145

Intelligence under the viewpoint of the concepts of complementarity and autopoiesis

V. Calenbuhr
C.R.E.A., Ecole Polytechnique
1, rue Descartes, F-75005 Paris, France

and

I.R.I.D.I.A, Université Libre de Bruxelles[1)]
C.P. 194/6, 50, Avenue F. Roosevelt
B-1050 Bruxelles, Belgique

Paper intended to be given at the ECAL '93 conference in Brussels (May 24-26, 1993)

1) Present mailing adress

Abstract

This paper deals with some of the conclusions that may be drawn from the study of the collective behaviour in social insects of the Brussels School. These conclusions are put into a more general context and some future research projects are discussed. There are two concepts that emerge as conclusions from the work on social insects. These concepts are associated with the terms "complementarity" and the "function of a pattern". By pattern we mean a structure that evolves from the dynamics of a self-organization process. The term complementarity is used to describe the relation between the members of a group of animals (or individuals in general) and the environment and is an extension of the Lorenzian complementarity principle to the collective level. The extension of the classical complementarity principle to the collective level via self-organization results in a phenomenon known as information compression. Further, it is argued that these concepts together with the notion of autopoiesis could be used to interpret some notions of the theory of evolutionary epistemology on a more physico-chemical basis which may give a perspective for the understanding of the phenomenon of intelligence. This discussion may henceforth be considered as a kind of outlook to future research projects and as a proposal to consider results obtained using self-organization approaches from a more global point of view.

1. Social insects and complex dynamical systems

On trying to devise complex dynamical systems that have the capacity of generating coordinated group behaviour one often tends to attribute the coordination of the various subunits to the complexity of the individual or to a central supervising control unit. Human group behaviour is generally considered to belong to the first category and a large number of engineering problems fall into the second class. A general tendency can be found in all these attempts. The capability of flexible behaviour is generally achieved by supplying the system with complicated rules of the game and a lot of information.

From a system-theoretical point of view social insects are confronted with the same problems. At first sight it is difficult to see how the (seemingly) erratic indidual behaviour results in a coordinated behaviour at the group level that is flexible enough to guarantee the insect society's functioning under strongly varying conditions. In the case considered here, there is now evidence that there are mechanisms which render complexity at the level of the individual or a central coordination superfluous.

Theoretical models that have been developped in the last few years in Brussels are based on the assumption that the individuals behave to a certain extent randomly and obey also a set of simple behavioural rules. These models explain a lot of interesting phenomena in social insects. It turned out that an ensemble of individuals could display remarkable feats. Flexible behavioural patterns are formed that represent adequate solutions to problems posed by various environmental conditions. Having the same behavioural rules emerge in a different environmental setting leads to another adequate behavioural pattern. This flexibility makes it unnecessary to foresee all possible cases and to provide a particular behavioural program for each case. The small number of behavioural rules needed leads to a considerable coding economy of genetic information (for an overview over these models see: Calenbuhr & Deneubourg, 1991; Deneubourg & Goss, 1990).

Chemical communication (that is the emission of an odorous substance and the behavioural response to this chemical signal) often plays an important role in the behavioural patterns of social insects (Wilson, 1971; Hölldobler & Wilson, 1990). Theoretical investigations on a microscopic level have shown that a kind of mirror image of the environmental conditions is created by the emission of a chemical signal. This mirror image represents the time dependent conditions for the animals' movements. These are determined by the behavioural rules at the level of the individuals and represent thus also a mirror image, namely for the chemical landscape (Calenbuhr & Deneubourg, 1991).

These mirror images per se may not represent anything of particular importance. We will have to discuss, however, this viewpoint below, since it may help us to draw an important conclusion. Another aspect that is important to us is that we are not only interested in the pattern as such, but that the pattern carries a function in very much the same way as a particular organ does. It could not only be shown that a small number of behavioural rules at the level of the individual is sufficient to generate flexible collective behavioural patterns, but also that the same rules can play different roles, can have a different meaning on different levels in the generated structure. This self-organization *ansatz*, where one has a few behavioural rules, allows us to observe the ontogenesis of a process. This approach represents also an example for the phenomenon of information compression. This way of compressing information or the inverse point of view the unfolding of some behavioural rules and the fact that the formation of "intelligent" solutions are generally made up of at least two components that have to be put together suggests to use the term complementarity in order to characterize this interplay of different aspects. (In this case the chemical landscape as well as certain boundary conditions, and the behavioural response can be considered as being mutually complementary.)

