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COMMUNICATION : THE KEY TO DEFINING « LIFE », « DEATH » AND THE FORCE DRIVING EVOLUTION. « ORGANIC CHEMISTRY-BASED- » *VERSUS* « ARTIFICIAL » LIFE

by

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SUMMARY

Plausible definitions of « life » and « death » can be simply derived by combining the principles of compartmental organisation of the living state, with the principles of communication and those of Ilya Prigogine's « dissipative systems ». Prokaryotes have only one compartmental level, but all other living systems have several, up to about fifteen in the tentative classification system we propose. From the principles of communication and information it can be understood why « life » is more than just part-and-parcel of chemistry and physics : information in itself has no units of force or energy. Since communication is the cornerstone of life, a living entity dies when it irreversibly looses its ability to communicate at its highest level of compartmental organization. It is not important that lower levels of compartmental organisation, if present, retain their ability to communicate. Since « death » is the irreversible end of « life », it follows that a compartment starts to live when it acquires the ability to communicate at its highest level of compartmentalisation. Therefore, « life activity » (L) of compartment S at moment t is the total sum of all acts of communication (C) performed by this compartment (with its different levels of organization, from 1 to j) at moment t. This can be mathematically expressed as :

$$L(S,t) = \sum_{1}^{j} C(S,t).$$

Biological life as contrasted to artificial life, cannot be sustained without transmembrane gradients because of their crucial role in communication. Therefore, « Life » could not exist before some primordial aggregate compartmentalized and acquired the ability to sustain a gradient over its limiting membrane and thus established a communication channel. Communication at the level of the plasma membrane requires a moderately « leaky » membrane to make transmembrane ion fluxes possible : thus « life » started with an imperfect (leaky) membrane in combination with a chemical gradient (which is by definition a thermodynamically far-from-equilibrium state) established through the membrane. Sustaining a chemical

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gradient requires energy, part of which is used to create order out of disorder. These are elements of dissipative systems. Gradient formation, which is a crucial event in life, which is often neglected in many fields of biology, is the primary force to self-selection and evolution. Thus, life on one hand and self selection and evolution on the other are inseparable as the two sides of a coin. Communication is not only the very essence of « life » but at the same time, it is a major driving force of (its own) evolution. This approach leads to a holistic type of biology in which communication plays a central role, and for which the name « dissipative biology » or « non equilibrium biology » is proposed. Our approach also allows to make the distinction between « organic chemistry-based life » and « artificial (man-made) life ».

Key words : definition of life, artificial life, artificial intelligence, dissipative systems, cell biology, endocrinology, cytoskeleton, evolution, Darwinism.

INTRODUCTION

The term « life » as it is daily used has different meanings in *e.g.* « life span », « life quality », « life cycle », « life as the difference making property between inanimate and animate matter », etc. This leads to the erroneous impression that « life » is such an abstract term that it cannot possibly be comprehended by the human mind and could not be defined.

According to SCHEJTER and AGASSI (1994), an adequate definition of « life » should include : « Apart from its not being trite and uninformative (circular, to use a traditional term), it should be neither too wide nor too narrow ; it should not exclude living things and it should not include dead ones. Furthermore, it should not make biology part-and-parcel of chemistry and physics. »

WHAT IS « DEATH » ?

In trying to define life and death, a variety of approaches have been used over the years (*e.g.* SCHRÖDINGER, 1946 ; DE DUVE, 1991) but none of them has as yet yielded a satisfying result. We have used a different approach of asking and answering some simple questions.

1. What is missing in following sentences ?

— « There is joy because of birth ».
— « There is sorrow because of death ».

These sentences are ambiguous because it is not known who or what is born or died : a baby, grandfather, the canary, a cat etc. This means that « death » and « life » have to be connected to what we refer to with a general term as a ***« compartment »*** in order to make sense. This raises the question what types of biological compartments exist in nature. One possible way of bringing some order in the multitude of possible compartments is shown in Fig. 1.

2. At what moment does a living organism, or a living system cease to be alive ? What is the difference between being alive, no longer alive, or not yet being alive ?

a. the multicellular organismal level :

A vertebrate is assumed to be dead upon decapitation, even though some vertebrates such as birds and eels continue to move for a while in an uncoordinated way. Immediately after decapitation the vast majority of the cells, tissues and organs of the body are still alive and can be used in organ transplantation or cell/tissue culture.

b. the eukaryotic cell level :

Upon homogenization a cell is no longer alive although its cell organelles that are prokaryotic in origin such as mitochondria and chloroplasts, may still be functioning. Isolated chloroplasts that are injected into a chicken egg that is properly illuminated, will multiply and colonize the chicken egg.

c. the level of the population :

The same duality is present at the highest level of organization, the population. Imagine that all individual members of a small population of animals are separated from each other until they completely and irreversibly lose contact. The individual members are still alive, they can metabolize, grow, cope with entropy, respond to a variety of stimuli and adapt to short term changing conditions in the environment, evidently within certain limits. Despite all of this, we conclude that the population does no longer exist.

d. the level of the prokaryotic cell or of membrane-limited cell organelles :

At the primitive end of organizational complexity (Fig. 1) dual existence is no longer found. After homogenization nothing remains alive. A mitochondrion, a chloroplast or a prokaryote ceases to live after irreversible disruption of its limiting membrane, *e.g.* by ultrasonic homogenization. Under proper conditions membrane fragments can still perform some metabolic functions, they are complex, but they are not considered to be alive. Disruption of the plasma membrane ends existing gradient(s) across this membrane.

From these four examples we conclude that : **« A compartment dies when it irreversibly looses its ability to communicate at its highest level of compartmental organization »**. It is the **highest** level of compartmentalization that matters. In a population, the highest level of organization is reached when individual members communicate. In the vertebrate the central nervous system makes communication possible at the organismal level : this coordination system is irreversibly destroyed by decapitation. In the eukaryotic cell the highest level of communication is at the level of the plasma membrane ; and in the prokaryote or organelle of prokaryotic origin, communication occurs with the outside world across the limiting membrane. If « Death » is the irreversible loss of the ability of a given compartment to communicate at its highest level of compartmental organization, it follows that a given compartment starts to live from the moment that it acquires the ability to communicate at its highest level of compartmental organization. **Therefore, a compartment is alive when it has the ability to communicate as a whole with its « environment ».**

