Chapter One

SYSTEMS

Origin and Evolution, Terms and Concepts

1.1. INTRODUCTION

We start this book with Theme A (see Figure P.1 in the Preface), which aims to develop an essential and fundamental understanding of systems science. So, what is systems science?

When asked to explain what systems science is all about, many systems scientists are confronted with a rather daunting task. The discipline tends to be presented and understood in a fragmented way and very few people hold an overview understanding of the subject matter, while also having sufficient in-depth competence in many and broad-ranging subject areas where the ideas are used. Indeed, it was precisely this difficulty that identified the need for a comprehensive well-documented account such as is presented here in *Dealing with Complexity*. As far as we are aware, there is not a single consolidated text on the nature and content of systems science that is both (1) an introduction to the systems terms, concepts, and principles that provide the structural components that make up the systems framework of thought, and yet (2) broad enough in its outlook to provide an insight into the breadth of understanding and application that can be achieved with such a framework.

The reader should note, however, that this introductory book cannot hope and does not pretend to chart the frontiers reached in systems thinking and its application. That special and important task continues to be performed in writings with a narrower focus of attention. The reader would need to consult the works of, for example, Ackoff, Bertalanffy, Beer, Boulding, Bunge, Checkland, Churchman, Forrester, Klir, Laszlo, Prigogine, Rapoport, Wiener, and the new wave critical systems movement for the major milestones of systems science.

In due course, *Dealing with Complexity* will necessarily touch on the main points raised by these scholars. First we need to develop an overview understanding of systems science, so let us now return to the question: What is systems science all about? A standard answer is that it is all about dealing with complexity. This identifies a need to clearly understand the concept of "complexity," but we have deferred discussion of that until Chapter 2. Before pursuing that path of inquiry, we should understand the fundamentals that underlie systems thinking and hence complexity. This is the task of Chapter 1.

Chapter 1 provides a historical overview of the development of systems science, asking why and where did it originate and how has it evolved? Later it offers a review of systems terms and concepts.

1.2. THE ORIGIN AND EVOLUTION OF SYSTEMS SCIENCE

Any subject area with "science" in its title traditionally implies a distinct branch of systematic and well-formulated knowledge and the pursuit of principles for furthering it. This suggests that science should have a clearly recorded and coherent historical development. This is not the case for systems science, which has a fragmented history. For instance, some fundamental concepts now used in systems science have been present in other disciplines for many centuries, while equally fundamental concepts have independently emerged as recently as 40 or so years ago.

★ [illegible]
as they cybernetics

Cybernetics is a good example of an area of systems thinking that has been in existence for many centuries. The origin of the word is the Greek *kybernetes* (steersman) and *kybernetics* (Plato's art of steersmanship). Subsequently, Maxwell in 1864 used the word *cybernetics* to describe feedback in mechanical governors, and Ampère in 1884 used the word to refer to the art of government in the context of social science (Robb, 1985). The contemporary definition of the word has rightly been attributed to Wiener (1948) and is the study of control and communication in animals and machines.

The principal coming together of systems ideas (those relating to wholes) occurred in the field of biology. The initiator of this consolidation is recognized as being Ludwig von Bertalanffy in the 1940s (e.g., recorded in Bertalanffy, 1950, 1968). Bertalanffy envisaged a framework of concepts and theory that would be equally applicable to many fields of inquiry. Mathematics is favored as the medium by which these ideas are best expressed. The original work is named general systems theory (GST) and has been pursued to contemporary times (e.g., Klir, 1969; Laszlo, 1972; Miller, 1978; van Gigch, 1978; Rapoport, 1986). It is based on the idea that homologies exist between disciplines that have traditionally been considered as being separated by their different subject matters. Homology means correspondence or sameness of relation. It would therefore be important to find out what these homologies are so that an efficient

[illegible] exp
drawing up of
[illegible]
species
★

science can be developed that stretches across disciplines. GST, a metascience, therefore promised to unify all sciences. Those early years must have been filled with great excitement.

The Second World War, with its attendant problems of logistics and resource management, acted as a catalyst for the growth of the systems idea in practice. The nature of the application area lent itself to a holistic and quantitative analysis, although the general systems idea as such was not popularized either in science or in practice. Operations research and management science (ORMS) emerged from these studies in the 1950s, and its close association with systems thinking is still evident today (see, e.g., Daellenbach *et al.*, 1983; Keys, 1991). The ideas spread to influence many forms of business and industry with the belief that they would make equally significant contributions in these contexts. This was not the case because the catalyst directed systems science toward "hard" quantitative analysis, which has subsequently been found to be inappropriate for most social situations. In the 1950s the Society for General Systems Research was established, now named the International Society for Systems Sciences; its yearbook, published from 1956, is still going strong today, providing a valuable source of history and information about systems science.

bd?,

The ensuing dreary 1960s, as they have subsequently been called, failed to achieve any substantive developments and gave rise to much criticism of the systems idea, which has not been easy to shake off, still surfacing today in less informed articles. Attempts were made to put systems science on a firm footing (e.g., Bunge, 1979; Laszlo, 1972; Mattesich, 1978). The stagnation was finally broken by a number of disillusioned operations researchers who developed qualitative soft systems thinking. First and of greatest significance was the philosophical contribution made by C. West Churchman in the late 1960s, pointing out the need to care for ethics and morality in our systems designs; his work led to a Nobel Prize nomination in the field of social systems (Churchman's main publications were in 1968a,b, 1971, 1979, 1981; see also the *Festschrift* edition of *Systems Practice*, Volume 1, Number 4, that celebrates his work). Then, in the 1970s, Churchman's close colleague and friend Russell L. Ackoff argued for interactive planning, wanting to involve the affected in "problem solution" (Ackoff's main publications were in 1974, 1978, and 1981; see also the *Festschrift* edition of *Systems Practice*, Volume 3, Number 2, that celebrates his work). Peter B. Checkland's action-research program, also influenced by Churchman, came to the fore in the 1980s, the main contribution probably being the redefinition of system as an abstract organizing structure rather than an entity in the real world, and showing how this shapes methodology for "problem solving" (Checkland's main publications were in 1981, and with Scholes in 1990). In particular, in the 1970s and 1980s, Stafford Beer developed cybernetics, working out the laws and concepts of viability, the viable design for any organization (Beer's main publications were in 1966, 1973, 1975, 1979, 1981, 1985; see also the special edition of *Systems Practice*, Volume 3, Number 3). Now, in the 1990s, the critical systems movement is bringing together all of these achievements within a complementary and emancipatory framework. (A comprehensive treatment of this process of change can be found in three readers; first is Emery's collection of papers—first published in 1969 as a single volume, available since 1981 as two volumes—that adequately deal with the general systems phase; second is the Open University's 1981 contribution which takes systems thinking into the soft phase; and third is Flood and Jackson's 1991a critically edited work which shows how and why thinking has moved on to a critical systems phase bringing all of these developments together.)

