Heylighen F. (1990): "A New Transdisciplinary Paradigm for the Study of Complex Systems?", in: *Self-Steering and Cognition in Complex Systems*, Heylighen F., Rosseel E. & Demeyere F. (ed.), (Gordon and Breach, New York), p. 1-16.

A NEW TRANSDISCIPLINARY PARADIGM FOR THE STUDY OF COMPLEX SYSTEMS?

Francis Heylighen

Transdisciplinary Research Group
Free University of Brussels

ABSTRACT: two paradigms for studying the relation between autonomy and cognition are reviewed and contrasted: the "artificial" paradigm, which sees autonomous systems as linear, information-processing organizations, and the "autopoietic" paradigm, which sees them as circular, self-producing organizations. It is argued that these two paradigms are not inconsistent but complementary, and that they can be synthesized in an encompassing paradigm based on the self-organization of complex systems through variation-and-selective retention, leading to the emergence of relatively autonomous subsystems. Some implications of such an encompassing paradigm on the level of science, technology, individual persons and society are outlined, with reference to the papers in this collection. It is argued that the further development of such a transdisciplinary approach will lead to a new "science of complexity".

1. Introduction

In the preface to this book it was argued that some recent trends in different disciplines seem to converge around the concepts of self-organization, autonomy and cognition. Whether these developments really announce the emergence of a new paradigm remains to be proven. Only time can tell. In this position paper, I will assume that they do, and investigate where this new paradigm would be coming from, and where it might be heading to. This will allow me to draw a first map of an as yet uncharted territory.

As my background is in theoretical physics, I will focus primarily on developments in the "hard" sciences and technologies : physics, computer science, chemistry, biology, ... However, I will also discuss some applications of these ideas on the level on persons and society. A more elaborate, personal view on the social implications of the emerging new paradigm can be found in Rosseel's position paper for this book.

Whereas the paradigm of classical cybernetics (which is related to the paradigms used in other disciplines such as classical physics, computer science, economy, and so on ...) stresses the mechanistic, causal, externally controlled aspects of general systems, there is now a general tendency to acknowledge the indeterministic, self-organizing, internally controlled character of complex systems. This tendency is not really new; it has already had quite some impact on disciplines such as thermodynamics, biology and psychology. Yet the concrete formal or operational expression of these ideas remains vague.

What I think is really new, is the beginning of an integration of this research trend with another one, whose conceptual base might be called the "cognitive paradigm". Although the idea of a cognitive process presupposes that the cognitive system is undergoing an influence of its environment, which proposes the perceptual data or information the system must process, the awareness has been growing that the development of cognitive structures is basically an autonomous, self-organizing, internally controlled process (see section 3 of the book). On the other hand, it has become clear that for a complex system to be really autonomous, it must be able to interact on a cognitive level with its environment. A third connection between autonomy and cognition appears on the highest level, where the system becomes conscious of its autonomy, and hence develops self-knowledge and -reflection.

2. Two paradigms : "artificial" vs. "autopoietic" systems

We should be aware, however, that there are two at first sight opposing views about the relation between cognition and autonomy. The first one might be called the "artificial" paradigm, and may be associated with the name of Herbert Simon. The origin of its main ideas could be traced back to the fifties, when Simon, in collaboration with Allan Newell, began his pioneering work on problem-solving. They thus laid the base for the field of Artificial Intelligence (AI), which attempts to simulate cognitive processes on computers. Simon's further work has shown, however, that the same ideas can be applied to the most diverse disciplines: economy, management, sociology, psychology, epistemology, systems theory, ...

The general paradigm underlying this approach was perhaps best expressed in Simon's book "The Sciences of the Artificial" (Simon, 1981, first edition in 1969). He defines an *artificial* system as a system which has a given form and behaviour only because it adapts or is adapted, in reference to a goal or purpose, to its environment. In other words, it is designed to fulfill a given function in a given environment. In this view both man-made artifacts and man himself, in terms of behaviour, are artificial.

The peculiarity of an artificial system is that its behaviour is almost completely determined by the complexity of the environment to which it is adapted. This behaviour will only reveal the internal characteristics of the system insofar that the adaptation to the external conditions is not perfect. In other words, two artificial systems which are perfectly adapted to the same environment, in reference to the same goals, will behave in the same way, even though their internal structures may be completely different. For example, a computer and a human, which are both expert problem-solvers in a certain domain, will approach the same problem in the same way. We can only learn something about the personality of the human by looking at the way he tackles problems if his behaviour is not optimal, but restricted by prejudices, lack of information or other cognitive constraints.

