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Full Papers

On the stability of cognitive processes

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Summary. An empirical and mathematical model for self-organization is proposed, based on elemental properties, on unique interaction and on the combination of hierarchical elements. In the model, higher elements are stabilized by the 'cognitive' (strong) interaction of subelements, disregarding intermediate elements. This is called 'elementary reductionism' and is illustrated by the sequence quarks – elementary particles – atoms – molecules – cells – organisms – societies. Optimal dynamic interaction of nonidentical elements is called 'cognitive stability'. This is compared with thermodynamic equilibrium. The principal differences are outlined.
Key words. Self-organization; cognitive processes; elementary reductionism; cognitive stability; thermodynamic equilibrium; hierarchical elements; dynamics of interaction.

Introduction

The applicability of the second law of thermodynamics to life processes has been being discussed for a long time[4,7,18,21]. Since the second law implies a tendency towards increasing disorder, and life phenomena create order, it has been difficult to reconcile the two. However, thermodynamics was originally developed to describe the gaseous state and was later expanded to include other phenomena such as electrons in conducting metals[20]. There exists a range of physical phenomena that cannot be adequately explained by thermodynamic formalism, for example quarks, photons, superconductivity or coherent molecular movement. Thus, there is a priori no reason to assume that thermodynamic formalism should adequately explain all types of life phenomena, since cellular life may be governed by laws that are not related to thermodynamics, just as these phenomena are. In the present paper, evidence is presented which supports this view. A model is presented which describes life phenomena not on the basis of weak thermodynamic interaction of elements as $n \rightarrow \infty$, but on the basis of strong and 'cognitive' interaction of elements with defined properties, defined interactions and finite number. Cognitive processes, not rigorously conceptualized or defined before, may occur not only in real systems in nature, but also in abstract systems, in societies and in the mental processing of the outer world.

Hierarchical elements in nature

In the model, elements are defined as building blocks which can be put together to form units of higher complexity. Such units may in their turn form elements in a higher hierarchy. When elements in a lower hierarchy form stable elements in a higher hierarchy, new properties arise. This is a general phenomenon in nature and is illustrated by the sequence ... quarks – elementary particles – atoms – molecules – cells – organisms – societies – ... (table 1). The elements may also combine to form dependent intermediates which do not behave as autonomous stable elements. Supramolecular structures, organelles, organs, species or groups in a society are examples of such dependent intermediates.

An important feature of fundamental elements forming elements of a higher hierarchy is that the fundamental elements themselves have different properties. For example, electrons are different from protons, but together with neutrons they occupy different energy levels and form atoms. Organisms are composed of cells with different functions, and the various cells themselves are composed of different molecules (enzymes). An ant is obviously different from an ant eater but together they form parts of an ecological unit, niche or society.

This situation is different from that when the elements form crystalline structures composed of identical subunits with fixed coordinates, like for example in a perfect crystal. In such cases, new properties do not arise, and, in the case of molecular crystals, the macroscopic properties directly reflect the molecular properties. If the crystal responds to the environment, e.g. to a change of temperature, this too reflects the molecular properties and is not related to any significantly new properties due to the crystalline state. On the other hand, the constrained electrons in an atom obey the Pauli exclusion principle and occupy different energy levels[12], and in superfluid helium, the energy levels of the systemic atoms are similarly differentiated, leading to an increased mean free path[15].

There is a tendency for there to be more elements in a higher than in a lower hierarchy. For example, there are only six quarks, approximately 5 × 10 elementary particles, and about 500 atoms, the isotopes counted separately. The number of molecules is considerably larger, but the various organisms are made up of similar or identical classes of molecules, and the number of known species exceeds the number of different molecules. Since societies and ecological niches are made up of individuals, their number probably exceeds that of the species.

Interaction between elements in one hierarchy

The survival, or stability, of an element belonging to a higher hierarchy depends on the equilibrium between its components, the fundamental elements. The equilibrium between the fundamental elements requires interaction between them, and therefore the elements are not only characterized by their properties, but also by their 'interaction surface'. If the interaction surface of two elements is complementary, then interaction can occur. This interaction contributes to the stability of the higher element and is cooperative. The stability of the higher element depends on the degree of complementarity, i.e. the quantity of interacting complementary surfaces in a given amount of fundamental elements. The term interaction surface (which implies specificity) can be given an abstract meaning and does not imply static interaction between the elements. An element may have several properties, and several interaction surfaces (see fig. 1). Since the interaction implies specific recognition between elements, it can in the most abstract sense be regarded as informa-

Table 1. Hierarchy of elements occuring in nature

Fundamental element	Dependent intermediate	Higher element
?		Societies
	Species (groups)	
Organisms		Organisms
	Organs	
Cells		Cells
	Supramolecular structures, organelles	
Molecules		Molecules
	?	
Atoms		Atoms
	?	
Elementary particles		Elementary particles
	?	
Quarks		?

tion exchange. Although the interactions are strong and specific it is significant that they are dynamic in order to distinguish them from cross-linking, a term which implies static interaction.