Let us now reconsider this development by employing a model that proposes four development cycles of systems science, as shown in Figure 1.1 (the development processes of systems thinking, theory, and application). Seen are four interlinked cycles, which we believe usefully represent the evolutionary process of systems science. We shall use this dynamic configuration as a base on which to mold our continuing discussion. We will systematically explore the main emphasis of each cycle.

DEVELOPMENT CYCLE 1. Systems thinking, when formalized, leads to systems theory, which promotes systems thinking.

Systems thinking is a framework of thought that helps us to deal with complex things in a holistic way. Giving an explicit, definite, and conventional form to this thinking is what we have termed systems theory (i.e., theory is the formalization of thinking). Conventions are subsequently adopted in the thinking process. In these terms, theory and thinking are never synonymous, as it is the latter that remains less concrete and acts as the lubricant for application. It is the case, however, that a portion of systems theory exists that is unlikely to be directly useful in application and thus will remain more or less isolated from practical experience. Nevertheless, these quasi-isolated components of systems theory provide an important contribution to the overall systems view.

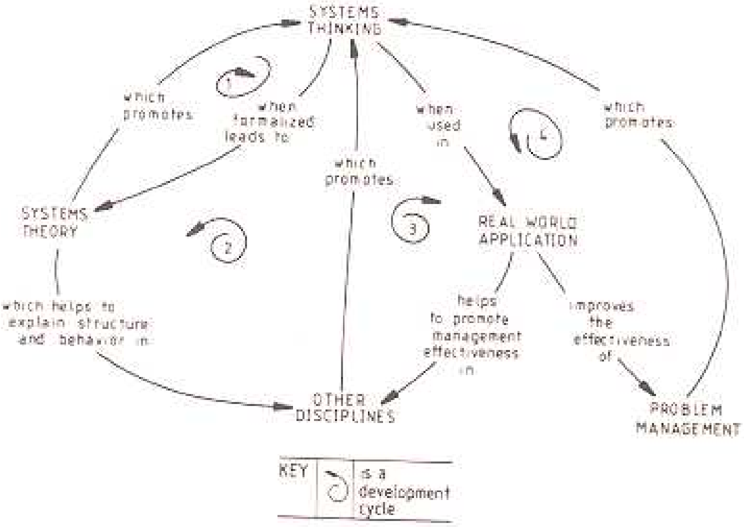


FIGURE 1.1. Four development cycles of systems science.

Examples of this cycle are the development of a theory on complexity as illustrated in Chapter 2, the modeling theory in Chapters 3 and 8–10, and the theory of measurement in Chapter 4, showing both practical and abstract dimensions

DEVELOPMENT CYCLE 2. Systems thinking, when formalized, leads to systems theory, which helps to develop thinking and theory in other disciplines, which promotes systems thinking.

During the initiation phase of GST, Development Cycles 1 and 2 were effectively the only ones in action. Thought revolved around the need to develop a metatheory that could be used to explain and bring together separate disciplines in a single operation. Thus, over the years, many systems writings (mostly of a GST nature) set about developing and introducing systems theory in other disciplines. This provoked criticism from Berlinski (1976) and Lilienfeld (1978) as pointed out by Checkland (1981) and Naughton (1979). Systems thinking was seen to offer a very limited functional biological metaphor and was found to hold a strong ideological position although its main protagonists were unaware of this. These warnings do sound a danger to early systems thinkers but hardly undermine the developments in the discipline that have been outlined above.

The criticisms should be considered in the light of Figure 1.1. To a large extent they have been made without fully appreciating all four development cycles of systems science. Many of the criticisms are unwittingly directed at Development Cycle 2 only, which is just one very necessary part of the overall development of systems science. It is only when formalization of thinking is significantly developed that it is possible to go on and effectively accrue tested knowledge as it stands up across disciplines. Only then will we be able to postulate further on the unification of sciences. Furthermore, as we shall see later, the systems idea has been developed by critical systems thinkers to employ many different metaphors and has recently adequately worked out an understanding of several ideological implications in different strands of work and has dealt with them. Chapter 11 focuses on the ideological issues.

A good example of Development Cycle 2 is the mutual development of international relations and systems science as presented in Chapter 7. Management and organization theory and systems science also have shared in each other's development as seen in Chapter 5. The same is the case in geography, ecology, biomedical sciences (see Chapters 8 and 10), economics, engineering, computing and the information sciences and others; with systems science offering new possibilities and a novel view.

DEVELOPMENT CYCLE 3. Systems thinking, when used in real-world application, helps to promote management effectiveness of other disciplines, which promotes systems thinking.

Real-world, or practical, application of systems science may be found in many disparate disciplines and domains of practice. Both quantitative and qualitative approaches have been employed seeking theoretical and/or utilitarian objectives; e.g., the development of systemic scientific knowledge leading to technological advances and the study of man's involvement in them. The case studies in Chapter 8 are a testament to the contribution of systems thinking, in this case to biomedical practice.

DEVELOPMENT CYCLE 4. Systems thinking, when used in real-world application, improves the effectiveness of problem management, which promotes systems thinking.

One major study area of systems science is the application of its concepts through methodologies to tackle modern-day "problem solving," planning, and decision making. Systems ideas are particularly powerful at helping us to organize our thoughts to make sense of very complex issues. In addition, the use of systems ideas in "problem solving" feeds back directly to promote understanding of their utility and value as frameworks for thought. Hence, practice promotes thinking.

In Chapter 6, Development Cycle 4 is given its clearest exposition, showing how systems thinking benefited from systems practice, for instance in the evolution of soft from hard systems approaches. In addition, the case studies show how problem management is made effective by the employment of systems approaches.

To summarize, in systems science, thinking leads to application, which feeds back to (re)thinking. Figure 1.1, then, defines the process by which systems thinking and theory have developed and identifies the role of application, not only in real-world use, but also in the further development of systems science itself. A detailed summary of the many facets of systems science, which are the output of the development processes discussed above, is given in Figure 1.2. Here we see according to one perspective how systems science has arisen from interdisciplinary studies, and how it can itself be categorized into distinct areas. A number of the major contributors in each area of systems studies are given. Many of these strands of study are discussed in this book. We will now turn our attention to terms and concepts.

1.3. SYSTEMS TERMS AND CONCEPTS

1.3.1. Introduction

In this section an introduction to systems terms and concepts will be presented. This will complement the appreciation of the history and development of systems science already in place.

