NEGENTROPY AND HISTORICAL ARROW OF TIME. THERMODYNAMICAL AND INFORMATIONAL ASPECTS OF THE DARWINIAN REVOLUTION

Giovanni F. Azzone
CNR Unit for Physiology of Mitochondria, Department of Experimental Biomedical Science, University of Padua, Italy

THERMODYNAMIC AND HISTORICAL ARROWS OF TIME

My purpose is to use concepts taken from thermodynamics and information theory to discuss basic features of the evolution of the natural world [1]. This leads to the question as to whether the nature of life can be described by the concept of negentropy.

About 60-70 years ago well known physicists pointed out that biological systems had behaviors in apparent contrast with the second law of thermodynamics. In fact, the tendency of biological systems is directed *1)* not to equilibrium but rather to maintenance of steady states; and *2)* to increase not of disorder but rather of complexity and of hierarchical organization during phylogenetic evolution. The answer to the steady state problem is relatively simple and given already in the forties in the famous book by Erwin Schrödinger *What is life* [2]. The maintenance of the steady state depends on the fact that living organisms are open systems, catalyzing a continuous exchange of matter and energy with the environment. The utilization of matter and energy provided by the environment leads to negentropic processes and development of negentropic structures, the main concern of Schrödinger in the forties. The answer to the second problem, that of the increase of organization, is just beginning to appear and it is much more complex.

The thermodynamic and informational problems of evolution are the following: *1)* Is the variation-selection mechanism responsible not only for diversification and increase of fitness but also for increase of complexity? *2)* Why should irreversible processes, entropy producing, give rise to phylogenetic evolution processes? The processes of phylogenetic evolution lead to an increase of information and a decrease of entropy and are defined as processes of the *historical arrow of time*. Thus these processes are different from the majority of natural world processes, usually leading to decrease of order and of information and defined as processes of the *thermodynamic arrow of time*. A proper answer to these two problems should also open the road for the answer to the Kantian problem: How does it come that dead elements dominated by the blind laws of physics are transformed into living organisms dominated by the biological laws of purpose?

About 20 years ago the famous book by Monod *Le hasard et la necessitè* [3] emphasized: *1)* the oscillation of the living systems between casual events and obedience to the physico-chemical laws, and *2)* the role of the casual events in biological evolution. But the casual events have a predominant role not only in biological evolution. Because of the large use of the terms casual events, unpredictability and chaos, a comment is here in order. The term unpredictability

leads usually our thinking to the famous three body problem of Poincarè or to the classical Hadamard problem of the behavior of complex systems with exponential evolutions and uncertain knowledge of the initial conditions. These systems, like many others, are unpredictable, and most of them are dealt with in the area of deterministic chaos. It is not with these systems that I shall deal but rather with the evolutionary systems, where casual events and unpredictability are accompanied by generation of new information. Thus the essential feature differentiating the evolutionary from the deterministic chaos systems is that in the former, but not in the latter, the entropic drive is accompanied by the generation of new information.

The processes of the *thermodynamic* and of the *historical arrow of time* are characterized by a decrease of order and information and by an increase of order and information, respectively. While information and order are often interconvertible, changes of order and of information do not proceed always in parallel. Processes involving a decrease of entropy and leading to formation of negentropic structures are not necessarily accompanied by generation of new information and then do not necessarily belong to the group of processes of the *historical arrow of time*. The most classical example is that of the ontogenetic evolution. The evolution from the fertilized egg to the newborn organism, although certainly a negentropic process, because accompanied by the development of the complex negentropic structures of the newborn, corresponds mostly to the decodification of a program and it is not essentially accompanied by generation of new information.

CASUAL EVENTS AND GENERATION OF NEW INFORMATION

The evolutionary conception, initially directed to explain the genealogy of the living systems, has gradually become a general gnoseological theory [4, 5]. The evolutionary conception is in radical contrast with the deterministic and inductivistic conceptions and covers an area which goes from biology to history, from philosophy of science to ethical philosophy. The conception can be utilized to explain a large variety of problems from the nature of the processes of the *historical arrow of time*, to the spontaneous evolution of the natural world toward the increase of hierarchical organization, and to the principles of an ethics freed from transcendental links.