The importance of dynamic as opposed to static interaction can be exemplified by DNA (deoxyribonucleic acid) which has a sufficient number of interaction surfaces to store most of the information a cell needs to multiply, and transmits the information using the complementarity principle. In this case, complementarity is defined as complementary electron orbitals of DNA, which fit like spikes and indentations. The information stored in DNA has no meaning unless it can interact dynamically with the surroundings, something which happens when it is transcribed into RNA. This implies dynamic interaction on the enzymic level, and the impact of the information is a direct function of the number of interactions or the number of copies of RNA synthesized, while the cross-linked DNA is silent. The adaptability of the species is not a function of the amount of cross-linked DNA, as evidenced by the fact that a frog cell contains more DNA than a human cell. Also when enzymes interact by exchanging substrates and products, the transfer of one molecule of product from one enzyme to make a substrate of the next enzyme can be considered to represent one interaction, a situation which is different from static cross-linking, since it implies dynamics. On the molecular level, interaction is likely to occur via resonance phenomena while in systems like the electron shells of an atom, strong informatory interactions would be necessary for the electrons to 'know' which quantum numbers are occupied[12].

Other examples can be found in the human society. Due to the variety of elements in human society, the 'interaction surface' of one person cannot possibly be complementary to that of all other individuals comprising the society. Such a unit is unstable because the interactions between its elements are not stable. On the other hand, groups of individuals in a society can be extremely stable if the interaction surfaces between the fundamental elements are numerous and the complementarity high. In these cases, complementarity of interaction surfaces can be defined as common interests or common experience. The group may form a 'crystalline-like' unit where interactions with individuals who are not part of it are lost, or a new element characterized by laws, regulations, cultural

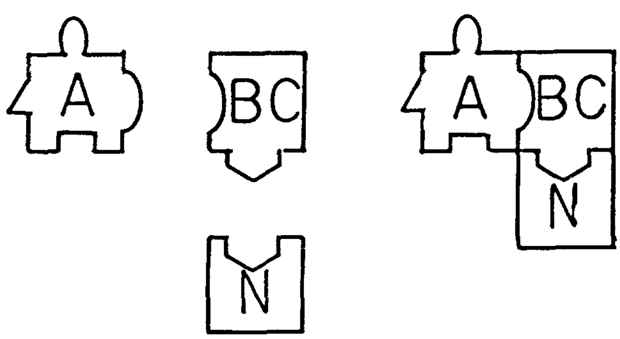

Figure 1. Illustration of elements and their characteristics. Properties are illustrated by capitals and the specific interactions by complementary key and lock patterns. On the left-hand side, the elements are solitary and on the right-hand side systemic.

patterns or loyalty may be formed. This increases the stability of the group, but also its inertia and may lead to a delayed response to environmental changes. In another hierarchy, that of living cells, such crystalline-like groups of fundamental elements are associated with stable environments, as will be discussed later.

The importance of systemic interactions between elements as opposed to nonsystems has been stressed in the economic literature[19] and is important in the cybernetic rules of technology assessment[23], management[11], organization[14] and decision making[5,22], where the systemic character is linked to a pattern of interaction obeying the right cybernetics in the interdependence of the elements forming the system[2,5,23]. Also in these approaches, based on the specific self-organizing principles of hierarchical systems, concepts like primary complex systems, exemplified by DNA, and higher systems, like ecosystems[7,16] are used.

The dynamics of interaction in a living cell

The living cell constitutes a good example of a system, or element, composed of fundamental elements which interact. The fundamental elements of living matter are molecules of a molecular weight in the range of 100,000 (g/mole). Particularly enzymes, carrier molecules and contractile proteins contribute to the ability of living cells to respond to the environment and are also partly responsible for the structure of the cells. Enzymes are proteins that catalyze an increase of the rate of chemical reactions. Carrier molecules transport chemicals of lower mol. wt across cellular membranes and contractile proteins mediate cell movement and are the main components of muscle cells. In addition to these fundamental elements that mediate the immediate response of the cells to the environment, the cells are equipped with a machinery for their synthesis and modification, and a protective coat that surrounds the cells.