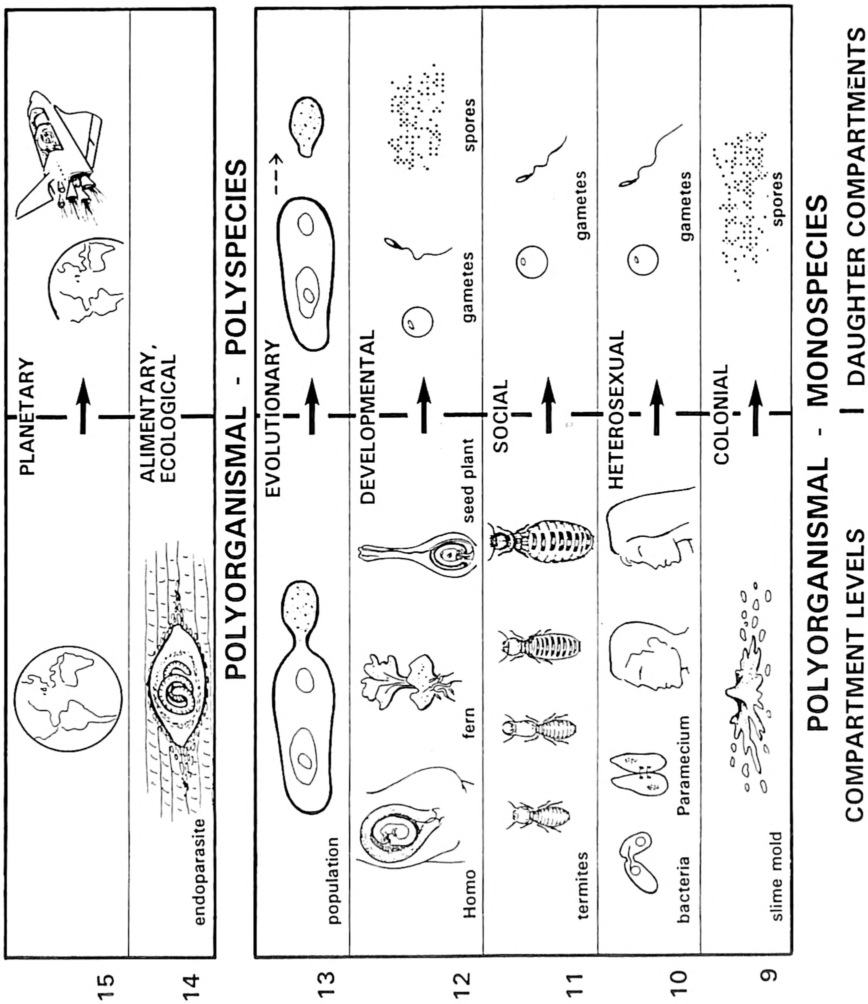
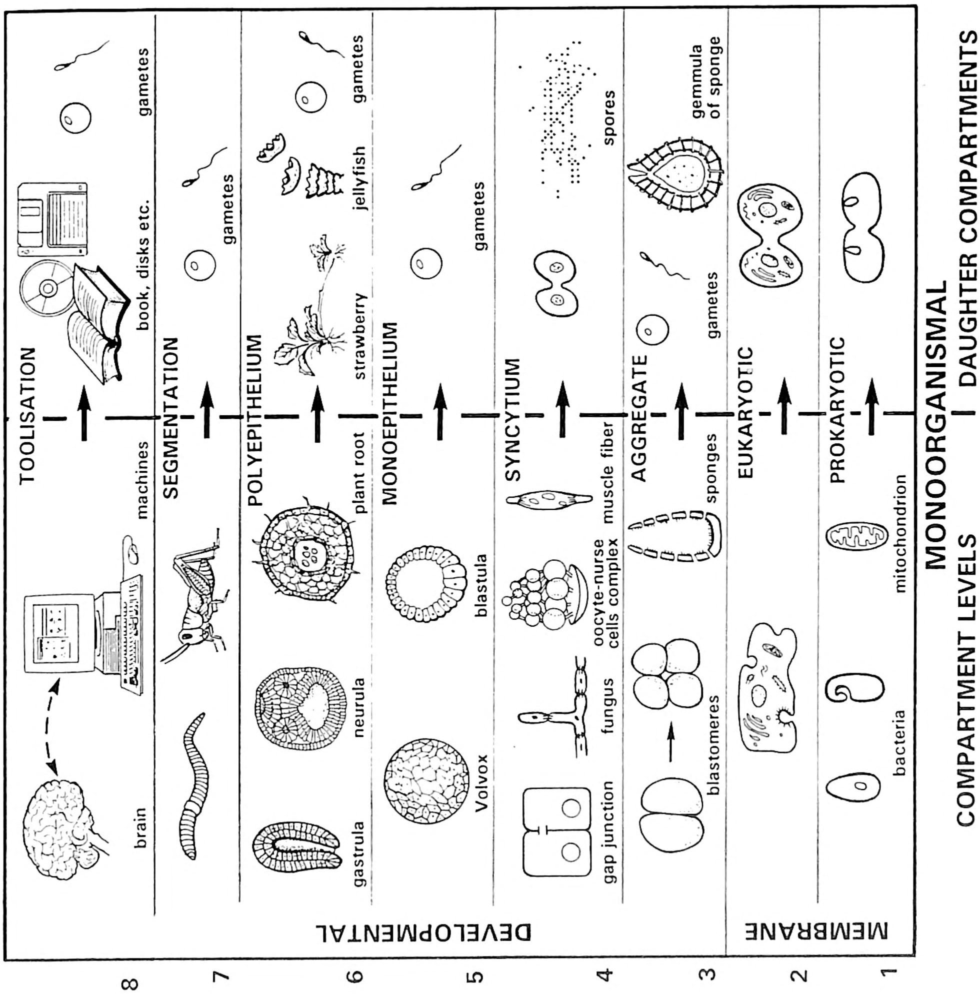


Fig. 1. — Levels of compartmentalization and means for generating daughter compartments.

The simplest level of compartmentalization is the monomembrane type to which belong the bacteria and membrane-limited cell organelles like mitochondria and chloroplasts (1). The most complicated one which is the one with the largest number of different subcompartments, is the planetary one (15). Different levels of compartmentalization are possible within one and the same organism (1-8), within one species- (9-13) and within polyspecies compartments (14-15).

For generating additional levels of compartmentalization, several systems are used. A widely used one is the internalization of novel compartments in existing ones : 1. membrane-limited compartments within an outer membrane compartment (the eukaryotic type, 2) ; 2. epithelium-limited compartments within an outer epithelium (6) ; 3. organism(s) within organism (12, 14) ; 4. subpopulation(s) within population (13). Another one is the aggregation of compartments (3, 4, 5, 9, etc.). The communication between the constituent compartments can be intermittent, *e.g.* through gap junctions between neighboring cells (4a) or more perma-



nent like in case of cytoplasmic bridges, *e.g.* in Fungi, or in meroistic insect ovarian follicles or in myoblasts which fused into a muscle fiber. A third system is segmentation (7). A fourth one is the enlargment of a compartment by tools (*tool* util*isation* or toolisation) (8). A fifth one is the spreading of the genes needed for reproduction over more than one individual (10, 11). For splitting off daughter compartments (reproduction), the variability in systems is rather limited : mitosis, meiosis, systems for asexual reproduction (*e.g.* 3, 6), systems for speciation (12) etc. Evidently, in some systems several mechanisms can be simultaneously operational. Other approaches for categorizing levels of compartmentalization than the one used in this figure are possible. The majority of the levels of compartmentalisation depicted in this figure correspond to revolutionary steps in macroevolution.

Linear biology mainly deals with the description of the generation and functioning of the different levels of compartmentalization as outlined in this figure.

