



Cybernetic Formulation of the Definition of Life

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A definition of life (a living individual) in cybernetic terms is proposed. In this formulation, life (a living individual) is defined as a network of inferior negative feedbacks (regulatory mechanisms) subordinated to (being at service of) a superior positive feedback (potential of expansion). It is suggested that this definition is the minimal definition, necessary and sufficient, for life to be distinguished from inanimate phenomena and, as such, it describes the essence of life. Subsequently, a quantitative expression for the amount of the biologically relevant (“purposeful”) information (as opposed to the amount of information in the thermodynamic sense) is proposed. This is followed by the application of the formulated approach to different phenomena of a dubious status existing presently on the Earth as well as to the process of origination of life on our planet.

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Introduction

Many definitions of the phenomenon of life have been proposed (see e.g. Maynard Smith & Szathmari, 1995; Muller, 1935, 1966; Gánti, 1975), usually overlapping to a considerable extent. They mostly draw on the fact that living organisms reproduce, inherit genetic information and evolve. Frequently, living individuals are also described as objects built of organic compounds, as dissipative structures (or at least dynamic low-entropy systems significantly displaced from thermodynamic equilibrium) (Prigogine, 1980; Prigogine & Stengers, 1984; Schrödinger, 1992), as a hierarchical organization of open systems (von Bertalanffy, 1960), as nonlinear and/or computational systems (Emmeche, 1992). All such proposals, of course, correspond strictly to the phenomenon of life we know presently on the Earth and/or quote necessary physical

conditions that have to be fulfilled for life to originate and exist. In the author’s opinion, however, they do not probe into the very core of the essence of life.

The aim of the present paper is to formulate possibly a minimal definition of life (a living individual), which would apply not only to the life presently existing on our planet, but also to the first living organisms on the Earth, as well as to life-like phenomena existing presumably on other planets in the Universe. To perform this task, it is necessary to find properties that can be attributed exclusively to living individuals, which will allow life to be clearly separated from inanimate matter. There are many properties characterizing the presently known living forms. The set of features usually mentioned in such contexts generally allows one to separate fairly well a phenomenon of life from inanimate phenomena, i.e. distinguish the former in a rather univocal way. There are two main reasons for this fact. Firstly, in spite of the enormous diversity of life forms,

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the most fundamental principles of biochemical construction and function are astonishingly similar (in fact: identical) for all organisms existing presently on the Earth. Secondly, even the simplest live entities, to which some bacteria and archeabacteria belong, still exhibit a very high degree of complexity (some much simpler forms, viroids and viruses, being parasites, are not able to live independently). Therefore, the complexity itself already seems to be a good determinant of life. However, a simple enumeration of the properties that characterize present organisms on the Earth can be misleading. On the one hand, we run the risk of assuming the accidental features of life—characteristic for terrestrial life forms, but not for what we would like to consider as life in general—to be inseparable attributes of life itself. On the other hand, the properties attributed to complex biological systems can be taken as inseparable features of life in general. In other words, the criteria for defining the phenomenon of life (a living individual) should be universal enough (and simple at the same time) to be applied to the forms of life that possibly exist on other planets, to the first living organisms on the Earth, as well as to some presently known phenomena that are still waiting to be classified as living individuals or not. The point is to define the very essence of life, its most immanent characteristics. In the present paper, a trial is made to extract the unique properties of life, and then to reduce the definition of life to the minimal form that would cover only the necessary and sufficient conditions for an entity to be classified as alive. Such a definition is formulated in cybernetic terms.

There are many properties, usually attributed to the life presently existing on the Earth. Living individuals are built of different organic compounds (proteins, nucleic acids, carbohydrates, lipids and so on); they have a complex, hierarchical structure; they possess a complex and hierarchical set of functions; there occurs in them the transformation of matter and energy, that is metabolism; they are characterized by the ability of growth and autonomous movement; they are able to perceive external stimuli; they reproduce, that is produce systems (individuals) similar to themselves; they inherit genetic information, that is their properties are transferred to progeny;

finally, they undergo evolution, that is transformation of some forms into other forms in subsequent generations.

Nevertheless, many of these properties characterize inanimate objects as well. Organic compounds can be synthesized outside living organisms; they originate even in cosmic space. Moreover, there is no reason we know of why living forms on other planets should not be built of slightly different organic compounds. (On the other hand, only organic compounds seem to be complicated and diverse enough to be components of highly complex structures of spontaneously originated life.)

There exist many inanimate objects of great complexity, both natural (e.g. Earth) and artificial (computers, robots). They can be more complex than the simplest organisms (e.g. bacteria). Therefore, it is rather the kind of complexity than its degree that seems to matter.