The elements of the living cell interact in a dynamic way with the environment. This means that in response to changes in the environment, the fundamental elements change not only in quantities and properties but also with respect to the interaction between them. This is a very important feature of surviving cells and several molecular mechanisms have evolved to accomplish such a dynamic response.

For example, the presence in the environment of a toxic chemical may induce synthesis of an enzyme which converts it to a harmless product, and the amount of enzyme synthesized may vary according to the amount of toxic chemical present. In this case, the survival of the higher element, the cell, depends on a single class of fundamental elements, the enzyme which converts the chemical. This element has the property of converting the poison, and one of its interaction surfaces is to adsorb the poison. However, the enzyme also depends on products from other enzymes for its action and thus has several interaction surfaces. In reality, there may be competition for those products by the detoxifying enzyme and other enzymes, which leads to a dynamic situation in which the flux of low mol. wt chemicals may mediate interaction in two or more possible constellations of enzymes. If the detoxifying enzyme is part of the constellation, the situation represents a case where the element of the higher

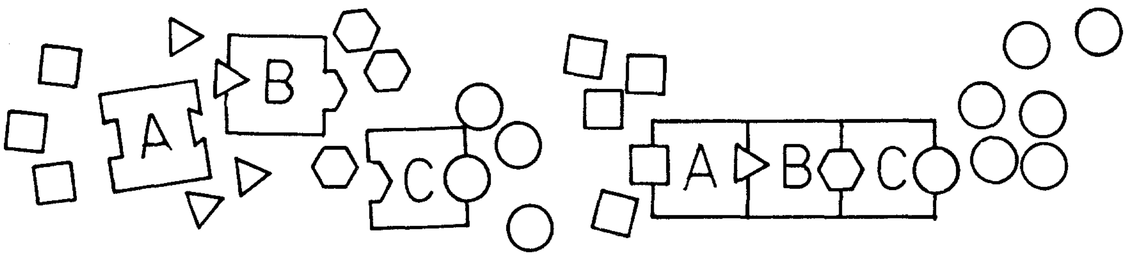

Figure 2. Grouping of nonidentical dynamically interacting enzymes in multienzyme clusters. Converting properties are indicated by capitals and interaction surfaces by contours. Substrates and products are indicated by small squares, triangles, hexagons and circles.

hierarchy (the cell) has survived thanks to recombination of its fundamental elements (the enzymes). There exists several molecular examples of this, most of them involving nontoxic chemicals.

There are also molecular examples of crystalline-like grouping of enzymes where the interactions mostly remain within the group. Such groups are called 'multienzyme clusters'[24] and convert chemicals in a multistep process without allowing competition by enzymes not belonging to the group (fig. 2). Multienzyme clusters usually carry out functions that are essential for the survival of the cell irrespective of its environment, and behave themselves like fundamental elements in their hierarchy. Because of a tendency of multienzyme clusters to break down to the actual fundamental elements, i.e. enzymes, not very much is known about them. Examples can be found in lipid and glucose metabolism.

The contractile proteins constitute a good example of fundamental elements that rearrange continuously and change their spatial coordinates. This occurs in response to changes in the environment of the cell. As a result, cell movement, possibly to a more favorable environment, occurs. The contractile proteins are also capable of maintaining crystalline-like structures composed of a great number of elements. Such crystalline-like structures are typical for cells that either rest in a nonchanging environment or have formed permanent substructures of contractile proteins where the whole structure behaves as one element. This limits the freedom of the higher element and diminishes the number of ways it can respond to the environment.

A simple molecular example to illustrate this can be found in the acto-myosin system, which is one of the most ubiquitous contractile systems, found in animal cells, algae, etc. The most important components of this system are myosin and actin, which interact within themselves and with each other. Thus, each fundamental element has two classes of interaction surfaces, for other identical elements, and for the nonidentical element. In the dynamic type of organization of these proteins, their interactions change continuously and the amount of crystalline-like grouping is low[9]. The contractile proteins then rearrange continuously and form groups of cooperative interaction that can appear and disappear in the cell at any time. This occurs as a response to environmental changes. The decreased order is typical for tumor cells[17] and may contribute to their survival at the expense of other 'normal' cells, which ultimately destabilizes the whole host organism. Contrary to tumor cells, the crystalline-like organization of myosin and actin in muscle cells permits movement in only one direction, parallel to the longitudinal axis of the muscle cell[10]. In this case, the response of the element of the higher hierarchy, the muscle cell, is limited by the crystalline-like grouping of its fundamental elements, the muscle proteins.