In the evolutionary processes the casual events, whatever the mechanism of their generation - whether by association, by variation or others - play a primer role [6, 7]. The casual events are followed by functional evaluation from the environment and then by selection of the most advantageous variation. The selection transforms the casual variations into new information. The gnoseological importance of the evolutionary conception originates from the fact that similar processes operate in the natural world as well as in human knowledge. Although the casual event increases the amount of uncertainty in the system, the uncertainty produced by casualty is transformed into new information after the rational evaluation and the subsequent selection. In the evolutionary theory the generation of new information is the result of chance, trial and selection.

Without generation of uncertainty no generation of new information can occur. The casual event is the generator of uncertainty and the primer of the process. Computers are the most classical systems unable to generate new information. Computer operation involves only transformation of informations on instructions. In these transformations there is no generation of uncertainty and therefore of new information. However also a computer can generate new

information when a particular procedure is followed: the computer is let generating a casual sequence of numbers and then one of the sequences is selected by the operator. Thus the generation of new information by a computer requires two distinct moments: first, the generation of casual sequences, second, the selection of one of the sequences by the operator.

The evolutionary conception explains the generation of an infinite amount of information from a finite amount. For example the immunological theories have to account for the production of an apparently infinite amount of types of antibody starting from a finite quantity of genetic code. The dilemma may be explained through the application of the variation-selection principle to the process of synthesis of antibodies.

THE GENERATION OF HIERARCHICAL ORGANIZATION

The question of the increase of organization during evolution may be seen under two perspectives. The first perspective is that of the general energy balance. The answer is similar to that provided for the increase of negentropy of living organisms. The variation-selection process is an expression of the operation of the second law of thermodynamics and the energy investment required for the increase of negentropy during evolution toward increase of complexity is paid by the environment.

The second perspective is that of the thermodynamic explanation for the specific mechanism of selection [8]. Why does selection favor an increase rather than a decrease of complexity? The minimum entropy production principle [9], favors a selection criterion based on the association between elements or structures. The idea is then that association among elements, molecules, supramolecular complexes, cells and apparatus determines specific links on elements, molecules, supramolecular complexes and apparatus, followed in turn by decreased entropy production per unit mass or specific entropy production [10]. The selection is favored because the entropy production of the complex is less than that of the free elements of the complex. Contrary to the view that increase of complexity is always accompanied by increase of dissipation [11], the thermodynamic explanation for the increase of complexity is that the higher levels of organization are favored due to decreased entropy production of the total thermodynamic system. The tendency of the more unstable complexes to bind and associate the free elements gives rise, at each new and higher level of organization, to a parallel new and higher stability level: the stratified thermodynamic stability is the explanation for the hierarchical organization.

PURPOSE AND PROGRAMS

A fundamental achievement of modern biology has been the elimination of the Aristotelian concept of biological purpose. The idea of Aristotle, accepted by Kant, was that every biological process had its purpose and that the understanding of the nature of the living organisms requires also that of the mechanism by which, during evolution, these organisms achieve increase of fitness to the biological purposes. The deterministic idea of Lamarck was that the increase of fitness was due to instructions received from the environment. The Darwinian revolution has replaced the adaptation by instructions from the environment with the variation-selection mechanism [12, 13]. With the discovery of the mechanism of generation, conservation and transmission of the hereditary information, the purpose of the living organism has been explained with the notion of projects,

analogous to computer programs [14]. The increased fitness requires the generation of new information, i.e. the formulation of new computer programs. These programs are then decodified during ontogenesis. Once the hierarchical organization is achieved, it can be reproduced indefinitely by the genetic code.

EVOLUTION AS MAXWELL DEMON

The metaphor of the Maxwell demon explains the generation of macroscopic thermal gradients in isothermal systems. The thermal gradient is due to the separation, effected by the demon, of molecules with higher and lower kinetic energy between the opposite corners of the room. This surprising thermodynamic result is explained by information theory, i.e. the selection operated by the demon is accompanied by the generation of new information. Consider now the transition from the lower to the higher organization levels during evolution. The casual variations produced by mutation or by chromosomal recombination undergo a functional evaluation from the environment and are then selected according to their functional properties. As the demon operates a selection on the basis of kinetic energy so the functional evaluation through interaction with the environment leads to the selection of elements, molecules, supramolecular complexes and apparatus. The elements, molecules, supramolecular complexes and apparatus surviving due to selection are equivalent to the molecules selected by the demon: They contain new information. If the newly generated information is conserved and transmitted, the selected structures, carriers of the information, become evolutionary agents. Since the efficiency of the systems is favored by increased complexity, the process leads to increased organization.