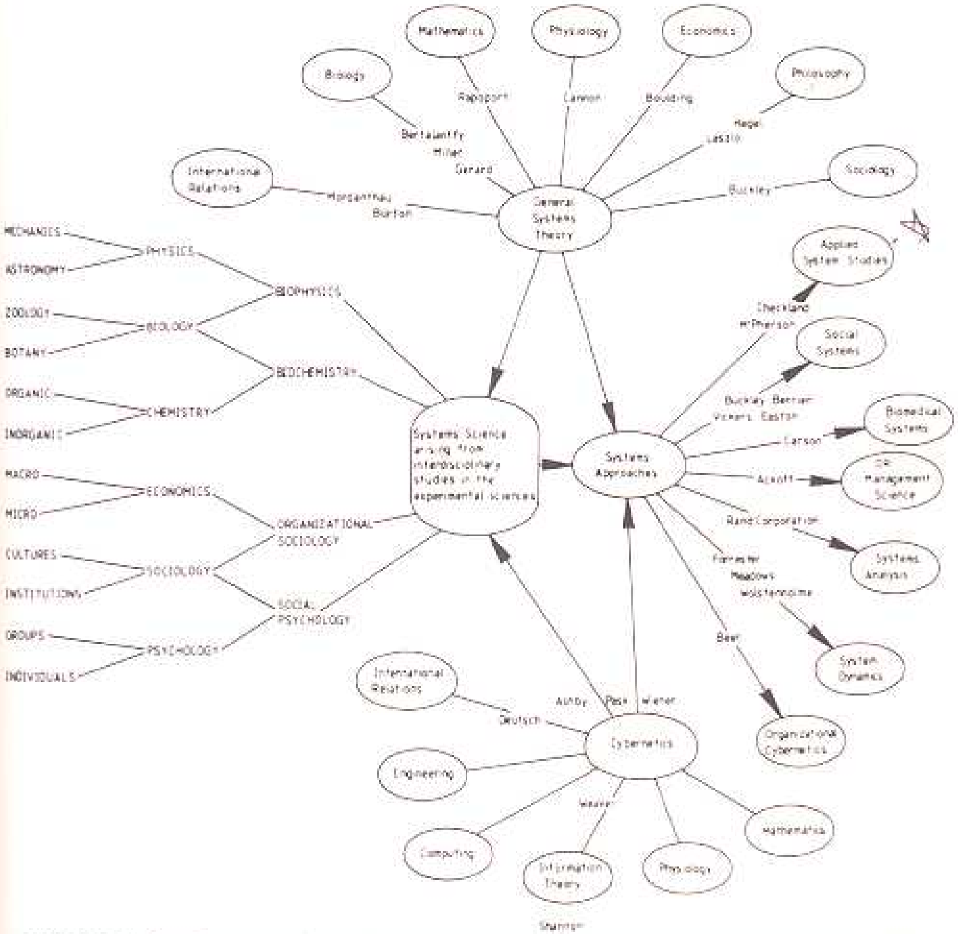


FIGURE 1.2. Systems science, its origin and evolution. (Modified from Beishon, 1980, with international relations and biomedical systems added. Reproduced by permission of Open University Press.)

1.3.2. Terms and Concepts

A system as a representation of a situation has the following characteristics: it is an assembly of elements related in an **organized whole**. An **element** is the representation of some phenomena of the natural or social world by a noun or by a noun phrase that informed observers agree exists, or could exist, or whose existence may be worth assuming in order to gain insight. An element must normally be capable of behavior such that it has some significant attributes that may change. A **relationship** can be said to exist between *A* and *B* if the behavior of either is influenced or controlled by the other (Jones, 1982). Relationships or **communication** between elements may be flows of materials, information, or energy.

Any characteristic quality or property ascribed to an element or relationship is termed an **attribute** of that element (e.g., color, texture, size, strength, shape, and permeability) or that relationship (e.g., intensity, speed, throughput, and rate). The changes in the elemental and relational attributes of interest are of prime concern.

Feedback is where the influence of an element impacts on other elements, but through a series of relationships the effect of its initial influence feeds back on itself.

A simple example of a system that captures our explanation so far is a system description of how predator–prey dynamics work. Let us assume that due to an increase in vegetation the population of a small herbivore explodes. This enables the population of a carnivore species that is partial in its diet to this herbivore to explode. Consequently, the herbivore population decreases. The increase in the herbivore population feeds back on itself through its relationship with the carnivore population.

The concentration of relationships between elements helps us to distinguish a system, with concentrated feedback relationships, from its **environment**, with which the system shares only **input** and **output** relationships. The demarcation between a system and its environment is made clear by defining a **boundary** around the system. This distinction is absolute in the theoretical construct of a **closed system** where no relationships are found or made between elements of a system and things external to it. Conversely, an **open system** exchanges material, information, and/or energy with its environment across a boundary. The difficult task of boundary identification is tackled in Chapters 4 and 6.

Other less influential component parts that indirectly affect behavior because they are able to change the environment, are represented as components of a **wider environment**. It is therefore useful to distinguish a **narrower system of interest** (NSOI) from a **wider system of interest** (WSOI). This may help when the application domain of a study focuses on a part of the SOI, the NSOI, but there remain some elements that are closely related (having feedback relationships), clearly do not belong in the environment, and must be taken account of. These then form a group labeled WSOI. These ideas are also expanded upon in Chapter 4.

The main terms and concepts of a system are organized and further explained in Figure 1.3. Here, (a) shows a set of elements devoid of relationships, which is no more than an aggregation of parts; (b) shows a set of elements with only limited relationships, which does not constitute a system; (c) is a system showing concentrations of relationships between elements, this concentration helping to identify the boundary of the system, its inputs and outputs; (d) shows that a system may comprise a number of subsystems, and each subsystem can be thought of as a distinct system with a boundary; and (e) shows that a system, comprised of a narrower and wider system, has an environment with which it will directly exchange material, information, and/or energy, while other factors that may influence the system indirectly via the environment are grouped together and termed the wider environment.

An illustration may help here. Let us take a business selling scientific products. We can conceive of this as a number of related elements. We will assume them to be corporate planning, marketing and sales, management information, personnel, accounting, research and development, and production.