This view corresponds to the engineering view in systems design, which views subsystems as black boxes fulfilling a predetermined function. This function is usually defined as the transformation (processing) of a certain input to a certain output. This can be modelled by a linear (sequential) scheme (see fig. 1). The way this transformation is carried out is not important, as long as the desired output is produced. The internal mechanism of the black box only becomes significant in those circumstances where the goal or function is not optimally fulfilled.

The difference between mechanical engineering systems and higher order, cognitive systems, however, is that the latter are supposed to process *information* instead of matter or energy. The goal or function which controls the processing can be viewed as a problem which is to be solved by the system. The input information corresponds to the initial data, given for solving the problem. The output corresponds to the solution derived by the system. Hence, according to this "artificial" paradigm, the cognitive processes characterizing intelligence and adaptation should be viewed as *information-processing, problem-solving* processes. Problem-solving can be viewed as a search through an internal space of problem states, which represents the space of actual or potential states of the environment, and hence embodies the knowledge the system has about this environment.

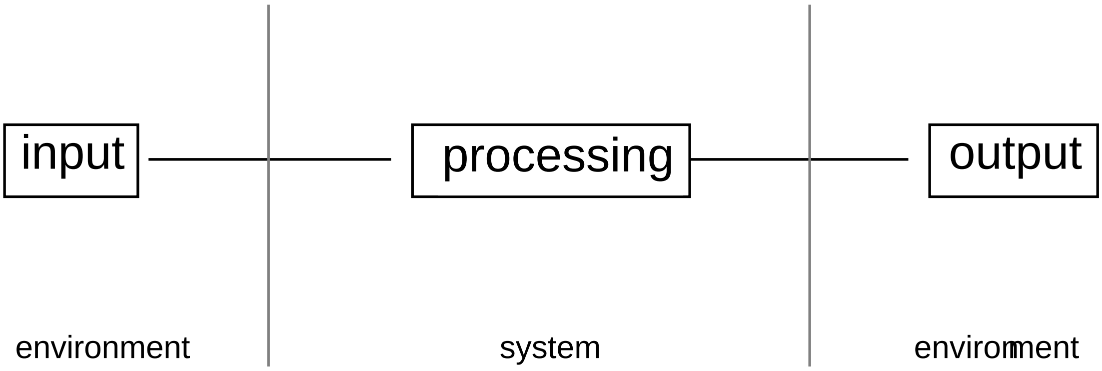

FIGURE 1. Linear scheme associated with the artificial paradigm.

A different view of adaptive systems was proposed by Maturana. It is based on his work on the neurophysiology of perception in the fifties and sixties. The basic concept of autopoiesis was formulated around 1974, and summarized in (Maturana and Varela, 1980). His conception is inspired by living, biological systems, instead of artificial systems, such as computers. He defines an autopoietic system as a system whose only goal is to produce itself (auto = self, poiesis = production), and hence to maintain an invariant organization. This implies that the internal processes are circular, they are closed upon themselves (organizational closure) (see fig. 2). Moreover it means that it is the system itself which specifies its topological boundary, and hence separates itself from its environment. The environment is important only insofar that it hinders or perturbs the system in its continuing attempt at self-production. The behaviour of the system is thus primarily determined by its internal organization, and not by its input.

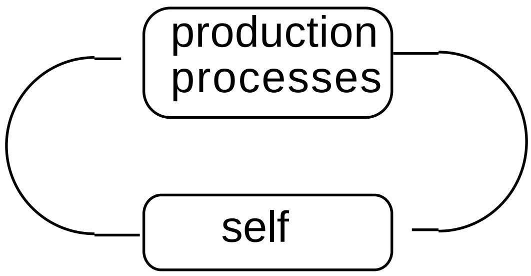

FIGURE 2. Circular scheme associated with the autopoietic paradigm.

Systems which function according to the input-processing-output scheme are called allopoietic systems by Maturana : they produce something (their output) which is different from themselves (allo = other). Hence they cannot be really autonomous : their behaviour is controlled by the function they fulfill in the larger system (environment) and by the input they receive from this environment. They can be viewed as instruments, as tools used by another, external system in order to reach its goals. Only autopoietic systems can be truly self-steering.

Therefore Maturana rejects the view of intelligent autonomous systems as information-processing systems. He interprets information as in-formation : a formation (structuring) of the inside of the system by the signals received from the outside. An autopoietic system, however, is not structured or determined by the external information it receives, but by its internal network of self-producing processes. Hence the cognitive structures used by the system are constructed by the system itself. They are not the result of the mapping of features of the outside world. Maturana calls this view of cognition *radical constructivism*. It leads him to reject the concept of knowledge as a representation or image of a hypothetical "external reality". In his view, the cognitive interaction between the system and its environment is restricted to a mere "triggering" of internal processes by external perturbations.

