations such as flying, hunting, nesting and so on; this new association can define a different Collective Being, such as a bird community;

- *Multi-Collective Beings*, characterized by the existence, not only of different components, but even of different levels of description and of operation; each component and each level is associated (in a variable way) with a set of possible labels; the forms of these associations depend upon the relationships existing between the different levels. Examples of multi-Collective Beings include the human cognitive system and human societies.

This book principally considers the study of Collective Beings and, in addition to a review of the existing approaches for modeling their behaviors, we will introduce a general methodology for dealing with these complex systems: the DYnamic uSAge of Models (DYSAM) (Minati, 2001). The latter will be applied to cases in which it is manifestly impossible, in principle, to fully describe a system using a single model.

This chapter will introduce the reader to some fundamental concepts of Systemics, by starting from a short history of Systemics and of the associated evolution from the concept of 'set' to that of 'system'. Several examples will help the reader in this introductory approach. The distinctions between sets, structured sets, systems and subsystems will allow the reader to better understand new theoretical concepts, introduced in subsequent Sections of this book, such as those of Collective Beings, of DYnamic uSAge of Models (DYSAM) and of Ergodicity, within the context of the tools used to detect emergence.

In the second part of this chapter reference will be made to some technical tools of Systemics both to complete the historic overview and because they serve as an introduction to Chapter 4, where we will deal with the problems of managing emergence.

1.2 What is Systemics ?

The father of Systemics was Ludwig von Bertalanffy (1901-1972). He was one of the most important theoretical biologists of the first half of the Twentieth Century. His interdisciplinary approach (researcher in comparative physiology, biophysics, cancer, psychology, philosophy of science) and his knowledge of mathematics allowed him to develop a kinetic theory of stationary open systems and General Systems Theory. He was one of the founding members and Vice-President of the Society for General Systems Research, now renamed as the International Society for Systems Sciences (ISSS). The "Society for General Systems Research" (SGSR) was formally established at the 1956 meeting of the American Association for the Advancement of Science (AAAS), founded in 1848. The SGSR was born under the leadership of Ludwig von Bertalanffy, the economist Kenneth Boulding, the neurophysiologist Ralph Gerard, the anthropologist Margaret Mead, the psychologist James Grier Miller and the mathematician Anatol Rapoport.

Von Bertalanffy held positions, to mention but a few, at the University of Vienna (1934-48), the University of Ottawa (1950-54), the Mount Sinai Hospital (Los Angeles) (1955-58), the University of Alberta (1961-68) and the State University of New York (SUNY) (1969-72).

A collection of his essays was published in 1975, three years after his death.. This collection (Von Bertalanffy, 1975) included forewords written by Maria Bertalanffy (his wife) and Ervin Laszlo. The latter added the following considerations about the term *General Systems Theory*:

> "The original concept that is usually assumed to be expressed in the English term *General Systems Theory* was Allgemeine Systemtheorie (or Lehre). Now "Theorie" or Lehre, just as Wissenschaft, has a much broader meaning in German than the closest English words *theory* and *science*."

The word *Wissenschaft* refers to any organized body of knowledge. The German word *Theorie* applies to any systematically presented set of concepts. They may be philosophical, empirical, axiomatic, etc. Bertalanffy's reference to *Allgemeine Systemtheorie* should be interpreted by understanding a new perspective, a new way of *doing science* more than a proposal of a *General Systems Theory* in the dominion of science, i.e. a *Theory of General Systems*.

In this book, instead of using terms such as *Theory of General Systems* or *General Systems Theory* we will use the word *Systemics*, widely used in English language systems literature (see par. 1.3, point i), keeping in mind the distinction mentioned above, and emphasizing that the reference is not only to the scientific domain, which is the topic of this book, but to an overall, general approach towards understanding phenomena in an interdisciplinary manner. The meaning adopted for the word Systemics, therefore, will be that specified in the introduction to this chapter, with the proviso that such an approach to the study of scientific questions will need the design of suitable methodologies and technical tools, which will be described in this book.

1.3 A short, introductory history

In this chapter a short introductory history of systems thinking will be outlined. The reader, by using some of the keywords and consulting a history of philosophy and science and encyclopaedic sources, some of which are listed in the bibliography, will be able to reconstruct a disciplinary framework adequate for his/her interest and background. Information about the history of systems thinking evolution is available in the literature in many books and papers (see, for example, Von Bertalanffy, 1968; Umpleby and Dent, 1999). References and key concepts are also described in Appendix 1.

a) The concept of System as a **mechanism** and as a **device.** From the idea of system as a configuration of assembled components, producing a *working* mechanism, based on the concept of *machine*, in its turn based on many concepts of classic physics, it is possible to extrapolate the powerful abstraction of *device.* The latter concept still makes reference to assemblies of components working as a whole, but having non-mechanical relationships among the components themselves; typical examples are given by electronic devices or software programs. In these cases we may refer to abstract entities, such as procedures, and within this context we will deal with *systems control, automata theory, control techniques.* This context is known as *Cybernetics*, a term coined from the Greek "pilot of the boat" (Ashby, 1956). This approach provided the basis for modern **systems engineering** (Porter, 1965).

b) **Cybernetics** has been very important in the process of establishing systems thinking. It has been defined as the science of behavior, communication, control and organization in organisms, machines and societies. One of its salient features was the introduction of the concept of *feedback*, viewed as a sort of self-management or self-regulation. Cybernetics as a scientific discipline was introduced by **Norbert Wiener** (1894-1964) in the Forties (Wiener, 1948; 1961), with the goal of studying the processes of control and communication in animals and machines. Initially, (Ashby, 1956; Heims, 1991) it was identified with information theory. A very well- known stereotyped example of a cybernetic device, often used in a metaphorical way, is Watt's centrifugal regulator designed for steam engines (see Figure 1.1): it is based on a feedback process able to keep constant the angular velocity of a steam engine. As can be seen in

Figure 1.1 the base R of the regulator moves upward or downward, its direction of motion depending on the rotation speed of the shaft A. If the base R of the regulator is connected to a regulating valve, the device is able to self-regulate by keeping the shaft rotation velocity constant.

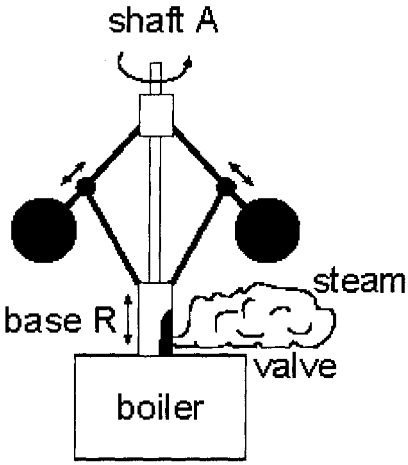


Figure 1-1. Watt's centrifugal regulator.

The behavior of Watt's centrifugal regulator can be easily described in mathematical terms, through the equation of motion:

$$m\ddot{\phi} = mn^2 \sin\phi\cos\phi - mg\sin\phi - b\dot{\Phi} \qquad (1.1)$$

where :
- ϕ is the rotation angle of the axis,
- m is the mass of the revolving pendulum,
- n is the transmission ratio,
- Φ is the rotation speed of the motor axis,
- g is the gravitational constant,
- b is the dissipation constant depending on the viscosity of the pivot.

Cybernetics allowed the creation of relationships among regulation models operating in different fields, such as those describing the operation of animal sense organs, where self-regulation processes are identifiable. One example is the eye which, when hit by light, automatically reduces the aperture in the iris thus regulating the amount of light entering the eye.

Another example may help to characterize the domain in which the concepts of Cybernetics can be applied.

The problem of computing the trajectory of an artillery shell, starting from the knowledge of all initial factors determining the shell's motion, cannot be considered as a cybernetic problem. On the contrary, it becomes cybernetic when the missile itself is capable of continuously correcting its trajectory, as a function of the information about the nature of the trajectory and the position of the target.

Other approaches to Cybernetics were introduced by:

- **Warren McCulloch** (1898-1968), neuro-physiologist, introduced the mathematical model of Neural Networks and considered cybernetics as the study of the communication between observer and environment;
- **Stafford Beer** (1926-), researcher in management, considered cybernetics as the science of organization (Beer, 1994);
- **Gregory Bateson** (1904-1980), anthropologist, introduced a distinction between the usual scientific approach, based on matter and energy, and cybernetics, dealing with models and forms (Bateson, 1972).

c) **System Dynamics (SD)**, in which a system is identified with a configuration of regulatory devices. The expression "System Dynamics" actually denotes a methodology introduced by **Jay W. Forrester** (1918-) in 1961, in his book "Industrial Dynamics" (Forrester, 1961) to study and implement systems of feedback loops (an example of a single feedback loop involving two elements A and B is shown in Figure 1.2), associated with configurations of interacting elements. A system consisting of interacting (through feedback) elements can exhibit global emergent behaviors, not reducible to those of the single individual elements nor to the feedback among them. Such behaviors, for instance, occur within electrical networks and traffic flows. This approach was assumed to be the most suited to describe the interactions among industrial departments which emerge within companies.