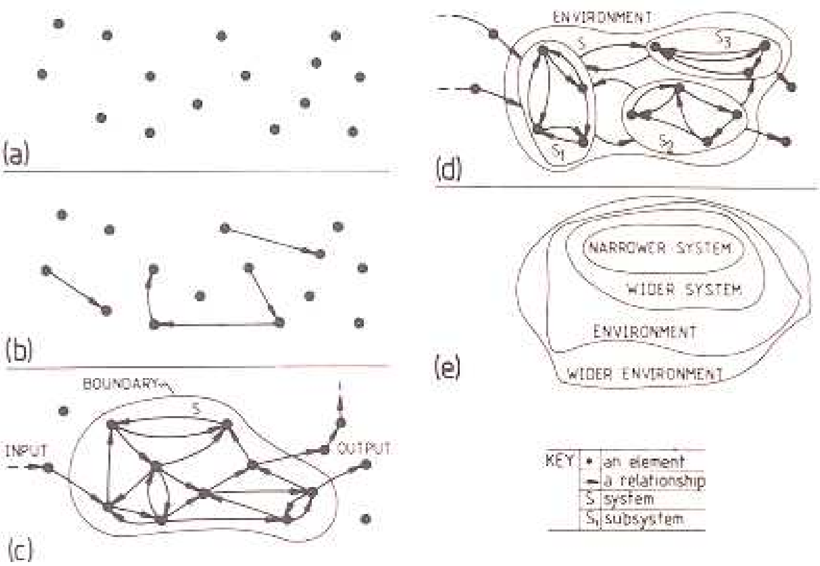


FIGURE 1.3. Defining a system: (a) a set of elements devoid of relationships; (b) a set of elements with only limited relationships; (c) a system with many relationships between elements, the boundary of a system, its inputs and outputs; (d) subsystems within a system (S is a system, S_1, S_2, and S_3 are subsystems); (e) narrower system, wider system, environment, wider environment.

Each of the elements can be thought of as subsystems of the system of interest. Production, for example, has a number of distinct groups and stages, all closely related, which make up a distinct subsystem. But this subsystem depends on personnel for staffing matters, marketing and sales to promote and sell the product, research and development to provide new innovative products, and so on. Each subsystem exchanges materials and information. Its actions may have direct impact by feedback upon itself. Research and development may decide upon a policy of weekly seminars to discuss their research, which may lead to a greater input from production concerning their needs, which may influence the way research develops. This feedback is desirable. Assuming this company is a quality company, external customers and suppliers should be represented as part of the system, and so the boundary which would normally be drawn around the organization's main functions would be extended to include external customers and suppliers, these being the WSOI. The business itself then becomes the NSOI. Scientific developments achieved by competitors would influence the WSOI, being a part of the environment, and other developments such as political, economic, or technological ones may influence the system in an indirect way and may be represented as a wider environment.

Any system is the unique creation of a person or a group. It is a representation shaped by interests and purposes as is suggested by "SOI." The United Kingdom, for example, could be seen as an economy by economists, a society by sociologists, a threatened chunk of nature by conservationists, a tourist attraction by travelers, a military threat by the old Soviet Union, and the green, green grass of home by the more romantic of us Britons.

Some elemental attributes of systems are known as **state variables** of the system (e.g., volumes of water in a series of reservoirs, population sizes of interdependent species, inventories in a warehouse), and thus the system can be described by a **state vector**:

the actual variable of a system at any given time

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

such that each x_i ($i = 1$ to n) of the state vector **x** represents one of the system states (e.g., represents the volume of water in one reservoir, the population size of one species, the number of one item in stock). The change in these states over time forms the **state trajectory**, as shown in Figure 1.4. The state trajectories of (a) a two-state variable system and (b) a three-state variable system are shown, with x_1, x_2, and x_3 representing, say, volumes of water in three reservoirs. The totality of the space in which the trajectory may move is termed the **state space** of the system. In the systems considered so far, the state variables of the system map on a one-to-one basis (the system is **deterministic**) with their future states:

$$\begin{aligned} x_1(t) &\rightarrow x_1(t+s) \\ x_2(t) &\rightarrow x_2(t+s) \\ &\vdots \\ x_n(t) &\rightarrow x_n(t+s) \end{aligned}$$

where $x_1(t)$ is the value of that state variable at time t (t is the present time), $x_1(t+s)$ is the value of that state variable at a later time $t+s$ (s might be, say, one month).

In more complex cases the state variables of the system may map on a many-to-one or one-to-many basis (the system is **indeterminate** or **probabilistic**).

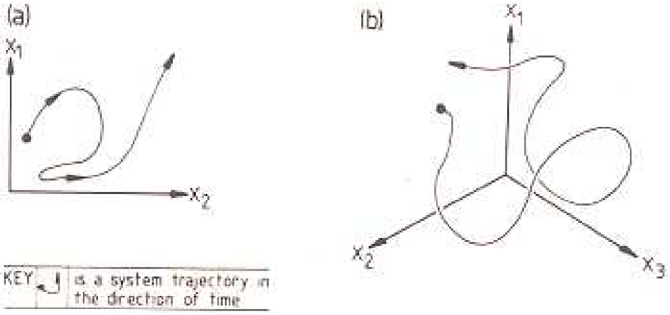


FIGURE 1.4. State trajectory: (a) a two-state variable system; (b) a three-state variable system (x_1, x_2, and x_3 are volumes in a reservoir).

In some cases, where many factors of complexity are apparent, the fuzziness can be extreme and our ability to understand the dynamics left severely wanting. We conceive of them as **poorly structured** and difficult to envisage in terms such as state variables, state trajectories, and state space; and boundaries are often very difficult to meaningfully identify. Real-world phenomena such as social and organizational groups are typically poorly structured or "messy" and fall to this difficulty. A ~~mess, incidentally,~~ is defined by Russell L. Ackoff as interacting problems or issues that are not easy to appreciate as a whole. Situations that can be usefully thought of as structured are relatively easy to understand in a noncontroversial way, and often lend themselves to quantitative analysis as we have discussed above. We can deal with this type of complexity by capturing phenomena in formal models. Poorly structured situations, however, are better studied using different approaches like picturing them as "human activity systems"—notional purposive systems that express some purposeful human activity (Checkland, 1981). This argument of context dependency will be pursued throughout the book.

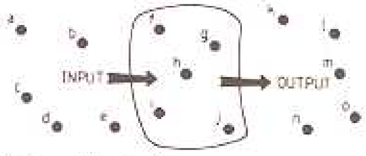
Let us now make some distinctions between what we have called structured and messy situations. This will act as an early reference point to the argument just mentioned that will unfold as each chapter is read. The definition comes from Flood (1987a). We consider the following key features to indicate structure:

1. Measurement can typically be realized in rigorous quantitative terms (statistics and mathematics are therefore permissible—see Chapter 3).
2. The quality of measurement is questionable only with respect to noise (interference on or distortion of measures) because the instruments of measurement are known to be measuring the attribute of interest.
3. The major difficulty with measurement, other than noise, is accessibility, that is, measuring the attribute of interest may destroy the integrity or change the behavior of that which is being measured.
4. A corollary of (1) (3) (each one expanded upon in Chapter 3) is that laws rather than theory are normally achievable.
5. Another corollary of (1)–(3) is that system identification (determining what is the system, boundary, environment, and so on, of interest—see Chapter 4) is relatively straightforward because the elements of the system can generally be agreed upon and, in many cases, parameters defining the structure and processes of the system can be estimated quantitatively.
6. In general, there is agreement about the function and purposes of the situation under investigation (a unitary rather than pluralist position may be achieved).