The questions raised in the beginning, namely the coordination and flexibility of group behaviour can be easily understood using this self-organisation *ansatz* and the concept of complementarity. In order to prevent misunderstandings a final note concerning the term complementarity and its use should be added: it is evident that an organism or even a group of organisms that is well adapted to its environment are somehow complementary to this environment. It shall also not be attempted to present Lorenz's parable of a fish's fin and the hydrodynamic properties of the water as something new. Also, the conclusions that can be drawn from these considerations which eventually result in the theory of evolutionary epistemology are well known to the author. What shall be shown, however, is the fact that Lorenz's idea as concerns animals' anatomy or individual behaviour can also be applied to processes in which many subunits take part and, even more important, that this idea leads immediately, at least in the framework of our self-organization *ansatz*, to the concept of information compression through this complementarity.

Monod (1971) once raised the famous question of where the meaning of the DNA could be localized. Hofstadter (1980) discussed that issue in detail a couple of years later and considered two extreme points of view. In the framework of what has been discussed so far Monod's question appears in a different light. Within the meaning of the concept of complementarity it is yet neither the DNA nor the physico-chemical properties of the environment where the meaning is localized. The process that takes place when the two components are brought together is in a certain sense the carrier of the meaning. By repealing Hofstadter's distinction in "information bearers" and "information revealers" and considering them instead as being mutually complementary and generating a certain function only when put together can one understand a lot of different problems, mainly in control theory, in a much simpler way. But we shall not go into these issues here. It also gives us a clue to the problem that biological systems need in general so less information to function.

It should be noted that the distinction in information bearers and information revealers, which also represents some kind of complementarity and which is fundamental to the classical theory of information in the sense of telecommunication, does actually not lead us any further as concerns information reduction when meaning comes into play. The reason for this is that it does not provide any hints concerning the problem of the meaning of a message. Pulling out the meaning of a message is not done by the information revealer, like a record player, a morse apparatus or any part in these technical devices, but resides in the faculty of the user to relate the obtained information to a certain context. Actually the problem of finding the localization of meaning has never been the goal of Hartley's and Shannon's work. They were only concerned with the problem of making telecommunication more efficient. The basic idea of Shannon was to quantify the amount of information transmitted from one point to another and to find an adequate coding. The fact that the classical theory of communciation has nevertheless been used as a tool for theorizing about the location of meaning and the roots of intelligence is surprising. Therefore the notion of information and its storage is different in both cases. In the classical theory of information there is no place for the meaning of a message (Shannon & Weaver, 1949, in v. Weizsäcker & v. Weizsäcker, 1972, who discuss various interpretations of the term information in relation to the mathematical theory of information.). Meaning in systems characterized by the principle of complementarity is generated through a functional relation between the complementary parts of the system and is not a general quality, property or value. The generation of meaning is closely related to the functional integration of a system and relates also to the concept of teleonomy. Teleonomy is a system property that is needed to understand goal-oriented behaviour in biological systems. The difficulties and misunderstandings one generally encounters using this concept are probably related to our incapacity of thinking in non-linear ways and possibly also because our own finalistic way of thinking (as one of the Kantian a prioris impossible to get rid of) blocks us the way. Our natural attitude of thinking in linear relations has found its philosophical manifestations in the work of Descartes, while our contemporary everyday way of seeing things is related to an abuse of Descartes' ideas based on Bacon, Locke and others. It is certainly not surprising that a concept like teleonomy cannot find a place in a world deemed to be ruled by causality and determinism. Another reason for the difficulties encountered with this notion is that many fundamental and rigorous results in the field of biology have been obtained by physicists. Teleonomy is a concept that is generally not found in physics. In what follows we will show how meaning and teleonomy can be related to physico-chemical systems, whereby we will encounter a concept that has as yet not drawn the attention of the majority of researchers in the field of complex systems, namely autopoiesis.

