Operators, the Lego-bricks of Nature: Evolutionary Transitions from Fermions to Neural Networks

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When Darwin wrote his 'On the origin of species…' (1859) he focused on evolution as a property of living organisms in interaction with abiotic and biotic elements in the world. This viewpoint is still dominant amongst biologists. For particle physicists and cosmologists evolution refers to a larger scale, ranging from quarks and atoms to galaxies, stars and planets (i.e. Pagels 1985, Hawking 1988). To close the gap between such different viewpoints, a wide range of perspectives on an interdisciplinary understanding of system development has been published (i.e. Teilhard de Chardin 1966, von Bertalanffy 1968, Varela 1979, Prigogine and Stengers 1984, Laszlo 1996). As an integrative concept, the construction of nature from a hierarchy of system layers forms a central tenet in general system research and the stepwise construction of this layered hierarchy can be regarded as an interdisciplinary evolution theory. Surprisingly, the literature offers no unequivocal rules to recognise a multilayer hierarchy in nature. This presents an obstacle for interdisciplinary approaches to evolution.

Searching a solution to part of the above hierarchy problem, the present paper is dedicated to the analysis of a special kind of layering in natural systems, which is based on transitions between 'building block' systems. To identify these building blocks, and the transitions from building block x at level A, to building block y at level B, the focus of this study is further limited to 'hypercyclic dynamics' and 'containment'. On the basis of these criteria, a hierarchy is created which shows no possibilities for 'bypasses'. It connects hadrons to atoms, atoms to cells, and cells to neural networks. Implications of this hierarchy for system studies and evolution are discussed.

KEYWORDS: system hierarchy, hypercycles, containment, units of evolution, building block systems, autocatalysis, quarks, hadrons, atoms, molecules, cells, neural networks, system transitions, emergent properties, topology

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INTRODUCTION

System thinking has opened up many ways for the examination of systems, their internal organisation and their external relationships. This has led to general laws on system organisation on the one hand, and a clearer view on the differences that exist between system types on the other.

A general aspect of all system studies is that reality is regarded as to show a layered structure, which is minimally represented by a system and its elements. Stressing the importance of hierarchy in science von Bertalanffy (1968) wrote that 'A general theory of hierarchic order obviously will be a mainstay of general systems theory'. That hierarchy is omnipresent in science is reflected in the many metaphors which have been proposed for it, including the 'worlds within worlds' approach, which according to Close dates back to the Japanese physicist Kaku (Close 1983), the 'cosmic onion' (Close 1983) and the 'Chinese boxes' (i.e. Simon 1962, Koestler 1967, Laszlo 1972). A hierarchy based on unit systems, which are characterised as being 'formed' and 'centred', has been proposed by Teilhard de Chardin (1966). Still other studies have explored the mathematical formalism of layered structures as consisting of units composed of interacting elements (Goguen and Varela 1978, Geiger 1990) or, with respect to ecosystem interactions, in the form of a 'biomatrix' (Jaros and Cloete, 1987).

The presence of hierarchy in different areas of system research can furthermore be inferred from the use of concepts such as transformation, emergent properties, the top-down viewpoint of reductionism, and the bottom-up viewpoints of holism and constructivism, the occurrence of transitions, symmetry breaking, bifurcation, attractor states, integrated elements building 'holons', autopoiesis, etc. (i.e. Feibleman 1954, Koestler 1978, Varela 1979, Labson 1985, de Kruijff 1991, Beloussov 1993, Laszlo 1994, Szathmáry and Smith 1995, Capra 1996).

Interactions which cause new system layers have been regarded as 'quanta of evolution' (Turchin 1995). The quantum aspect of these transitions results from an all-or-nothing restriction of processes in the original system, which creates new structures and associated dynamic properties (Heylighen 1995). For example, the cyclic restriction of enzymatic interactions in the cell is required before the arisal, or 'emergence', of reproduction is possible and a new layer in the hierarchy can be recognised.