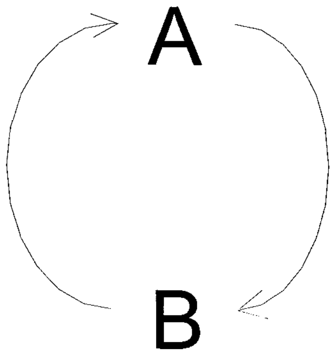


Figure 1-2. System of feedback loops

To summarise, Systems Dynamics deals with conceptual networks of elements interacting through feedback loops. This approach is mainly used for software simulations of corporate dynamics and social systems (Forrester, 1968), but also to model organized social systems (Meadows *et al.*, 1993).

d) **The theory of dynamical systems**

System Dynamics (SD) must be not confused with *Dynamical Systems Theory*. In the mathematical literature often a *continuous dynamical system* in an open interval w is described by an autonomous (i.e. whose right hand members are time independent) system of ordinary differential equations which hold for a vector of dependent variables x:

$$dx/dt = F(x) \qquad (1.2)$$

The theory of dynamical systems, implemented on the basis of the fundamental intuitions of **H. Poincaré** (1854-1912), showed the coexistence of ordered and chaotic behaviors in the study of almost any kind of system which can be represented in mathematics and physics. Simple systems, such as a pendulum or the Moon moving along its orbit, can be described by using the equations of motion of classical mechanics. A dynamical system is associated with two kinds of information:

- One which deals with the representation of the system's state and with basic information about the system itself;
- Another specifying the dynamics of the system, implemented through a rule describing its evolution over time.

The time evolution of a dynamical system may be geometrically represented as a graph in a multidimensional space, the so-called *phase* *space*. It should be noted that by looking only at the form of the orbits in the phase space, we do not describe the geometrical movement of the system, but only the relationships among its independent variables (see Appendix 1).

e) **Gestalt Psychology** introduced an important new approach, related to systems thinking. It originated in Germany, in 1912, under the name of *Gestaltpsychologie*. In the same period in the U.S., *Behaviorism* (Skinner, 1938; 1953), holding an opposite view of psychology, was born.

The German term *Gestalt* refers to a structure, a schema, a configuration of phenomena of different natures (psychological, physical, biological and social) which are so integrated as to be considered an indivisible whole having different properties from those of its component parts or of a subset of them.

Gestalt Psychology is part of the anti-mechanistic and anti-reductionistic movement deriving from the crisis of positivism.

According to this approach it is not possible to reduce psychological phenomena to a chain of stimulus-response associations as, on the contrary, is held by the Behaviorist approach.

Gestalt Psychology triggered a thinking movement, which led to the establishment of systemic psychology.

f) The term **organicism** refers to a view which, in contrast with positivism, assumes that a living system is a finalistic organized whole and not simply the mechanical result of the sum of its component parts. This conception, of biological origin, has been more generally expressed, for instance, by (Whitehead, 1929) who used the word 'organicism' to denote his general philosophical conception. In the field of sociology Compte and Spencer adopt this approach.

g) The term **vitalism** refers to conceptions according to which the phenomena of living beings are so peculiar as to make their reduction to physico-chemical phenomena of the inorganic world impossible. In the second half of the 18th century vitalistic doctrines opposed mechanicism, by hypothesizing, to explain the phenomena of life, a force acting as an organizing principle at the molecular level, separated from the soul or spiritual values. This force, called from time to time 'life force', or 'life surge', is the key aspect of such a conception. This concept began to wobble with the synthesis of urea, representing the birth of organic chemistry, and Darwinism.

Recent advances in genetics and molecular biology have reduced interest in the confrontation between vitalists and mechanicists.

Even today a *theory of living* is still lacking, even though very important progress in the *physics of living matter* has been made (Vitiello, 2001).

h) The term **complexity** relates to problems and conceptual tools (Flood and Carson, 1988) which have chiefly emerged from physics. Brownian motion provides an important historic example. In this case random fluctuations are directly observable, and this circumstance gave rise to the basic concepts of complexity. Brownian motion is the irregular, disordered, unpredictable motion of a speck of pollen in water. The motion is caused by interactions with water molecules, moving in their turn with thermal energy. As a consequence, it becomes impossible to build a deterministic model of this phenomenon. According to classical physics the reason why deterministic models of phenomena like this are not available is because of an incomplete knowledge of all physical features of the components of the involved systems.

On this point, there are two conflicting views:

- The *mechanistic* view, based on the so-called *strong deterministic hypothesis*, according to which we can reach a presumed infinitely precise knowledge of position and speed of all components of a physical system and this knowledge, in principle, could give rise to a deterministic theory of the system itself. Among the holders of this view we can quote Newton (1643-1727) and Laplace (1749-1827). Faith in this conception was shaken for the first time by the failure of classical mechanics to solve the so-called *Three-Body Problem* (Barrow-Green, 1997), tackled by mathematicians including Eulero (1707-1783), Lagrange (1736-181), Jacobi (1804-1851), Poincarè (1854-1912), (see *chaotic* in Appendix 1). Another key principle of the mechanistic view is that of Descartes, according to which *the microscopic world is simpler than the macroscopic one.*
- The view based on the theory of complexity, according to which a complex system can exhibit behaviors which cannot be reduced to those of its component parts, even if it were possible to know with absolute precision their positions and velocities. This view also acknowledges that in most cases it is practically impossible to obtain complete information about microscopic positions and velocities, hypothesized by Newton and Laplace. This circumstance has been proven by many experiments, whose explanation needs more effective conceptual tools. With the term *complexity* reference is made to themes such as (see Appendix 1) *deterministic chaos*, *role of the observer* (Chapter 2), *self-organization*, *science of combined effects* or *Synergetics* (Haken, 1981). A typical example of a complex system, containing a huge quantity of elements and interconnections among them, is the **brain**.

i) **Systems thinking** may be dated back to cultural frameworks of different natures, all oriented towards recognizing *continuity* and unity in a reality fragmented and desegregated into different disciplines, languages, approaches and conceptions (Checkland, 1981; Checkland and Scholes, 1990; Emery, 1969; Flood and Jackson, 1991). Thousands of references relating to different domains are available (introductory ones include, Bohm, 1992; Boulding, 1956; 1985; Briggs and Peat, 1984). References to approaches, currently denoted as *systemic*, may even be found in the Biblical theme of the confusion of languages in the story of the *Babel tower*; in the Talmudic way of thinking in Hebrew culture, as told by S. Freud [1]; in Heisenberg's autobiography with the original German title "The share and the whole" (Heisenberg, 1971); and in many others cases quoted by Capra (Capra, 1996), where systems thinking and its birth are discussed. The expression *General Systems Theory* refers to the fundamental work by Von Bertalanffy (Von Bertalanffy, 1968). Von Bertalanffy states in that book (in which, by the way, a sound introduction to the history of systems thinking is presented) that he introduced the idea of a General Systems Theory for the first time in 1937 during a philosophy conference in Chicago. Around the concept of 'system', suitable for generalizing concepts previously formulated within different contexts, intense research activity has grown. The goals of the latter include both the study of invariant system features and the search for conceptual and methodological (Churchman, 1968; 1971) application to different disciplinary contexts, General Systems Theory (Rapoport, 1968; Sutherland, 1973) was introduced to describe a system as a phenomenon of **emergence** (see Chapter 3) (Von Bertalanffy, 1950; 1952; 1956; 1968; 1975). As introduced at the beginning of this chapter, this expression refers to a general cultural approach more than to a real theory. Actually, *theory* is a very strong word in science (Kuhn, 1962). Following the approach proposed by Popper it must be possible to falsify a scientific theory, if we want to adopt a scientific and not a *pseudo*-scientific attitude (see Appendix 2). The hypotheses on which a theory is based must be validated. It must be possible to design an experiment, a validation test which, if a given result is obtained, would confute the hypothesis on which the theory itself is based.

Usually people speak of

- Systemic approach, with reference to a methodological framework;

[1] S. Freud (1908), to Abraham, May 8th , in Correspondence (1907-1926), Paris, Gallimard, 1969

- Production Systems, a term having different meanings in management science and in a logic-mathematical context;
- System analyst, which is a profession in the field of Computer Systems;
- Electronics and telecommunications systems;
- Systemic therapy, in a psychotherapeutic context and so on.

General Systems Theory looks like a cultural framework, a set of disciplinary meanings extrapolated from theories sharing the topic of systems. A structured and formalized organization of this approach may be found in Klir (Klir 1969; 1972; 1991).

For the reasons presented in the previous section, the term **Systemics** (**Systémique** in French, **Sistemica** in Italian and Spanish) has thus been introduced. The term is used not only in academic literature for referring to holistic concepts (Smuts, 1926), but also with reference to other conceptual extensions of the word 'System'. Systems Research Societies, such as the International Society for Systems Sciences (ISSS), as well as a number of national societies, use this term. It is also used in modern expressions when referring to applications in various disciplines, in order to emphasize the complexity, the web of relations, the interdependency between components. Typical cases are net-economy, software development, organizations, medical applications, pharmacology, electronics, biology, chemistry and so on.

At this point it is important to make a fundamental clarification of the terms introduced so far. This will avoid ambiguities and serious conceptual mistakes in assuming Systemics as referring to a traditional scientific domain (the so called "hard" sciences, such as mathematics, physics, biology, chemistry, etc.) rather than to a general cultural approach.

As introduced at the beginning of this chapter, the term Systemics refers to a cultural framework which crosses various disciplines. Disciplinary applications of this crossing within the scientific context, although particularly important, are only a part of the possible outcomes. The systemic contributions from various disciplines are fundamental for the emergence of Systemics. In its turn, Systemics is a source of innovative approaches within each particular discipline.