COMMUNICATION IS TRANSFER OF INFORMATION

Since communication is essential for living, a few words about its nature may be helpful for the non-specialists.

The basic anatomy of a communication system is : a *sender* produces a (coded) message which is released into a *communication or transmission channel* through which it is transmitted to a *receiver-decoder-amplifier-responder* (GERAERTS *et al.*, 1994). This is illustrated in Fig. 2.

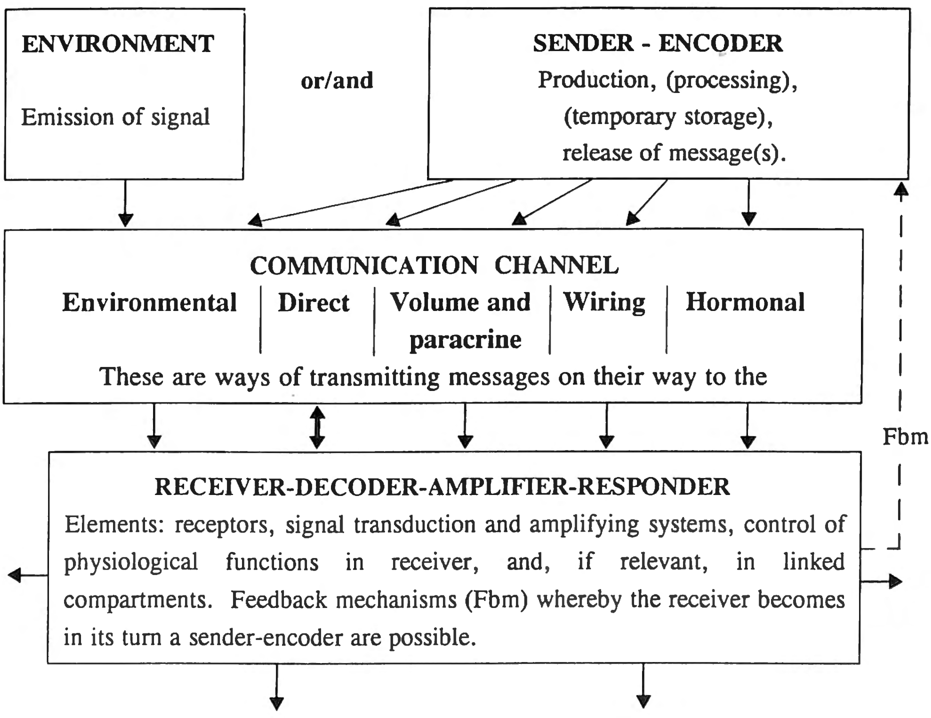


Fig. 2. — Schematic representation of the different elements of a communication system.

Information can be defined as any change within a communication system which affects any component of that system (VAN POECKE, 1994).

The essence of the different aspects of communication can be summarized as follows : « Communication is transfer of information which in itself does not have units of force or energy. This works as follows : either the environment or a sender-encoder delivers some sort of (encoded) message, which is transmitted through a communication channel. After having been perceived by a competent receiver-decoder, the message controls there (and perhaps as well in compartments inter-linked with this receiver through some communication channel) the use of a specific form(s) and quantity of **prestored energy** at a specific time(s). This energy can then be used for doing some kind of « work » as this is defined in physics, to engage in other acts of communication (*e.g.* feedback mechanisms) and/or to counteract entropy (*i.e.* to prevent the system's break down). » In biological systems the role of communication and signal perception is most probably to adapt or change the use of biochemical and gradient-energy to the present or future needs of the system, especially according to changing « environmental » situations. This does not imply that all communication acts are (equally) useful or meaningful.

INTERMEDIATE ACTS OF COMMUNICATION

A living system communicates with its environment, it reacts upon changes and, in some instances and to some extent, it even learns to control its own direct environment. Biological communication systems are very complex and cannot be discussed in detail in this paper ; a summarizing cartoon is given in Fig. 3. To transform incoming information and translate it so that an organism will react to it, intermediate processes named *« pathways »* and *« networks »* are involved. An example is a hormone that binds to a receptor, causing an ion channel to open, the membrane potential changes, there is a Ca^{2+} explosion in the cytoplasm, the cytoskeleton contracts, protein synthesis is influenced, etc. : such intermediate processes are analogous to different steps in a chain-reaction. We will refer to them later as **« acts of communication »**. Besides the qualitative complexity, there are also quantitative differences : *e.g.* a given « intermediate process » can have a greater impact than other ones. Biological systems manage to **integrate** (« add up ») all these acts of communication. Therefore, the result of this integrative process (the « total sum of all acts of communication ») performed by a given compartment can be regarded as the **« Life activity »** that is produced by this compartment. This Life activity can be considered at a given moment t or over a given interval of time (t_2-t_1).

GENERAL DEFINITIONS OF « LIFE ACTIVITY »

Let us consider the « life activity » **(L)** generated at the level of a given population **(P)**. If **« L »** of population P is the « total sum (Σ) of all acts of Communication » at the level of this population and if P is alive, this sum is larger than zero. This can be represented mathematically as :

$$\mathbf{L(P)} = \sum^{\text{population level}} \text{Communication acts (P)} > 0.$$

Since life is never constant, the acts of communication change all the time. Therefore, one has to indicate the moment (t) at which the acts of communication are considered :

$$\mathbf{L(P,t)} = \sum^{\text{population level}} \text{Communication acts (P,t)} > 0.$$

If a given compartment (or system) is represented by S and its (highest) level of compartmentalization is j, the general formula becomes :