The two paradigms we have sketched (perhaps in a somewhat oversimplified manner) might be considered as the two opposing poles of a continuum of viewpoints towards intelligent, adaptive systems. Whereas the first one stresses the external determination of the systems behaviour, governed by the information from the environment, which flows in a linear way through the system, the second one stresses the internal determination of this behaviour, which originates in the organized whole of circular, self-producing, internal processes. The two views, however, may not be as inconsistent as they appear. The aim of the present book is to explore the middle ground between both positions, and to examine the interaction between internal and external determinants of autonomy and cognition. This might lead to an integration of the "artificial" and "autopoietic" paradigms (cfr. Bråten, 1984) into an encompassing new paradigm. We will now try to sketch a possible way to unify both views by looking at the self-organization of a complex system into a set of interacting complex subsystems.

3. Self-organization in complex systems : towards an integrative paradigm?

A complex system could be characterized by the multitude of its elements and their interconnections. Moreover the interaction between these elements is such that the system is continuously changing, evolving. This makes it very difficult to predict the processes inside the system, or even to describe its structure in a static way.

However, there is one principle which can always be used to describe complex evolutions : the principle of natural selection. This principle states that, whatever way a complex of elements has interacted, the chances are great that after a sufficiently long period the process has produced a more or less stable assembly. The reason is simply that of all the assemblies of elements produced the unstable ones will be the first to disappear. The more stable an assembly, the greater the probability that it will still be there some time after it was created (i.e. "survival of the fittest").

However, this reasoning does not say anything about the initial probability that a stable assembly would be created, compared to an unstable assembly. In practice, the chance that a random interaction of elements would produce a complex whole which is stable is rather small. However, this probability is greater for smaller sets of interacting elements. Indeed, the probability that a particular stable structure, consisting of a large number of interconnected elements, would be formed by a sequence of random "collisions", in which each element would "fall" into its right position, is roughly equal to the product of the probabilities that each individual collision would result in the right position. Clearly, the greater the number of collisions needed, the smaller the product of their probabilities for success. (For an elaboration of this argument, see "The Architecture of Complexity", reprinted in Simon, 1981.)

Does this mean that only relatively simple stable assemblies can be formed through natural selection ? No. Indeed, once a stable assembly is formed, it will interact with other stable assemblies, as if it were a new kind of element inside the global complex system. Hence, different stable assemblies may form a more complex stable assembly, which can itself functions as a building block for even more complex stable assemblies. In this way arbitrarily complex stable systems may be formed. Each system, however, can be analysed as an assembly of less complex stable subsystems. This property of complex systems, which have evolved through natural selection, was called near decomposability by Simon (1981). This means that the system is not completely decomposable, since there is an interaction between its stable subsystems, but that this interaction is much smaller than the interaction between the elements inside its subsystems. Hence, the description of the complex system as a set of interacting subsystems is a good approximation.

The evolution of a complex system towards near decomposability can also be viewed as a development of structure : the stable subsystems can be seen as coherent elements or modules, which are in a first approximation separated from their surroundings. In second approximation there is a relatively simple, clear-cut interaction between these modules. The (more complex) interaction between the submodules of these modules will only appear in a third order approximation and can hence be neglected if the system is considered from a more abstract viewpoint. To describe such a structure formed by the (weak) interconnection of relatively independent modules, we shall adopt a term from computer science : modularity. The spontaneous evolution of a complex system towards modularity can be seen as a form of self-organization.

Let us illustrate these concepts by the example of an aquatic ecology. Consider the sea before the appearance of life on earth. This is clearly an unstructured complex system, consisting of a multitude of different organic and inorganic molecules suspended in water. The random interactions between the molecules will lead to the formation of certain larger, stable molecules : amino acids, proteins, DNA ... These can be seen as a first level of modules : the connection between the atoms or submolecules within such polymers is much stronger than that between the molecules which do not belong to the same polymer. On a second level of modularity the polymers will aggregate to form living cells. Here again the interaction of the polymers within a cell is much larger than that between separate cells. On a yet higher level the modules will be formed by the organization of separate cells in a multicellular organism. Once again the interaction between different organisms is much weaker than that between the cells within one organism.