However, the term Systemics does not mean a particular disciplinary context in which this approach takes place, but a general strategy for approaching problems, emphasizing the need for a generalised view of events, processes and complex entities in which they are interrelated (see Appendix 2). This is not a trivial observation such as: *arithmetic is applicable to apples, people and trains*. The difference is that, when Systemics is applied within a given context, a model designed for the latter is enriched with new disciplinary concepts and becomes a *systemic invariant* (i.e. a concept, an approach which can be used within other contexts) As such, it allows the use of approaches and strategies designed in other contexts. *Systemic invariants* cannot qualify single elements but the behavior of the whole emerged system. General examples of *systemic invariants* identified within individual disciplines are listed in Appendix 1 and *Systems Archetypes* are discussed in Chapter 7. The concept of systemic *openness and closeness* applies for instance to biology, physics and economics. Moreover, even in *multidisciplinary* fields such as **Cognitive Science**, *when science studies itself, its own processes*, there is a continuous enrichment among applications of mathematical models, computer processing techniques based on Neural Networks, psychological experimental activities, modeling, language research and representation. The same circumstance occurs in domains, which are multidisciplinary *in principle*, such as **Environmental Science** which combines physics, chemistry, biology, economy and engineering.

Thus, the important relationships between *interdisciplinarity* and Systemics can be emphasized. To summarise:

- *Mono-disciplinary* approaches take place when specific domains are studied by designing specific tools. Different fields of interest deal with individual disciplines, such as mathematics, arts, economics. Education is usually *fragmented* into individual disciplines.
- *Multidisciplinary* approaches require the use of several different disciplines to carry out a project. For instance a project in telecommunications needs individual engineering, economic, legal, managerial competences working in *parallel*. Implementation of projects requires more and more multidisciplinarity. Multidisciplinary education means teaching one discipline while discussing another, i.e. language and history, mathematics and economy and so on.
- *Interdisciplinary* approaches involve problems, solutions and approaches (and not just tools) of one individual discipline being used in another following from systemic concepts such as those listed in Appendix 1. This is different from just using the *same tools*, such as mathematical ones. For instance, the use of the systemic concept of openness in physics, economics and biology allows scientists to deal with corresponding problems, solutions and approaches even using the same tools.
- *Trans-disciplinary* approaches are taken when problems are considered between, across and *beyond* disciplines, in a *unitary* view of knowledge. In this case the interdisciplinary approach is reversed: it is not a matter of an inter-crossing, cooperative use of disciplinary approaches looking for conceptual invariants using the same concepts in different

disciplines, but of finding disciplinary usages of the same trans-disciplinary knowledge. Trans-disciplinarity refers to something beyond individual disciplinary meanings and effects. It refers to the multiple levels and meanings of the world, the multiple levels of descriptions and representations adopted by the observer. While disciplinary research concerns *one disciplinary level*, trans-disciplinary research concerns the *dynamics between different levels of representation* taking place at the same level of description. Examples include multi-dimensional education focusing on the development of different, simultaneous, cognitively and ethically related disciplinary interests (Gibbons *et al.*, 1994; Nicolescu 1996) and in the approach to phenomena by *simultaneously* using different representations, descriptions, languages and models. These aspects are introduced in the DYnamic uSAge of Models (DYSAM) in Chapter 2.

The most significant contribution of the systemic approach is its ability to demonstrate that a strategy based only on the identification and study of the behavior of single, isolated components is ineffective and unsuitable for problems carrying the complexity of emergent processes and systems. At one level, this approach, in systems engineering, is based upon using, designing and controlling input-output and feedback-controlled devices as considered by System Dynamics (Forrester, 1968). In other words, societies, corporations, biological systems, the human mind and even a magnet or a superconductor can not be studied as if they were made up of individual component parts such as: pendula, levers and bolts. The machine paradigm, in short, is adequate only for machines and it is useless and ineffective in all other cases. To recognize this idea implies a very profound conceptual revolution, given that our scientific tools (mathematical, physical, biological, medical, economical models), as well as our legal and social frameworks have all been designed for a world where the machine concept and model is a fundamental element, within a more deterministic than probabilistic context. The mechanistic view is used as a touchstone to represent and design any other kind of operational device. Systemics, on the other hand, produces conceptual tools, devices and methodologies to deal with situations in which classical mechanistic approaches are ineffective.

Attempting to explain everything by using the available conceptual tools is an understandable and unavoidable human attitude. The following story may be illuminating. *In a dark room only one corner is lit up by a small bulb hanging from the ceiling. The light falls on a disordered set of objects. In this narrowly lit area a person is desperately searching for something. A friend arrives and asks: are you looking for something? Yes, the other says, I have lost my keys. The friend asks if he can help. Sure! After some fruitless* *searching the friend says: "There is nothing here! Are you sure you lost them here?" "No", says the other, "I lost them over there". "Then why are you searching here?". "Because here there is light".*

We must underline that the systems approach is a scientific, cultural approach and not an **ideological** one. The systemic approach is very appropriate and effective, *today*. Systems scientists must not only be ready for the emergence of a new paradigm, but also welcome it, search for it (Minati and Pessa, 2002).

Due to a systemic understanding of social processes it is now possible to realize how often technological solutions have been designed for *functions* more than *uses*, that is, designed for **problems rather than for people having the problems**. This process has led to very poor human-machine interfacing, as well as the prevalence of non-learning systems.

In the same way it becomes clear how solutions to problems have been designed with no awareness that **solutions to old problems may generate more complex and more difficult new problems**, requiring new approaches, such as the use of drugs, technologies for food conservation, energy production, temperature control and so on.

It should also be recalled here that a complete *history* of Systemics is not yet available in the literature. One might say that the field is too young to have a *history*. We believe that the reason for this is not related only to chronological events, nor to contributors to Systemics including those quoted above. The point is to **recognize** cultural events which form part of Systemics. In order to decide whether an element belongs to a set or not we need a rule and, in the same way, a very important first step is to have such criteria for the recognition of systemic thinking in processes where there was no *awareness* of it. The reason for finding such criteria and events is to establish general paths and trends in system thinking, to prepare for going *beyond* Systemics, by designing the *logistic curve* (see Figure 1.3 in Section 1.4.4) of this approach.

1.4 Fundamental theoretical concepts

Before starting a short exposition of some fundamental concepts of Systemics, a general point should be made about its history. Until the early 1980s, advances were made using concepts deriving from classical physics, according to which a knowledge of general, abstract laws and rules was sufficient to account for the whole range of phenomena observed in the real world. After this point in time, however, it major questions were posed in the description and treatment, of processes of emergence observed in ecological (and not abstract) systems, that is in the presence of noise, disturbances, context-dependent constraints together with the influence of the observer. Thus, the need arose for new methodologies and tools able to deal with real-life questions, avoiding the pitfalls of the abstract descriptions. These methodologies were not seen as being opposed to the previously used ones, but rather as generalizing them. This chapter presents a description of some of the tools traditionally used within the first phase of the development of Systemics, which can be denoted as *pre-emergence Systemics*. A knowledge of these tools could be considered as a sort of pre-requisite for designing a systemic approach. The methodologies introduced in *post-emergence Systemics* will be described in Chapter 4.

1.4.1 Set theory

As we will see in the following sections, various approaches and definitions of systems have been based on set theory.

This requires a clarification of exactly what constitutes a set of elements and how their relationships can be defined, detected or controlled. A number of different approaches are possible. The first, and most popular of them, is based on a mathematical theory, known as *Set Theory*. Within this theory the concept of *Set* is taken as *primitive*, together with that of *belonging to a set.*

Why is it usually assumed that a system may be established by interacting components *belonging to a set* and not just to an aggregate lacking any rules of membership?

The concept of set has been studied and analysed in the fields of logic, philosophy and mathematics by authors including Cantor, Dedekind, Russell, Zermelo, to mention only a few). For our purposes it is sufficient to recall that a set is characterized by elements having *at least one common property* (as we will see it is not possible to leave aside the role of the observer *detecting* the property, and having a *cognitive model* of it). A *set* may be defined as a group of elements for which there is a criterion, a rule, allowing one to *decide* whether an element belongs to it or not.

The reason for starting from the consideration of a *Set* and not just of an aggregate of elements is based on the logical power of the definition of a set. Within Set theory (Cantor, 1884), introduced by **Georg Cantor** (1845 - 1918), a set is defined when a rule of membership is defined. In such a way it is always possible to decide whether an element belongs to a set or not. In this theory sets are collections of objects in which ordering has no significance. Intuitively, the purpose was to have a theory with which it would be possible to state properties which, when valid for one element, were valid for the entire set and, when valid for the entire set, were automatically valid for *each* element.

The rule of membership assures a logical homogeneity which is very useful for the observer. This rule may even be represented by a list.

Set theory has been of great relevance, as a conceptual framework, for mathematics and science in general.

Briefly, it should be mentioned how its logical power has been *limited* by the discover of antinomies in the concept of set, especially when applied to the set of (all) sets and when dealing with the concept of infinite. Two classic antinomies can be mentioned:

1) Russell's Antinomy

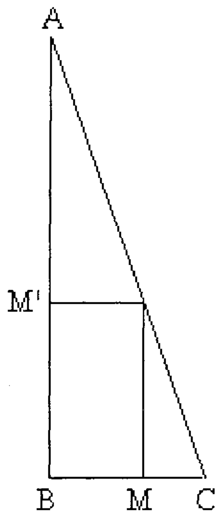
The set of all sets having more than k elements is an element of itself. The set of all books is not a book. Consider the set of all sets which are not elements of themselves, as in this example. If this set is an element of itself, then it is not an element of itself by definition. If it is not, then it is so.