The fundamental elements of living matter operate within the framework of the cell, which is the first independent structure that forms an element in a higher hierarchy. When forming supramolecular structures such as multienzyme clusters and organelles the fundamental elements, in analogy to the formation of atoms from elementary particles, must be able to: 1) identify the interaction surfaces of the neighboring elements, and 2) combine with other elements in such a way that the element of the higher hierarchy can respond properly to the environment. The identification process is governed by the properties and interaction surfaces of the fundamental elements themselves, and may require joint synthesis of the enzymes from RNA. The outcome of the combination process reflects a tendency towards maximum stability of interaction between the fundamental elements in a given environment, i.e. a high degree of complementarity between the interaction surfaces of the fundamental elements in that particular environment.

The interaction of the elements is based on two principles. One is the free interaction when the elements find their own most stable combination in a given environment. Recombination of elemental interaction is typical for changing environments. Another type of interaction is when the elements maintain strong grouping. This requires a nonchanging environment to prevent breakdown of the combination which is stable in that particular environment. In the former case, the elements interact unrestrictedly within themselves and with the changing environment while in the latter case, the loyalty of the fundamental elements to the coherence implicit in grouping prevents the evolution of new combinations of elements.

A concrete molecular example of this can be found in tissue cells resting in the constant environment of an organism. In such cells, the contractile proteins are in a crystalline-like arrangement, forming fibres beneath the cell membrane. If the environment changes, for example due to tissue injury, the previously stable crystalline-like grouping dissolves, and the elements begin to interact freely and find their most stable combination in the new environment[6]. The result of this is that the cell begins to move similarly to a tumor cell and temporarily acquires a more dynamic behavior compared to that when the proteins were in a crystalline-like arrangement.

Elementary reductionism during external constraint

The immediate response of living cells to the environment is particularly evident in the case of single cells that do not form part of higher elements; organisms. Single cells, like bacteria, solitary amoebae, and white blood cells, are exposed to a changing environment and have often retained their ability to move. During external constraint, when cells aggregate to form organs, the cells become more specialized and lose their ability to respond as independent elements to the environment. The total number of responses is then distributed over cells having different functions. This means that the organism behaves as a giant element whose response to the environment derives from the fundamental elements of living cells, irrespective of cell borders. The importance of the cellular level has then diminished, the organism behaves as an entity and its response derives from the total number of responses of the fundamental elements of cells, i.e. enzymes, etc. This is particularly evident in the case of *Dyctiostelium discoideum* which can exist both as solitary individuals, amoebae, responding without delay to the environment, and, when a slime mold is formed, as differentiated individuals in a society under external constraint[3].

A similar type of elementary reductionism during external constraint can be found at the subcellular level. Cells are composed of molecules that behave like independent elements when purified and studied. However, in the presence of external constraint represented by the cell borders of the intact cell, supramolecular structures are formed. Such structures are held together by forces derived from elementary particles, particularly electrons and protons. As a result, phenomena belonging to lower hierarchies, like electrical fields and proton gradients appear in the cell and many of the molecular responses of cells are actually mediated by such fields or gradients.

A corresponding situation exists in atomic nuclei where the elementary particles protons and neutrons can be disregarded and the properties of nuclei derived from the behavior of quarks. In the molecular hierarchy, it is conspicuous that in the superconducting state, the lifetime of Cooper pairs of electrons suffices to span several atomic diameters, thus extending beyond the atomic level (see table 1).

If the same principle holds in human society, a general ideology, belief or common culture, representing the external constraint, would reduce the degree of grouping and favor elementary interaction at the fundamental level.

The principle of elementary reductionism during external constraint seems to be based on ample evidence. In terms of the present model, it can easily be understood from the principle of maximized stability or increased cooperative interaction when two or more elements which are themselves stable, but composed of dynamically interacting fundamental elements are brought into close contact so that new interactions between the fundamental elements can occur. When this happens, new arrangements are more stable, as illustrated in figure 3.

Time evolution of cognitive processes

The history of the system comprising the element and the environment is important to bring about a stable combination of fundamental elements. The evolution of the enzymes and metabolic pathways can be deduced from changes in the cellular environment, of which the appearance of oxygen in the atmosphere has had the strongest impact. Other examples of time-evolving cognitive processes would be the elemental composition and interaction structure in societies responding dynamically to the environment or in companies responding to the market. In the atomic hierarchy, the isotopic composition of elements in a given sample may reflect the history of that sample and may be evolving by decay or be stable.