You should remark that we now have reached the level of the previous discussion : organisms and cells belong to what Maturana calls "autopoietic systems". They are complex systems which try to maintain some form of autonomy within a larger complex system, which is formed by the global marine ecology. As Maturana points out, their behaviour is primarily determined by their internal organization, by the self-producing network formed by their inner processes. Yet on a higher level of abstraction we can neglect this internal structure and regard the system as a module interacting with the other modules (other organisms in the biotope) so as to maintain a global equilibrium for the ecology. It is just the stability of the autopoietic organization, which allows to abstract away the internal structure, and to view the system as a black box performing a certain function in the larger system formed by the ecology. For example, the function of green plants (e.g. algae) could be said to transform carbon dioxide to oxygen, and hence to allow the survival of organisms which need oxygen. The survival of the plants, on the other hand, will depend upon certain substances produced by these other organisms.

However, as Maturana would argue, if we look at an individual organism, we cannot say that its goal is to produce oxygen : its goal is to maintain its identity, to survive. The oxygen is just a waste product of the processes ensuring this survival. Is it then a pure coincidence that this waste product is required for the proper functioning of the other modules of the complex system ? We would say that if you look at the evolution of the complex system as a whole then it is natural to expect that the pattern of interactions between modules will self-organize in such a way that both the modules and the pattern will reach some sort of stability. This entails the existence of stable channels of exchange between modules, such that the output of one type of module can be used as input for another type of module. Yet every module remains in a first approximation separate from its surroundings, so that these interactions can always be considered as mere perturbations of the internal dynamics of the module.

This discussion allows us to reformulate the aim of this book as : to study how a complex system ("module") can maintain a stable identity within a complex environment (higher order "module" or system). The identity of a module is determined by its boundary, i.e. that which distinguishes the system from its environment, which separates strong (internal) interactions, from weak (external) interactions. The problem might therefore also be formulated as : how do boundaries (distinctions, differentiation, structuration) appear and maintain within a complex system ?

This problem can be approached in two complementary ways : either we look at the inside of the boundary and consider the outside situation as merely a potentially perturbing boundary condition for the internal self-organizing, autopoietic processes, or we look at the outside interactions and consider the inside as a black box, processing input and producing output. The first viewpoint corresponds to the autopoietic paradigm, the second one to the artificial paradigm. The two views are just stressing opposite sides of the same phenomenon : the relation between inside and outside, determined by the boundary, and the way it develops. Hence there is no contradiction, only complementarity.

The integration of both views in one scheme may be summarized by fig. 3. Remark that in this scheme more than one process or information flow is considered: the system does not interact with only one system (the environment) but with several subsystems of the global system it is part of. The most important of these subsystems is the system itself. This "internal" interaction is by definition stronger than the other "external" interactions, and is separated from them by the systems boundary. If we extend the scheme in order to include several subsystems, we get a "network" consisting of nodes (representing subsystems), which are connected by arrows (representing process flows).

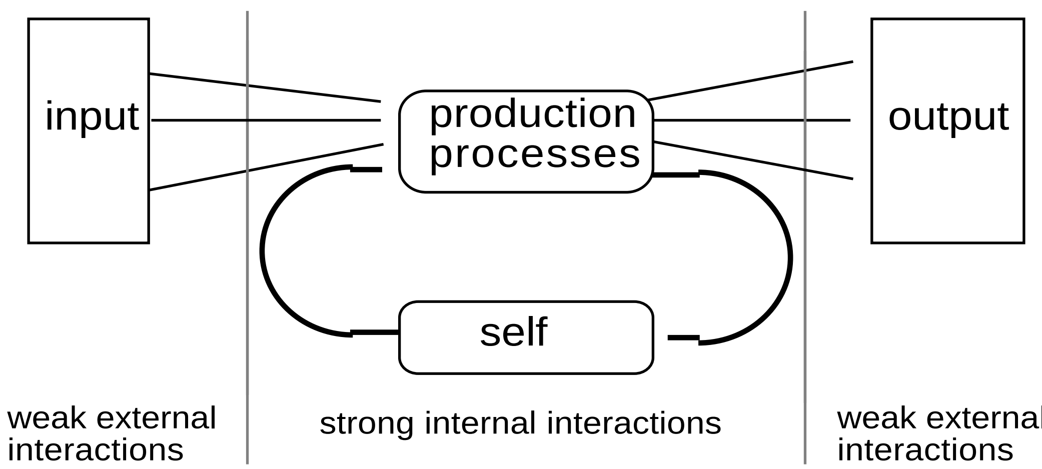

FIGURE 3. "Network" scheme associated with the integrated paradigm.