2) Cantor's Antinomy

Referring to the concept of *power of a set*, expressed by its *cardinality*, that is the possibility of a one-to-one correspondence of its elements with the elements of another set, many questions arose, such as: Can a set having an infinite number of elements have more or less elements than another set having an infinite number of elements? Is a part of an infinite set finite or infinite?

Consider the following example.

In the triangle ABC



it is possible to identify on AB a point corresponding to any point of the segment BC. This does not mean that they have the same length, even though they have *same number of points*. Actually, the same may be done with another triangle having BC in common where AB has a different length.

The length has nothing to do with the number of points. It makes no sense to refer to the *number of points*, but to the *power of a set*.

A set is a finite or infinite collection of objects in which order has no significance, and multiplicity is also generally ignored (unlike a list or multi-set). Members of a set are often referred to as elements and the notation $a \in A$ is used to denote that a is an element of set A.

Symbols used to operate on sets include $\cap$ (which means "and" or intersection) and $\cup$ (which means "or" or union). The symbol $\varnothing$ is used to denote the set containing no elements, called the *empty set*.

Let E, F and G be sets. Then the operators $\cap$ and $\cup$ fulfil the following properties:

1) Commutative $E \cap F = F \cap E$, $E \cup F = F \cup E$
2) Associative $(E \cap F) \cap G = E \cap (F \cap G)$, $(E \cup F) \cup G = E \cup (F \cup G)$
3) Distributive $(E \cap F) \cup G = (E \cup G) \cap (F \cup G)$, $(E \cup F) \cap G = (E \cap G) \cup (F \cap G)$

1.4.2 Set theory and systems

One of the first *definitions of system* was proposed by A. D. Hall and R. E. Fagen in 1956. According to them, a system is defined as "a set of objects together with relationships between the objects and between their attributes" (Hall and Fagen, 1956).

Other more structured definitions of systems based on set theory have since been introduced.

Mihajlo D. Mesarovic introduced his mathematical approach in defining systems (Mesarovic, 1968, Mesarovic, 1972). In his research two lines of development have been followed:

a) via abstraction (Mesarovic and Takahara, 1989)

In this approach starting from well-established, specific theories (examples include automata and systems of differential equations) it is possible to embrace the common features of the initial assumptions. The main problem for Mesarovic is that "the new concepts are not general enough, so that one is bogged down by technical problems of minor conceptual importance." (Mesarovic, 1972).

b) via formalization (Mesarovic, 1968; 1972)

The idea was to first define concepts verbally, then define them axiomatically by using the *minimal mathematical structure*.

Let us recall that the *Cartesian Product*, after René Descartes (1596-1650), of two sets A and B is a set containing all possible ordered combinations of one element from each set: A x B = {(a, b) | a in A, b in B}. This definition can be extended to products of any number of sets.

Obviously, A x B # B x A. When the elements of sets A and B are considered as points along perpendicular axes in a 2D space then the elements of the *Cartesian Product* are the *Cartesian Coordinates* of points in this 2D space.

In this approach the general system $\boldsymbol{S}$ is the starting notion, defined as: $S \subset V_1 \times \ldots V_n$

The components of the relation, V_i, are the objects belonging to the system. The set V_i is to be intended as the "totality of alternative ways in which the respective feature is observed or experienced." (Mesarovic, 1972). In this way a system may be defined as a set (of relations, for instance).

There are two ways of specifying systems, by distinguishing a relationship with another made on the same objects:

a) the input-output approach, also referred to as stimulus-response;
b) the goal-seeking approach, also referred to as problem solving, decision-making.

During the same period, **George Klir**, starting from a compilation of definitions of system, introduced a definition of system at five levels (Klir, 1969). First of all Klir introduces some basic definitions:

- *The ST-Structure (State transition state)*: "The complete set of states together with the complete set of transitions between the states of the system."
- *The UC-structure (Structure of the universe and couplings)*: "A set of elements together with their permanent behaviors and with a UC-characteristic".
- *The space-time resolution level* is the feature of the observations or measurements (quantities to be observed, accuracy of measurements, frequency).
- *Permanent (real) behavior*: is defined by the relationships linking given quantities at the resolution level.

The five definitions introduced are:

1. *Definition by a set of external quantities and the resolution level*: The System $\boldsymbol{S}$ is a given set of quantities regarded at a certain resolution level.
2. *Definition by a given activity*: The system $\boldsymbol{S}$ is a given ensemble of variations in time of some quantities under consideration.
3. *Definition by permanent behavior*: The system $\boldsymbol{S}$ is a given time-invariant relation between instantaneous and/or past and/or future values of

external quantities; every element of the relation may, but need not be, associated with a probability of its occurrence.

4. *Definition by real UC-structure*: The system S is a given set of elements, together with their permanent behaviors, and a set of couplings between the elements on the one hand, and between the elements and the environment on the other.
5. *Definition by real ST-Structure*: The system S is a given set of states together with a set of transitions between the states; every transition may, but need not be, associated with a probability of its occurrence.

Klir (Klir, 1969) presents a complete formalization of his approach which was very innovative for its time.

He has since developed his views of systems theory in many publications of fundamental importance for Systemics (see, for example, Klir, 2001).

Another way to define systems, based on the concept of set, was introduced by **James Grier Miller** (1916-2002). In his book *Living Systems* (Miller, 1978) he introduced the following definition: "A system is a set of interacting units with relationships among them. The word set implies that the units have some common properties." (p. 16).

He distinguished between different levels, such as conceptual systems, concrete systems, abstract systems, structure and process. In basic concepts he made reference to emergence: "I have stated that a measure of the sum of a system's units is larger than the sum of that measure of its units.... Because of this, the more complex systems at higher level manifest characteristics, more than the sum of the characteristics of the units, not observed at lower level. These characteristics have been called *emergent*" (p. 28).

This way of introducing the concept of system is based on the concept of set, but without using the formalization introduced in set theory.

The simultaneous usage of the concepts of *relationship* and *interaction,* as well as the reference to *emergence* is particularly interesting.

The concept of set has been metaphorically used in other approaches and ways of introducing systems. The metaphorical usage refers both to the common properties of the elements considered and to their grouping, considered as components having relationships and interactions between them. In this case the formalization introduced in set theory is not used to describe, nor for making inferences about, systemic properties. Examples are sets of values, laws, organizational schemas and strategies, which we assume to become systems when common features, relationships and interactions among them are also considered.

This book will mainly consider the formalizations of the concept of system based on set theory. **This is the path followed in *systems theory,* and allows the reusability of concepts, approaches and results. This reusability is not based on metaphors or analogies, but on modeling and simulating activities grounded within conceptual frameworks, in turn granting high levels of coherence, robustness and validity in specific corresponding domains.**

In any case, it will be possible to extrapolate general concepts and metaphorical knowledge suitable for approaches based on *other kinds of knowledge*, such as artistic, religious, political, managerial and so on.

It is also possible to consider concepts of systems not based on the classic concept of set even within a scientific framework. One example is the introduction of *fuzzy sets, fuzzy logic and fuzzy systems* by **Lofti Zadeh** (Zadeh *et al.*, 1996). Fuzzy set theory is a subject of current scientific discussion (see Fuzzy Sets and Systems, An International Journal in Information Science and Engineering, Official Publication of the International Fuzzy Systems Association (IFSA)). Lofti Zadeh, in 1991, also introduced the concept of *soft computing* thus highlighting the emergence of computing methodologies focused upon exploiting a tolerance for imprecision and uncertainty to achieve tractability, robustness and low solution costs (Klir and Yuan, 1995).

Another approach, introduced by the theoretical biologist **Robert Rosen** (1934-1998), should also be mentioned. He introduced the concept of *anticipatory system* (Rosen, 1985): "An anticipatory system is a system containing a predictive model of itself and/or of its environment, which allows it to change its state at an instant in accord with the model's prediction pertaining to a later instant."

Formally, an anticipatory system is a system X whose dynamical evolution is governed by the equation: $X(t + 1) = F(X(t), X^*(t + 1))$ where $X^*(t + 1)$ is X's anticipation of what its state will be at time (t + 1).

In this theory Rosen uses a mathematical approach known as "category theory" (Rosen, 1978).

The relation between systems theory and category theory is based on the original definition of systems introduced by Bertalanffy: "A system is a set of units with relationships among them" (Von Bertalanffy, 1956). The notion of category is very suitable for use with this definition.

Category Theory is a mathematical domain which unifies a large part of mathematics by developing a general theory of relations and structures. Eilenberg and MacLane (Eilenberg and MacLane, 1945) introduced this approach to transform difficult problems of Topology into more accessible problems of Algebra.

Consider a graph constituted of vertices linked by arrows. In an arrow *a:* $V \rightarrow V_1$, V is the vertex representing the domain, and V_1 the target, represents the co-domain. Several arrows may have the same source, the same target, and may even be closed (when source is equal to target). A category is a graph combining different arrows in such a way that each pair of consecutive arrows, such as *a:* $V \rightarrow V_1$, *b:* $V_1 \rightarrow V_2$, is associated with a composite arrow *ab* from V to V_2 satisfying the conditions of:

- Associativity. States that paths a(bc) and (ab)c equal. There is a unique composite for a path of length n, whatever n is;
- Identity. There is a closed arrow from V to V for each vertex V. This arrow is called the *identity* of V whose composite with any arrow beginning or ending in V is this other arrow.