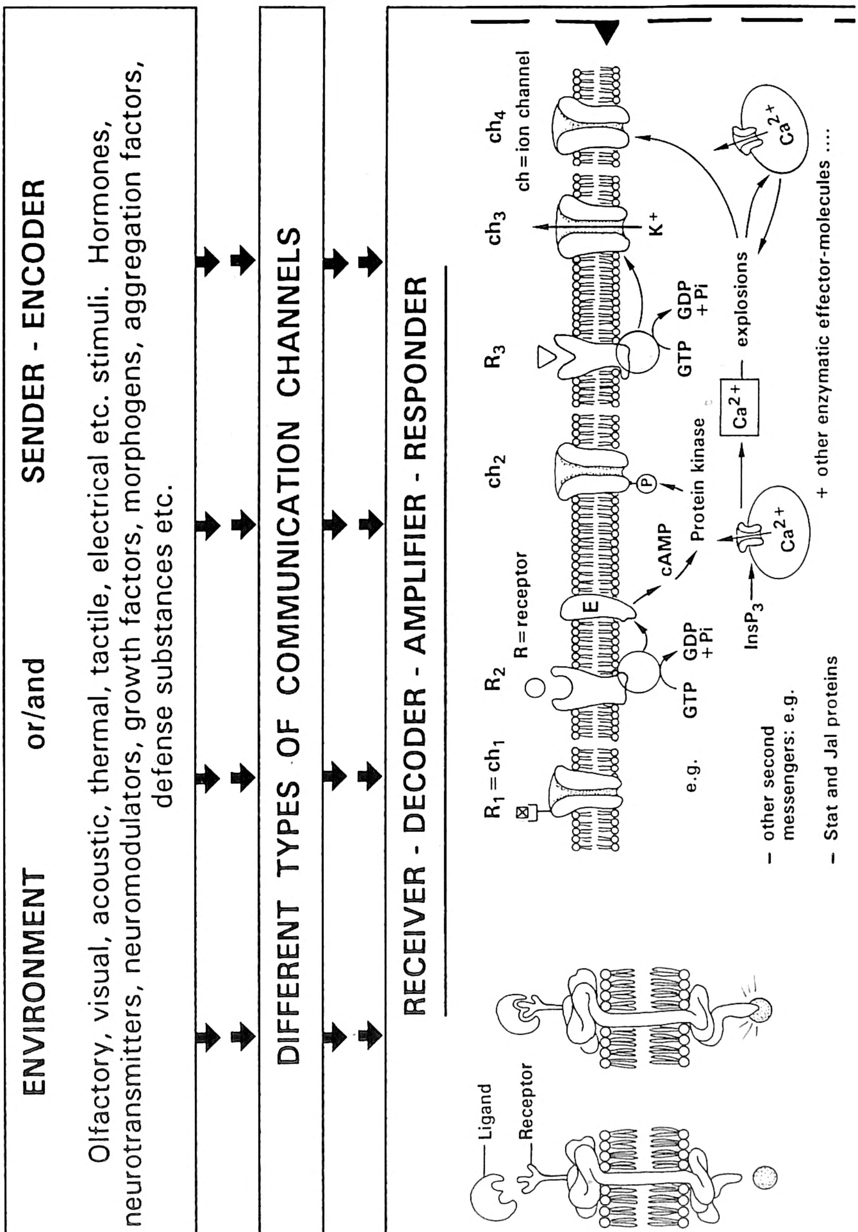
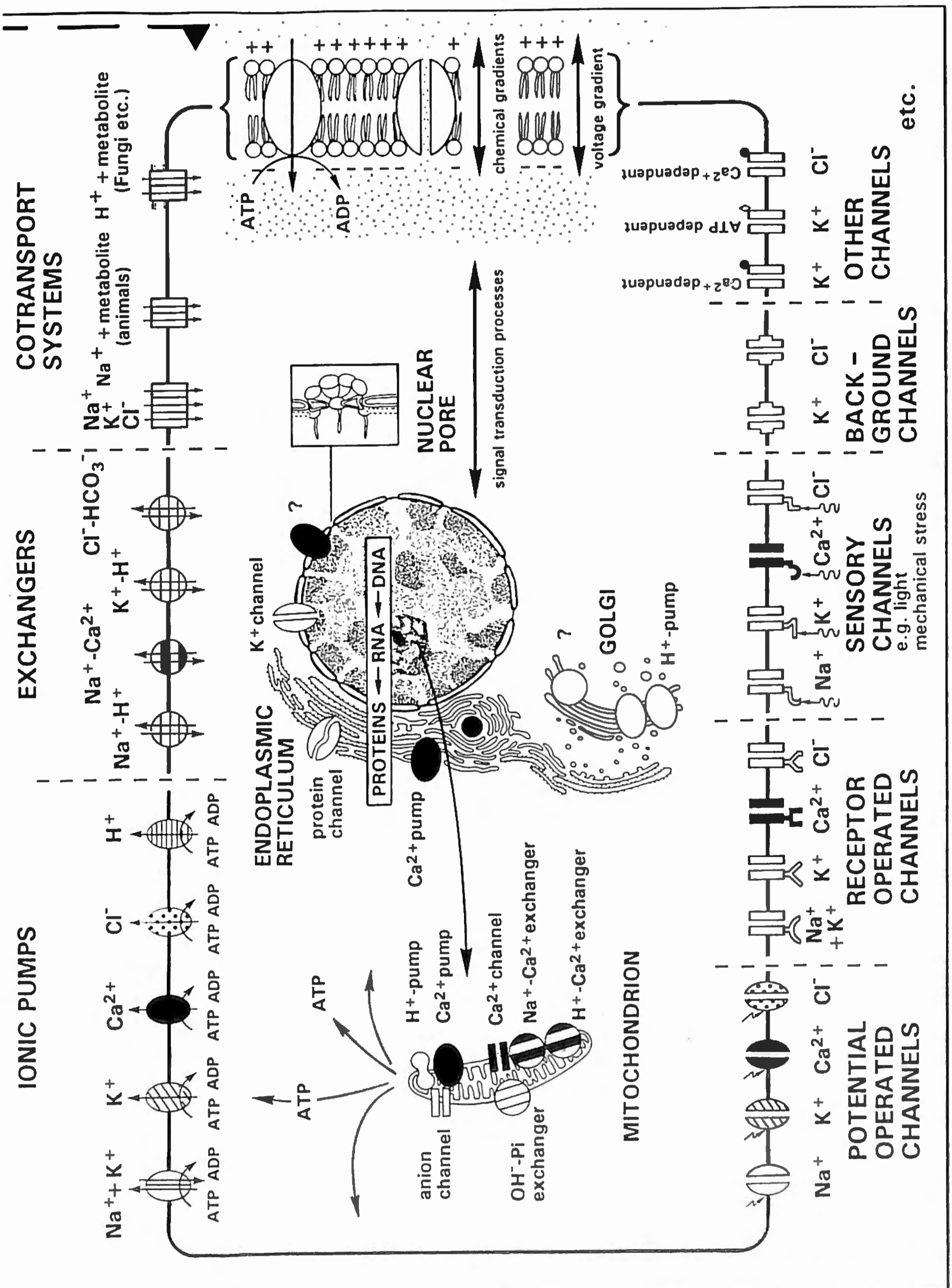


Fig. 3. — Schematic but evidently incomplete overview of the major systems for communication present at the cellular level.

Messages, whatever their nature, have to be « interpreted » either by receptors (R_1, R_2, R_3) present in the plasmamembrane (2a, b, c) or/and in subcellular compartments (1, 2). Inorganic ions/electrical events play a predominant role in communication systems (1, 2 : $ch_{1,2,3,4}$ = ion channels). The arrows in the ionic pumps are not meant to indicate the actual



direction of the transport of the ionic species involved. Other cell organelles than the ones drawn here can also have ion transporting proteins and receptors in their limiting membrane (De Loof *et al.*, 1992).

Dissipative biology mainly deals with the interplay of all the systems for communication as outlined here.

$$L(S,t) = \sum^{\text{compartmental level } j} \text{Communication acts } (S,t) > 0.$$

In the preceding formula it has been assumed that, when compartment S is functioning well at level j, all lower levels of organisation that are essential for the well-being of S (at level j) are present. However, when the « Life activities » at all levels of compartmentalization are indeed taken into account, starting from the lowest one (level 1, the cell organelle level) to the highest one (level j), the formula becomes :

$$\mathbf{L(S,t) = \sum_{1}^{j} C(S,t)}$$

where **L** = Life activity, **C** = communication act, **S** = system or compartment, **j** = the highest level of compartmental organisation, **1** to **j** = a given level of compartmentalization, **t** = the moment at which the acts of communication are considered. Conditions are that Σ^j**C (S,t) > 0 and that, when adding up the acts of communication at successive levels, the same act is added only once.**

We are aware of the fact that « time » is difficult to define and may form a major problem in mathematical expressions of the form, but it is not the task of biologists to solve this philosophical-physical problem. We also have to stress that the life activity of a given system is considered at a given moment t (or time interval) : time only matters (as a variable parameter) as long as the system S remains alive.