Before going into the details we will define how autopoiesis is understood in this discussion. Autopoiesis is a concept that was developed in the attempt to characterize those features that are common to all living systems, and that distinguish living systems from non-living ones (Varela *et al.*, 1974, and Maturana & Varela (1973) therein; Varela, 1979)). The term autopoiesis means self-generation. Varela *et al.* in their paper defined the concept of autopoiesis in the following way: "The autopoietic organization is defined as a unity by a network of productions of components which (i) participate recursively in the same network of productions of components, and (ii) realize the network of productions as a unity in space in which the components exist". The authors also presented a tesselation model that displays autopoietic organization. A dynamical theory in space and time, based on physical laws, was not developed. Schwegler and co-workers put the concept of autopoiesis on a thermodynamical and physico-chemical basis by introducing the concept of self-maintenance (mathematical models are described in: Schwegler *et al.*, 1985; Schwegler & Tarumi, 1986, Tarumi & Schwegler, 1987). While a self-generating system can be characterized as a thermodynamical, metabolizing process with an autonomous boundary, a self-maintaining system is characterized as a self-generating system that can persist in a fluctuating environment although the system's boundary and its internal structures are locally degraded permanently by fluctuations (an der Heiden *et* *al.*, 1985) Schwegler and co-workers demand that the system has the capacity to keep itself in thermodynamic non-equilibrium to be a self-maintaining system. Schwegler (1981) writes: “An autopoietic or organizationally closed composition of a system could be considered as a causal explanation of its self-maintenance.” I personally could imagine that Schwegler's statement could even be correct if it was inverted. For reasons that will become clear in section 2 and 3 we will use the term autopoietic for a system that is capable of self-maintenance, since physico-chemical models of self-generating systems seem to be able to maintain themselves (Schwegler *et al.*, 1985; Schwegler & Tarumi, 1986, Tarumi & Schwegler, 1987). It is, however, important to note that the precise relation of the term autopoiesis is not relevant for what follows. In a rather loose sense (and which does neither contradict Varela's nor Schwegler's interpretation) we will use it as a system's faculty to maintain itself in a state of non-equilibrium. Therefore, instead of pumping energy artificially into the system, we expect the system's and the environment's properties such that they are sufficient to maintain the non-equilibrium. Schwegler and coworkers show that there are no tautologies or thermodynamical paradoxa involved.

In sections 2 and 3 we will see that it becomes more and more difficult to interpret in purely physico-chemical terms a system’s capacity to keep itself in thermodynamic non-eqilibrium when looking at different levels of biological organization. This is particularly true if organizational features come into play that can until now not be linked to physical laws in an easy way, as is the case for behaviour. The latter is another reason why we interpret the autopoietic organization as a necessary condition for self-maintenance and will thus use it as the characteristic feature for a system’s capacity to maintain itself.

2. The quest for the roots of intelligent behaviour: Funtional patterns and autopoiesis

In very much the same way as was shown in the context of the flexibility and coordination problem one has proceeded in the domain of artificial intelligence research. Inspired by the idea that any problem could be translated into a binary code, that is into a seemingly context-free and -independent form, the way was paved for systems that became continuously more complicated. Although a certain progress has been achieved, especially as far as expert systems and high-level languages are concerned, it has not been possible to improve our conception of the phenomenon of intelligence. This approach is characterized by the philosophy that logic and intelligence would exist independently of the system that is used to generate them (i. e., the brain), that means that they would have a reality per se.

Philosophically inspired minds that are more influenced by biological aspects, especially the school of Konrad Lorenz (1943, 1977), see the brain and its actions as a product of phylogenesis, as a reflection of and as reflecting certain environmental conditions. H. v. Ditfurth (1981) once suspected that intelligence is not created by brains but that they are only a means of "visualization" (realization) of some already existing property inherent to the system. It is, however, not discussed which system properties might be important or how the system could be defined or characterized.

After all there is no way to prove whether a link between the concept of complementarity and the roots of intelligence can be established. Nevertheless, I shall advocate a conclusion by analogy that does not seem to be bolder than the enterprise taken so far in the domain of artificial intelligence, but that does take into account biological points of view.

We have seen that many collective behavioural patterns of social insects could be interpreted as the result of the unfolding of a couple of behavioural rules at the level of the individual. We also have seen that the flexibility of the solutions found by a group of animals was due to the fact that they represented a kind of mirror image to the posed problem and that it was these two complementary parts which made up the solution, namely the meaningful behavioural pattern. It is these two complementary parts that define the system and its properties and that realize a potential intelligence in the sense of v. Ditfurth. At least in the case of social insects and - phylogenetically on lower levels - namely at the level of social bacteria, societies of unicellular organisms, that is generally in chemotaxis-diffusion (-reaction)- (and maybe also in reaction-diffusion) systems can one define the system and its environment in a relatively clearcut way.