The analysis of hierarchy forms the main topic of the present study. As a point of special interest, we investigate the possibility for a general, yet strict hierarchical classification of special 'building block' systems. For any hierarchy, we consider the construction of sound layers a necessity to avoid that the layering is corrupted via 'bypasses'. An example of what we consider a corrupt hierarchy is the sequence planet–stones–sand. It is perfectly possible to construct a planet from sand alone, and in this way bypass the 'intermediate layer' of the stones. In robust hierarchies such bypasses do not exist and complexity can be ranked solely in a strict layer-by-layer fashion.

In the present search for a rigorous hierarchy in nature we deliberately restrict our efforts to 'building block systems' or 'unit systems'. The idea is, that the use of a kind of natural 'Lego-bricks' allows a dissection of system complexity in stepwise transitions from building block x at level A to building block y at level B, etc. As we will explain below, the building blocks that can be identified in this way include the hadrons, the atoms, the molecules, the cells, the multicellular organisms and a special kind of neural networks. All other natural systems do not fulfil the present building block definition. Instead, they are regarded as 'interaction systems' and enter the present discussion only on special occasions, for example when we discuss hypercyclic interactions and their containment. Examples of interaction systems include stars, planets, ecosystems, society, a football, etc. The present focus on building block systems requires, however, that we define clear criteria to recognise them.

As the criteria for building blocks we used *hypercycle formation* as the primary aspect, and different forms of *compartmentation* as the secondary aspect.

Hypercycle formation. Elements which perform a cyclic process can interact to create a secondary reaction cycle. Such a 'cycle of cycles' is called a 'hypercycle' (Eigen and Schuster, 1977). Hypercycles have highly special unit-properties. The enzymatic hypercycle, for example, makes reproduction possible (Eigen and Schuster 1977, Eigen 1985, Kauffman 1993). A schematic representation of an enzymatic hypercycle (Eigen and Schuster 1977) is shown in Figure 1A to illustrate the close relationship between structural and functional aspects of such systems. A less abstract version (Kauffman 1993) is shown in Figure 1A to indicate that actual physical hypercycles look rather like 'webs' of interactions without that the central hypercycle can be recognised structurally.

Compartmentation. Within each large group of systems based on the same type of hypercycle, the mechanism of compartmentation is used to recognise internal subsets. The most fundamental kind of compartment formation involves the containment of a hypercyclic set of elements by a layer, or 'interface', which mediates the interactions between the elements of the hypercycle and the world. As such, it offers a natural system limit for thermodynamic considerations. An example of an interface are the electron-wave clouds which surround nuclei and mediate interactions with neighbouring nuclei. A different way of compartment formation is observed when two or more systems with a contained hypercycle interact to form a multiplet structure, for example when atoms interact to form molecules. As we will discuss below, the mechanisms of hypercycle formation and subsequent compartmentation can be used to create an unambiguous hierarchy of building block systems.

For reasons of clarity, the term 'operator' is introduced as a common name for all the building block systems which consist of a contained hypercycle, and the systems which are multiplets hereof. Accordingly, the present approach is regarded as the 'operator approach' or 'operator framework'. The recognition of operators as a special group of systems has several advantages. First, it helps to distinguish between operators, the building blocks, and other systems, which, as was discussed above, consist of interacting operators without being operators themselves and were called 'interaction systems'. Another advantage of using the operator concept is that it separates operator evolution from biological evolution, biology being limited to the subset of operators based on cells and the forces which cause diversification and selection at that level.