THE INTERRELATIONSHIP BETWEEN GRADIENTS, PRESTORED ENERGY, COMMUNICATION AND THE DISSIPATIVE NATURE OF LIVING SYSTEMS

At present, very few biologists are familiar with the name and work of the belgian mathematician Ilya Prigogine who received the Nobel Prize for his innovative concepts in the field of thermodynamics of far-from-equilibrium systems. Prigogines work mainly deals with the question how order can arise out of chaos, and this is evidently of outmost importance for biological systems. Without some knowledge of this theory (PRIGOGINE, 1980), it is impossible to understand the very nature of life. Therefore, we will briefly mention some major points of interest. A most important term, which did as yet not appear in common handbooks of biology, is ***« dissipative system »***. It is a far-from-equilibrium system in which order is created out of chaos by investing energy. All living systems are dissipative in nature : when the investment of energy (food supply) stops, the ordered state changes into chaos. The explanation why living systems are thermodynamically always far-from-equilibrium systems is simple. We have hypothesized earlier that communication is essential for life and that communication is not possible when there is no ***prestored*** or ***instantly available energy*** in the system. In any cell, part of the energy which is used for communication and doing « work » in general (this includes creating order) is stored in the form of an ***ionic-voltage gradient*** over the plasma membrane. ***Gradients*** are by definition out of equilibrium systems. They are essential in driving communication and evolution at the same time (see text). A second very important term in this field is ***« bifurcation point ».*** The term has first been introduced and is commonly used in the nonlinear mathematical literature. When one deals with bifurcations in a rigorous manner, it refers to a situation where beyond some critical parameter value a particular solution becomes unstable and the system spontaneously evolves to another stable regime. In a biological context, the term is loosely used, depicting a point where a choice has to be made (gene a or b to be switched on etc.). But bifurcation points are also very important in communication (see text for the example of the flute and the music) : they are a tremendously rich, but largely overlooked source of variability in communication.

« LIFE » IS COMMUNICATION

The following definitions of « Life » may meet with varying degrees of accuracy the criteria mentioned in the introduction :

— *« Life » of a compartment S at moment t is the « total sum of all acts of communication » performed by this compartment S at moment t.*
— *« Life » of a given dissipative compartment (S) at a given moment of its existence (t) is a dynamic state resulting from the combination of all acts of communication carried out by this compartment S at its different levels of compartmental organisation (from 1 to j) at moment t. This living state should exist at all vital levels of organisation of compartment S.*
— *The term « Life » denotes the state of a thermodynamically open, but compartmentalized dissipative system that has reached a (high) level of internal organisation which allows it to produce coordinated (active) responses to « environmental » changes (including the communicative interactions with other living systems) in order to prolong this state (and to create an even higher level of compartmentalization).*

Our definitions of life imply that :

1. Life and communication are not possible without a **gradient**(s) had been formed first. By definition, a gradient is not a state of stable equilibrium. Exactly because they depend upon gradients, living systems cannot be else than far-from-equilibrium situations, in which order can be created and maintained only by investing energy. Thermodynamically, living systems have the essential properties of **« dissipative systems »**. Irreversible collapse of essential gradients means the end of life. Viruses are not alive because they do not build up an ionic gradient over a plasma membrane.
2. A compartment can only communicate with the outside world or with other compartments if its boundary is not perfectly tight. A cell with a limiting « membrane » made of glass could not be alive. Communication at the level of the

plasma membrane requires a moderately « leaky » membrane to make transmembrane ion fluxes possible. Thus, some 3,7 billion years ago, « life » started as an *imperfection* in a membrane in combination with a chemical gradient over this membrane. The important but usually overlooked role of the cytoskeleton and the distinction between the « prebiotic » and « biotic » era have already been described elsewhere (De Loof, 1993).

3. Life has both **quantitative and qualitative** parameters (types and steepness of gradients).
4. Since in many fast acts of communication **ionic/electrical** processes are involved, life is to a large extent an electrical phenomenon.
5. Communication is transfer of information. Information does not have units of force or energy. This explains why life is not part-and-parcel of chemistry and physics. Life is above the chemistry and physics that are required to form the compartments, the instruments for communication. In our third definition, the term ***coordinated*** is important because it is the coordination which makes the realization of the highest level of compartmentalization functional : this means that **« the whole is more than the sum of its constituting parts »**, a crucial fact which is often overlooked in the philosophy of reductionistic experimentation.
6. In order to allow a system to transfer and integrate incoming messages it has to contain the « information » (or programme) needed to do so. Therefore, living compartments can build up **some kind of memory** (short-term and/or long-term storage of information).
7. A compartment has to communicate to preserve or augment its chances for survival. Therefore, **life and survival are interdependent** and, as will be discussed later, cannot be separated.
8. Life has a different meaning not only for each individual creature, but also at each moment of its existence ; life is never constant. Life started to change and to evolve from its very beginning, and will continue to do so as long as there is life on earth (Evolution).

GRADIENT FORMATION, SELF-SELECTION AND EVOLUTION

The consequence of defining life in terms of communication, implies that **biological evolution includes changes to the communication systems in the course of geological time.** These changes are made by increasing 'complexity', thus by reaching higher levels of compartmentalization by changing the nature of and/or the number of communication acts that can be performed.

Life is the driving force of its own evolution

Life on one hand, and self-selection, natural selection and survival of the fittest (Darwins' terminology) on the other, are as inseparable as the two sides of a coin. The reason for this is simple. Imagine in pregradient era-conditions a compartmentalized aggregate in which the concentration of solutes is the same on both sides of the limiting membrane. At a given moment this compartment starts to build up a gradient, *e.g.* because a membrane protein starts to cotransport an uncharged amino acid together with the uptake of an inorganic ion, *e.g.* H^+ (theoretical example). If at the same time there are *e.g.* H^+-channels in the membrane through which H^+-ions can leak out at a (slow) rate that depends on environmental conditions, the prerequisites for a primitive communication system with the environment are present. Thus, in our view, this compartment starts to live. If we assume that no strong buffering system is present, the changes in H^+-concentration (pH changes) will be experienced by molecules present in the cytoplasm : enzymes, structural proteins etc... may change conformation and as a result become more active while others may become less active. At the same time the increase in solute concentration in the cytoplasm will lead to osmotic effects. A cell that cannot cope with all these changes will lose its gradient and die. The self-selection of life goes on as long as there is life. This self-selection process which is based on many trials and errors and which can only be achieved in concert with environmental conditions, is probably the most fundamental mechanism that drives evolution. The driving force could be called « gradient drive » or « communication drive ». The entities with the best « communicative skills » (the fittest in neo-Darwinian terminology) have the best chances for survival. « Communication fitness » and « Communication environment » might be useful terms in this context.