Similarly, inanimate objects can have hierarchical structure (again, e.g. the Earth and the computer) and be characterized by complicated internal processes ("functions"). As a matter of fact, a regularity of repeatable substructures (e.g. cells) is a characteristic property of a living organism. However, the same property applies to electronic systems and crystals. One of the very typical properties of living organisms consists in the "purposefulness" of their function that manifests itself in the form of various regulatory mechanisms (mostly negative feedbacks). Nevertheless, negative feedbacks are also built into many devices constructed by people, thermostats or robots, for instance.

In the majority of inanimate systems, there occurs the process of transformation of matter and energy (or even interconversion between matter and energy, according to the Einsteinian equivalence between energy and mass). Inanimate objects can also be capable of growth (crystals in a saturated solution of salt) and autonomous movement, where the reason of the movement lies within the system under consideration (Earth's mantle and crust, cars). Moreover, an analogue of perception can be found in different kinds of devices (e.g. robots). Therefore, none of the above-mentioned properties seems to be exclusive for the very core of life.

Life on the Earth (and, in the author's opinion, life in general) seems to possess three properties (strongly related to each other and in fact being different aspects of the same thing) which are absent in inanimate systems. Namely, life is (1) composed of particular individuals, that (2) reproduce (which involves transferring their identity to progeny) and (3) evolve (their identity can change from generation to generation). Reproduction of living organisms consists in the production of descendants with the same (or similar) identity, that is such-and-not-another set of properties. In the case of terrestrial life, this identity is recorded genetically (in the sequence of nucleotides in DNA) and expressed (among others) as the production of specific proteins (consisting of specific sequences of aminoacids) in an appropriate amount and time sequence. The identity of parental individuals is inherited by their progeny. In this aspect, living organisms differ from, e.g. some simple (monomeric) autocatalytic chemical molecules, because the latter have no identity (that is the way they must be: their unique structure results unequivocally from the physical laws), and therefore they cannot inherit it. (On the contrary, the structure of complex polymeric, composed of different monomers, organic compounds on which the terrestrial life is based, namely nucleic acids and proteins, is by no means completely determined by physical laws: there can exist a huge number of molecules of these groups of compounds differing in the sequence of nucleotides and aminoacids, respectively.) In order to describe the sequence of aminoacids in a protein molecule, one must supply a large amount of information. On the other hand, no information is needed, in a sense, to describe the structure of a simple monomeric autocatalytic molecule: this structure results from the laws of quantum mechanics. In the author's opinion, reproduction of individuals involving inheritance of identity is a unique property of living organisms. (Of course, many detailed examples given above and below—e.g. those concerning the genetic apparatus composed of nucleic acids and proteins—refer only to the present terrestrial life, and not to life in general.)

The identity of particular organisms can change slightly in a random direction between

parental individuals and progeny due to mutations in the genetic record. Mutations are inevitable, because of the physical nature of the genetic record: a perfect copying of DNA strands (as well as of any physical carrier of information) is not possible for fundamental, thermodynamic reasons (e.g. chaotic thermal movement of chemical molecules). Different individuals, possessing different identities, will therefore compete for the accessible resources of the environment (at least potentially, there are more descendants produced than that can survive). Only these individuals will survive and transfer their identity to progeny, whose identity is best adapted to the present conditions of the environment (to be more precise and less deterministic, the statistically expected number of progeny is the only parameter that really matters). The identity will therefore undergo evolution in time, from generation to generation, according to the mechanism of natural selection.

The third aspect of life—impossible to be considered separately from the other two aspects—is the fact that life is composed of particular individuals, and does not constitute a certain continuous mass. It is an individual that is the “carrier” of identity, that reproduces and evolves (an individual is understood here to be the whole life cycle of a given organism, with all its stages from birth to death). An individual, reproduction and evolution are three strictly connected faces of life. Therefore, in order to define life, one has also to define a living individual. The classical paradigm considers an individual to be a structurally and functionally integrated entity. This paradigm, however, faces certain difficulties. It applies just as well to a living organism and to a robot. Moreover, it does not state univocally if such objects of doubtful status as colonial coelenterates, myxomycete, insect societies, viruses and viroids, cancer cells, prions, plasmids, parasitic DNA and symbionts are to be classified as living individuals or not (see Discussion).

In the present article, attempting to formulate possibly a minimal definition of life, a living individual is defined within the cybernetic paradigm, as a system of inferior negative feedbacks subordinated to (being at service of) a superior positive feedback. Subsequently, a quantitative expression for the amount of

biologically relevant information is proposed. Finally, the cybernetic definition is referred to the process of origination of life in our planet, as well as to different phenomena of dubious status mentioned above.

Cybernetic Definition of Life

In the present article, a living individual is defined within the cybernetic paradigm as a system of inferior negative feedbacks subordinated to a superior positive feedback. The full set of negative feedbacks (regulatory mechanisms), working on different hierarchical levels and representing the cybernetic aspect of the function of a living individual, has the "purpose" of sustaining the identity of the individual. In turn, the only "purpose" of this identity is to reproduce itself in as many copies as possible. Furthermore, from the cybernetic point of view, the identity of a given individual is nothing but such-and-not-another unique complex of negative feedbacks. Therefore, life can be presented as a set of different identities focused on themselves, on their own survival and reproduction. Below, a detailed explanation of the above-presented definition will be given.