In essence, (1) (6) describe situations typically found in the natural sciences (Theme B of this book). Messy situations of the social sciences (Theme C) are, at least in part, given some expression by exclusion from (1) (6). We will now return to defining fundamental concepts.

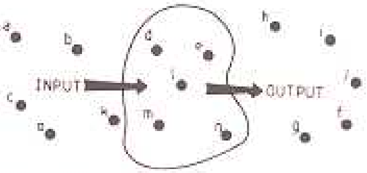
The important concept of **homeostasis** can be explained in state space terms. Mature organisms, for example, appear to remain more or less unchanged over discrete periods of time (one month, say s). A state vector representation of this suggests little change over time: $x(t) \approx x(t + s)$. The fact is, however, that an organism exchanges materials, information, and energy with its environment in order to survive. So at $t + s$ the identity of the organism may appear to be unchanged, but the actual materials that make up the organism at time t will be partially or totally replaced by time $t + s$. This idea of dynamic equilibrium, with fluxes in and out, is termed homeostasis. The open system of Figure 1.5 is a simplified representation of homeostatic dynamics. Let us say that each dot denotes a water molecule, and the labels a to o are permanently attached to the molecules for identification purposes. In Figure 1.5a, the cell at time t comprises five molecules f, g, h, i, j, and on general inspection will appear to be like the cell at $t + s$, having five molecules. However, the molecules in the cell have been completely exchanged by $t + s$. The change in the system between t and $t + s$ can be recorded as inputs = outputs, or $(d + e + l + m + n) - (f + g + h + i + j) = 0$, or (5 molecules) − (5 molecules) = 0 molecules. The five-water-molecule cell is in dynamic equilibrium with its environment. It is a homeostatic system that needs to exchange material, information, and energy in order to maintain its identity.

The concept of **entropy** is closely related to homeostasis. It refers to the tendency of things to move toward greater disorder, or disorganization, rather than maintaining order as homeostasis describes. Entropy is a "force" working against homeostasis. It emphasizes the importance of having an open system to import energy, information and materials which can be used to offset the tendency toward disorganization. The second law of thermodynamics is an example of entropy. The law states that heat dissipates from a central source and the energy becomes degraded, although total energy remains constant (the first law of thermodynamics). An analogy of this is given in Figure 1.6. Here, at time t, there is a high degree of order and the ink is organized as a distinct whole. At time $t + 1$ the ink droplet has fallen into a beaker of water, where it



KEY	
•	molecule
a-o	labels on molecules
t	time

(a) cell at t



(b) cell at t+s

FIGURE 1.5. Homeostasis: (a) living cell at time t; (b) living cell at time $t + s$.

Paper chosen
Teleology
Homeostasis vs. Entropy
Pos. Feedback cycle - exponential
+ + − feedback
Hierarchy
Emergence
Metasystem — higher cybernetics
Autopoiesis
Adaptation
cybernetics
Requisite variety
Putting boundary around complexity
- office example
- who's up

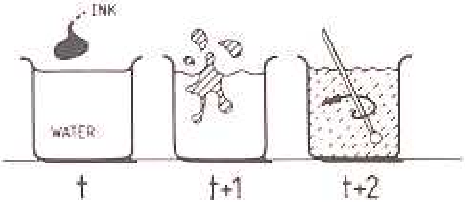


FIGURE 1.6. Entropy; ink (heat or energy) dissipating in a beaker (the universe).

immediately tends toward disorder. At time $t + 2$, and after stirring, the ink particles have become randomly displaced and the probability of the ink returning to total order is effectively zero. Entropy suggests that machines, organisms, organizations, societies, and so on will rapidly deteriorate into disorder and collapse. The reason they do not is because animate things can **self-organize** using imported stuff and inanimate things may be serviced by human beings who bring the stuff along. These are **negentropic** or perhaps homeostatic activities. Attempts to create order can seem rather daunting in the entropic scheme of things. Holding back entropy, however, is one of the challenging tasks for the systems scientist.

The activities of a system are thought of as relationships, or processes, within or even forming a **structure**. Structure defines the way in which the elements can be related to each other, providing the supporting framework in which processes occur (refer back to Figure 1.3c or 1.3d). Sequential observations on the system at times $t_1, t_2, \ldots, t_s$ characterize **behavior**. Behavior may be appreciated in the light of particular purposes and is said to be **goal-seeking**. For instance, a commercial firm's goal might be considered to be increasing profits as a percentage of sales (efficiency), to increase productivity, or to strive for quality. Consider another example. The most obvious basic requirement of an organism is survival. To this end it needs energy and nutrients, and until these needs are satisfied the organism seeks the necessary sources of supply. National political groupings, a third example, direct their activities toward gaining governmental power and, having achieved it, maintaining that position.

Adaptation is a type of goal-seeking behavior. Darwinian evolution of life forms is a theory of adaptation. Similarly, certain management and organization theory has argued that a commercial firm needs to adapt to external changes—e.g., adaptation to changes in demand patterns, competitors' actions, technological change; and to significant changes on the international scene like oil price increases or cuts, and wars. Adaptation is necessary for survival where the environment is subject to change. Adaptation occurs to deal with **environmental change**. If an environment is largely constant, then a system's survival is not threatened (at least, not by exterior forces) and adaptation is not of critical concern. In other circumstances, changes in an environment will occur and throw the system out of balance. Such changes are termed **environmental disturbances**. They may be thought of as having an acute or chronic impact on the functioning of the system. Acute impact requires short-term adaptive behavior and this means that a system must rapidly employ **regulation** and

control procedures. If the changes are chronic, longer-term regulation and control mechanisms will be required to maintain a system's integrity. Thus, a system needs a variety of short and long-term control mechanisms designed to cope with a range of environmental changes (see Ashby's law of requisite variety, discussed later).

Human beings' attempts to control, service, and/or design in the face of very complex situations have, however, often been fraught with disaster. The news presents clear enough evidence of this. A major contributory factor has been the unwitting adoption of **piecemeal** thinking, which sees only parts and neglects to deal with the whole. The effects of feedback loops often confound our thinking. It is naive to think that, for example, we can optimize parts when with systems thinking we know that these efforts may be undone by unforeseen feedback. The net result is that we experience **counterintuitive** behavior; outcomes of our actions rarely occur as we expect. But this is not an intrinsic property of phenomena; rather, it is largely caused by our neglect of, or lack of respect being paid to, the nature and complexity of phenomena that we are trying to represent. That is one reason why we need systems thinking, methodologies, and models. We argue that without this formal thinking we see only parts, the extremes, the simple explanations or solutions.