An arrow a is said to be an *isomorphism* if there exists another arrow b such that ab and ba are identical; b is unique and is the inverse of a.

Category theory is a stratified or hierarchical structure without limits, which makes it suitable for modeling the process of modeling itself.

The conceptual approach of *anticipatory systems* has been and is applied in different fields, such as biological, engineering, computing, cognitive, physical, economical, fuzzy systems (see the proceedings contained in the International Journal of Computing Anticipatory Systems, published by CHAOS, Center for Hyperincursion and Anticipation in Ordered Systems, Institute of Mathematics, University of Liège, Belgium).

1.4.3 Formalizing systems

The mathematical biologist **Ludwig von Bertalanffy** (1901 – 1972), considered the father of *General Systems Theory*, described a system S, characterized by suitable state variables Q_1 , Q_2 , . . . , Q_n ,, whose instantaneous values specify the state of the system. In most cases the time evolution of the state variables is ruled by a system of *ordinary differential equations*, such as:

$$\begin{cases} \dfrac{dQ_1}{dt} = f_1(Q_1, Q_2, \dots, Q_n) \\ \dfrac{dQ_2}{dt} = f_2(Q_1, Q_2, \dots, Q_n) \\ \dots\dots\dots\dots\dots\dots\dots\dots \\ \dfrac{dQ_n}{dt} = f_n(Q_1, Q_2, \dots, Q_n) \end{cases} \tag{1.3}$$

The system (1.3) specifies how the change in value of a given state variable, affects all other state variables. This is **interaction**. An interaction between elements is said to take place when *the behavior of one affects the behavior of another.* For instance, the behaviors of the elements belonging to a given system may be mutually affected by physical interactions due to collisions, magnetic fields and energy exchanges. When the interacting elements are autonomous agents, assumed to have a cognitive system, interactions can take place through *information processing*, in order to *decide* which behavior to follow.

In the case of a system characterized by only one state variable, the previous system becomes a single differential equation:

$$\frac{dQ}{dt} = f(Q) \tag{1.4}$$

It should be noted that, in general, interactions can take place only among elements possessing suitable *properties*. For instance, in order to have magnetic interactions among elements they should have the property of being able to act as magnetic poles.

When interactions are based on *cognitive processing* and *information exchange,* single elements are assumed to have *cognitive systems* and be able to interact using specific *cognitive models.*

Before proceeding some terminological definitions will be made, starting from the frequently used word **Reductionism**, an approach which attempts to describe every entity as a set, or a combination, of other simpler, smaller, basic component entities. Within this approach each feature of a given entity is considered as *reducible* to the features of its component parts. As will be seen below, this approach can be classified as anti-systemic, as it excludes the concept of *emergence* (see Appendix 1).

Modern reductionism, however, is no longer based on the naïve assumption that the whole is the sum of its parts and that the whole can be understood by studying only its components. Modern reductionism, (see, for instance, Crick, 1994), states that " ... while the whole may not be the simple sum of its separate parts, its behavior can, at least in principle, be *understood* from the nature and behavior of its parts plus the knowledge of how all these parts interact".

Another important term is **emergence**, which roughly denotes the occurrence of properties of the whole which are not deducible from those of its components. *A system is considered to be such when, acting as a whole, it produces effects that its parts alone cannot.*

It follows that the occurrence of an interaction among components is a **necessary condition** in order to describe a system. *Many* different interactions may occur simultaneously within a given system. In some cases the interactions may influence every component, whereas in other cases they may affect only certain specific kinds of components. In the latter case, the system of differential equations (1.3) should be rewritten by taking into account that each variable is affected only by other specific variables. The usefulness of this remark will appear later, when the concept of **multiple-systems** is introduced, in which different interactions affect different kinds of interacting components (see Section 3.4).

Moreover, the occurrence of interactions among components is not a **sufficient condition** for the appearance (or *emergence*, as we shall see later) of a system. A sufficient condition, on the other hand, is when the interactions among components give rise to suitable cooperative effects endowing the system with properties that the individual components do not possess.

In general cooperative effects can occur when different components:

- play different roles (e.g., within electronic devices, a living body, a company), or
- perform the same tasks in certain specific ways, depending upon the phenomenon being considered (typical cases are flocks, traffic, laser light).

In both cases we observe the appearance of a new entity possessing specific *emergent* properties. Here, *interaction* is the key word. The concept of system is based upon the assumption that, during interaction, components have:

- distinguishable roles and functions, even though endowed with the same characteristics, as in an anthill,
- cooperative, synergic behaviors, as in ecosystems.

A system may in turn interact with other systems contributing to the appearance of another higher-order system. In this case the systems are considered as **subsystems**, like departments in a company or organs in a living system.

One further observation: Systemics develops within a cultural context (as mentioned below) which takes into account the key role played in the modeling activity by observation, in addition to the observer's classical role of relativity and noise generator. When it is stated that the appearance (emergence) of a system requires an observer, the reference is not only to a device able to physically *detect* the appearance itself. It also refers to the need for a *cognitive model* suited to *acknowledge* rather than *detect* the appearance, i.e., for processing the related information. Lack of knowledge, of attention, of interest may make the agent completely insensitive to the presence of a system: in this case there is no observer even though the phenomenon physically exists.

1.4.4 Formalizing Systemics

In this paragraph we will introduce some approaches to the problem of formalizing a framework for Systemics, in order to develop models of systems suitable for simulations and for understanding their theoretical features. In this context we will introduce several models which have played a crucial role in the conceptual evolution of systems thinking

The cultural and scientific basis of Systemics came from studies in various disciplinary domains, as mentioned in 1.3. The unifying concepts of Systemics introduced by Ludwig von Bertalanffy allowed recognition and conceptual organization of the systemic meaning of the different studies and approaches (see Appendix 1).

The most important of these, for the formalization of Systemics and associated modeling activity, came from disciplines including physics, engineering, mathematics and biology.

Classical **thermodynamics**, for instance, implicitly uses a systemic view of physical problems. This discipline deals with the study of the exchange of energy between a system and its external environment and, in particular, most attention was attracted to the transformation of heat into work within machines.

The more advanced topics of thermodynamics refer to subjects such as: equations of state, phase equilibrium and stability, molecular simulations, statistical mechanics, statistical thermodynamics, stability in multi-component systems, energy and energy analysis of open systems, entropy, irreversibility, general thermodynamic relationships, external-field effects, low temperature thermodynamics, irreversible thermodynamics, energy conversion.

The problems dealt with by thermodynamics are inherently *systemic*, such as that which constitutes the subject of Statistical Thermodynamics: the relationship between macroscopic thermodynamic variables and the microscopic variables describing the dynamics of the individual components of a macroscopic system such as, for instance, the molecules of a gas. Statistical Thermodynamics deals with this problem by considering only systems consisting of very large numbers of particles and neglecting the details of their individual behaviors.

The generalizations of Thermodynamics take place conceptually when trying to apply its concepts and laws to generic systems, for instance when considering that the problem of energy exchange with the environment may be studied in the same way within different contexts such as a star, a living system, a machine. Classical thermodynamics is based upon two laws:

a) First law: "It is impossible to design a machine that operates in a cyclical manner and performs work without the input of energy to the machine itself" (impossibility of perpetual motion) or "Energy can neither be created nor destroyed but it can be converted from one form to another." (Energy conservation);

b) Second law: "It is not possible to design a thermal machine integrally transforming heat into work"

There have been different formulations of the second law, a circumstance which underlines its great physical importance. For instance: "Elements in a closed system tend to seek their most probable distribution", or "in a closed system entropy always increases."

Heinz von Foerster (1911-2002) collected the following reformulations:

1. Clausius (1822-1888): It is impossible that, at the end of a cycle of changes, heat has been transferred from a colder to a hotter body without at the same time converting a certain amount of work into heat.
2. Lord Kelvin (1824-1907): In a cycle of processes, it is impossible to transfer heat from a heat reservoir and convert it all into work, without at the same time transferring a certain amount of heat from a hotter to a colder body.
3. Ludwig Boltzmann (1844-1906): For an adiabatically enclosed system, the entropy can never decrease. Therefore, a high level of organization is very improbable.
4. Max Planck (1858-1947): A perpetual motion machine of the second kind[2] is impossible.
5. Caratheodory (1885-1955): Arbitrarily near to any given state there exist states which cannot be reached by means of adiabatic processes.

The great importance of the second law is related to its implications on *irreversibility*. William Thomson (Lord Kelvin) introduced the second law in 1852, in a publication on the journal *Philosophical Magazine* entitled "On the universal tendency in nature to the dissipation of mechanical energy".

Ilya Prigogine (1917-2003) introduced a very innovative view of thermodynamics. In his book "From being to becoming" (Prigogine, 1981)

[2] A perpetual motion machine of the *first order* is one which produces power without energy uptake. A perpetual machine of the *second order* is one undergoing a cyclic process that does nothing but convert energy into work (i.e. without *any* dissipation or *other* use of the energy).

he states that the second law seems more a program than a principle. This is the main reason why thermodynamics focused upon the problem of equilibrium. In advanced thermodynamics he introduced a total change of perspective by looking at irreversible processes in a new way, particularly for systems far from equilibrium. Irreversible processes were considered for their constructive aspects more than for their usual degenerative ones. He introduced the very powerful notion of *dissipative structures* having profound consequences for our understanding of biological systems (see Appendix 1).