Although this study focuses on structural aspects of systems, these are considered as the inseparable mirror image of the underlying dynamics. The mechanism for all dynamics lays in entropy increase. For discussions of the application of the laws of entropy to non-linear systems is referred to studies by Schrödinger (1944), Prigogine and Stengers (1984), Eigen and Winkler (1983),

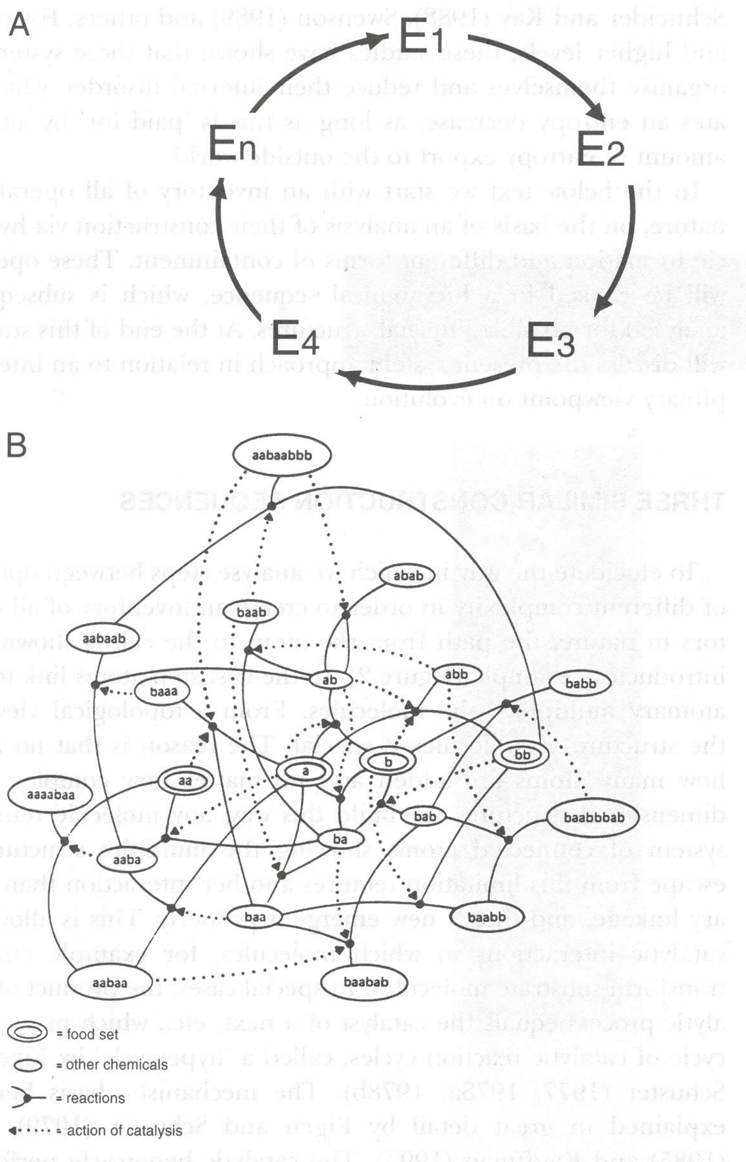

Figure 1 Two representations of an enzymatic hypercycle. Part A shows a more abstract, cycle oriented representation, which can be found in the work of Eigen (1977). Here E_1 to E_n represent enzymes. Part B shows a network representation of cyclic enzymatic processes (after Kauffman (1993) 'The origins of order'. With permission of Oxford University Press). Essential of both graphs is that the enzymatic reactions in themselves form cyclic events, which via their linking in an overall cycle have become functionally unified into a catalytic hypercycle.

Schneider and Kay (1988), Swenson (1989) and others. For cellular and higher levels, these studies have shown that these systems can organise themselves and reduce their internal disorder, which creates an entropy decrease, as long as this is 'paid for' by an equal amount of entropy export to the outside world.

In the below text we start with an inventory of all operators in nature, on the basis of an analysis of their construction via hypercycle formation and different forms of containment. These operators will be ranked in a hierarchical sequence, which is subsequently analysed for possible internal structures. At the end of this study, we will discuss the present system approach in relation to an interdisciplinary viewpoint on evolution.