Thus, the history of cognitive processes comprises not only recombinations of, but also the creation of new fundamental elements and environmental changes, giving each system uniqueness.

Mental cognitive processes, creativity and the evolution of science

As was mentioned above, cognitive processes *evolve*, and stable atomic nuclei, molecules, cells, organisms, or societies cannot be created from 'scratch'. Also ideas mature from fundamental components, or pieces of information. During this process, the existing fundamental elements are continuously recombined, and new ones are added. The evolution of science has occurred in a similar way to the creation of elements from fundamental elements. New general concepts have been deduced by putting together detailed knowledge of experimental phenomena. The more a concept in science can explain, the more important it is. Science resembles a jigsaw puzzle that can be put together in several ways. If one piece does not fit, the pieces have to be reassembled. The history of science is full of examples of this. It closely resembles the situation with recombining fundamental elements in cells in a changing environment or with individuals in a dynamic society.

Creativity may be defined as the ability to put together the pieces in new combinations. A great scientific

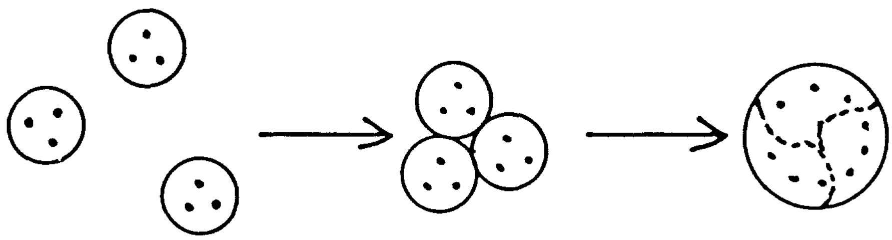

Figure 3. Illustration of 'elementary reductionism during external constraint'. As elements (circles) composed of dynamically interacting fundamental elements (points) are brought together to form higher elements, new, more stable interactions between their fundamental elements become possible.

achievement is characterized by the fact that a new combination of data accomodate data which have not previously fitted into the picture, and that more can be explained by the same general principle. This closely resembles the situation when fundamental elements recombine to increase the amount of complementary surfaces and the cooperativity and stability of the system. When this happens, the pieces of experimental information must be compared with each other, i.e. interact, so as to give a physical meaning to the mathematical or conceptual generalization of the data[13].

Thus, it is evident that cognitive processes like those occurring in atoms, cells, organisms, societies or in concept-forming mental activity operate according to principles that are similar. These principles are:

1) The existence of fundamental elements which recombine to form higher levels of organization. The elements have different properties and the amount of any element with a given property may vary.

2) Preferred combinations between the elements exist. This may be described by assigning 'interaction surfaces' to the elements. When the interaction surfaces are complementary, a cognitive process occurs and the fundamental elements can 'bind' or exchange properties. If this happens to a great extent, the cooperativity or stability of the system is high. During the process of recombination or time evolution, elements of a higher hierarchy with new properties may arise. In a changing environment the fundamental elements recombine continuously, while in a nonchanging environment, fewer combinations are stable.

3) The history of the system is important. The time evolution comprises recombination of elements and the creation of new elements in one hierarchy, which gradually leads to increased interaction between the elements i.e. increased 'cognitive stability'. In the case of particles having dimensions, this implies that the volume of the structure also enlarges. When elements form crystalline-like groups devoid of all but a few dynamic interactions with elements not belonging to the group, the evolution slows down, or the 'creativity' of the system decreases.

4) In addition, a fourth principle, not obviously related to mental processes, has emerged from this analysis. It has been termed 'elementary reductionism during external constraint' and denotes the finding that, when elements of an intermediate hierarchy combine by stable interaction to form an element of a higher hierarchy, then the response of the higher element can be regarded as being due to the lower elements, irrespective of their assignment to intermediate elements.

In the present model, elementary reductionism during external constraint is supposed to be a mechanism for self-organization and creation of order in the Universe.

Cognitive stability versus thermodynamic equilibrium

The processes that have been described differ from thermodynamic processes like those occurring in gaseous matter in that there is *strong* and *specific* interaction between the elements. Thus, conventional thermodynamic treatment, which is based on *weak* interacting forces between the elements cannot be expected to be applicable to the processes described. Furthermore, cognitive stability involves a finite number of elements while thermodynamic equilibrium based on the laws of statistics requires that $n \to \infty$. The most significant difference may be that cognitive processes are driven by nonstatistical elemental properties and interactions while thermodynamic formalism derives from macroscopic statistical properties. These differences are summarized in table 2.