Thermodynamics has been studied by contemporary physics with reference to new problems such as the relationships between order and disorder, reversibility and irreversibility, static and dynamic stability, the role of bifurcation, symmetry-breaking, self-organization. In this way scientists deal with new theoretical problems within different frameworks, and this domain is usually referred to as the study of **complexity,** as introduced in Section 1.3. The term "complexity" does not denote the topic of a single discipline, but rather a category of conceptual problems. In other words, it refers to the need to use conceptual approaches and theoretical tools having in common the ability to use and deal with different levels of description, representation, modeling using different computational approaches and simulation tools, taking into account different observational scales, the observer being an integral part of the problem.

In short, generally, the common theoretical feature of complexity studies is the need to deal with **emergence**, a notion introduced above which will be discussed in detail throughout this book as the key theoretical concept.

An example for illustrating the switch from classical physics to the physics of complexity is the **Three Body Problem**, i.e., the problem of computing the orbits resulting from the mutual gravitational interaction among three separate masses. This problem is surprisingly difficult to solve, even in the case of the so-called *Restricted Three-Body Problem*, corresponding to the simple case of the three masses moving in a common plane. It is an example of the lack of adequacy of the classical mathematical models used in science to deal with an aspect of complexity, i.e., many body interactions. The strategy of looking for a deeper, more complete knowledge of the single components was absolutely inadequate for dealing with the behavior of many body systems.

The study of dynamical systems described by evolution equations is the subject of *dynamical systems theory*, dealing mostly with non-linear and chaotic systems. The problem of carrying out theoretical analyses on the structural properties of a system independently from its practical implementation, was dealt with by resorting to different approaches, all based on suitable mathematical descriptions. Mathematical modeling allows the exploration of the structural features of the asymptotic state of a system on the basis of the description of the structural properties of its evolution, independently from particular interpretations of the state variables.

One of the first domains of application of dynamical systems theory was the mathematical description of **Population Growth**.

In 1798 **Thomas R. Malthus** proposed in his essay, "An Essay on the Principle of Population" a simple mathematical model of population growth for modeling the time evolution of biological populations.

Malthus observed that, without environmental or social constraints, human populations doubled every twenty-five years, regardless of the initial population size. The principle was that each population increased by a fixed proportion over a given period of time and that, in the absence of constraints, this proportion was not affected by the size of the population.

In the Malthusian model of population growth the only hypothesis is therefore that a population grows at a rate proportional to itself. The model equation is

$$dP/dt = k\,P \tag{1.5}$$

where P (which is a function of time, t) stands for the population density at time t and k is a proportionality factor.

Malthus's model is an example of a model with one *variable* and one *parameter*.

One of the first models of population growth which took into account some social constraints was that describing the interactions between predator and prey. It was proposed in the Twenties by the US biophysicist Alfred Lotka and the Italian mathematician Vito Volterra. To be precise, the Lotka-Volterra (LV) model was originally introduced in 1920 by A. Lotka (Lotka, 1920) as a model for oscillating chemical reactions. It was only later applied by V. Volterra (Volterra, 1926) to predator-prey interactions. Like the Malthusian model, the **Lotka-Volterra** model is based on *differential equations*.

The Lotka-Volterra model describes interactions between two species in an ecosystem, one acting as a predator and the other as a prey. Since it deals with two species, the model involves two equations, one describing the time evolution of the density of individuals belonging to the prey population, and the other describing the time evolution of the density of predators. The explicit form of the model equations is:

$$dx/dt = ax - cxy$$

$$dy/dt = -bx + cxy \tag{1.6}$$

where x is the density of prey individuals, y the density of predators, a is the intrinsic rate of prey population increase, b the predator mortality rate, and c denotes both predation rate coefficient and the reproduction rate of predators per prey eaten.

The model of Lotka and Volterra is not very realistic. It does not consider any competition among prey or predators. As a result, prey population, in the absence of predators, may grow infinitely without any resource limits. Predators have no saturation: and their consumption rate is unlimited. The rate of prey consumption is proportional to prey density. Thus, it is not surprising that model behavior is unnatural, showing no asymptotic stability. However, there exist many variants of this model which make it more realistic.

As the model lacks asymptotic stability, it does not converge towards an attractor (i.e., it does not "forget" initial conditions) and its solutions consist of periodic behaviors, whose amplitude depends on the initial conditions. An example is given in Figure 1.3.

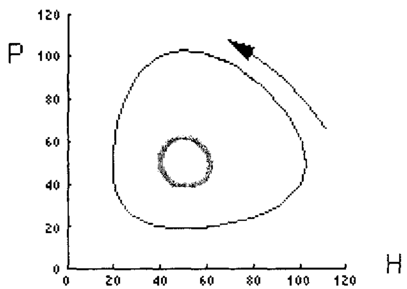


Figure 1-3. Periodical solutions of the Lotka-Volterra equations.

The LV model has become a classic example of a nonlinear dynamical system (Hernandez-Bermejo and Fairén, 1997; Minorsky, 1962; Verhulst, 1990) and has been applied to very different kinds of problems, including population biology (Tainaka, 1989), epidemiology (Roussel, 1997), neural networks (Noonburg, 1989), and chemical kinetics (Noszticzius *et al.*, 1983).

Another, earlier model was introduced by the Belgian mathematician **P. Verhulst** (1804-1849) with reference to the study of population growth within the context of limited resources. The mathematical solution of this model is given by the well known *logistic curve* (Figure 1.3).

To illustrate the Verhulst model, we start from the definition of system introduced in Section 1.2.1 and refer to the particular case of a single state variable, described by equation (1.4). Introducing a Taylor series development of the right-hand member of this equation around $Q = 0$ (assumed to be an equilibrium point of this equation), we obtain:

$$\frac{dQ}{dt} = a_1 \cdot Q + a_{11} \cdot Q^2 + \ldots \tag{1.7}$$

Keeping only the first order term $a_1 Q_1$, system growth will be directly proportional to the actual value of Q and the growth will be exponential, the dynamical evolution equation having the form

$$\frac{dQ}{dt} = a_1 \cdot Q \tag{1.8}$$

In this case the solution will take the form $Q = Q_0 e^{a_1 t}$, where Q_0 is the number of elements at time $t = 0$. This is the *exponential law* used in many contexts. Now, if terms up to the second order in Eqn. 1.7 are kept we have:

$$\frac{dQ}{dt} = a_1 Q + a_{11} Q^2 \tag{1.9}$$

A solution of (1. 9) is $Q = \dfrac{a_1 C e^{a_1 t}}{1 - a_{11} C e^{a_1 t}}$, the equation of the so-called *logistic curve* (see Figure 1.4).

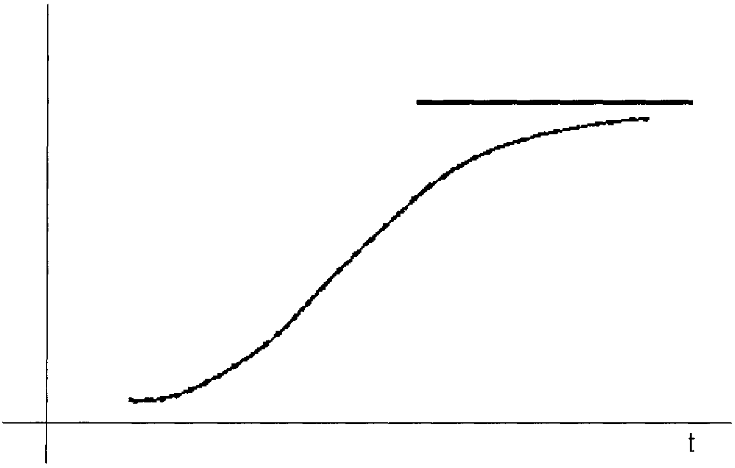


Figure 1-4. An example of a logistic curve

A different class of models was introduced by **Balthasar Van der Pol** (1889–1959), who introduced the concept of *limit cycle*. The latter term denotes a self-sustained stable periodic oscillation which occurs, after a certain transient behavior which, together with frequency and amplitude, are independent of the initial conditions themselves.

Van der Pol was the initiator of modern experimental laboratory dynamics during the 1920s and 1930s. He studied electrical circuits employing valves and found that the behavior of the state variables characterizing them showed stable oscillations, corresponding to the *limit cycles* mentioned above.

In 1927 Van der Pol and his colleague Van der Mark published a paper (Van der Pol and Van der Mark, 1927) in which they reported that in electronic valve circuits an "irregular noise" was observed at certain driving frequencies, differing from the natural entrainment frequencies. We now know that they had experimentally discovered *deterministic chaos*.

The mathematical model introduced by Van der Pol regarded electronic circuits, but it is also very suitable for describing general features of some kinds of nonlinear dynamical systems. Namely, the very nature of the solutions of the equations describing the model can change as a function of the value of a parameter contained within those equations. As a matter of fact, the appearance or not of a limit cycle is determined by whether these values fall within a given interval. This aspect was absent from previous models, such as those of Lotka-Volterra and of Verhulst.