BRAIN AND MIND AS MAXWELL DEMONS

The concept of the spontaneous evolution of natural processes toward increase of hierarchical organization has striking implications in the area of brain and mind [15]. Structures of great plasticity such as ionic channels, neuronal cells, synapses and neural networks undergo a continuous structural turnover parallel to their intense functional activity. As predicted by the biochemical mechanisms of down and up regulation, rapid turnover coupled to active function favors reproduction of the most active structures. The application of the variation-selection mechanism transforms the brain into an evolutionary structure. In the evolutionary conception, the brain operates a continuous selection of variations and then it generates continuously the new information corresponding to the generation of new structures.

The evolutionary theory explains also the operation of the mind as a structure capable of generating new hypotheses by free association, followed by functional evaluation and selection. The behavior of a new idea resembles that of a new species performing its Darwinian fight for survival. The generation of new knowledge, in individuals as well in societies, requires the generation of new information. This occurs through the generation of new casual ideas and then through their selection. The process can be compared to the selection of the molecules operated by the Maxwell demon. The application of the evolutionary thinking and of the concept of stratified stability to the mind-brain problem leads to the view of a parallelism between the hierarchical organizations of the neural networks and of the mental processes. Abstract thinking may be seen as depending on a high complexity of the neural networks.

WHAT IS LIFE?

Can thermodynamics and information theory help to identify the nature of life? Is the nature of life entirely written in the genome or explained by the negentropy concept? Biologists have emphasized the role of autoreproduction, of the genetic code, of the assimilation of material from the environment, of the responsiveness to external stimuli, of the adaptation and of the purpose. By so doing, biologists have connected the nature of life to the decodification of programs since all these properties are just written in the genome. Thermodynamicists have emphasized the features of the indefinite maintenance of the steady state and of the increase of *negentropy*. But while the concept of *negentropy* was surprising at the beginning of the century it has become almost trivial with the development of non-equilibrium thermodynamics. It is only the information theory which provides the most original definition of living organisms and therefore of life: living organisms, made of structures capable of continuous generation of new information, are the main result of the *historical arrow of time*.

By using the information theory it is possible to emphasizes the distinction between those steps where information is transmitted and decodified and those steps where information is generated, the steps where there is a movement from the probable to the improbable. This is the principle distinction between ontogenetic and phylogenetic evolution. Both ontogenesis and phylogenesis imply the formation of negentropic structures, and thus both require energy supply from the environment. However, while the formation of the negentropic structures during ontogenesis is the result only of decodification of programs, the development of new negentropic structures not yet codified and the increase of hierarchical organization during phylogenesis is the result of the generation of new information. The achievement of each new level of organization is a factual and logical jump: from the appearance of the cell structure, to the development of conscience and finally to the evolution of culture.

There is, however, generation of new information not only during phylogenesis but also during the life of each individual. Each individual is partly the result of decodification of programs and partly the result of the *historical arrow of time*. The immunological and the brain-mind systems undergo continuously casual events and interaction with the environment. The variation-selection process of these two systems results in continuous generation of new information. In summary, transmission and decodification of information as well as generation of new information are essential features of the evolution of the natural world as well as of each individual.

The information theory identifies more deeply than thermodynamics the nature of the evolutionary process and indicates a major philosophical question. Which of the two statements is correct: *Natura facit saltus* or *natura non facit saltus*? Is the difference between two levels of organization a *saltus* or not? Is evolution a continuous or a discontinuous process? There are two answers to this question, one empirical and another logical. The empirical answer is that the choice between continuity and discontinuity depends to a large extent on the actual knowledge and on the time perspective. A process may appear continuous because in a temporal sequence the moment of appearance of a new property cannot be exactly identified. For example, it is difficult to identify the structure corresponding to the first cells or to the first living organism endowed by the property of conscience. Furthermore, the closer one comes to the analysis of the details of the evolutionary process the more one has the impression of continuity.