THREE SIMILAR CONSTRUCTION SEQUENCES

To elucidate the way in which we analyse steps between operators of different complexity in order to create an inventory of all operators in nature, the path from the atom to the cell is shown as an introductory example (Figure 2). In the first step atoms link to form atomary multiplets, the molecules. From a topological viewpoint the structure of molecules is special. The reason is that no matter how many atoms are added and no matter how complex three-dimensional structures are build this way, any molecule remains a system of connected atoms showing the multiplet structure. An escape from this limitation requires another interaction than atomary linkage, and thus a new emergent property. This is allowed by catalytic interactions in which molecules, for example enzymes, transform substrate molecules. In special cases, the product of a catalytic process equals the catalyst of a next, etc., which may cause a cycle of catalytic reaction cycles, called a 'hypercycle' by Eigen and Schuster (1977, 1978a, 1978b). The mechanistic basis hereof is explained in great detail by Eigen and Schuster (1979), Eigen (1985) and Kauffman (1993). The catalytic hypercycle performs a new dynamic property, that of 'autocatalysis', normally referred to as reproduction. As long as the set of autocatalytic enzymes lacks a boundary, or 'interface', it can not be considered an operator. If the interface is formed by a molecular membrane, we can regard the

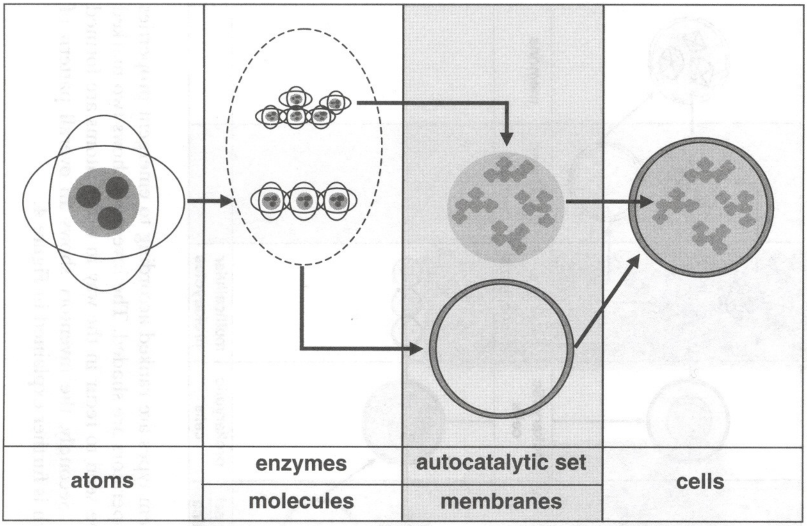

Figure 2 Example of a basal pattern in operator evolution: interactions leading from atoms to cells. The steps being explained in more detail in the text, the following phases can be distinguished. Atoms combine to molecules, some of which can act as enzymes. Sets of enzymes may show catalytic closure and form an autocatalytic hypercycle. When this is surrounded by a membrane, the cell is 'born'. Phases during which system types are not considered operators are shaded.

resulting unit a living cell. The formation of the cell thus requires the *simultaneous* occurrence of two emergent properties; hypercyclicity and containment by a membrane. The requirement of the simultaneous occurrence of these properties favours explanations of contained autocatalysis from a 'seed' instead of from a 'soup', which possibilities were recently discussed in a review of theories about the origin of the cell by Edwards (1998).

As is shown in Figure 3, two additional construction pathways, similar to that from atom to cell, can be recognised in the range of all operators known to science. The first describes the sequence from quarks to atoms, the other that from cells to neural networks.