Behavior of this kind, in which a structural change of behavior sets in only when the value of a parameter crosses a given *critical point*, occurs very often in physical, biological, and socio-cognitive phenomena. Let us consider, for example, *fluid mechanics* systems. Generally, a fluid is *viscous*. This means that a source of energy is necessary to sustain its motion. Consider a layer of fluid heated from below. In this case the fluid at the bottom becomes warmer, less dense and tends to move upwards. When a sufficiently large temperature difference between the bottom and the top layer occurs, *convection rolls* develop. If the temperature difference is high enough to allow convection rolls, the velocities are time-independent. This fluid motion is called a *steady flow*. In general, a very large number of variables (as large as the number of its constituent molecules) is necessary to describe the state of the system, but a steady flow may be represented as a *point* in this large, ideally infinite-dimensional phase space. When the temperature difference is increased, periodic time-dependent patterns appear. On further increasing the temperature difference, intricate time-dependent motion emerges. This sequence of changes is called the *onset of turbulence*.

In the case discussed above, the difference of temperature plays the role of a *control parameter* and the change of its values can give rise to profound changes in the nature of the fluid behavior. However, an understanding of the effect of changes in control parameter values is difficult in complicated mathematical models, such as that describing fluid motion. The importance of the Van der Pol model stems from the fact that it happens to be one of the simplest dynamical system models in which the role of a control parameter value can be fully understood. The explicit form of the Van der Pol model is described by the following pair of first-order equations:

$$dx/dt = y + ax^3 - x$$

$$dy/dt = -x \tag{1.10}$$

where a is the control parameter. When a is negative, the system is "trapped" in an attractive fixed point. When a is positive but not too large a *limit cycle appears*. When the value of a crosses the zero value, from negative becoming positive, the structural change of system behavior (a limit cycle suddenly appears) is called *Hopf bifurcation*.

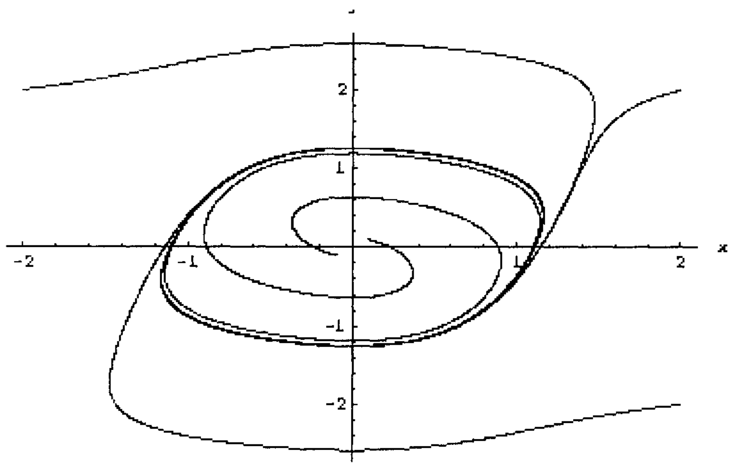


Figure 1-5. Some phase curves for the Van der Pol equation with a=1.

reactants, A and B, leading to products C and D, formed through unstable Figure 1.5 shows graphically that the Van der Pol differential equations exhibit a limit cycle, i.e., there is a closed curve in the phase plane corresponding to a periodic behavior.

Another interesting class of models are those formulated in terms of partial differential equations. In this case, besides the usual time independent variable, there are other independent variables, such as the spatial positions. Generally systems of this kind allow for an infinite number of solutions, whose general form cannot be discovered through the introduction of suitable parameters. Namely, the difference between two solutions of a partial differential equation is given, in general, by a completely arbitrary function. However, even within these models it is possible to have locally stable solutions, attracting the behavior of the entire system. This circumstance allows the description of self-organization phenomena. The simplest and most celebrated of such models is the so-called **brusselator** (from its origin in Ilya Prigogine's group in Brussels) introduced by Prigogine and Lefever in the Seventies to model tri-molecular reactions (*cfr* Nicolis and Prigogine, 1977; Babloyantz, 1986).

This model was found to be very useful for describing the most-studied self-organizing chemical reaction-diffusion system, known as the *Belousov-Zhabotinsky reaction*, discovered by the Russian chemist Belousov in 1958 and later studied by Zhabotinsky and many others (see Appendix 1). The Brusselator models the reaction between two intermediates X and Y. The model equations are:

$$d\phi/dt = D_1\Delta_2\phi + A - (B + 1)\,\phi + \phi^2\,\psi$$

$$d\psi/dt = D_2\Delta_2\,\psi + B\phi - \phi^2\,\psi \qquad (1.11)$$

where:

- ϕ and ψ are to be interpreted as concentrations of appropriate chemical substances;
- D_1, D_2, A, B are control parameters of the model;
- Δ_2 is the *Laplace operator* which, in the case of three spatial dimensions has the explicit form $\Delta_2 f = d^2f/dx^2 + d^2f/dy^2 + d^2f/dz^2$.

The *Laplace equation* $\Delta_2 f = 0$ was introduced by the French mathematician and astronomer Pierre-Simon Laplace (1749-1827); the operator appearing within it was named the *Laplace operator* by James Clerk Maxwell in his *Treatise on Electricity and Magnetism*, published in Oxford in 1873. The solutions of the Laplace equation are called *harmonic functions* and have wide applications in physics in the description of *gravitational, electrostatic* and *magnetic potentials*.

Since the reactants (A and B) are maintained at constant concentration, the two dependent variables are the concentrations of X and Y. The behaviors of some numerical solutions of this system of equations are plotted in Figure 1.6.

The interesting feature is that, whatever the initial concentrations of X and Y, the system settles down into the same periodic variation of concentrations. The common trajectory is a limit cycle, and its period depends on the values of the rate coefficients.

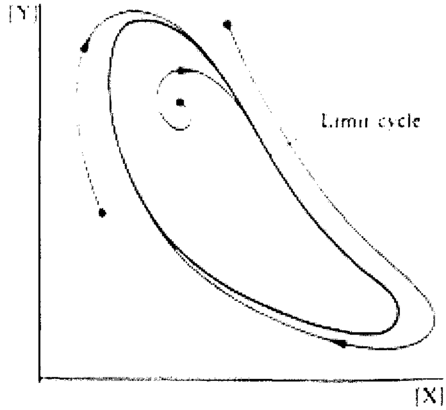


Figure 1-6. Some oscillating reactions approach a closed trajectory whatever their starting conditions.

The Brusselator has been used to study a range of phenomena. One, relevant for Systemics, is the formation of so-called *dissipative structures*. The term was introduced by Prigogine (Prigogine, 1978; Nicolis and Prigogine, 1977) to denote self-organizing structures in non-linear systems far from equilibrium (*i.e., whirlpools* existing for as long as they are continuously fed by a running fluid).

Another model based on a system of ordinary differential equations, the so-called *Lorenz equations*, is of special interest to scientists studying the occurrence of deterministic chaos (the latter can be identified with an apparently random motion stemming from deterministic equations). The Lorenz equations were discovered by **Ed Lorenz** in 1963 (Lorenz, 1963) as a very simplified model of convection rolls in the upper atmosphere. Later these same equations appeared in studies of lasers, bacteria, and in a simple chaotic waterwheel (Sparrow, 1982; Zwillinger, 1997).

The Lorenz equations are:

$$\dot{x} = \sigma(y - x)$$

$$\dot{y} = rx - y - xz$$

$$\dot{z} = xy - bz \tag{1.12}$$

where r, b, and σ are control parameters.

The Lorenz *butterfly* attractor refers to the so-called "Butterfly Effect", or more technically the "sensitive dependence on initial conditions", which is the essence of deterministic chaos. In simple terms, this means that, in a situation where deterministic chaos occurs, the difference, at any point in time, between two behaviors, associated with two different initial conditions, grows exponentially with time, *however small* the initial value of that difference. Therefore, if we perturb, even very slightly, a chaotic deterministic behavior, the effect of this perturbation, instead of fading away, will grow in a disordinate manner, thus reaching macroscopic levels. In other words, when a butterfly beats its wings in one part of the globe, this circumstance alone could ultimately give rise to a hurricane in another.

The Lorenz attractor is a solution to the Lorenz equations displaying some rather remarkable behavior and represents one of the landmarks in the field of Chaos. These equations were originarily designed to describe the 2D flow of a fluid in a simple rectangular box heated from below. This simple model was intended to simulate medium-scale atmospheric convection.

By plotting the behavior of its numerical solution three-dimensionally we obtain, instead of a simple geometric structure or even a complex curve, a structure which weaves in and out of itself.

Projected onto the X-Z plane (Figure 1.7), the attractor looks like a butterfly; on the Y-Z plane, it resembles an owl mask. The X-Y projection is often useful for glimpsing the three-dimensionality of the attractor.

As the Lorenz Attractor is plotted, a strand will be drawn from one point, and will start weaving the outline of the right butterfly wing. Then it swirls over to the left wing and draws its centre. The attractor will continue weaving back and forth between the two wings, its motion seemingly random, its very action mirroring the chaos that drives the process.

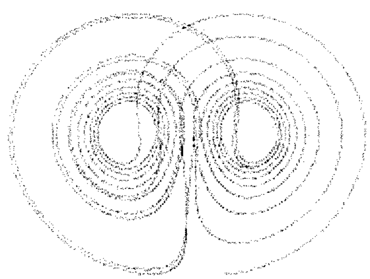


Figure 1-7. The Lorenz attractor projected onto the XZ plane.