One might wonder whether these examples are a matter of intelligence as we conceive of in the case of human beings. This is probably not the case. In the light of the evolutionary theory of epistemology one has yet to pose the question, whether intelligence can still be considered as it has been for a long time. Namely, as an independently of all reality existing capacity of finding ways in an equally independent system that transcends all laws that nevertheless relate to reality. The behaviour of the insects appears intelligent to us because they find solutions that are accessible to us only by means of thinking. And these structures that appear so intelligent to us have one property in common: they often represent optimal or near-optimal solutions taking the given constraints into account.

The most important conclusion of the theory of evolutionary epistemology is the recognition and appreciation that our brains and the central computing organ in all animals represent a kind of image of the surrounding world and that this central computing organ has evolved under the functional pressure to keep the individual (seen in an anthropocentric way) alive, that is the capacity for autopoiesis (Riedl, 1981; Vollmer, 1990). In the case of social insects evolution has led to a mapping device that carries out all tasks - both, on the long-term time-scale of evolution as well as on the shortterm time-scale of cognitive capacities - in a spatially distributed manner. Other spatially distributed working systems such as enzymatic networks or the immune system that are capable of performances reminiscent of human features such as anticipation are generally characterized by the principle of complementarity.

The classical works in the field of behavioural physiology have revealed large parts of the circuitry that make up the central computing organs of an animal, i.e. "the reverse side of the mirror" - to use Lorenz's beautiful parable - in the light of the properties of the incoming light. The way in which that mirror reflects (= computes) has remained, however, intangible. It might be possible that our brain or an animal's brain does not carry out computations on the lowest level the way we do when adding or multiplying consciously and also not like a computer, that is on a symbolic level. It is possible that the computation is carried out in an analog fashion and that functional patterns play a role, as was described in the beginning in the context of social-insects.

Something else is needed in order to complete our line of argument. The question of what makes a pattern useful is quite important. Having a function means that something serves a certain purpose. Purposeful behaviour for a living being can be considered as being something that helps to maintain the organism's or a group of organisms' state, that is, keeping them alive. Every action that serves to fulfill this goal, be it an animal's behaviour or be it some biochemical reaction can be considered to be of functional value.

At the molecular or cellular level staying alive means to keep the system always in a thermodynamical nonequilibrium state. Everything that serves to maintain this autopoietic capacity is useful in a certain sense and can be considered to be purposeful. If we go to more complex organisms on the phylogenetic tree then we find that it becomes always more difficult to specify what makes a system autopoietic. Although a single cell in a multi-cellular organism may still have its autopoietic capacities, at least the actions that serve to fulfill one of the requirements to keep the system in a non-equilibrium state, namely the energy supply, can be found at the level of the organism's behaviour.

To us a pattern may appear useful or to have a function in many different ways. Whether this usefulness is also considered to be useful at the level of the organism is quite a different question. For an organism or a group of organisms a pattern can be termed useful if it is part of what makes the organism or the group of organisms autopoietic. (This does not exclude the possibility that there may exist patterns that are not useful at all.) Goal-oriented behaviour can be found at all levels of biological organization. Contrary to those approaches that try to understand intelligence as a web of complicated rules I believe that the smartness of a system and its finalistic behaviour can only be understood if we require the system to be autopoietic. Instead of trying to find nice patterns that are artificially maintained we should look at the benefit that the organism can get from a limited number of system-theoretical architectural designs: namely those that keep the system out of thermodynamic equilibrium. Instead of prescribing what is useful the system should decide on its own. Its these designs which make a system smart. Could one even say - certainly in a sort of sloppy way - that a system will hardly display a smart behaviour if it is not required to do so?

3. Conclusion

It will certainly not be possible to understand the phenomenon of intelligence following only these lines of thought. The mere quantity of possible questions related to that issue is already too large. The presented conclusion by analogy can, however, serve as a working hypothesis for a couple of projects that might justify this hypothesis a posteriori. I have come to the conclusion that there are two central questions that seem to be promising under the presented premise. Further these projects might turn out to be testable in experiment.