Cybernetics (Wiener, 1948) defines the negative feedback as the main regulatory mechanism, in which any deviation of the value of some parameter from the assigned value exerts an effect which counteracts this deviation and leads eventually to maintaining the parameter value on a more or less constant level. The thermostat in a refrigerator is a typical example of the negative feedback in the inanimate world. From the point of view of purposeful action (involving purposeful regulatory mechanisms), living organisms are in fact "built of" a huge amount of hierarchically organized negative feedbacks. Some of them will be discussed below.

On the biochemical level, many aminoacids block the pathways of their own production when present in high concentrations (Umbarger, 1978), while a decrease in [ATP] (and thus an increase in [ADP]) during elevated energy demand is at least partially responsible for the stimulation of the ATP-producing block (e.g. oxidative phosphorylation in mitochondria) (Chance & Williams, 1956). On the genetic level,

the synthesis of particular proteins (e.g. enzymes) is adjusted to the rate of their decomposition, in order to keep their concentrations constant. The optimal concentration of a given protein can depend on several conditions: the presence of lactose in the environment switches on the production of enzymes belonging to the pathway of decomposition of lactose in bacteria (the operon model) (Jacob & Monod, 1961). Thus, the assigned value of a certain parameter (protein concentration in this case) that functions as an element of a negative feedback on a lower level of hierarchy (maintaining a constant supply of building material and fuel, and therefore constant concentrations of metabolites), can be changed by some other negative feedback on a higher level of hierarchy (limiting energy expenses for production of proteins that are not currently needed). On the cellular level, the frequency of cell divisions is regulated by the ratio of the amount of DNA to the amount of cytoplasm. On the physiological level, two hormones, namely insulin and glucagon, are antagonist signals in the steering loop of the negative feedback which maintains a constant level of glucose in blood (Cryer, 1991). On the behavioural level (entire organisms), the exhaustion of reserves of nutritional substances (lipids, sugars) in the body of an animal after a longer period of starvation stimulates the activity of the animal, that undertakes appropriate action directed at acquisition of food. Numerous negative feedbacks regulating the function of the nervous system and motion system (sets of muscles) are involved in the realization of this task.

All these negative feedbacks are organized hierarchically and mutually interconnected (directly or indirectly). For example, insulin and glucagon are proteins. Therefore, their synthesis involves (among others) the above-mentioned negative feedbacks responsible for the regulation of aminoacid synthesis, ATP production and protein synthesis. A similar connection exists, for instance, between the muscle contraction system and the energy (ATP) production system. Plenty of analogous examples can be easily found. In general, all the negative feedbacks within an individual form a hierarchically organized network, where all negative feedbacks are mutually dependent (directly or indirectly). Of course, negative

feedbacks on low levels of the hierarchy are also correlated with the feedbacks on high levels of hierarchy; e.g. the intake of food on the behavioural level ensures the respiratory fuel for the biochemical (bioenergetic) level. Therefore, the “purpose”, in the functional sense, of each particular negative feedback is determined by the context of the whole complex of negative feedbacks, constituting the identity of a particular living individual. In the cybernetic sense, it is exclusively by an appropriate network of negative feedbacks (its functional identity) that the function of an organism can be described.

The only “purpose” (in the biological sense) of this identity is to preserve its own existence in time, that is to survive in current, specific environmental conditions, as well as to produce as many copies of itself as possible. The entire network of negative feedback mechanisms is ultimately directed at the latter task. Within the cybernetic paradigm, however, reproduction is nothing but a positive feedback.

In the positive feedback, faster the rate of increase of a given parameter value is, the greater this value already is. For example, in the case of a nuclear chain reaction (or a stony avalanche), the increase in the number of free neutrons (rolling stones) is proportional to the current number of free neutrons (rolling stones). The same property characterizes the reproduction of living organisms, e.g. bacteria in a medium or freely reproducing rabbits: their number increases exponentially in time (the increase in the numerical force of rabbits in time is described by the famous Fibonacci sequence). Of course, the increase in the number of living individuals is normally limited by the capacity of the environment. In stable ecosystems, their number is approximately constant in time. Therefore, in this case, there is no expansion of living individuals (increase in their numerical force), so characteristic for the positive feedback. Nevertheless, even here the positive feedback (resulting from the network of negative feedbacks underlying it) sustains a potential of expansion (imposed by the pressure of reproduction), which can express itself as a competition of a given individual with individuals carrying different identities (of either the same or different species), or as the process of populating new areas (or habitats).

Therefore, even in populations remaining in stasis, the realization of the superior positive feedback remains the main “purpose” of the regulatory mechanisms that underlie the function of living organisms.