The mechanisms behind the first sequence are being studied by particle physicists. The most fundamental particles that science has experimental access to are the particle-like Dirac-fermions, which include the quarks and leptons, and the force carrying bosons, such as photons and gluons (Close 1983, Feynmann 1985, Pagels 1985,

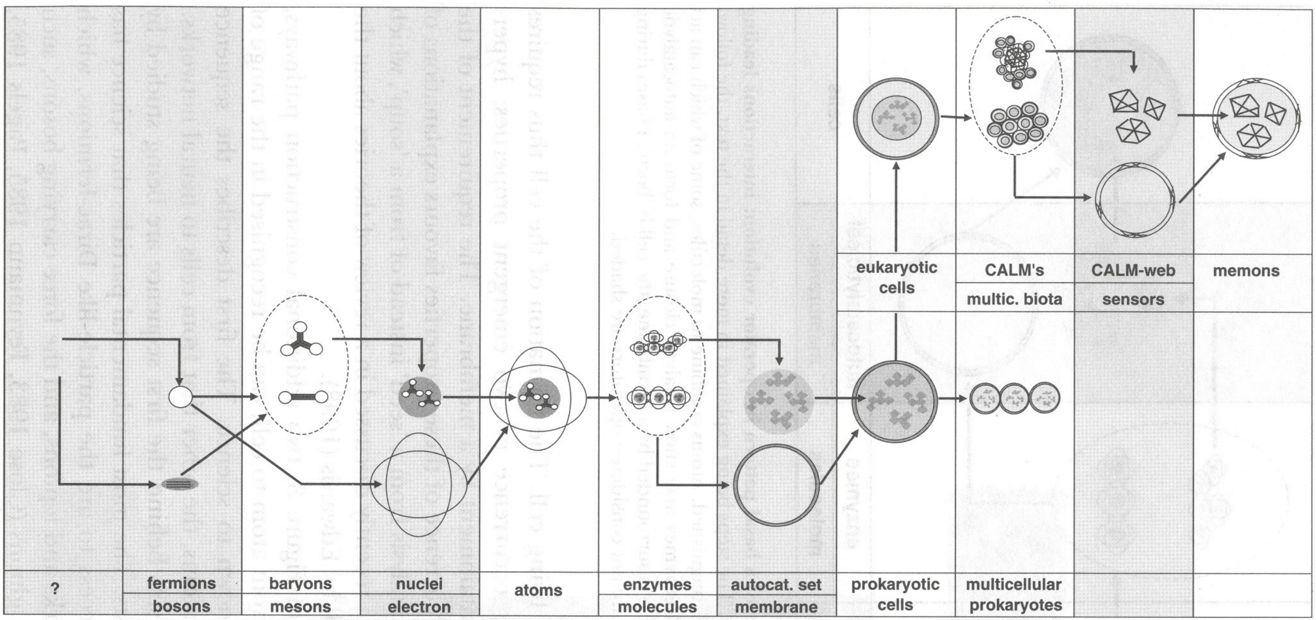

Figure 3 Inventory and ranking of all operator systems known to science. System types are ranked according to emergent properties as is explained in the text. Phases during which systems types are not considered operators are shaded. The inventory shows two marked regularities. Firstly, the sequence showing the formation of cells from atoms can be seen to recur in the way in which atoms are formed from quarks, and hypercyclic neural networks are formed from eukaryotic cells. Secondly, the inventory shows an overall pattern of increasing possibilities for compartmentation and differentiation in operators, which is further explained in Figure 4.

Kaku 1987, Witten 1988, Hawking 1988, 't Hoofd 1992, 1994, Wilczek 1998). Quarks continuously emit and reabsorb clouds of gluons which can 'bind' the quarks forcefully into a multiplet structure. Pairs of quarks are called mesons and triplets are called baryons. Well known baryons are the proton and neutron. All baryons posses the special property that they can emit and re-absorb small mesons without loosing their triplet structure. For energetic reasons such emission–absorption cycles involve predominantly the lightest possible mesons, the pions. Recurrent pion exchange between baryons causes what is called the 'strong force', binding protons and neutrons into lumps regarded as nuclei, representing a novel hypercyclic structure. When the temperature of the environment drops below 3000°K, electrons furthermore lack the energy to escape from the electric force of the protons in the nuclei. A cloud of orbit-fitting electron 'waves' now surrounds the nucleus as an interface. A new operator has emerged; the atom.