There are two main problems: firstly, one would like to know where the autopoietic properties of a system are actually localized from a system-theoretic point of view. Which is - by the way - not at all an easy task. (As far as I know, the first truly autopoietic system (in the thermodynamic sense) has been described by Schwegler *et al.*: Schwegler *et al.*, 1985; Schwegler & Tarumi, 1986, Tarumi & Schwegler, 1987). Subsequently one would investigate the functional features of the patterns produced by the autopoietic system under the viewpoint of complementarity and information compression. Being biologically fit or adapted means primarily being able to solve the problems posed by life itself. Or in other terms, fitness means to be able to solve problems in such a way as to stay alive. (This is of course Darwin's "Survival of the fittest", but stated in such a way it does not sound so opportunistic.) If we define a system using the concept of complementarity we conclude that among all possible (behavioural-) patterns only those are considered as meaningful that are not in contradiction with the requirements imposed by autopoiesis. Solutions which are not autopoietic are excluded. We can imagine that there are systems which have the capacity to solve problems in a meaningful way and that are at the same time reflections of their environments. This will not only be the case at the level of social insects but also at phylogenetically lower levels. On a cellular, or even molecular level, the aspect of gathering energy or matter will appear more transparent than at the level of social insects. The mathematical description, however, remains quite analogous. Transitions to higher degrees of differentiation such as the introduction of division of labor by the invention of organelles or organs, the appearence of multicellularity or social integration draw our particular attention on a phylogenetic time-scale. The higher one goes in the hierarchy, the more an individual cell resembles a CSTR (continuously stirred tank reactor) from a thermodynamic point of view. (That remains true for the function an individual cell plays in the whole organism even if the cell in such an organism may still possess the capacity for autopoiesis.) The system-theoretical realization of autopoiesis, however, can be found more and more at the level of behaviour in its broadest sense, as we have seen above. Since structures that have been successful will in general be used after the transition to a higher level, one can expect that there could be different mapping properties of a system at different levels of organization, but that there will be also basic features as concerns mapping properties and functionality that can be found at both levels, that is the old and the new level. Different parts of the brain also have different functions, as is well known. The building material, however, that is the nerve cells, remain the same. If we are looking for the building blocks that could be associatied with certain intelligent qualities at a certain level, we can expect to find something quite different at two different levels. However, the quality at the higher level has to be compatible with what is found at the lower level. In essence I suspect that intelligence can somehow be associated with functional patterns that fulfill the requirement for autopoiesis and that some of the basic properties of functional patterns in highly complicated systems that also lie on higher levels on the phylogenetic time-scale still bear characteristics of the archaic functional patterns.

4. Suggestions for projects

In case that I have been misunderstood in such a way as to subsitute words like autopoiesis for survival or functional pattern for behaviour I shall add some remarks firstly and give then some suggestions how the ideas presented here could be tested experimentally. Firstly, almost everything of what I have said is known to biologists. However, things have not been put together in the way presented here. Artificial and natural intelligence may and may not be the same thing very much the way as a plane resembles a bird more than a helicopter or a submarine more a fish than a container carrier. No engineer would, nevertheless deny that a plane is still another thing than a bird. On the other hand it has become quite fashionable to learn certain designs from nature and to try to implement them in engineering, e.g. AI. In order for that to function, however, one has to know what to look for. I do not claim having achieved that goal. However, by putting together the concepts of autopoiesis and complementarity (which are well known) we may get the tools to identify those conditions that can serve as selection criteria in developing a smart gadget.

The lesson of social insects is by now well known and every other distributed system could do as well. Before going to a more fundamental levels of biological organization, let us nevertheless have again a look at social insects. In general, we translate a problem into a symbolic representation which is accessible to mathematical analysis. For social insects nature has invented another way, based on complementarity: a property of the problem is translated into a mirror image via the emission of the pheromone, whose profile reflects the topology of the problem, the state of the food source, etc.. Besides this, a system is needed which is capable of using this mirror image. This is achieved by the insects' behavioral response. What is needed at the level of the individual is no more than the storing capacity for this simple behavioural rule and the emission. The dynamics of the system resides in the boundary conditions defined by the environment and some physico-chemical properties as well as in the biological part of the system, namely the group of interacting agents. The complementarity lies in having a system which generates a mirror image of the problem which in turn permits the system to relax into a solution. As far as boundary conditions and its interaction with the system's components concerns, autopoiesis can help us as the selection criterion when trying to model such behaviour. Instead of having simulated individuals running on a computer screen (which can already give rise to behaviour that looks quite intelligent) we would require the agents to take care for their proper energy supply.