Since evolution is driven by the communication drive, it actually means that life is its own driving force (self-selection). This results from following reasoning :

If « Life » is « Communication »
and « Communication » drives « Evolution »,
then it follows that « Life » drives its own « Evolution ».

Thus, life cannot exist without evolving. It drives its own evolution.

« Cultural Evolution »

Is there any form of evolution which is independent from mutations of the genome ? Let us therefore analyze what happened to the social compartment formed by our species, *Homo sapiens*. The behavior of *Homo* (and even to some extent his morphology, *e.g.* the increase in body length) has evolved substantially in the 20th century. This social and economical evolution is due to epigenetic factors (*e.g.* our diet), to the development of specialized tools, to the production of machines that do a great deal of our work, to the drastic changes in communication systems that we can use etc. The speed of acquisition of novel (*e.g.* scientific) information is so fast that genetic evolution is not fast enough to generate larger and better functioning brains. Mechanical and electronic tools (letters, books, journals, radio, television, telephone, fax, computers, compact discs etc.) are used as extensions of the « natural » communication systems (controlled by the brain) to transfer, store, reproduce or select this additional information. In classical terms this type of evolution would be called *« cultural evolution ». But what else is cultural evolution than evolution based on communication and learning at the (highest) level of the* Homo

TABLE I: BASIC PHILOSOPHY OF LINEAR VERSUS DISSIPATIVE BIOLOGY.

	LINEAR BIOLOGY	DISSIPATIVE BIOLOGY
1. study object	living matter	communication
2. basic unit	organism	communicating compartments
3. smallest unit	cell	monomembrane communicating compartment
4. organism	- instrument for metabolism and reproduction - product of its genes and environment - complex because of large number of genes	- instrument for communication - product of its genes and communication environment - extremely complex because of high number of genes and very high number of communication bifurcation points
5. major functions	- growth - development - reproduction	- communication - prevention of transition from order to chaos
6. basic rules biology	DNA --> RNA --> proteins	- idem but Nernst equation equally important - no life without gradients
7. basic physics	- classical linear Newtonian physics - 1st and 2nd law of thermodynamics - time in principle reversible in some processes - mainly deterministic - 4 dimensions of spacetime - living matter consists of aggregated stardust	- modern Newtonian physics - non linear Prigoginean far-from-equilibrium thermodynamics - time in principle always irreversible - indeterministic - idem plus electrical dimension - all matter is creative and self organising

8. basic chemistry	synthesis of organic molecules in "saline" environment	idem plus bioelectrochemistry
9. information carrier	nucleic acids	nucleic acids and memory
10. genetics	eugenetics (Mendel, molecular)	idem plus epigenetics
11. variability due to	- mutations, meiosis, etc. - changes in "macromolecular environment" around the genes	- idem plus bifurcation points - changes in "macromolecular and ionic environment" around the genes
12. evolution	- evolution of macromolecules - changes in genes - mutated protein force - slow - selection follows mutations - survival of fittest	- communicational evolution - changes in communication systems - gradient/commmunication force - fast - self selection results from life itself - survival of fittest in communication - evolution field (Cramer, 1993)
13. definition of life and death	impossible	possible (this paper)
14. scientific approach thinking	- reductionistic experimentation and holistic thinking - sum of parts approximates the whole	- reductionistic experimentation and - the whole is more than the sum of its parts
15. feedback systems	for coordinated functioning	for interactive communication
16. feelings, emotions, etc.	largely irrelevant	where present, essential part of communication

compartment ? This process is not restricted to the *Homo sapiens* compartment, but it is a basic and thus general feature of all living systems.

Changes in some communication acts may be due either to mutations or to another almost completely overlooked but nevertheless very important source of variability, namely the bifurcations which are inherent to far-from-equilibrium systems (dissipative systems such as living beings). Mutations allow evolution to proceed at a slow rate, whereas bifurcations at a very fast rate.

With respect to communication at the level of the plasma membrane, bifurcations are especially important in those processes where fluxes of *inorganic ions play a role and which are not directly controlled by genes.* For the relationship between bifurcations and selection, we refer to KAUFFMANN (1993).

Bifurcations, the overlooked companion of mutations

The following analogy between life and music may help to clarify the point we want to make, namely that for driving evolution, mutations or genomic changes in general are only part of the story. *To produce music* **(communication)**, one needs an instrument **(compartment)** *and one has to play* **(to live)**. This means that in order to understand what drives evolution *one has to make the distinction between the evolution of the compartment, and the communication produced by this compartment :* these are quite different things, but they depend on each other. Imagine a musician who plays a flute. At first, the flute has only one finger hole. The resulting music will be rather monotonous. If a second finger hole is introduced, which means a ***mutation*** for the flute, the resulting complexity (***degrees of freedom***) of the music does not double, but multiplies. The reason for this is that the musician can now continuously decide whether to use the upper hole or the lower or both, and for how long : thus he makes use of the possibilities of *an imaginary « bifurcation point »* (an important term in the Prigoginean thermodynamics of systems far-from-equilibrium, see later) located between the two holes. The introduction of a third fingerhole results in a much higher complexity of the music. The more fingerholes the greater the possibilities, provided the musician manages to coordinate the movements of his fingers. But once there is a hole for each finger, the music can nevertheless further evolve in the course of time without additional fingerholes. The instrument could perhaps still be improved by changing the size or location of the holes. The higher the possible number of bifurcation points, the less important are changes in the instrument itself, and the greater the possibilities for evolution of the music. The situation is very similar in biological systems : gene mutations will have drastic effects in simple systems, but in more complex systems there can be situations where additional changes are only to a minor extent responsible for changes in communication.

An almost literal biological equivalent for the fingerholes in the flute are the holes in the plasma membrane through which inorganic ions can flow (ion channels, ion pumps etc.). In addition to these, other components of the communication system can also « generate » imaginary bifurcation points (Fig. 3). Because of the high number of ion transporting membrane proteins in each cell and other components of communication systems, the number of possible bifurcation points is very high. This results in nearly infinite variability and low predictability in organisms consisting of many cells, especially in organisms with well developed brains (*e.g.* our brain consists of about 100 billion cells). No organism « knows » what all his acts of communication will be the next day, not even the next hour, minute or fraction of a second : it all depends on the interplay of circumstances that contribute to decide which bifurcation points will be involved, and which one of its two sides will be chosen. The communication-future is thus unpredictable. Bifurcation points allow to explain phenomena we are familiar with but which cannot be easily explained by genetics. Imagine that genetically identical twins are born in Brussels. One baby stays in Brussels and is raised in a bilingual dutch-french family, the other is moved to Tokyo and raised there by a japanese family. Despite their genetic identity, the twins will eventually speak totally different languages and behave each according to the cultural standards of their local environment. Mutations do not play any role in generating the differences because the instruments for communication, the bodies of the twins, do not change by being raised either in Brussels or in Japan. Nevertheless the communication produced by the twins is different under the influence of the environment and learning : these do not act through mutations but through bifurcations just like different musicians can produce totally different music with the same flute. Imagine now that genetically identical twin lambs are treated the same way. The mèèèèèèè-language of the japanese lamb, once grown up to a sheep, will probably not be that different from its counterpart in Brussels. The reason for this difference humans-sheep is to a large extent due to the number of possible bifurcation points in the brain of humans, allowing a much higher flexibility corresponding with a higher number of degrees of freedom. This allows the modification in the cited example to occur. Evidently, the muscles involved in sound production play an important role.