Adaptation, regulation, and control bring us to the subject area called **cybernetics**. As already indicated, this is the science of control and communication in animals and machines. It describes natural laws that govern communication and control of dynamic situations.

In traditional cybernetics a system is described as a **black box** whereby the whole of a system's generative mechanisms (those mechanisms that generate behavior) are lumped into a single transfer function (TF). A TF describes quantitatively the action on an input that produces an output (see Figure 1.7a). The output of the TF is brought back into its input where the difference between the desired and actual states of the system is determined (Figure 1.7b). This information can be acted upon by the control element of the TF to achieve the desired goal(s). Homeostasis, for example, can be achieved by monitoring and controlling system states, choosing critical variables which must remain within vital limits. This idea can also be applied to a system when we wish to move to a new steady state. The new desired state is compared to the actual state

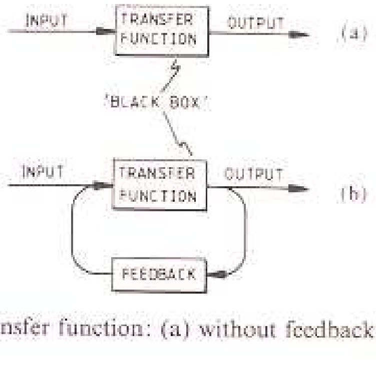


FIGURE 1.7. Transfer function: (a) without feedback; (b) with feedback.

and control action is brought to bear to bring about desired change. These sorts of control require either negative or positive feedback.

Negative feedback helps to achieve defined objectives as set in control parameters. Control parameters may be man-made or may occur naturally. If a system moves out of its steady state, then either control action is taken or natural feedback occurs to reverse this. Let us take an example of naturally occurring negative feedback. The predator–prey model described earlier is dominated by negative feedback. As soon as the population of herbivores increases, the population of carnivores increases, which feeds back and controls the population of herbivores, stabilizing it and bringing it back toward earlier numbers. The increase in the herbivore population will also have led to increased grazing, which will have cut back on the expansion of vegetation. As the carnivores impact on the population of herbivores, the vegetation has the opportunity to expand again and so the cycle continues. Negative feedback ensures an overall stabilizing effect on the related species of vegetation, herbivore, and carnivore.

Positive feedback helps to achieve contained contraction or replication and growth or leads to uncontained and unstable contraction or growth. Positive feedback may be desirable but can lead to structural changes and possibly to structural collapse. Both desirable and undesirable cases are illustrated in the following example. When we run, we need to increase oxygen intake and lung ventilation by increasing respiration rate. Positive feedback loops in the body temporarily dominate bringing about a desirable increase in respiration that enables the running to happen. In healthy people, however, the limits of human capability are dictated by negative loops, so that we can only run so far for so long. This is for our own good and prevents us from burning out. If the negative loops are broken leading to an undesirable domination by positive ones, as happens when athletes take certain types of drugs, superhuman achievements can be realized. This may not be so good. The history books tell of a number of tragic cases where the biological processes of athletes were unable to cope with uncontrolled demands which led to collapse and death.

A control system must have adequate variety. **Variety** can be used as a measure of the number of possible distinguishable states of a system, an environment, or the control element of a system. The variety of the controller must be greater than, or equal to, the variety of the system to be controlled, or the environment to be dealt with. This must be achieved if the system is to have a guarantee of remaining under control. Ashby in 1956 described this requirement and called it the **law of requisite variety**.

So far we have described and explained concepts that are covered by the umbrella sister concepts of communication and control. Another pair of umbrella concepts are hierarchy and emergence. These four together are Checkland's (1981) notion of the essential ideas of systems thinking. We will now change our focus to describe and explain hierarchy and emergence.

Two cybernetic concepts that pertain to control are metasystem and metalanguage. A **metasystem** is one that sits above a system in a hierarchy of control. If you like, it is the control system of the system of interest. In human beings one metasystem is the conscious brain, in a typical business it is the board of directors, in an army it is the command center, and in a family with young children it is often the parents. We talk of a metasystem having a metalanguage of control. **Metalanguage** is developed, understood, and used by the metasystem to explain the behavior of the system so that it can raise effective control over it. Subordinate systems may have no understanding of the metalanguage, possessing only their own object language. This idea is not too seriously illustrated by the situation represented in Figure 1.8, an example familiar to many of us. Here we see a metasystem using its metalanguage to command an object system that operates using its object language. Owing to the limited vocabulary and lack of syntax and structure of the object language, the object system is not capable of understanding the higher-level metalanguage. In order to effect the desired control over the object system, the metasystem has to switch from its own metalanguage to the language of the object system, whereupon the commands may be understood and obeyed. The difficulty arising in this illustration is, of course, that the object system is developing its own metalanguage wishing to independently control itself. A fully developed metalanguage, however, is needed to be able to put together an adequate understanding of what can be done, how it can be done, and why it should or should not be done.

The astute reader will, by now, be concerned that the systems idea might be autocratic and coercive. It is true that cybernetics is all about control at different hierarchical levels. Control can be coercive. It can be used in that way but need not be. In fact, we want to show with this book that systems thinking can be employed to use only that amount of control which is necessary to help to achieve things efficiently and effectively. As Stafford Beer said, how can we

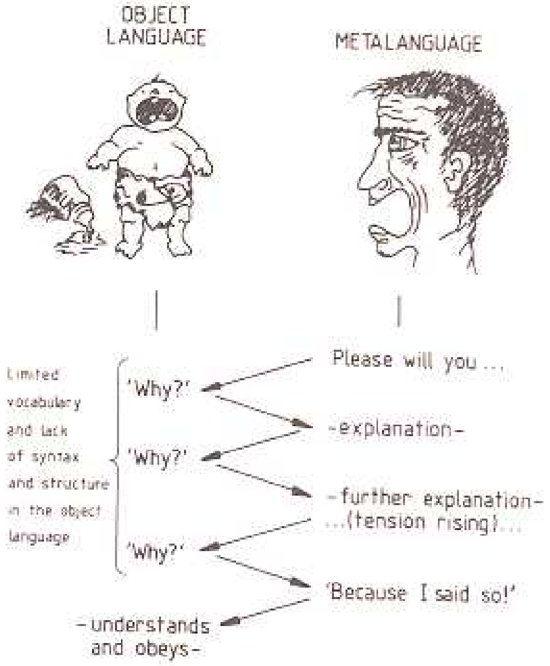


FIGURE 1.8. Metalanguage.

resolve issues of, for example, poverty, poor housing, and pollution when we are so damned inefficient that things become out of control?