The other sequence, at the opposite side of the operator framework, leads from cells to neural networks. These systems are studied both by biology and by the neuro-sciences. The completion of the sequence from cell to neural network has either only been possible, or has simply developed quicker on the basis of the, more complex, eukaryotic cells. Some prokaryotic species, for example the cyanobacteria, have also reached primitive multicellular interactions, but only the eukaryotes developed to multicellular life forms within which neural cells evolved which were capable of forming units of cells showing recurrent interactions. Modern versions of artificial neural networks, as were pioneered by Hebb (1949, 1955), show that modules of cyclically interacting nerve cells can perform unsupervised categorisation and learning tasks. Accordingly, they have been called 'Categorising And Learning Modules', or CALMs (Murré, Phaf and Wolters 1989, 1992, Murré 1992). Biotic equivalents of CALMs are present in the form of so called minicolumns in the cerebral cortex in mammals (Mountcastle 1975). In a number of experiments Happel (1997) has linked CALMs in a recurrent way and investigated the properties of hypercyclic neural networks. Although a series of subsequent CALMs can be compared with a multilayer feedforward network, the recurrent coupling of CALMs would require an endless number of linearly coupled layers. As was explained by Happel (1997), recurrent interactions make CALM networks fundamentally different from feed forward networks, because a recurrent architecture creates fractal category boundaries, hereby allowing for infinitely more distinctions between input patterns than are possible when using a linear organisation (Happel 1997, p. 69). But an isolated hypercyclic neural network does not yet fit our operator definition. It still lacks an interface. In the form of the neural interface offered by sense organs and activation organs this has co-evolved in the multicellular body as efferent and afferent extensions to the hypercyclic network. It is the simultaneous presence of the hypercyclic neural network and the interface which marks the operator that we call the memon. With respect to the evolution of neural networks in animals, it should be noted that the hypercyclic network must be considered to have evolved within the context of a non-hypercyclic brain, in which structure and functioning had a strong genetic basis. The reason is that the genetic control of neural architecture, and therewith behaviour, originally had a direct survival value for the organism because it prevented low fitness during a learning phase such as is inherent to hypercyclic functioning.

AN OVERALL PATTERN IN SYSTEM TRANSITIONS

In addition to the recurrent pattern of the three sequences discussed above, the operator framework also shows an overall pattern. This is most clearly visible after rearranging the elements of Figure 3 in a staircase-like manner, as is shown in Figure 4. Now, each new hypercycle with interface is placed at the beginning of a row, whilst the end of each row is formed by the multiplet configuration, this being the most complex system type which is possible on the basis of structural interactions between the operators in any row. Figure 4 shows that in subsequent rows the number of ways in which systems can differentiate before the multiplet stage is reached, increases with one each layer. At the quark level, the possibilities are limited to quarks and hadrons. The nuclear level ranges from nuclei, via atoms, to molecules. The autocatalytic level includes autocatalytic hypercycles, prokaryotic cells, eukaryotic cells and multicellular life forms. The scientific knowledge of the last