The neo-Darwinistic theory of Evolution versus our holistic « double continuum » approach

Evolutionary biologists usually define evolution as the *change in the genetic make-up of a population* with time. The centerpiece of the neo-Darwinian synthesis is that natural selection, acting upon individual variations within a population to substitute one allele (= a variant of a gene at the same locus) for another, is the major force driving adaptive evolutionary change (KAUFFMAN, 1993). By doing so, neo-Darwinists only take into account relatively small evolutionary steps due to genomic changes that are fixed in a population.

We defined Evolution as the *change in compartments and in their acts of communication* in the course of geological time. Due to the « communication drive », which is — in our opinion at least — the most prominent selection principle, this process leads to changes in the nature and/or in the number of possible bifurcation points. This approach is not at all in contradiction with neo-Darwinism, but it integrates the principles of this neo-Darwinism with those of thermodynamically far-from-equilibrium systems (such as living compartments) and of communication.

It takes into consideration the entire interplay of elements affecting the communication acts that can be generated by a given compartmentalized system and the way by which these can be integrated (« added up »). These elements include both the gene products as well as the other organic (*e.g.* lipids, carbohydrates, steroids, amino acids, nucleotides, second messengers etc.) and inorganic molecules (*e.g.* ions arranged by the system into gradients across membranes) which are part of the system's communicative machinery.

In the neo-Darwinian view, however, biological systems are generally still considered as « discontinuous » systems which get born, live and die and which eventually transfer their genetic information to a next generation. In our holistic approach, life and survival are highly interdependent. Therefore, life can be considered as a ***double continuum***. First, there is the continuity of the physical compartments, which are the instruments which are needed for communication. Second there is also the continuity of communication and some types of information themselves. Both do not necessarily overlap because some types of information and communication present in a population can last longer (or shorter) than the individual organisms of which a population consists : *e.g.* the information present in a book can last longer than the person who wrote it. Neo-Darwinism largely limits itself to the study of the evolution of the « physical compartments » as such : it is a « ***single continuum*** » theory.

The communication which is produced is never constant and changes in concert with environmental as well as internal conditions. Gene duplications and mutations are just the mechanism by which long-term changes in the properties of such continuously evolving communication systems can be created and preserved. These duplications and mutations generate a higher variability by which a population may have better chances for its survival : the « fittest » individuals will survive.

The process of reproduction circumvents the problems that arise by system breakdown (death) : life of an individual far-from-equilibrium system is not endless, since it will have to cope with entropy sooner or later. The population, however, may survive during longer periods of time via reproductive processes. An offspring is usually created via pinching off daughter compartments that then may « regenerate » to form novel adult compartmentalized systems. In the case of sexual reproduction, the zygote obtains mixed genetic information derived from maternal and paternal compartments. This allows more variation by generating different genetic combinations within a population. Besides that, what else is sexual reproduction than an extreme form of regeneration through a process which we call embryonic development ? A mature oocyte is an example of a daughter compartment that is pinched off from the maternal system. It contains the information and the programme that is necessary to « regenerate » into a novel fully developed system (in concert with some essential environmental and/or social conditions). This daughter compartment formation process as well as embryonic development are the result of a long evolutionary process. They make use of the genetic information (DNA is a form of phylogenetic molecular memory which contains the sequential information to build up complicated macromolecules) and of the communicational machinery which is essential for life (cfr. our definition of « Life ») and thus for survival. The entire oocyte system is organized in such a way that the « life activity » that it produces, will normally lead to the formation of a regenerated system via a certain developmental programme. It is not surprising at all that this (ontogenetic) developmental programme appears to be a fast recapitulation of the system's phylogenetic history.

In our approach, selection is evidently very important : it can act at many different levels of organization. However, probably like chemists and physicists, we have difficulties in accepting the rigourous statements of KAUFFMAN (1993) that selection is both the driving force of evolution and essentially the only source of order in the biological world.

« ARTIFICIAL LIFE » ?

The technological innovations which have been developed in fields such as molecular biology, electrophysiology with artificial membrane vesicles but especially in the field of cybernetics make the question whether the *Homo sapiens* can make « artificial life » relevant. Molecular biologists have the tools to genetically transform existing life, but not to create new life. Collaborating teams of molecular biologists and membrane physiologists may be able in the near future to make a very primitive form of a communication system in artificial membrane vesicles. But, most of all, some man-made mechanical and/or electronic devices (or robots) have become so sophisticated that they start to look like being alive : *e.g.* imagine a man-made computer in which the electrical energy comes from a solar cell. A system like this can have all the necessary elements of a communication system as outlined above (stockpiled energy, a built-in programme to act as a receiver-decoder-amplifier and the possibility to use energy for carrying out specific types of work). When a signal via a key board is send, the system will work. In principle, such a system is not basically different from the one in which a hormone binds to its receptor (= the equivalent of typing on the key board the right code) which initiates signal transduction to mobilize previously stockpiled energy for doing work. Intuitively everybody will reject the idea that the computer is alive, although we sometimes use a similar vocabulary : *e.g.* we say the computer is « dead » like we say that the radio is « dead », meaning that its communication system has failed.

Do we have good arguments to firmly say that a computer is not alive as we think we have ?

1. *Computers cannot reproduce themselves.* But neither can a castrated bull, and nobody will claim that this bull is not alive. Some parasites and symbionts cannot reproduce without a host. On the other hand, it is possible to make identical copies of all information on computerdiskettes, when the right « signals » are given. Reproduction only comes into play when life is considered *over a period longer than one generation :* for time spans not exceeding the lifetime of a compartment, reproduction is not an essential parameter of the living state (« short-term » life versus « long-term » life : DE LOOF, 1994).