The (identity of the) cybernetic individual—defined above as a system of negative feedbacks at the service of a superior positive feedback (potential of expansion)—automatically becomes the subject of evolution. It is exactly the identities of different individuals that compete for accessible resources of the environment and evolve from generation to generation. Therefore, the author would like to introduce the term “evoluon” as a synonym of a living individual defined within the cybernetic paradigm. As the Discussion below will show, in many situations the cybernetic individual (evoluon) is not equivalent to the “classical” biological individual, defined mostly according to structural criteria as some internally integrated entity that is clearly separated from the surroundings.

Biologically Relevant Information

Being dissipative structures (Prigogine, 1980; Prigogine & Stengers, 1984), living organisms are systems essentially displaced from thermodynamic equilibrium. They are characterized by low entropy, and therefore by a large amount of information (Shannon, 1949). However, this thermodynamic information is not directly related to the essence of the phenomenon of life, since it does not concern the “purposefulness” of living organisms. Therefore, it does not allow one to distinguish life from other dissipative structures, e.g. convective currents, or generally, from physical systems displaced from equilibrium that are also characterized by a large amount of thermodynamic information. What is needed is the definition of the biologically relevant, “purposeful” information. This information would measure not the degree of general order, what the thermodynamic information does, but the amount of the type of order that is specific for life.

The purposefulness of living individuals is strictly correlated with the network of regulatory mechanisms (negative feedbacks) serving their main purpose: survival and reproduction, as it was discussed above. Therefore, the author

would like to propose the following expression for the amount of the biologically relevant (purposeful) information:

$$I_B = \log_2(n \cdot 2), \quad (1)$$

where I_B denotes the amount of biologically relevant (purposeful) information (in bits) and n stands for the number of the negative feedbacks present in a given biological individual. The number 2 in the brackets corresponds to the minimal number of states a negative feedback loop can distinguish (and adequately respond to): the value of the regulated parameter differs (state 1) or not (state 2) from the assigned value. It is possible to extend this definition and to include a greater number of different values of the relevant parameters recognized by particular negative feedbacks.

While the cybernetic definition of a living individual allows one to decide in a given particular case whether one deals with life or not, the amount of biological (purposeful) information provides information on the "amount" of life one is dealing with (how functionally complex a given individual is). The amount of biological information is also useful as a measure of the degree of integration of two symbionts (see Discussion).

Discussion

The aim of the present paper is to propose a minimal necessary and at the same time sufficient definition of a living individual, which would be able to distinguish unequivocally life from among inanimate phenomena. Such a definition is formulated within the cybernetic paradigm, where a living individual is defined as a system of inferior negative feedbacks subordinated to a superior positive feedback (potential of expansion). It seems to be difficult to quote a more concise (and therefore "more minimal") definition of life. Nevertheless, the main question remains: does the above-presented definition actually constitute a clear-cut criterion, allowing one to classify any phenomenon either as a living being or as an inanimate object?

Many examples of positive feedbacks and negative feedbacks can be found among inanimate phenomena. On the other hand, they never

occur there in the above-quoted combination. The positive feedback is present in both natural phenomena (stony avalanche, nuclear chain reaction) and artifacts built by people (amplifiers). Let us consider the stony avalanche. Here, the parameter the value of which increases exponentially in time (at least at the beginning) is the number of rolling stones. However, rolling stones do not have any purposeful regulatory mechanisms (negative feedbacks) to sustain their movement and eventually the whole avalanche decays at the bottom of a slope. Moreover, the "identity" of rolling stones adopts only a rudimentary form: it is just their movement. Therefore, of course, a stony avalanche is by no means alive in terms of the cybernetic definition quoted above. However, as it will be discussed below, the case of an avalanche (or nuclear chain reaction) is formally strictly analogous to prions (protein-infecting factors).

Negative feedbacks do not seem to occur in the realm of the inanimate. However, they are quite frequent in artificial devices built by people, such as robots or a mere thermostat in a refrigerator. Robots can even possess a hierarchically organized network of negative feedbacks. All such devices perform a purposeful function directed at some task: maintaining constantly low temperature, manipulating objects and so on. However, they lack the superior purpose—the positive feedback. Instead, they serve aims imposed on them by people, and not their own interests. Although they have some identity (at least robots), they cannot propagate this identity by themselves. As such, they are not autonomous in their purposeful action—they are a part of some bigger system (human technical civilization).

So far, the cybernetic definition of life (living individual) seems to distinguish unequivocally living organisms from inanimate objects. If so, it will be applied below to different phenomena of dubious status that are known presently on the Earth.