Systems are also representations in the form of levels in **hierarchical** structures and organizations. The previous discussion focused on control hierarchies as structures. Figure 1.9 represents a different type of hierarchy which is a hierarchical organization at a number of levels. It focuses on biological, ecological, and sociological phenomena. Hierarchical organization is a logical representation of phenomena as systems and subsystems. This type of organization is made and understood by employing systemic reductionism. We reduce the breadth of analysis from system to subsystem characterizing what we find as systems in their own right. Here, reduction to subsystems and sub-subsystems increases the **level of resolution** of analysis. We can see systems in greater detail. By reversing the direction, we decrease the level of resolution and see systems in less detail. An important part of any study drawing upon systems ideas is to ensure that an appropriate level of resolution is chosen to focus our attention on. This is particularly important in "problem solving" because it defines to some extent the issues that will be dealt with. The level of resolution that we choose to work on is termed the **system-in-focus**. To be an effective systems scientist we must at the same time be both a **holist**, looking at the system as a whole, and a **reductionist**, understanding the system in more detailed forms (M'Pherson, 1974).

* use for Sys in detail

Ascending hierarchical organizations reveal an important phenomenon that has provided the words of the systems anthem for many years: "**the whole is greater than the sum of its parts**," that is, systems have **emergent properties**. The classic case comes from human biology. Cells form into distinct wholes like the liver, pancreas, heart, lung, kidney, eye, ear, nose, tongue, neural network, knee joint, rib cage, skull, each with their own function or role to play, and each having different properties from the cellular parts. Together the parts formed from cells form a whole with different emergent properties. They are organized through communication and control in a hierarchy of bodily parts that gives rise to an observing, listening, feeling, smelling, tasting, walking,

* use this example

✓

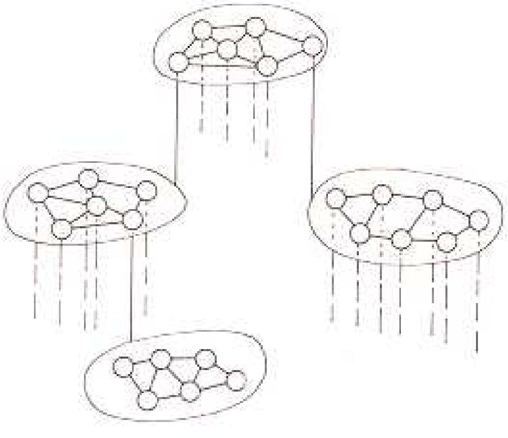


FIGURE 1.9. Hierarchical organization.

talking, working, thinking, emotional person. A human being is not an aggregate of bodily parts. Nor is a business an aggregate of management functions, nor a society an aggregate of social groups. In each case, things come together to form wholes whose properties are different from the parts.

Emergence, not surprisingly, has an instantaneous appeal because it offers insight into many phenomena across many disciplines. The worry is that it does seem a little mystical compared to usual rational scientific explanations; e.g., if we exert a known amount of energy on a ball of given size that will roll on a surface that has specific frictional qualities in a medium subject to known gravitational force, then it will move so far in a given direction. Laws can be used to define physical phenomena like action–reaction that we have just mentioned. But can laws define the emergence of a human being from the parts of which we are comprised? Strictly speaking, the answer is no. Emergence is not a law. Nor is emergence a belief as the mystical interpretation might have it. Emergence is nothing more or less than a characterization of phenomena that otherwise leave us wanting for explanation. Emergence is a characterization.

We have already used emergence to characterize biological phenomena at several levels of resolution. What other examples can we give? Let us think about a case close to home. Bricks, mortar, wood, tiles, plaster, wires, carpets, cooker, furniture, and so on, when put together in a well-**designed** manner, produce a whole labeled a "house." A house is a controlled environment in which we, whole organisms as already described, have reduced uncertainty, increased our safety, and are able to do the familial and social things that we want to. The whole bringing together of these parts can be conceived of as a system. Now, if you take a number of people from their homes, transport them to another larger man-made structure, add many machines (conceivable as separate mechanical systems), then input material, information, and energy, a new organized whole emerges that we label a "factory." The factory transforms inputs and has outputs, such as finished products. The factory is a place of work that helps people to achieve goals and material well-being, providing jobs and remuneration for work done. If we now think of people, homes, and factories, we have the basis of whole societies. The emergence of each society can be characterized by its culture. Cultures become distinct wholes when placed against others, when we contrast norms, roles, values, and beliefs. Add other components to this type of whole, national governments and international organizations, and what emerges can be characterized as an international system. The international dimension points to another emergence. The discipline called international relations has developed to study this level of phenomena and is introduced in Chapter 7. Clearly, hierarchy and emergence are concepts that transcend and link all disciplines.

Figure 1.10 offers a more abstract insight into emergence. It has the added benefit of showing the relationship between emergence, state trajectory, and systems behavior. In this figure we have a representation of qualitative change of an object, say x, in its state space $s(x)$. Each coordinate axis represents one property of the object, and the trajectory, or behavior, of the system is described by the direction of s. During the first part of the existence of x, point s (which represents x's instantaneous state) moves on the b–c plane until it transcends

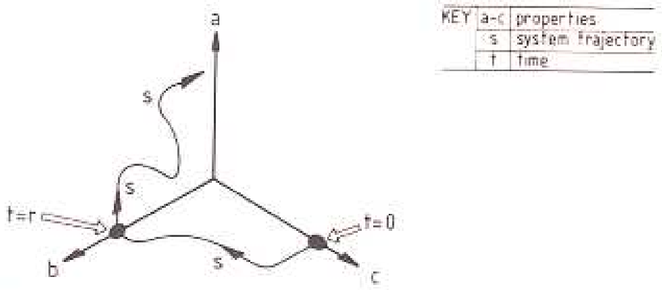


FIGURE 1.10. Emergence. (From Bunge, 1977; reproduced by permission.)

the vertical plane at $t = r$. It loses property c at this time and gains property a, moving on to plane a–b (Bunge, 1977). Each plane would have its own emergent properties.

Synergy is a term that is also used to describe the emergence of unexpected and interesting properties. It is often used in management and organization theory as a way of explaining the benefit of group work. It is argued that the synergy of a group leads to much greater creativity in, for example, strategic thinking and "problem solving." However, as any manager will know, where conflict of interest arises it often seems that the whole is less than the sum of its parts.