2. *A computer has no DNA.* Red blood cells of mammals eject their nucleus when their cytoplasm gets filled with hemoglobin. Such « cells » (erythroplastids) have no DNA but nevertheless may continue to live for a few weeks. A fertilized egg of an amphibian can be enucleated, thereby loosing its DNA (but retaining the DNA present in its mitochondria). Such an egg can still undergo a number of cleavages like a normal one.
3. *Computers use different principles of communication.* Not true : similar principles as outlined in Fig. 2. are used in computers and in our brain. Computers are designed to take over some of the communication in our brains.
4. *A computer cannot think, it is not autonomous and it has no emotions.* Can an amoeba, a red blood cell, a plant, a fungus think ? How autonomous are they, and do they have feelings ? A computer equipped with a solar cell coupled to a battery for storing the solar energy can be autonomous for a longer time than an amoeba that has to find enough food. Specialists in the field of artificial intelligence think that it will not take that long before « emotional phenomena » will be generated in computers. Any kind of feeling is mediated through the nervous system, and invariably involves ionic-electrical phenomena.
5. *A computer cannot cope with entropy, it will break down after some time.* In that it does not differ from living systems which also age and get sick.
6. *A computer does not carry out metabolic reactions.* It is true, but not a good argument, because the main purpose of metabolic reactions is to mobilize energy and use it for doing work. In our example the computer uses light energy while organisms usually use chemical energy. However, this chemical energy provided in the form of food is the same as solar light energy that plants transformed into chemical energy during photosynthesis.
7. *A computer cannot come and stay into existence without the help of humans.* True of course, but we could not come into existence or stay alive as youngsters either without the help of our parents. A more valid argument is that we and our parents belong to the same species, the computer needs help from outside the « computerworld ».
8. Computers do not use carbon chemistry like true living beings do. True again and a good argument. The basic chemistry of computers is inorganic chemistry as opposed to the organic chemistry of true life. Computer chemistry is based on silicon and metals, with some organic polymers which are mainly used for insulation purposes. Since computers are very recent inventions, there is a possibility that in the future carbon chemistry may perhaps become more important in computer technology.
9. *Computers use a different carrier of electricity.* True and again a good argument. In biological systems electricity, which is the movement of charges, is carried by inorganic ions, in computers it is carried by electrons. Electrons can move at the speed of light, namely at about 300 000 km per second while ion-carried electricity is many orders of magnitude slower. This is the major reason why computers are so efficient : they can work much faster than our brain.

10. *Computers cannot adapt themselves to a changing environment.* If one analyzes the success story of computer development, one cannot escape the conclusion that computers seem to adapt « themselves », of course with the help of humans, much faster than organisms do. Research in the domain of artificial intelligence shows that in certain circumstances man-made robots adapt themselves and even install a sort of hierarchy among each other without having been programmed to do so. It is not that difficult to make computer programmes that allow changes and errors.

What is then the point ?

The point is that one should not a priori discard the possibility that novel man-made forms of « life » can (have) emerge(d). The entire human compartment has become populated with mankind on one hand, and its tools on the other. Computers are electronic-mechanical extensions of the brain, man-made tools which only exist for a few decades. Nevertheless, they have become so sophisticated that they start to look like being alive. One could say that man created a novel type of life, « artificial or man-made life ». The entire *Homo* compartment has therefore reached a higher order of organisation (toolisation : level 8 in Fig. 1) containing « organic chemistry-based » life forms, « artificial » life forms (as « symbionts ») and non-living elements (tools). The « Life activity » produced by this supercompartment thus is the result of the integration of acts of communication which are performed by biological as well as by artificial components. Communication in our body uses organic chemistry and ion-carried electricity, while our electronic-mechanical « companions » are metal- and silicon-based and their electricity is carried by electrons. To make the distinction between « organic chemistry-based » life forms and « artificial » life forms, the formula that represents « Life activity » of a given compartment can be made more specific as follows :

$$\mathbf{L}(\mathbf{S}_{(\mathbf{TC},\mathbf{TE})},\mathbf{t}) = \sum_{1}^{j} \mathbf{C}(\mathbf{S}_{(\mathbf{TC},\mathbf{TE})},\mathbf{t})$$

where **L** = « Life activity », **S** = a given system or compartment which uses the Type of Chemistry, TC, and the Type of Energy, TE, to produce its communication acts **C.** The condition is that Σ^j C > O and that acts of communication are « added up » only once.

In his evolution, *Homo sapiens* has reached the point that his coordination center, the human brain, has become so highly developed that the mutational evolution rate (that could result in bigger and better functioning brains) cannot keep pace any longer with the fast increase in information-processing capacity and variability that can be achieved by expanding his communicational avenues via cultural evolution and via the creation of novel and very efficient tools for communication. Whether one likes the idea or not, the fact is, that transfer of information (*e.g.* from one generation to the next) and work can be carried out very efficiently by « artificial » life forms and/or electronic-mechanical tools. This is (and will probably remain) one of the big problems of our times, leading to unemployment with all its deleterious effects.

CONCLUSIONS

The combination of the principles of communication and of dissipative systems may result in a more *holistic* philosophy of biology for which the name **« dissipative biology »** or **« non equilibrium biology »** as opposed to the **« classical »** or **« lineair »** biology (Table I) is proposed. This is analogous to the terminology which is used in physics (CRAMER, 1993). Linear biology, which is the *reductionistic* biology as it is taught today, mainly deals with the formation, functioning and evolution of the physical support (cells, organisms etc.) of life in an ever changing physical environment. It describes the different levels of compartmentalization and their functioning. Its basic unit is the « cell ». Dissipative biology mainly deals with communication of compartments in an ever changing communication environment. Its basic unit is the « communicating compartment », and its smallest unit is the « monomembrane communicating compartment ». It studies the interplay of the communication systems which are described by linear biology. Linear and dissipative biology as observed for their historical context, are not at all mutually exclusive, but *complementary*. An easy way to understand and compare « linear » and « dissipative » biology is to have a second look again at figures 1 (for linear biology) and 3 (for dissipative biology).

In dissipative biology links can be made that were not evident before : by its very nature it is *holistic* biology and therefore it allows a much more coherent concept of Life and Nature than is possible with the classical, reductionistic or « linear biology ». No doubt, because of their *indeterminate* nature, dissipative systems are more difficult to analyze than linear ones. This is the major reason why relatively few biologists are engaged in this type of research. However, several basic principles of dissipative biology have already been reported, some of them decades ago : the principles of basic membrane physiology (the Nernst- and related equations *e.g.* : see HAROLD, 1986), the chemiosmotic theory of MITCHELL (1979), ionic-electrical control of development (JAFFE and NUCCITELLI, 1977) and gene expression (VANDEN BROECK *et al.,* 1992), the electrical dimension of cells and self-electrophoresis (WOODRUFF and TELFER, 1980 ; DE LOOF, 1986), epigenetics (LØVTRUP, 1974), the evolution field (CRAMER, 1993), self-organisation as applied to biological systems (PRIGOGINE, 1980 ; PRIGOGINE and NICOLIS, 1971) and the hypercycle theory of EIGEN and SCHUSTER (1977, 1978) are some examples. Some of them were awarded a Nobel Prize. What has been missing so far is the conceptual context in which these « peripheral aspects » of biological functioning, as some of them have been considered for shorter or longer spans of time, fit in. One of the goals of this paper is to fill this gap. Another goal is to show that in biology, as in physics, both reductionism and holism have their merits. As a result of the successes of reductionistic experiments, biology has rapidly evolved towards a technological science. If it could become more centralized around its key issue, which is communication, a more harmonious view of the place of man in Nature and in the cosmos would result. Teaching biology as « dissipative biology » or « non equilibrium biology » might substantially contribute to achieve this goal.

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