The sterile casts (workers, soldiers) of social insects (Wilson, 1971) are individuals in terms of the classical (structural) paradigm of an individual (they possess a head, abdomen, legs and so on, lacking only a functional reproductive system). However, they are not cybernetic individuals (evoluons), for they serve a superior

purpose of some greater entity (the entire colony) and are not self-sufficient in the realization of this purpose (a worker is connected to the entire colony by a rich network of behavioural negative feedbacks, including pheromonal regulation of the numerical force of particular casts, exchange of food and so on). Also the queen, although capable of reproduction, is not an evoluon, because it is not self-dependent in the realization of this task either, as it (and its progeny) needs to be fed and defended by other members of the colony (in other words, it is dependent on the network of negative feedbacks in which asexual casts are involved). On the other hand, the entire colony is a cybernetic individual (evoluon), as it is an autonomous, self-reproducing entity, self-sufficient in the realization of this task as equipped with a rich network of negative feedbacks. Similarly, human body is, in a sense, a colony of particular cells, but the whole organism (and not its somatic or generative cells) is a cybernetic individual. Of course, in the case of people, a cybernetic individual is (almost) identical to the classical (structural) individual (on the other hand, compare the discussion below concerning cancers, mitochondria and parasitic DNA). The main difference between human body and a social insect colony is that the former is structurally much more integrated (the insects in a colony are also not identical genetically—this problem is discussed below, in the context of the kin selection). The functional (regulatory) integration, however, plays the most important role in the framework of the cybernetic definition of life.

In the case of myxomycete (or slime molds), doubts could arise whether a particular amoeba or a whole plasmodium (formed for the aim of producing spores in conditions of resources shortage) is a cybernetic individual (subject of evolution). In the author's opinion, the solution of this problem depends on the genetic identity of amoebas forming a given plasmodium. If such an identity is present, the plasmodium (and earlier—the local population of amoebas which can be regarded as an "individual in dispersion") should be treated as an evoluon (particular amoebas are not able to produce and disseminate spores, and therefore they have to cooperate with other amoebas; only some of them transfer their

genetic material to spores, while others form the wall and stem of a sporangium). It is likely that the local population of amoebas comes from one spore, which clarifies the situation.

In the case where a plasmodium is formed by a few genetically different groups of amoebas, we deal with some kind of an intra-species reproductive symbiosis (the purpose of forming plasmodium is dissemination of spores) between a few cybernetic individuals. However, an interesting case of reproductive parasitism can be encountered here (this possibility deserves appropriate experimental studies), for if one group of genetically identical amoebas (an evoluon) is able to become the main actor in the production of spores, outwitting the other groups that are pushed out to realize somatic functions (formation of sporangium), then such a strategy will be evolutionarily successful (this, however, depends on some other factors such as, for instance, the probability of meeting its host by such a parasite). A quite similar situation is encountered in the case of social parasitism in ants (Wilson, 1971).

In the case of colonial coelenterates, especially if particular polyps possess gonads, a colony differs little from a clone of bacteria or a population of parthenogenetically reproducing plants on a meadow. Of course, a clone of bacteria (or population of parthenogenetic plants) is not a cybernetic individual: particular bacteria (plants) constitute evoluons. This is so, for there is no cooperation (and therefore negative feedbacks) between particular bacteria (plants) and the first mutation will result in differentiation of their identities. The situation is not so clear in the case of colonial coelenterates, because there exists some cooperation between particular polyps—they are connected by a network of negative feedbacks (due to which a polyp that has been successful in catching a prey will share its nutritional reserves with less lucky polyps). In this case, the degree of "individuality" D_i of a given polyp can be expressed quantitatively as the ratio of the purposeful information [eqn (1)] related only to internal negative feedbacks I_{Bi} of this polyp to the general amount of its purposeful information (being the sum of the information related to internal negative feedbacks and the information related to the external negative feedbacks I_{Be} , which integrate

the polyp with the rest of the colony):

$$D_i = I_{Bi}/(I_{Bi} + I_{Be}). \quad (2)$$

The same measure of the degree of “individualness” can also be implemented in the case of symbiosis (see below). Therefore, the cybernetic approach is able not only to supply a criterion for deciding if we deal with a living individual or not, but also to offer a measure of the degree of integration of different individuals, provided that at least one cybernetic individual (evoluon) is present.

Prions are pathogenic protein molecules causing brain diseases in animals and people (Prusiner, 1998). They are encountered in two forms: normal form that has the structure of α -helix and pathological (infective) form that has the β -structure. Normal molecules are produced in the animal brain and fulfil some (still unknown) function. Infective molecules can stimulate transformation (by a change of conformation) of normal molecules into other infective molecules. Those molecules can, in turn, transform yet other molecules, which adds up to a typical positive feedback. Are prions evoluons? Of course, they are not. Formally, they are strictly analogous to an avalanche. The “identity” of prions simply consists in their pathological conformation, similarly as the “identity” of stones consists in their movement. Prions have not got at their disposal any network of negative feedbacks which would sustain their potential of expansion—the phenomenon of transformation is a simple physical process. They cannot evolve in order to increase their infective efficiency either, since their structure is recorded in DNA, over which they have no control (it is not prions that undergo replication in the brain, but only their infective conformation at the cost of the normal conformation). Therefore, the phenomenon of prions seems to be an accidental failure in the functioning of the organisms producing them, something resembling to a certain extent auto-allergy. Prions, by themselves, are not alive.