A last comment about this integrating view of complex systems should add something about the role of self-steering and cognition. What does it imply that a complex module is stable with respect to a complex environment ? First, that the module possesses some form of autonomy : the further existence of the module is relatively independent of its interactions with the environment. Even if we consider the module from the outside, as an artificial system which is fulfilling a certain function in the larger whole, we must grant that the internal operation, the way the function is performed, cannot be controlled from the outside. With respect to its internal development the system may be called "self-steering". (In organization theories this relative independence of subsystems within a larger organization is called "functional autonomy").

On the other hand the module should be able to cope with the changes in the environment, which would perturb its internal organization. In order to do that, it should compensate a perturbation before it can damage the module in an irreparable way. In other words, the module must anticipate the effects of external changes. This requires some form of "knowledge" about these effects and the way they can be counteracted. In relatively simple systems this knowledge may take the form of a particular static structure which guarantees stability with respect to a given environment. Such knowledge may be found in the DNA, which codes the set of innate responses of an organism. In more complex systems, the knowledge is dynamic and can adapt to the changes in the environment. In this case we may call the system "intelligent". The emphasis of the present volume will be on those more complex types of cognitive systems.

We might further speculate that there is a parallelism between the structuration of knowledge about a complex system (module + environment) and the structuration of the complex system itself. This does not mean that knowledge would be formed by a "mapping" of the structure of the environment on the cognitive structure of the module (in-formation of the module). However, since both the inside and the outside of a complex system are formed by self-organization, leading to modularity, and since there always is a (limited) interaction between them, we might expect that they would develop some form of "relatedness". This relatedness should not be interpreted as isomorphism, but as an incomplete coupling of systems governed by similar structuring principles. One way to extend this idea in a more concrete way is by analysing the (incomplete) correspondence between internal, cognitive distinctions and external differentiations (cfr. the paper by Heylighen).

4. Implications for science and technology

The general conceptual framework which was sketched can be applied to all scientific disciplines. Indeed, each non-trivial research enterprise will sooner or later be confronted with the study of complex systems. The general way of evolution for complex systems is self-organization, and this leads to the appearance of autonomy. This autonomy in turn may lead to the development of cognition. Even when the system under study is not sufficiently complex to exhibit cognition, there is always a cognitive system in direct interaction with it : the observer himself. If the observer wishes to understand his interaction with the system, he should have at least a basic insight in what cognition is. The fact that this influence of the observer on the cognized object cannot be evaded is clearly shown by quantum mechanics (cfr. the paper by von Lucadou).

This universality of application of a framework may be called *transdisciplinarity*. It means that the framework is not merely an aggregate of concepts from different disciplines (*multidisciplinarity*), or an approach standing in between disciplines (*interdisciplinarity*), but a way a way of viewing scientific problems which transcends the existing boundaries between the disciplines. In this sense the framework follows the tradition defined by the General Systems Theory (von Bertalanffy, 1967). What is added with respect to this tradition is the emphasis on autonomy and cognition. In this last respect it is also related to the field known as Cognitive Science (Bobrow and Collins, 1975), which is, however, less interested in the self-organizing capacities of general systems.

The framework, however, is not only concerned with epistemology and conceptual problems about the interrelations between the different disciplines, it is also applicable to concrete technological problems. Indeed, the aim of technology could be defined as the design of (artificial) systems which can be efficiently steered by their human operators in order to reach their objectives. We have seen that artificial systems too, in order to be efficient, should have some form of autonomy (self-steering), and that this autonomy can be enhanced by cognition. It is obvious then that a greater insight in the mechanisms of autonomy and cognition will help us to build more intelligent (and hence more efficient) machines. In this respect there is a continuity with the tradition of Cybernetics (Wiener, 1947), which attempts to model steering or control, as well in natural as in artificial systems, and which has been used for the design of many technological systems in the past.

We shall now give an overview of some more direct applications of concepts from the framework in recent research domains, as well in pure science as in technology. Of course, considering the universality of the framework, this list of potential applications is quite incomplete. We only wish to highlight some topics were the cross-fertilization of ideas from the framework with existing research traditions appears particularly promising.

In physics and chemistry there are two domains which are directly connected to the complex systems paradigm : quantum mechanics and thermodynamics. In quantum mechanics there is a (cognitive) interaction between the observer and the system to be observed. This can be interpreted as a form of organizational closure (cfr. von Lucadou, this volume). In thermodynamics we are directly confronted with self-organizing processes in complex systems (dissipative structures). Their basic mechanism can often be conceptualized as a form of self-reference (non-linearity), where a chemical reaction produces the very substances it needs as input (cfr. Prigogine, 1979). These self-organizing systems have also technological applications : a.o. lasers (cfr. Haken, 1978), and the preparation of the so-called "new materials".