Autopoiesis means self-producing systems. A cell produces its own components that in turn produce it. Living systems can be thought of as autopoietic since they are organized to enable their processes to produce components that are necessary for the continuance of these processes (Maturana and Varela, 1975, 1980; Maturana, 1980; and for a clear explanation, Mingers, 1989a). Controversy arises over the use of autopoietic ideas of autopoiesis in social sciences (Mingers, 1989a,b; Robb, 1989a,b).

In summary, the systems idea proposes a way of organizing our thoughts about phenomena that are complex. We can consider phenomena as complex sets of interacting networks, each understood as elements and relationships, and each transforming inputs to produce outputs by operating a set of feedback and/or feedforward control procedures. Other concepts can be introduced to help enrich the basic systems idea. Examples are hierarchy, emergence, adaptation, metalanguage, variety, entropy, and homeostasis. There are plenty of others. If we succeed in interesting you enough in this book, then no doubt you will go on to find out about the other ones for yourself. Before concluding, we would like to explain one important way to make use of the systems idea to deal with complexity.

☆ use as oth example in sys in depth

Metaphor and analogy, i.e., ideas of "likeness," can be used to gain insight into difficult-to-understand phenomena. We can use ideas that we are familiar with to bring meaning to phenomena that are difficult to understand. We are now familiar with the systems idea and so this can be drawn upon as a metaphor to generate understanding. That's all right as it stands, but by adding in different flavorings to the systems idea, we can have a range of **systems metaphors** that offer a great diversity to aid our thought processes. Let us briefly work through a few.

The most obvious metaphors that can be used are the organic ones. This is not surprising because, as already stated, the systems idea emerged from the biological sciences. So we can use the idea of an organism, an ecological system or an evolutionary system, to cast insight into phenomena. Each is a systems metaphor because it relies on the systems idea for its very essence. Each is a complex network of elements and relationships with a transformation effected by feedback control. . . . But each metaphor is distinct because it emphasizes particular systems concepts and brings out different meanings with and from them. Examples of their use to explain organizational phenomena abound. We can think of organizations adapting, surviving and evolving. We could even employ a neurocybernetic metaphor, the organization being like a human brain.

Other metaphors can be identified. The machine age brought forth the machine metaphor. This also uses the network idea, but as a closed system with set goals to be achieved in a rigid hierarchy of control. Organizations can and most often are thought of in this way. Culture as a metaphor encourages us to think of networks of values, beliefs, and norms. Cultures are very powerful control systems that shape human behavior. And then there are networks of interacting interests that people pursue and may achieve by having more "resources" to bring to bear in the struggle. This coercive activity of course employs the political metaphor. We can think of organizations as political systems.

At least five systems metaphors have thus been identified—machine, organic, brain, culture, and political. These can be used in systems thinking. Chapter 6 provides an example of this for systems "problem solving."

To tie up this chapter, we will look more broadly at the term "system" and its adjective derivatives. "System" has two adjectives, **systemic** and **systematic**. "Systemic" refers to holistic thinking as discussed above. "Systematic" refers to step-by-step procedures, and from the point of view of some systems scientists is important during problem management. The adoption of a systematic approach forms the basis from which methodologies have evolved. Traditional **systems methodologies** are essentially systematic, although they may incorporate systemic thinking at appropriate steps, for example, to develop systemic models. Some contemporary methodologies are systemic, however, as will be seen in Chapter 6. A distinction has been made between systematic and systemic methodologies, popularized in the literature as **hard** and **soft** systems methodologies. Each is appropriate for different contexts. A hard context is suitably dealt with by hard systems methodologies. Hard contexts are easily and noncontroversially structured (defined earlier), and so are relatively easy to measure and quantify, behave according to known laws, and have a high degree of predictability (natural sciences typify this). The key task of a hard methodology is to get to know the structure of organization and to use the information to determine the best way of doing whatever has to be done. Soft contexts, in contrast, are difficult to capture through one structure, are very difficult to quantify, and usually have a number of conflicting theories associated with them. There are no generally accepted laws and it is difficult to reach a consensus view about purpose, function, or behavior (human sciences typify this).

Finally, it is important to recognize that the discipline of systems science in fact claims to be a **metadiscipline**. Systems science is not multidisciplinary. It is not concerned with lots of disciplines separately, but rather with disciplines brought together in an integrated fashion; it is an interdisciplinary **metasubject**. The framework of thought can be transferred from discipline to discipline, it is **interdisciplinary**, and from situation to situation, it has multiple theoretical and practical uses. Of course, this simple transfer on its own is not enough to be able to cast adequate insight into all disciplines and to help out in all situations. We must pay full and due respect to the richness of each discipline and its own theories, and to each situation and its unique features.

1.4. CONCLUSION

In this chapter we have introduced systems science by identifying its origins and evolution, and then by presenting the fundamental concepts and terms that underlie systems thinking, theory, and application. This chapter is an essential introductory chapter that provides the systems concepts and framework of thought that, we will show, can help us to deal with complexity.

There are other important concepts in systems and cybernetic thought, such as second-order cybernetics and bifurcation. As stated at the beginning of this chapter, we cannot hope and will not pretend to be able to chart the frontiers of systems science where some of these concepts are to be found. Our aim is much more modest. We wish to introduce you, the reader, to systems science and to interest you in the subject matter. If we achieve that aim, then you may wish to go on and explore systems science in greater detail. We hope so. Now let us move on to an essential task for this book, to draw up an understanding of what we mean by complexity.

QUESTIONS

1.1. What are the four main development cycles of systems science discussed in this chapter?

1.2. In what way can the four main development cycles of systems science help to explain its evolution?

1.3. Briefly describe the following systems terms:
   1. Element
   2. Relationship
   3. Attribute
   4. Boundary
   5. Environment

1.4. What are the main differences between "open" and "closed" systems?

1.5. Do "closed" systems exist only as theoretical constructs, or can you identify a real-world example?

1.6. Briefly describe the following systems terms:
  1. State variable
  2. State vector
  3. State trajectory
  4. State space

1.7. By considering a situation of interest to yourself, explain the meaning of homeostasis.

1.8. Explain why "structure," "process," and "systems behavior" are the three basic concepts associated with dynamic systems.

1.9. What effect can a "system's environment" have on a "system's behavior"? How is "environmental change" catered for in a stable system?

1.10. Is "counterintuitive behavior" a property of phenomena?

1.11. Draw a "black box" with feedback from the output to the input. Explain the concept of "negative feedback" making reference to this diagram.

1.12. Explain the meaning of the concept of "metalanguage."

1.13. Explain both in words and using diagrams the concept of "entropy."

1.14. Describe in words an example of a hierarchically structured or organized situation. Now present your example diagrammatically.