Viroids, like prions, are single organic molecules (in this case: RNA molecules). Therefore, by themselves, they do not perform any functions (negative feedbacks included). However, they are parasites able to force the host cell to

produce their copies, which disturbs the metabolism of the cell (deprives it of energy and building substances), leading to its death. In other words, viroids are able to enter into the system of negative feedbacks of the host cell and change its course, changing the parameter whose value is optimized. The purpose of the system becomes now the production of a possibly great number of copies of the viroid molecule, while the regulation of the values of such parameters as ATP level or nutritional substance concentrations is neglected. The sequence of nucleotides in the viroid RNA strand has been evolving for millions of years, in order to increase their efficiency. Viroids, although they lack their “own” negative feedbacks, are able to use (after a slight modification) the network of negative feedbacks of their hosts. Such an exploitation of the host’s network of negative feedbacks constitutes in fact the essence of parasitism. This resignation from own separate negative feedbacks has adopted the extreme form in viroids—virtually all negative feedbacks they use for their multiplication come from the host cell. Viroids, however, are able to modify their hosts’ network of negative feedbacks, in order to realise their own purposes (therefore, the system “viroid + host cell” is a system of negative feedbacks subordinated to a superior positive feedback). In the light of the above discussion, we should acknowledge viroids as cybernetic individuals.

Viruses are quite similar to viroids, but their structure and function is more complicated. Their nucleic acid (RNA or DNA) is encapsulated in a protein hood and encodes some proteins, including those responsible for its replication in the host cells. Bacteriophages inject actively their nucleic acid into bacteria cells, while many viruses encode their own enzymes which optimize the velocity of multiplication of descendent virus particles in the host cell. Therefore, viruses have already some negative feedbacks of their own and certainly deserve the status of evoluon, which has already been awarded to viroids.

Cancers are yet another interesting case. Cancer cells are traditionally not regarded as biological individuals. From the cybernetic point of view, however, they are individuals (evoluons). The act of tumorous transformation of a normal

cell can be treated as breaking loose from the realization of the superior purpose of the entire organism and establishing another superior purpose, that is the reproduction of cancer cell. Cancer cells are a subject to a normal Darwinian natural selection in the "environment" of a "host" organism. Only those cells survive and reproduce that create (as a result of mutations) some purposeful mechanisms (negative feedbacks) causing, for example, resistance to the immunologic system or other defensive reactions of the host organism, adaptation of the metabolism to a lowered oxygen concentration, stimulation of angiogenesis or a great rate of growth, reproduction and migration. Therefore, cancer cells possess a network of negative feedbacks directed at their own reproductive success. Of course, cancer cells "do not know" that their evolution will terminate at the moment of death of the host organism (dinosaurs, however, did not know that they would not survive the collision of the Earth with an asteroid at the end of the Mesozoic period as well). The inability to infect other host organisms constitutes the main difference between cancer cells and normal parasites. There exists, however, at least one known example of cancer that has become a normal parasite: in the case of the venereal sarcoma in dogs, cancer cells can infect another host organism, transferring themselves from a dog to a dog during sexual contact (Barski & Cornefet-Jensen, 1966). For all these reasons, cancer cells are undoubtedly cybernetic individuals (evoluons), although their evolution leads usually to a dead end.

Parasitic DNA (Doolittle & Sapienza, 1980; Orgel & Crick, 1980) is another ambiguous case. Two main classes of parasitic DNA are some repetitive DNA sequences in normal chromosomes and supernumerary chromosomes B. The repetitive parasitic DNA (transposones) seems to fulfil no useful function in the host organism. On the other hand, its replication causes considerable expenditure of energy, while a greater volume of chromosomes containing this DNA makes the process of karyokinesis more difficult. Therefore, the question arises as to why host organisms do not get rid of their transposones. The only explanation is that transposones possess some mechanisms that enable them to avoid being removed from the genome (and therefore

they are transferred to daughter cells). Additionally, transposones can replicate themselves independently of cell divisions (they encode proteins responsible for this), as well as transfer and incorporate themselves into different places of the genome. Moreover, transposones, of different identities most probably compete with each other for a limited place in the genome (the size of chromosomes cannot increase much in order not to cause a significant dysfunction of the cell). Additionally, transposones can spread by way of sexual reproduction of their hosts: when the genome of one parent contains less transposones than the genome of the other parent, the free space in the chromosomes of their progeny inherited from the former will be invaded by transposones originating from the latter. Therefore, transposones exhibit both the potential of expansion (the positive feedback underlying it) and a set of negative feedbacks sustaining this potential. They can evolve in order to optimize their stability in the genome as well as their potential of expansion. As opposed to viroids (that are also mere segments of nucleic acid), transposones cannot infect other hosts and therefore they remain intragenomic parasites that are not able to spread horizontally to other genomes. Nevertheless, in the "environment" of a given genome, they are cybernetic individuals, probably the simplest existing evoluons.