It is easily shown that hierarchical systems of elements and fundamental elements as described can have self-structurizing properties (cf. Haken[8]). A necessary requirement is that stable combinations of fundamental elements exist and that they interact dynamically. If this is the case, the number of permutations of fundamental elements reflects the probability that stabilizing interactions will appear when elements are brought together to form a larger structure. This is an increasing function of the number of elements in the structure, provided that the added elements can provide stabilizing fundamental elements. The rate of recombination reflects the time evolution of the system and the rate at which it approaches cognitive stability.

As a simple example, consider the interaction between elements composed of the fundamental elements indicated by the numbers 1, 2, and 3. As required by the empirical observation that higher elements with new properties are formed from fundamental elements having different properties, the combinations 1,2; 2,3; and 1,3 provide stabilizing interaction contributing to the unique properties of the higher element, while the combinations 1,1; 2,2; and 3,3 may be inert in this respect. When two elements composed of the fundamental elements 1,2 and 2,3 respectively, interact, the total number of combinations (permutations) increases from $2! + 2!$ to $4!$ and in the general case to $n!$. Since the interactions between like elements do not contribute to the unique properties of the higher element, the number of stabilizing permutations is $4!/2!$ and $n!/k_1!k_2!k_3!\ldots$ in the general case of different elements k_i and in the most favorable circumstance that all combinations of different elements contribute to stability. The maximal cognitive stability S_{max} may be defined according to:

$$S_{max} = K \ln \frac{n!}{k_1!k_2!k_3!\ldots} \cdot \qquad (1)$$

This defines a growing function for the addition of any element composed of fundamental elements k, capable of unlimited stabilizing interaction with nonidentical fundamental elements. In practice, unlimited interaction may not exist so that the added fundamental elements m_c capable of cooperative interaction with elements in the cluster k_c contribute to stability according to a term $(k_c + m_c)!/k_c!m_c!$. At the same time, competition occurs, so that elements m_d dissociate from interaction with ele-

Table 2. Comparison between thermodynamic equilibrium and cognitive stability

Thermodynamic equilibrium	Cognitive stability
Infinite number of elements	Finite number of elements
Weak interaction	Strong interaction
Statistical interaction	Specific interaction
Macroscopic properties	Elemental properties
(Causal behavior)	(Noncausal behavior)

ments k_d in the cluster according to $(k_d + m_d)!/k_d!m_d!$. If this is the case, the addition of an element to a group of elements implies self-structurizing properties if the following holds for the interaction between the fundamental elements:

$$\Pi \frac{(k_c + m_c)!}{k_c!\,m_c!} > \Pi \frac{(k_d + m_d)!}{k_d!\,m_d!}. \quad (2)$$

In summary, elementary reductionism comprising dynamic interaction of different elements may cause self-organization or dissolution of existing organization, e.g. by environmental impact, in several real systems found in nature, and may also be relevant to phenomena in human society including economics and politics and to mental concept-forming processes including pattern recognition and the evolution of science. To explore the exact conditions for self-organization in these systems in terms of increased cognitive stability would be a challenging scientific task.

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Origin of life: Oceanic genesis, panspermia or Darwin's 'warm little pond'?

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Summary. The average abundances of chemical elements in crustal rocks, river water and biological material are compared with the Suess-Urey[22] abundances distribution (representing the most primitive distribution of the elements on earth). Crustal rocks can be considered still to have the most primitive elemental composition, whereas seawater shows the largest deviations form the cosmic Suess-Urey element distribution. Biological material ranks, in the series considered, between river water and seawater, still showing primitive characteristics. The relative elemental composition of biological material resembles river water more strongly than contemporary seawater: the ratios between the quantitatively most important elements (C, N and P) in living matter are almost equal to those in river water; also the concentration factors for the other elements are less variable than those in seawater. The latter appear to be inversely related to their concentrations in seawater: in living organisms, the elements having lower concentrations in seawater are concentrated more strongly. This differential concentration cannot be obtained by evaporation. The stability of the composition of biological material (evident by comparing species of widely diverging evolutionary development) and its similarity to the Suess-Urey distribution suggest an oceanic genesis early in the earth's history, before the oceans reached their present compositions.
Key words. Origin of life; Suess-Urey abundance distribution; elemental composition of biological matter; river water composition; seawater composition; oceanic genesis; river water, evaporated.