A new approach in studying complex systems was introduced by **Hermann Haken** (Haken, 1983a; 1983b; 1987). This approach, named

Synergetics, focuses on the emergence of order from chaos. Synergetics is an interdisciplinary field of research founded by Hermann Haken in 1969 (Graham and Haken, 1969). Synergetics deals with complex systems where interacting components give rise to self-organized functional, spatial or temporal, structures. It searches for general principles of self-organization in different disciplinary fields, such as physics (lasers, fluids, plasmas), meteorology, chemistry (pattern formation by chemical reactions), biology (morphogenesis, evolution theory), economics (financial markets), brain activities, computer sciences, sociology (e.g. urban growth).

Synergetics deals with systems in which *cooperation* among subsystems creates organized structures on macroscopic scales (Haken 1993). Problems dealt with by Synergetics are, for instance, the study of *phase transitions,* (see Chapter 3 and Haken, 1983), of convective instabilities, of bifurcations, of coherent oscillations in lasers, of nonlinear oscillations in electrical circuits, of social and economic behaviors, of population dynamics, etc.

One of the many important new ideas introduced by Synergetics is related to the concept of *order parameter.* When complex systems undergo phase transitions, a special type of ordering occurs at the microscopic level. Instead of addressing each of very large number of atoms of a complex system, Haken (1988) has shown, mathematically, that it is possible to address their fundamental *modes* by means of *order parameters.* The very important mathematical result obtained using this approach consists in drastically lowering the number of degrees of freedom to only a few parameters. Haken also showed how *order parameters* guide complex processes in self-organizing systems.

When an *order parameter* guides a process, it is said to *slave* the other parameters, and this slaving principle is the key to understanding self-organizing systems. Complex systems organize and generate themselves at far-from-equilibrium conditions:

> *"In general just a few collective modes become unstable and serve as 'order parameters' which describe the macroscopic pattern. At the same time the macroscopic variables, i.e., the order parameters, govern the behavior of the microscopic parts by the 'slaving principle'. In this way, the occurrence of order parameters and their ability to enslave allows the system to find its own structure".* (Graham and Haken, 1969, p. 13).

> "In general, the behavior of the total system is governed by only a few order parameters that prescribe the newly evolving order of the system" (Haken, 1987), p. 425.

1.5 Sets, structured sets, systems and subsystems

In this Section several practical examples are presented with reference to what has been discussed above.

a) Sets

As introduced above, this concept refers to collections of elements having a common property, defined through the rule of membership.

It is, for example, possible to consider the set of *all* electronic components as well as the set of electronic components within a box. In the latter case the rule of membership makes reference to more then one property: being an electronic component *and* being contained within a box (tested components, components selected by the designer for a project, etc.).

b) Structured sets

The next step is based on the consideration of elements having a *suitable* (for an observer) structure, an organization. In this way order, synchronization, hierarchy may be established. The single elements have relationships amongst them: one may come before another, one be heavier than another, one may have a particular position in a configuration, etc. Relationships amongst elements allow actions upon them to be more effective, by amplifying and multiplying their properties, as may occur, for example, when we scan a structured database in order to retrieve a particular piece of information.

Regarding the example of the electronic components which are, in this case, assembled, structured on a circuit board: they are structured, arranged in a given configuration.

We have moved from the concept of *set* to the concept of *structured set.*

c) Systems and subsystems

Another conceptual step takes place when it is not so much the structure of relationships among elements which characterizes the new entity, but rather the *interactions* among them.

In this case the circuit board is supplied with power and the components interact.

From the interacting elements a new entity having its own characteristics, non-deducible from those of component elements, *may* **emerge**: a system.

Due to interactions, sets of elements become *something else* both with reference to the elements themselves and with reference to the structured set. Most of the situations we are dealing with relate to **emergent** phenomena, i.e. systems created by interacting elements through cooperative, synergistic effects and based upon the creative role of the observer who recognizes, realizes this process of emergence by using a suitable *cognitive model*. This is the case of electronic devices considered to be *working* if the observer has a suitable cognitive model and expectancies. A formal definition of emergent properties was introduced by Baas (Baas, 1994), as reported in Chapter 3. If we denote with:

- S^1, a set of interacting elements having observable properties at the level of single elements Obs1 (S^1), and
- S^2, a second order structure, which is the result R of applying interactions Int^1 to the elements of S^1, whose observable properties are Obs^1 (S^1) : $S^2 = R(S^1, Obs^1(S^1), Int^1)$,

then a property P of S^2 is *emergent* if and only if it is observable at the S^2 level but not at a lower level, i.e. at the S^1 level.

It is possible to identify **subsystems**. These are intended as systems having roles and functions within an overall system (e.g., a company).

The observer identifies subsystems. In any case, it is possible to consider them with their identity and boundaries independently (*autopoietic* systems are an example, see Appendix 1). Different subsystems may be superimposed with respect to some variables giving rise to structures showing interdependence, e.g., among economy, education and government, intended as three subsystems of society.

Some examples are introduced in Table 1.1. See Chapter 3 for more theoretical discussions related to *emergence*.

Sets	Structured Sets	Systems	Subsystems
Electronic components	Electronic components structured on a board, following a circuit design	An electronic circuit board with components which interact when power is supplied.	Group of components classed by function such as amplifiers, regulators, decoders.
Students	Students grouped by sex or in alphabetical order	School	Classrooms
Cells	Cells by type	Living being	Organ
Words	Words in alphabetical order or in a syntactical structure	A book, a story, a poem	Verses, Stanzas, Chapters
Musicians	Musicians grouped by their language, sex or age	Orchestra	Musicians playing same kind of musical instrument
Soldiers	Ordered by age	Army	Division
Workers	Ordered by activity	Corporation	Department
Animals	Animals by type, ordered by age, grouped by color, staple food, etc.	Herds, swarms, flocks, packs	Single animals considered *while* part of a system, such as parents

Table 1-1. Examples of sets, structured sets, systems, subsystems.

Systems, resulting from processes of emergence (Chapter 3), are not just extensions and amplifications of the characteristics of their elements. Systems have their own identity and peculiarities, and have to be specifically understood and managed. When a device is said to be **working** it shows this kind of transformation: a working device is no longer the same as an inactive one. Examples are: radio, TV, HI-FI systems, cars and computers.

We have moved from the concept of *structured set* to the concept of *system*.

This transformation presents many interesting aspects which must be taken into account when managing systems. Depending on the level of description it may be:

a) predictable or unpredictable;
b) reproducible or irreproducible;
c) reversible or irreversible;
d) stable or unstable.

The transformation *from a set to a system* is not *equivalent* to the process of *only* setting new configurations of elements or new relationships between them. As described above, it is a process of *emergence*. When considering the patterns in which atoms are arranged in a solid we see that they depend on parameters such as chemical composition, temperature and magnetic field. A **phase transition** is a change in the arrangement of atoms. In Physics a *phase transition* is the transformation of a system from one *phase* to another. A phase is a set of states having uniform physical properties such as liquids, solids and gases. In Systemics phase transitions are considered as occurring not only in physical systems, but also in other contexts such as learning or economic processes.

It is also possible to consider processes of **degeneration:**

- from systems to sets, when for any reason the interactions between elements are not active anymore;
- from structured sets to sets, when for any reason the elements no longer interact by following a *suitable* (for an observer) structure;
- from systems to structured sets, when the interactions, making *emergent* a system because of *cooperative, synergic* effects between components, cease to be of cooperative nature.

In Chapter 3, dedicated to *emergence,* emphasis will be placed upon different conceptual levels of occurrence of systemic properties: from systems to multiple-systems, to Collective beings.

1.6 Other approaches

Different disciplinary approaches to Systemics have already been introduced in Section 1.3. Several others (ordered by year of the cited publication), are listed below.

- **Max Wertheimer**, **Wolfgang Köhler** and **Kurt Koffka**, who founded Gestalt Psychology at the beginning of the Twentieth century. **Kurt Koffka** wrote a celebrated book about the principles of Gestalt theory (Koffka, 1935);
- **Kenneth E. Boulding** in *economics* and *management* (Boulding, 1956);
- **Magoroh Maruyama** for the *second cybernetics* (Maruyama, 1963);
- **C. West Churchman** founding father of the *systems approach* (Churchman, 1971; 1979) as well as of the fields of *operations research* (Churchman, 1961) and *management science* (Churchman and Verhulst, 1960);
- **Gregory Bateson** in *anthropology* (Bateson, 1972);

- **Aurelio Peccei and Alexander King** founders in the late 1960s of the *Club of Rome* introducing the need to study possible alternative to growth for global evolution of the world (Meadows *et al.*, 1972; 1993);
- **Russell L. Ackoff** in *social systems* (Russell, 1974);
- **Humberto Maturana** (1929-) and **Francisco Varela** (1946-2001) introduced in the 1970s the concept of autopoiesis (the process whereby an organization produces itself) later discussed in the book (Varela *et al.*,1974; Maturana and Varela, 1980);
- **John P. Van Gigch**, in *systems applications* (Van Gigch, 1978), *epistemology* (Van Gigch, 2003);
- **Peter Checkland** in *systems practice* (Checkland, 1981);
- **Stafford Beer** in management (Beer, 1972);
- **Peter M. Senge** in *system dynamics* (Senge, 1990) and *learning organizations* (Senge *et al.*, 1994);
- **B. H. Banathy** in *education* (Banathy, 1991) and *social systems design* (Banathy 1996; 2000);
- **Ian I. Mitroff** in *management* (Mitroff and Linstone, 1993);
- **Michael C. Jackson** in *management science* (Jackson, 2000).

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