Supernumerary chromosomes B (Jones, 1975; Bougourd & Jones, 1997) are found in many species of plants and animals. They are not needed for normal functioning of their carriers, because the individuals of a given species that do not possess them do equally well, if not better, as the individuals containing chromosomes B. Chromosomes B are replicated by their hosts and transferred to progeny, at considerable energy cost. It seems that organisms try to get rid of their chromosomes B, for example by loosing them during cell divisions, and that chromosomes B have some purposeful mechanisms which allow them to counteract those attempts. Therefore, chromosomes B seem also to be, like transposones, cybernetic individuals (the main difference is a structural one: a chromosome is a much more complicated object than a mere short segment of DNA). Chromosomes B are usually only slightly harmful to their hosts. However, in the

case of the chromosome B from the wasp *Nasonia vitripennis* (Nur *et al.*, 1988), which is transferred in sperm, this chromosome B eliminates after fertilization all chromosomes in the zygote coming from the father, thus ensuring that the entire progeny will develop as males (*N.v.* has the haploid/diploid type of sex determination). Therefore, the chromosome B is here completely lethal for the genome of which it is temporarily a part. It would be difficult to avoid the conclusion that it is an evoluon, equipped with a set of purposeful regulatory mechanisms (negative feedbacks) directed at the propagation of its identity.

Cancers and parasitic DNA are examples of something that can be called "life within life". They are a result of an escape of some semi-autonomous systems within the entire organism from its control. Multicellular organisms have evolved from unicellular organisms, and therefore cancer cells are, in a sense, cells which have regained the freedom of their ancestors. The free-living "ancestors" of parasitic DNA were perhaps separate self-replicating strands of RNA in the "RNA world".

The above examples describe the situation where one individual splits into two or more individuals. An opposite process, however, is also possible, namely two initially completely separated individuals form a certain entirety. In the case of symbiosis, the networks of negative feedbacks of two partners of different origins become partially interconnected in such a way that both partners profit from the cooperation (the balance of profits and harms is positive for both of them). The intensity of symbiotic coexistence can change gradually from case to case, from very loose facultative relations to an utter and complete dependence of partners on each other. The "degree of individualness" of each partner in symbiosis can be, at least in principle, expressed in a quantitative way, by means of eqn (2) applied above to measure the degree of "individualness" of particular polyps in colonial coelenterates (in fact, a colony can be regarded as a kind of symbiosis of different individuals within the same species; the main difference is that particular polyps in a colony of coelenterates are identical genetically). Mitochondria in *Eukaryota* are an example of a very close coexistence of two

partners in symbiosis. Initially, mitochondria were free-living bacteria that entered into endosymbiosis with eukaryotic cells (Margulis, 1981). For the present, most of their genes have been transferred to the nucleus and their divisions are under the control of the cell. Nevertheless, they can mutate and therefore have different identities, that can, in turn, compete with each other (which can cause the so-called intragenomic conflicts). Therefore, mitochondria are still cybernetic individuals, although only to a rudimentary degree.

Plasmids (Kado, 1998) are small circular molecules of DNA that are found in bacteria cells and are able to transfer themselves from one cell to another. Their status also seems to be extraordinary. Plasmids can carry genes responsible for, e.g. sex or resistance for antibiotics, and therefore they can be profitable for their hosts. Their replication is independent of the replication of the bacterial chromosome, but their number seems to be to some extent controlled by the cell. They can also transfer some genes between different bacteria cells and therefore constitute a substitute for sexual recombination of genetic information. On the other hand, their replication is connected with energetic costs and in many conditions they are not needed by bacteria and are apparently eliminated from the cell (after all, not all bacteria cells contain a given type of plasmid). They also possess some limited reproductive autonomy and can "infect" other bacteria cells. Therefore, being undoubtedly evoluons, plasmids seem to exhibit the properties of both symbionts and parasites (their exact status depends on particular conditions).

In the text above, the quoted cybernetic definition of the living individual was correlated with different phenomena existing presently on the Earth. However, the cybernetic paradigm can also be applied to the origination of life on our planet. The relevant question is at which moment evolving chemical systems become alive. In the author's opinion, this happened when there emerged the first self-replicating entities possessing identity and capable of transfer of this identity to progeny. The structural identity of such entities was expressed as the sequence of monomers in nucleic acids and/or proteins. Nucleic acids were needed as a carrier of genetic