From chemical to biochemical self-organization is but a short step. In addition to being a dissipative structure, a biological system is also characterized by its autopoietic organization. This invariant self-producing structure is realized by means of the DNA, which is produced by the proteins and enzymes whose production it controls. It is clear that a further development of biotechnology (genetic manipulation, cloning, ...) will require a deeper insight in these self-referential and precognitive mechanisms governing the autonomy of living systems.

The next level, after the biological one, is the neurological level. That the brain is a complex, autonomous, cognitive system is fairly obvious. Present research on brain functioning is only scratching the surface of a vast, seemingly unlimited problem domain.

However, there seems to be some hope for a better understanding of this problem : the study of neural networks appears to be a first step towards the integration of low level physiology and high level cognition. The basic idea is that activation spreads through a network of interconnected "neurons", and that this complex, "distributed" process will self-organize in some way so as to form patterns of activation which embody higher-level concepts (cfr. Schreter and Maurer, this volume).

From neurology we come to psychology. It does not seem necessary to elaborate on the importance of research on autonomy and cognition for fundamental psychology (see e.g. Stadler and Kruse, this volume). We shall have more to say about the applications of such research on the personal and the social level in the next section. The same goes for the other social sciences : sociology, economy, ...

The technology associated with this research on mental processes is based on the use of a computer as a mechanical, information-processing device for the simulation of cognitive processes. It is clear that the more tasks a computer will have to perform, the more intelligent it will have to become. This is the main concern of the field of Artificial Intelligence. Whereas this domain was originally based on the "artificial" paradigm, there is now a clear trend towards an integration of ideas associated with the "autopoietic" paradigm. The most spectacular example seems to be the controversial "conversion" of Winograd, one of the most important AI researchers, to the Maturana framework (Winograd & Flores, 1986). However, also in mainstream AI there is a notable shift towards an emphasis on autonomy and self-organization (see also Maurer & Schreter, this volume). It is motivated by a general feeling that the existing sequential formalisms for the solution of well-structured "toy" problems are too limited to model an intelligence capable of coping with the complexity of the real world.

On the one hand it is noted that complex, ill-structured problem domains demand a constant revision or adaptation of the representations used for approaching them. This leads to research on the learning or discovery of new concepts (e.g. Lenat, 1983) and on the transformation of problem representations (Korf, 1980). To make this learning more realistic it is proposed to confront the learning system with feedback from a real environment. This means that the computer system must be equipped with a sort of sensory-motor apparatus which allows it to perform actions and to sense information in the physical world. This leads to the construction of intelligent, autonomous robots.

On the other hand one is becoming aware that the way information is processed in the brain is much more efficient than the way it is handled in sequential computers : most processes proceed in parallel instead of being performed one after the other. This leads to the construction of computational models of "parallel distributed processing" (McClelland and Rumelhart, 1986). Through the framework of "connectionism" (see Maurer & Schreter, this volume) these are related to the models of self-organizing neural networks we discussed in the paragraph on neurophysiology.

A last scientific domain which is directly influenced by developments associated with the complex system paradigm is logic and mathematics. On the one hand there is a growing mathematical literature on the modelling of self-organization processes (e.g. by means of non-linear differential equations or so-called "cellular automata"). On the other hand there is a general interest in the formalization of "self-reference" and its pitfalls (e.g. logical paradoxes and the Gödel theorem) (cfr. Löfgren, this volume). This is paralleled by the development of different types of non-classical logic (e.g dynamical and dialectical logics), which aim to provide a more realistic picture of the cognitive processes of reasoning.

5. Implications for persons and society

The newly emerging way of viewing complex systems has profound implications for our own daily life : our personal aspirations, our interpersonal contacts, the organizations we work in, the society we belong to. Everybody will agree that our present society is extremely complex, and so are the lives of the people who must cope with its demands. On the other hand this society can be characterized by its valuation of (personal) autonomy : we all desire to be free and independent. Hence we come to back to the basic problem discussed in this volume : how can a complex system (a person, or an organization) maintain its autonomy within a complex environment (society at large) ?

The person-oriented version of this question may perhaps best be approached through the concept of *complex problem solving*. A problem can be defined as a situation (state of the environment) which is to be changed by an actor (the person, or the organization) so as to secure the survival of the actor (Heylighen, 1988). The problem is well-structured or simple if the initial situation, the goal situation, and the available means for transforming the initial situation into the goal situation are well-defined. Otherwise the problem is complex (Dörner & Reither,1978; Dörner et al., 1983).