On the other hand, a process may appear discontinuous when taking into account the principle distinction between systems with or without cell properties or organisms with or without conscience.

The logical analysis on the other hand provides a different answer. Gödel's theorems and Russell's theory of logical levels indicate that the description of the structure originating a behavior is of a logical level inferior to the description of the behavior. Similarly, the logical level pertaining to the propositions of a language is inferior to the logical level pertaining to the propositions of the metalanguage relative to the language. The conclusions are: *1)* In hierarchical systems the structure of the superior logical level can never be completely interpreted on the basis of that of the inferior logical level; there is an infinite hierarchy of logical levels. *2)* In hierarchical systems structures and behaviors belonging to the higher level of organization can never be fully deduced from the structures and the behaviors of the lower level of organization; they can merely be observed.

COMPLEXITY AND SPEED OF EVOLUTION: IMPACT ON SOCIOLOGY AND ETHICS

Since the rate of evolution may be predicted to depend on the rate of generation of the variations, and since the higher the complexity of the structure the higher the probability of generation of variations, it may be predicted that the speed of evolution increases with the increase of complexity. The transition from lower to higher levels of organization, for example from the unicellular to the multicellular organisms, is accompanied by an enormous acceleration of the speed of evolution. The speed increases even more with the increased dimension of the central nervous system, undergoes a further acceleration with the appearance of mind activities and conscience, and finally with the cultural products. The acceleration accompanying the development of mind activities is due to two reasons. First, with respect to the transmission of information the generation of cultural products becomes equivalent to a hereditary mechanism. However, the transmission of information via cultural products is much more efficient than that via the genetic code, *i.e.* more flexible and dynamic, because open to the rapid insertion of new information. Second, the absolute casualty of the biochemical and physiological evolution is partially modified in the culture-dominated evolution owing to the role of the mind-generated programs. This has dramatic consequences not only on the natural world and the environment but also on the economic, technological and social development. Societies achieving faster transitions to the higher levels of hierarchical organization acquire also dramatic advantages in the economic and social development. On the other hand, societies more rigid in structure and less open to generation of new information are predicted to evolve toward stagnation. This conclusion applies to all types of human-generated structures: the more rigid the less open to transformation.

The evolutionary conception has implications not only of gnoseological, epistemological, economical and social but also of ethical nature. If evolution of the natural world is an open project without program, the result of a casual variation-selection mechanism, and if man is the highest product of this evolution, the only one endowed by the capacity to produce culture and ethics, then man is the only ethical subject, the only producer of all ethical laws. Is it man who has the right and the duty to attribute values to the objects of the natural world, objects which have no values by themselves but only the values attributed by the ethical subjects? The evolutionary conception by putting man at the center of the universe transfers over man the personal responsibility of the ethical principles by which life

of the human societies must be regulated.

REFERENCES

1 Azzone GF (1994) *Il senso della vita*. *Laterza*, Bari-Roma
2 Schrödinger E (1944) *What is Life? The Physical Aspect of the Living Cell*. Cambridge Univ Press, Cambridge
3 Monod J (1970) *Le Hasard et la Necessitè* Paris: Seuil
4 Popper KR (1972) *Objective knowledge An Evolutionary Approach* Oxford at Clarendon Press
5 Campbell DT (1974) Evolutionary Epistemology In: *The philosophy of K Popper* (Schilpp PA, ed), Open Court Publishing Company, La Salle, Illinois
6 Wicken JS (1987) *Evolution, thermodynamics and information Extending the Darwinian program*. Oxford Univ Press, New York
7 Brooks DR, Wiley EO (1986) *Evolution as Entropy*. Univ Chicago Press
8 Bronowski J (1970) *Zygon* **5**: 18-35
9 Prigogine I (1967) *Introduction to Thermodynamics of Irreversible Processes*. Wiley-Interscience, New York
10 Hamilton HJ (1977) *Zygon* **12**: 289-335
11 Onsager L (1931) *Phys Rev* **37**: 405
12 Eigen ME, Schuster P (1977) *Naturwiss* **64**: 541-565
13 Mayr E (1981) *The Growth of Biological Thought*. Harvard Univ Press, Cambridge, Mass
14 Jacob F (1977) *Science* **196**: 1161-1166
15 Edelman GM (1989) *The Remembered Present*. Basic Books, New York