information, while proteins were effective “executors” (catalysts) capable of purposeful action directed ultimately at the realization of the superior purpose: survival and reproduction of the system to which they belonged (in the author’s opinion, the enzymatic activity of some RNA molecules is rather weak and exhibits a limited diversity; in ribosomes, for example, rRNA molecules seem to recognize specific nucleotide sequences in mRNA and aminoacyl-tRNA rather than perform true catalysis, that is lowering the activation energy of the protein synthesis reaction). Therefore, mainly proteins were able (in the case of the origination of life on the Earth) to “realise” a more complicated network of regulatory mechanisms (negative feedbacks). (In the author’s opinion, the replication and functioning of nucleic acids in the “RNA world” was from the very beginning supported by polypeptide molecules of random aminoacid sequence, which were concentrated together with RNA molecules in coacervate-like objects for purely physical reasons, but were not yet encoded by nucleic acids.) On the other hand, proteins alone could not inherit their identity: nucleic acids were indispensable to achieve this. For this reason, the first truly living individuals emerged (in the author’s opinion) from inanimate matter together with the origination of the first primitive genetic code, which linked separate autocatalytic cycles of nucleic acids (RNA) and proteins into hypercycles of nucleic acids and proteins (Eigen & Schuster, 1979), where nucleic acids encoded proteins, while proteins catalysed replication of nucleic acids, translation of the sequence of nucleotides in RNA into the sequence of aminoacids in proteins, as well as some other processes. Only such hypercycles were capable of producing a set of negative feedbacks (i.e. functional biological identity), and therefore of evolution. Additionally, it seems probable that hypercycles were not “dissolved” in water but that they were concentrated (initially, for totally physical reasons) in some self-reproducing bubbles, resembling Oparin’s coacervates or Fox’s microspheres (and therefore constituted structural individuals). The first thing such hypercycles did (in the evolutionary sense) was to improve and develop their systems of negative feedbacks in order to increase their efficiency in surviving and propagation. Therefore, one can

say the first living organisms (evoluons) originated when there emerged the first negative feedbacks sustaining the superior positive feedback (self-replication of the individual’s identity).

It must be emphasized that the above-presented scenario of the origin of life on the Earth is to a large extent the author’s personal opinion. Many scientists prefer to think that RNA molecules can have sufficiently strong and diverse catalytic activity to form only (without proteins) efficient self-replicating entities. If this is true, then, of course, just such entities, and not hypercycles “encapsulated” in coacervates, were first evoluons (cybernetic individuals).

The proposed cybernetic formulation of the definition of life can also be applied to different phenomena existing on other planets. If we find there a system equipped with a network of purposeful regulatory mechanisms (especially negative feedbacks) directed at the replication of the identity of the system, we should identify such a system as a living entity, regardless of the details of its structure and function. Therefore, the proposed cybernetic definition of life seems to be a universal one and is not limited to the present terrestrial life.

Regulatory mechanisms in living organisms can be more complicated than simple negative feedbacks discussed above. For example, it has been proposed (Korzeniewski, 1998) that the main mechanism adjusting the rate of ATP supply by oxidative phosphorylation to an increased energy demand during muscle contraction is a parallel direct activation by an intracellular effector of all steps of this process, while the negative feedback via [ADP] constitutes only a secondary, fine-tuning mechanism. Therefore, a parallel activation of different steps should be considered as another purposeful cybernetic mechanism of regulation, in addition to a negative feedback. Nevertheless, the parallel activation mechanism works within the network of negative feedbacks of the entire organism and constitutes an integral part of this network. Therefore, the fact of existence of the parallel activation mechanism does not affect much the general cybernetic definition of life quoted above.

There are important cases where living individuals do not transfer their entire identity to

each descendant, but only participate genetically (together with other individuals) in constructing the identities of progeny. The most important examples of this phenomenon are sexual reproduction and kin selection (the latter plays an important role in e.g. insect societies). In these cases, it pays to transfer e.g. a half of one's own identity to more than $2n$ descendant individuals, instead of transferring the entire identity only to n descendants.

The definition of life proposed in the present paper is very abstract and therefore says nothing about the physical conditions that must be fulfilled in order to enable a spontaneous coming into existence of a network of negative feedbacks subordinated to a superior positive feedback. Most probably, however, living individuals have to be dissipative structures, and therefore systems essentially displaced from thermodynamic equilibrium. They should also have some kind of metabolism (transformation of matter and energy) and be built of organic compounds of carbon (as the only molecules complicated enough to be the building material of spontaneously originated complex entities possessing their own identity). Nevertheless, these properties are not necessary for the definition of the essence of life, since they can also be present in many inanimate systems.

In conclusion, the cybernetic definition of life (a living individual) as a network of negative feedbacks sustaining the superior positive feedback (potential of expansion) seems to allow for distinguishing in a sharp and unequivocal manner between living entities and inanimate objects. It also supplies a measure of how many living individuals we deal with in a given case and offers a quantitative expression for the amount of biologically relevant (purposeful) information. According to this definition, the phenomenon of life consists in a directed-at-itself identity of living organisms. Of course, the validity and usefulness of the cybernetic paradigm will have to be further tested by examination of its applicability to existing and newly discovered objects.

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