This means that in the limit everything is ambiguous, fuzzy, undetermined. We know that something is lacking in the present situation, we are convinced that the situation must be changed, but we do not know what to change, how to change it, or what the result of such a change would be. The different aspects of the problem are entangled and hence difficult to explicitly distinguish. In such a case a profound analysis of the relation between actor and environment must be made. This entails basic questions such as : Who am I ? What do I want ? Where do I come from ? Where am I going to ? ... Such "philosophical" questions must not be tackled on the level of metaphysics, however. They must be approached in a very pragmatic manner, so that the practical implications for daily life become clear.

One of the domains where such an approach is common, is psychotherapy (see the papers by Kenny, and Goudsmit, this volume). Psychotherapy should no longer be seen as the treatment of psychical "illness" or disfunction, but as a (partially) externally steered process of personal growth, during which the "client" redefines his identity and his objectives so as to feel better adapted to his personal situation. The interaction between the external interventions of the therapist and the internal cognitive processes of the client results in a complex process of self-organization of the therapist-client system. The duality between autopoietic and allopoietic ("artificial") modes can provide useful concepts for understanding such a process (see Kenny, this volume).

Another domain of application of this paradigm of "complex problem solving" is education. The view of educating as making children memorize all the facts they need to know for using in their adult life has long ago become untenable. We are all convinced about the necessity of permanent education : our society evolves so rapidly that we must continually be studying in order to be able to cope with the latest developments. But we cannot demand that people remain at school during their entire life. Hence we must stimulate autonomous learning, i.e. without supervision (steering) by teachers. Such cognitive development, however, presupposes the ability to find the relevant facts and rules, to organize them in a simple and coherent framework, and to apply this framework to concrete problems. In environments as complex as those encountered in the present scientific, technological and political domains, this is extremely difficult. Hence we must develop systems or schemes which help persons to structure these complex problem domains (Heylighen, 1988; de Zeeuw, 1985).

A field in which such support systems are already well-established is organizational decision-making (cfr. Masuch, LaPotin & Verhorst, this volume). In order to decide about the course of action that an organization must take, a manager must dispose of the relevant data. This information must be easily accessible and well-organized, so that it can be easily manipulated and interpreted. Storage and processing of information are handled efficiently by conventional computer technology. However, the organization of complex information systems is still carried out by specialists, who rely mainly on experience and intuition. The automatization of this task of "systems analysis and design" (see e.g. Senn, 1985) demands a high level theory of complex systems. Such a theory would not only allow to determine the most effective way of designing information networks, but it would also provide a way to analyse the necessary decision-making and even policy-formation in the organizational or social context. This model could be implemented on computer by means of the recently developed "symbolic" methods of knowledge representation (e.g. object oriented programming, logic programming, production systems, ...). Examples of high level computer systems which are already used for supporting complex organizational or social problem solving are expert systems and multi-actor/multi-level simulations (cfr. Hornung, and Klabbers & Scheper, this volume).

The social domain of application (which is sometimes called *socio-cybernetics*) of the theory of complex systems we are looking for should not only give insight in the interaction between one actor (person, organization) and his environment, but also in the interaction between several autonomous actors. One of the main issues here is the understanding of "conversation", as a cognitive interaction which is bidirectional, and during which new shared concepts are constructed (cfr. Pask, this volume). Another one is the shifting between self-referential and other-referential modes of cognition during social interaction (cfr. Rosseel; Van der Linden, this volume). A third aspect consists in the emergence of complex interaction patterns (self-organization) in social systems (see e.g. Krohn & Küppers; Starkermann; and Masuch, LaPotin & Verhorst, this volume). Here too, computer technology, and in particular artificial intelligence techniques (Masuch, LaPotin and Verhorst), can be used for simulating these phenomena.

6. Conclusion : towards a science of complexity

We have attempted to give an overview of some recently emerged approaches in a variety of disciplines. These approaches are related by their emphasis on the concepts of self-organization, autonomy and cognition. Two apparently contradicting paradigms, the artificial and the autopoietic paradigm, allow to characterize the relation between autonomy and cognition. It was argued that these two views are not inconsistent, but complementary, and that they can be both subsumed under a more general paradigm, based on the self-organization properties of complex systems.