We will now try to transpose these ideas to lower level of biological organization. A large part of the considerations presented here has been based on systems that make extensive use of chemical communication. A transition of primordial importance has taken place when under the viewpoint of division of labour and amendment of information transfer the neural system was invented. I propose to study model systems that are characterized by pure chemical communication and those where chemical communication has been spatially reduced, that is systems like the neural system where chemical communication takes place only at the synapses (which is done anyway). These systems should be studied and compared with regard to two aspects, complementarity and autopoiesis (this is new). Moreover, it would be quite interesting to investigate the mapping- and autopoietic properties of systems that work distributed but with locally fixed working units as the brain and distributed working systems whose units can move, as for example cellular and bacterial societies. The possibly infinite number of solutions to such systems will in all cases be limited by considering only those that fulfill the requirement of autopoiesis (because this is our selection criterion). There will possibly not be many solutions which pass this test. While autopoiesis is the criterion for selection, complementarity may help us to understand why the system behaves the way it does.

Acknowledgements

This work was supported by the Volkswagen-Stiftung (Forschungs-Schwerpunkt Synergetik) and carried out when the author was staying at the Service de Chimie Physique, Université Libre de Bruxelles, where G. Nicolis created a beautiful working atmosphere. I would like to thank also my mentor J.L. Deneubourg for teaching me the organization of social insects, my collegues R. Beckers and D. MacKernan for many discussions and O.E. Rössler (Tübingen) for the encouragement to pursue these lines of thinking.

References

Calenbuhr, V. & Deneubourg, J.-L. (1991). Chemical communication and collective behaviour in social and gregarious insects. In: Mathematical Ecology and Evolution (Weidlich, W, Ebeling, W. Peschel, M. eds.). Berlin : Akademie Verlag.

Deneubourg, J.L. & Goss, S. (1990). Collective patterns and decision making. Ecology, Ethology and Evolution **1**, 295-311.

von Ditfurth, H. (1981). Wir sind nicht nur von dieser Welt. Hamburg: Hoffmann & Campe.

an der Heiden, U., Roth, G., Schwegler, H. (1985). Die Organisation der Organismen: Selbstherstellung und Selbsterhaltung. Funkt. Biol. Med., **5**, 330-346.

Hofstadter, D.R. (1980). Gödel, Escher, Bach. New York: Vintage Books.

Hölldobler, B. & Wilson, E.O. (1990). The Ants. Heidelberg: Springer Verlag.

Lorenz, K. (1943). Die angeborenen Formen möglicher Erfahrung. Zeitschrift für Tierpsychologie, **5**, 235-409.

Lorenz, K. (1977). Die Rückseite des Spiegels - Versuch einer Naturgeschichte menschlichen Erkennens. München: dtv.

Monod, J. (1971). Zufall und Notwendigkeit. München: Piper.

Riedl, R. (1981). Biologie der Erkenntnis. Berlin, Hamburg: Paul Parey Verlag.

Schwegler, H. (1981). Structure and organization of biological systems. In: Self-Organizing Systems (Eds.: G. Roth & H. Schwegler). Frankfurt, New York: Campus Verlag.

Schwegler, H., Tarumi, K., Gerstmann, B. (1985). Physico-chemical model of a protocell. J. math. Biology, **22**, 335-348.

Schwegler, H. & Tarumi, K. (1986). The "protocell": A mathematical model of self-maintenance. BioSystems, **19**, 307-315.

Tarumi, K. & Schwegler, H. (1987). A nonlinear treatment of the protocell model by a boundaty layer approximation. Bull. math. Biology, **Vol.49, No. 3**, 307-320.

Varela, F. J. (1979). Priciples of biological autonomy. New York: Elsevier-North Holland.

Vollmer, G. (1990). Evolutionäre Erkenntnistheorie. Stuttgart: S. Hirzel.

Varela, F. J., Maturana, H. R., Uribe, R. (1974). Autopoiesis: The organization of living systems, its characterization and a model. BioSystems **5**, 187-196.

v. Weizsäcker, E. & v. Weizsäcker, C. (1972). Wiederaufnahme der begrifflichen Frage: Was ist Information? Nova Acta Leopoldina, Nummer **206**, Band 37/1. Leipzig: Johann Ambrosius Barth.

Wilson, E. O. (1971). The social insects. Cambridge, Ma.: The Belknap Press of Harvard University Press.