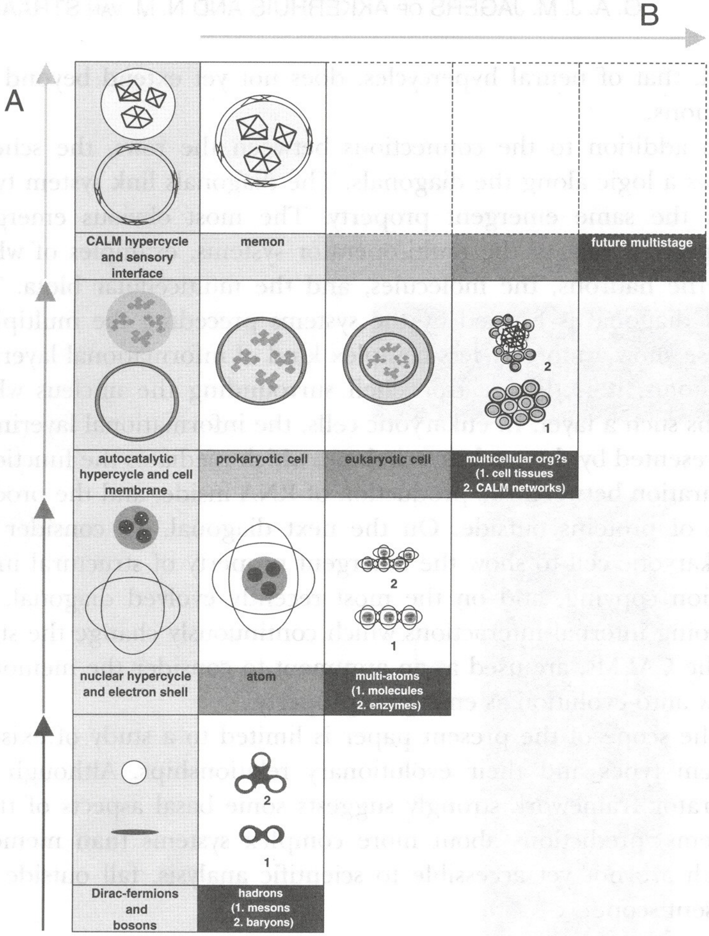

Figure 4 A 'periodical system of operators'. The inventory of operators shown in Figure 3 has been split up into segments starting with a particular hypercycle (the grey bands in Figure 3) and ending with multiplets of operators which contain this hypercycle. The vertical axis (A) indicates the occurrence of new hypercycles. The horizontal axis (B) indicates the different possibilities for compartmentation within each group of systems based on the same hypercycle. The lengths of the rows illustrates the number of different operator types possible within a layer. Quarks (fermions) and gluons (bosons) directly form hadrons. The atomary nucleus first obtains an electron shell, which may bind to form molecules. The autocatalytic hypercycle becomes confined by a membrane which creates the prokaryotic cells. These may either directly develop into a primitive multicellular stage, or differentiate further to obtain an internal compartment around the basis of their hypercycle, and then form more advanced multicellular stages. Finally, groups of neural cells, called CALMs, are interacting cyclically and obtain an interface of sense organs and activation organs. This we have called the memon.

level, that of neural hypercycles, does not yet extend beyond the memons.

In addition to the connections between the rows, the scheme shows a logic along the diagonals. The diagonals link system types with the same emergent property. The most obvious emergent property is that of the multi-operator systems, examples of which are the hadrons, the molecules, and the multicellular biota. The next diagonal is formed by the systems preceding the multiplets. These show a more or less complex kind of informational layering. In atoms, it is the electron shell surrounding the nucleus which forms such a layer. In eukaryotic cells, the informational layering is represented by the nuclear envelope, which mediates the functional separation between the production of RNA inside, and the production of proteins outside. On the next diagonal, we consider the prokaryotic cell to show the emergent property of structural information copying, and on the most recently evolved diagonal, the ongoing internal interactions which continuously change the states of the CALMs, are used as an argument to consider the memon to show auto-evolution as emergent property.

The scope of the present paper is limited to a study of existing system types and their evolutionary relationships. Although the operator framework strongly suggests some basal aspects of these systems, predictions about more complex systems than memons, which are not yet accessible to scientific analysis, fall outside the present scope.

CONSEQUENCES OF THE OPERATOR APPROACH

If the structural and associated functional organisation of operators is referred to as their complexity, the operator framework describes the steps via which operator evolution created complex building blocks from smaller ones. The requirement that smaller building blocks exist and interact before larger ones can be constructed, implies a direction in evolution, but does in most cases not imply a directionality in the sense that the interacting operators know in which direction they should evolve, or that they are motivated by some kind of invisible hand with a 'guiding' capacity.