It was shown how the spontaneous evolution of a complex system will in general lead to the appearance of a modular organization, consisting of different levels of relatively autonomous, yet interacting, subsystems. A subsystem (module) can be considered as well from the outside, as a black box interacting with the other modules through its input and output, as from the inside, as an autonomous system which tries to maintain its identity by internally compensating the external perturbations. Higher order modules maintain their identity through self-production (autopoiesis), and this leads further to cognition, as a mechanism for anticipating the effect of perturbations.The connection or interface between internal and external viewpoints is determined by the module's boundary. The evolution of a complex system can then be modelled through a dynamics (creation, destruction, shifting) of boundaries.

Such a paradigm could be considered as a basis for establishing a new scientific discipline, the *science of complexity* (cfr. Heylighen, 1988b; Vullierme, 1987; Mesjasz, 1988). This theory would integrate existing approaches such as cybernetics, systems theory, cognitive science, artificial intelligence, theories of self-organization and autopoiesis... The theory could be operationalized by computer simulations of theoretical models and by psychological experiments (cfr. Dörner & Reither, 1978).

The domain of application of this new discipline would consist in complex problem solving, i.e. the tackling of problems arising from the complexity of the system which is to be managed, or to which one is adapting. More specific applications may consist in : design of support systems for decision making in ill-structured problem domains (politics, education, psychological problems, economy, ...); coping with the information explosion by designing more intelligent information systems; management of scientific research and interdisciplinary integration; systematization of psychotherapy and education ...

References

Bobrow D.G. and Collins A. (eds.) (1975) : Representation and Understanding. Studies in Cognitive Science, (Academic Press, New York).

Bråten S. (1984) : The Third Position : Beyond Artificial and Autopoietic Reduction, Kybernetes 13, p. 157-163

De Mey M. (1982) : The Cognitive Paradigm, (Reidel, Dordrecht).

de Zeeuw G. (1985) : Problems of Increasing Competence, Systems Research 2, p. 13.

Dörner D. & Reither F. (1978) : 'Über das Problemlösen in sehr komplexen Realitätsbereichen', Zeitschrift für Experimentelle und Angewandte Psychologie 25.

Dörner et al. (1983) : Lohhausen : Vom Umgang mit Unbestimmtheit und Komplexität (Hans Huber Verlag, Berlin)

Haken H. (1978) : Synergetics. Non-Equilibrium Phase Transitions and Self-Organization in Physics, Chemistry and Biology, (Springer, Berlin).

Heylighen F. (1988) : Formulating the Problem of Problem-Formulation, in : Cybernetics and Systems'88, R. Trappl (ed.), (Kluwer, Dordrecht).

Heylighen F. (1989) : Building a Science of Complexity, Proceedings of the Cybernetics Society, (Birckbeck College, London).

Klir G.J. (1985) : Architecture of General Systems Problem Solving, (Plenum, New York).

Korf R.E. (1980) : Toward a Model of Representation Changes, Artificial Intelligence 14, p. 41.

Lenat D.B. (1983) : EURISKO : A Program that Learns New Heuristics and Concepts, Artificial Intelligence 21, p. 61.

Maturana H. and Varela F. (1980) : Autopoiesis and Cognition : the realization of the living, (Reidel, Dordrecht).

Mesarovic M.D. and Takahara Y. (1975) : General Systems Theory : Mathematical Foundations, (Academic Press, New York).

Mesarovic M.D., Macko D. and Takahara Y. (1970) : *Theory of Hierarchical, Multilevel Systems*, (Academic Press, New York).

Mesjasz C. (1988) : *Simplifying Approaches to Systems Complexity - an idea of loopholes*, in : Cybernetics and Systems'88, R. Trappl (ed.), (Kluwer, Dordrecht).

Prigogine I. (1979) : *From Being to Becoming : Time and Complexity in the Natural Sciences*, (Freeman, San Francisco).

Rumelhart D.E. & McClelland J.L. (eds.) (1986) : *Parallel Distributed Processing : Explorations in the Microstructure of Cognition* (Bradford Books/MIT Press, Cambridge, MA).

Senn J.A. (1985) : Analysis and Design of Information Systems, (McGraw-Hill, New York).

Simon H.A. (1981) : The Sciences of the Artificial,(2nd ed.), (MIT Press, Cambridge, Mass.).

von Bertalanffy L. (1968) : General Systems Theory, (Braziller, New York).

Vullierme J.L. (1987) : Cybernétique, auto-organisation, cognition. La marche des sciences de la complexité, Revue Internationale de Systémique 1, p. 123.

Wiener N. (1961) : Cybernetics or Control and Communication in the Animal and the Machine (2nd ed.), (Wiley, New York).

Winograd T. & Flores F. (1986) : Understanding Computers and Cognition : a new foundation for design, (Ablex publish. corp., Norwood NJ).