Below the memon stage, the operators involved have never been capable of constructing an internal representation of their surroundings to evaluate their actions. In contrast, memons and higher level operators are not only aware of their surroundings, but can also understand the meta-evolutionary processes therein. These operators, therefore, may show evolution in relation to this insight. This renders evolution a directed process in which, however, the unpredictability of interactions remains a chance aspect. Only the existence and the direction of this process are open to scientific inquiry. We see no way of how to study any possible 'goal' or 'meaning' associated with teleological viewpoints.

We emphasize that the necessity for complexity to increase between operator stages typically applies to hypercycle formation and containment steps in the operator hierarchy. This is by no means in conflict with the decrease that any particular operator may show in capacities when these have lost their survival value, for example moles losing their sight.

The patterns in Figures 3 and 4 offer a unique possibility to study the properties that operators need to show in order to become a link in the evolutionary chain. Such properties can be regarded as the recipe nature has used to 'cook' subsequent operators. We have deduced that the following operator aspects are necessary for any operator to act as a link in the chain:

(1) Operators must show a stable internal organisation. If the operator's internal organisation is not stable under prevailing conditions, this will have a short term fatal effect on its functioning.
(2) Operators (in general) must maintain integrity in interactions (in general). This represents an extension of the survival of the fittest to all operators below and above organism-level. Of course the laws which govern evolutionary success vary between layers, the requirements to animals in ecosystems being of a rather different kind than to elementary particles in a newly developing universe.
(3) Operators must be able to interact with each other and form systems which allow for the creation of more complex operators. If, for example, at any place and time in the universe the most complex multi-operator does not give rise, in the system that it is part

of, to the formation of a new hypercycle, this represents a local end to evolution. The third aspect is a *unique* result of a between-operator viewpoint on evolution. It cannot be discovered by any approach which focuses on evolution of operators within their class.

In the light of the chaotic system that the universe seems to be, it is surprising how rigid a backbone for evolution is suggested by the operator framework. This rigidity is caused by the limits that emergent properties set to the formation of new system types. There remains much freedom, however, for the actual form in which any particular system is realised, and the moment and place in the universe where it will occur. This freedom increases with increasing complexity of the operators. There exist relatively few elementary particles, many atomary nuclei, very many autocatalytic sets and an unimaginably large number of neural network topologies. The sequence of increasing complexity operators is directly linked with chronology (see also Teilhard de Chardin 1966, 1969, Pagels 1985) because emergent properties of any operator are always preceded by the operator not showing this property, or by interactions between lower level operators in a parental system.

IN CONCLUSION

The principles discussed above allow a ranking of the building-block systems underlying all other systems in the universe. This ranking is based on emergent properties. The marked regularity of the resulting classification seems to indicate that nature has little choice with respect to the kind of steps it can make between system types. Apparently, the only freedom it has, is to let chance determine the exact players in the game, and the moments and places of the transitions.

The mechanisms behind most of the binary steps in the operator scheme are in principle known to the separate branches of science dealing with these systems. The overall regularity of the scheme, however, can be regarded as an elaboration of the cosmic onion approach by a more precise indication of the layering of nature.

Regularities in specific groups of operators have helped to unravel underlying mechanisms in different realms of science. Examples hereof are the 'eight-fold way' for quarks (Gell-Man and Neeman 1964) and the periodical system for atoms (Mendeleev 1871). In analogy, we expect that the periodical structure of the overall operator scheme suggests an underlying logic. The main aspect of this logic is the sequence of hypercycles showing increasing complexity from the quark, via the nucleus and the autocatalytic set, to the memic hypercycle. The formulation of the algorithm connecting these hypercycles is the closest, we think, one can come to an inclusive viewpoint on operator evolution, covering the whole range from quarks to neural networks, and possibly beyond. Formulating this algorithm in more detail presents a challenging field for future research.

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